DISSERTATION

ESSAYS ON SUSTAINABLE DEVELOPMENT: RENEWABLE ENERGY, REGIONAL GROWTH, ENVIRONMENT, AND WELFARE

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ABSTRACT

ESSAYS ON SUSTAINABLE DEVELOPMENT: RENEWABLE ENERGY, REGIONAL GROWTH, ENVIRONMENT, AND WELFARE

Given the growing concerns about the consequences of climate change, development of renewable energy has attracted significant attention as a creditable alternative to fossil fuels. As a result, renewable energy has experienced significant growth in the U.S. as receiving government subsidies and support in the past decades. In order to confirm the efficiency and effectiveness of renewable support policies, this dissertation explores the role of renewable energy on regional economic growth, environmental quality, and residential electricity price in the U.S.

Chapter 1 examines the effects of electricity generation from both types of energy sources on sustainable state economic growth. For the analysis, I extend the theoretical framework which incorporating the environmental externalities from energy use. Based on the theoretical model, I use the panel data set for 47 U.S. states from 1999 to 2017 by employing the two-step Generalized Methods of Moments (GMM) model. The results show that renewable energy generation has a positive impact on state economic growth whereas non-renewable energy generation hampers economic growth. Furthermore, this paper finds that the effects of renew- able energy generation on economic growth are different at a level of development stage: at an early stage, electricity generation from renewable energy resources hampers economic growth while at an advanced-stage, renewable energy helps to grow the economy. The results imply that the very low operating costs for renewable energy could offset the huge financial burden of high initial investment costs in the long run.

Chapter 2 demonstrates the linkages between energy-related CO2 emissions, economic growth, and renewable energy consumption for the 48 U.S. states over the period 1997-2017 by employing panel fixed-effects and the Method of Moments Quantile Regression with fixed effects developed by Machado and Silva (2019). The results provide strong evidence of an inverted U-shaped relationship between economic growth and environmental degradation, consistent with what is known as the Environmental Kuznets Curve from fixed-effect estimation. Furthermore, this paper confirms that renewable energy consumption, electricity prices, and primary energy prices have negative impact on emissions whereas Heating Degree Days have a positive im- pact on emissions. Moreover, the panel quantile regression models confirm that the effects of all explanatory variables on CO2 emissions are heterogeneous at different quantiles.

The main purpose of Chapter 3 is investigating the effect of renewable energy generation on retail residential prices while confirming the policy influences from Renewable Portfolio Standard (RPS) on the prices by using a sample of 48 U.S. states during the period 2001-2018. The empirical results of the feasible generalized least squares, and the two-step GMM models provide evidence that renewable energy generation leads to a reduction in residential electricity prices. Also, the renewable support policy, RPS, tends to increase residential electricity prices. The results imply that implementation of RPS requires additional fixed costs in the short-run however, these costs would be offset by very low operating costs of renewable energy generation in the long-run.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

Electricity represents an essential factor in both consumption and production of goods and services in the economy as a major contributor to improve the standard of living and enhance economic growth (Apergis and Payne, 2011). Because electricity promotes the productivity of labor, capital, and other factors of production; further, increased consumption of electricity signifies high economic status of a country (Jumbe, 2004). Given the growing concerns about the consequences of climate change, however, the economic welfare is threatened with increased electricity demand, which associated with increased consumption of fossil fuels (Armeanu, Vintilă, and Gherghina, 2017). Therefore, increasing the share of renewable energy is the main requirement for sustainable development by reducing damages from non-renewable resources (Destek and Aslan, 2017). Along with trends, the U.S. federal government spent $15.3 billion in 2013 and $6.7 billion in 2016 to enhance renewable energy generation, which are equivalent to 52% and 45% of total energy subsidies (EIA, 2018).

The main purpose of Chapter 1 is examining how electricity generation from both types of energy sources helps to sustainable state economic growth in the U.S. For the analysis, I extend the theoretical framework which incorporating the environmental externalities from energy use. Specifically, this theory model illustrates four unique conditions which describe how non-renewable energy development affects to long-run growth. Based on the theoretical model, I use the panel data set for 47 U.S. states between 1999 and 2017 by using the two-step Generalized Methods of Moments (GMM) model. The results show that renewable electricity generation positively affects state economic growth while non-renewable power generation negatively influences economic growth due to the negative environmental externalities, which pollution impact.

This implies that increasing renewable energy generation would create economically and environmentally positive effects in local economy. Because development of renewable energy resources helps not only to reduce average costs to generate electricity but to improve environmental quality, which enhances productivity. Even though non-renewable energy can create economic benefits as a main factor of production, burning fossil fuels generates pollutions, which directly threatened the productivity of labor and capital. As shown in the theoretical framework, non-renewable energy generation does not help sustainable economic development, unless the economic gains exceed the productivity losses due to the negative environmental externalities.

Since 2005, the United States has been recorded as the second largest greenhouse gas contributor around the world. In particular, almost 81% of U.S. greenhouse gases was originated from CO2 emissions, and 93.1% of total U.S. CO2 emissions was caused by fossil fuel combustion in 2018. In general, boosting economic activities requires more energy consumption, and consequently, generates CO2 emissions. Given the great importance of achieving sustainable economic growth, however, it has been suggested that the replacement for fossil fuels by renewable energy sources can reduce environmental pollution. Renewable energy can decrease emissions caused by economic activities through increasing renewable energy consumption in energy-intensive-polluted sectors and adopting environmental-friendly technologies in production. Chapter 2 investigates the linkages between energy-related CO2 emissions, economic growth, and renewable energy consumption under the Environmental Kuznets Curve framework.

The results of the empirical analysis, which employed the panel fixed-effects, illustrate that there is an inverted-U shape relationship between economic growth and CO_2 emissions, supporting the EKC hypothesis at state-level. Also, this paper provide evidence that increases in renewable energy consumption and electricity prices help to reduce CO_2 emissions, and an increase in heating degree days tends to generate more CO_2 emissions. Moreover, the Method of Moments Quantile Regression results implies: 1) high–CO_2 emission states may have more stricter environmental regulations than low–CO_2 emission states; 2) even though higher CO_2 emissions states may consume more fossil fuels compared to states with lower emissions, economic activities can be less harmful to environment by replacing renewable energy resources or adopting cleaner technologies, and 3) transportation or electric power sector is the main driver of total energy consumption in high–CO_2 emission states while residential sector accounts for greater proportions of energy consumption in low–CO_2 emission states. The findings of this paper provide evidence of the environmental benefits of promoting in renewable energy and suggest policy tools to reduce emissions through energy price mechanisms.

As mentioned above, renewable energy is characterized as having high capital investment and very low marginal operation costs. Due to the financial burden of renewable energy installation, however, supportive government policies play an important role in making renewable energy cost-competitive. For instance, the total U.S. electricity production subsidy for renewable energy resources was $10.2 billion in 2016 which accounted for 12% of total energy production subsidies (EIA, 2018). And these financial supports are reflected in the wholesale electricity price and then translated into electricity bills, which paid by consumers. On the other hand, given the characteristics of the price formation in the electricity market and the low marginal costs, it is expected that use of renewable energy can reduce the retail electricity prices by the so-called merit-order effect. The main objective of Chapter 3 is to empirically examine the impact of renewable electricity generation on residential retail electricity prices to evaluate the distributive welfare impact of renewable support schemes.

For the empirical analysis, I use dataset of 48 U.S. states over the period 2001-2018 with employing both feasible generalized least squares and two-step generalized method of moments. The empirical results of the feasible generalized least squares, and the two-step GMM models provide evidence that an increase of the share of renewable sources leads to reduction in residential electricity prices. Furthermore, it is confirmed that the renewable support policy, Renewable Portfolio Standards (RPS), and the fossil fuels price have significantly positive impact on residential prices whereas the residential electricity consumption has significantly negative impact on the prices. In addition, this paper also shows that increases of the share of hydro and wind power generation cause decreases residential prices. The results imply that implementation of RPS may cause the excessive financial burden to the end-user consumers but these costs would be offset by falling renewable generation costs.

Chapter 2

Energy and Economic Growth: A Theoretical Approach and Empirical Evidence from the U.S.

2.1 Introduction

U.S. renewable energy has experienced significant growth partially due to subsidies and support from both the national and the state levels in the past several years. In order to promote renewable energy production, the U.S. federal government spent \$15.8 billion in 2010, \$15.3 billion in 2013, and \$6.7 billion in 2016, which are equivalent to 42%, 52%, and 45% of total energy subsidies (EIA, 2018). Additionally, the net electricity generation by renewable energy in the U.S. has increased from 392,862 GWh to 680,088 GWh between 1999 and 2017, which account for 11% and 17% of total electricity generation, respectively. Figure.2.1 shows the trends in net electricity generation by resource types for the period 1999-2017. As one of the key elements in economic growth, the U.S. annual net electricity generation has a growing trend from 3,695 Terawatt hours (TWh) in 1999 to 4,034 TWh in 2017. Based on the type of non-renewable energy resources, the share of electric power generation from coal has been decreased from 50.9% to 29.9% while electricity generation by natural gas has been increased from 15.4% to 32.4%. Among renewable energy resources, wind power production has been significantly increased from 0.1% to 6.3%.

Increasing trends in renewable electricity production is consistent with the fact that policymakers encourage development of renewable energy in states. One of the most common policies to promote development of local renewable energy generation is known as the Renewable Portfolio Standard (RPS). Under the RPS, retail electric providers are required to deliver eligible forms of renewable energy for a certain amount of their electricity supplies over time. As of October 2018, 29 states, Washington DC, and three territories have enacted RPS with different policy designs across: the specified types of eligible renewables of energy; the required amount of their retail load from renewables, and the deadline for target achievement (Rountree, 2019).

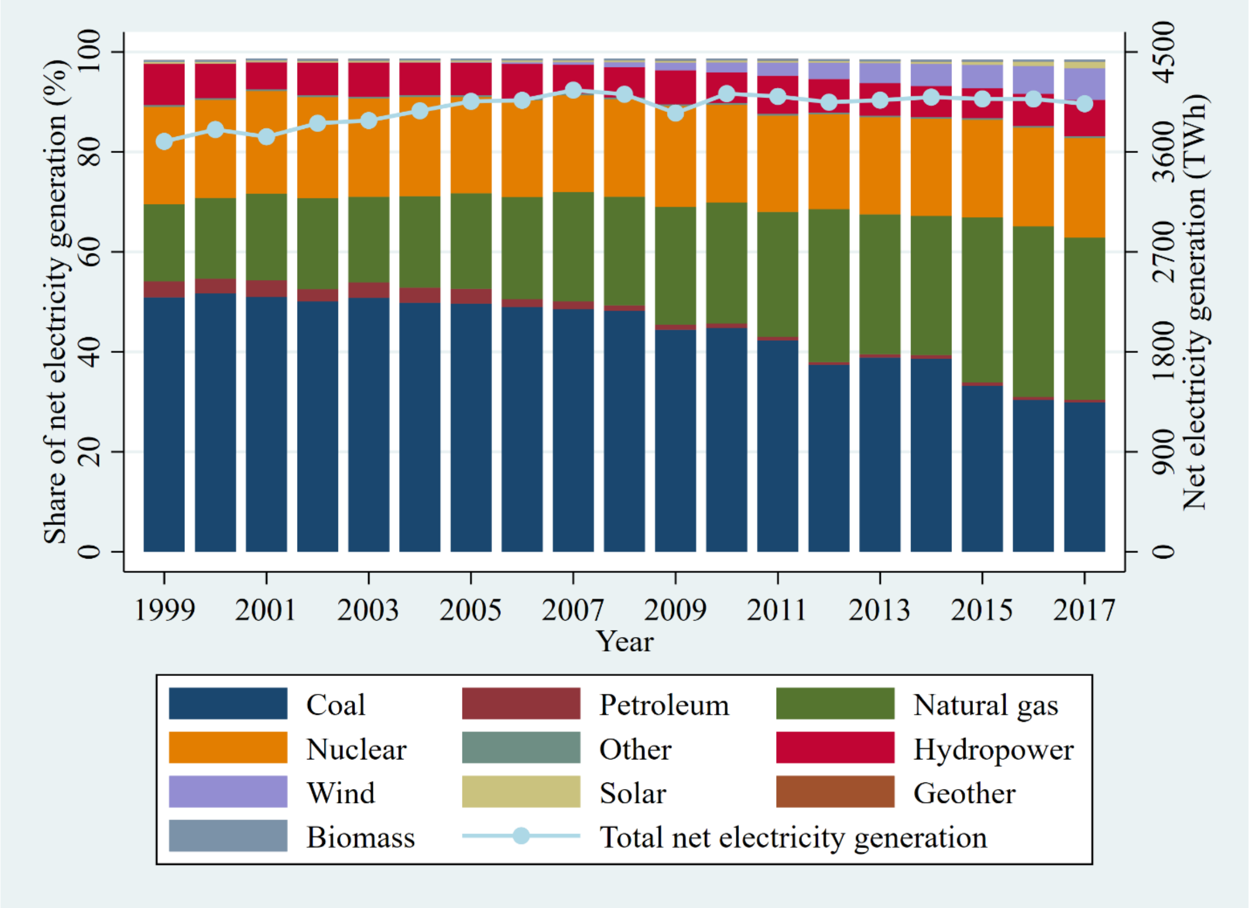

FIGURE 2.1: Trends in net electricity generation by resource types

Additionally, most states provide financial incentive programs to support or encourage the adaptation of renewable energy technologies. These incentives include tax credits, deductions, exemptions, and various forms of subsidies such as production incentives, rebates, loans, and grants (Menz and Vachon, 2006). Given the large amount of government expenditures to support renewable energy development, however, the impacts of these investments in renewable resources on state economic growth remain unclear. Therefore, it is important to examine whether electricity generation from renewable energy resources would be helpful to boost economic activities to determine the efficiency and effectiveness of renewable support schemes.

This study contributes to the literature in three fronts. First, this paper extends the theoretical framework of a growth model with both renewable and non-renewable energy resources by incorporating the environmental externalities from energy use. Second, most previous studies on the relationship between energy and economic growth mainly use a panel of aggregated country-level data. One of the weaknesses of an aggregated level of study is that it does not allow to capture the complexity of different economies, environmental policies, and histories that are unique to each individual country (Burnett, Bergstrom, and Dorfman, 2013). Therefore, this paper seeks to fill the gap in the literature by conducting a disaggregated state-level empirical analysis of the energy-growth nexus which covers 47 U.S. states over the period 1999-2017. Third, one potential issue with a state-level panel data is cross-sectional dependence across states. In order to eliminate the serial correlation and heterogeneity, this paper uses the two-step Generalized Methods of Moments model (GMM), suggested by Arellano and Bover (1995) and Blundell and Bond (1998).

The rest of the paper is structured as follows. Section 2 is devoted to review existing research. Section 3 discusses the theoretical framework for this study. The used data and descriptive statistics of variables are discussed in Section 4. Section 5 presents econometric methodology. The empirical findings are described in Section 6. Finally, Section 7 concludes the analysis and provides policy recommendations.

2.2 Literature review

At present, there is a large group of studies provides theoretical and empirical evidence that both renewable and non-renewable energy generation have significant influences on the economy. By reviewing the existing literature, I summarize how both types of energy are linked to economic growth by understanding the possible externalities of energy generation in Fig.2.2.

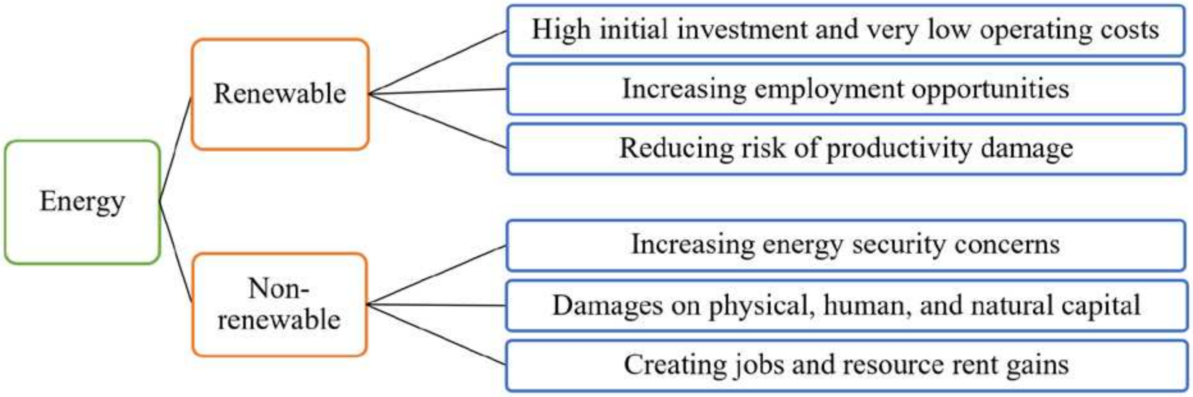

FIGURE 2.2: The framework for energy-economic growth research

2.2.1 Renewable energy

In terms of renewable electricity generation, it is assumed that increasing renewable energy generation leads to economic growth in the long-run as being a more cost competitive factor in production. In general, many renewable energy techniques are defined as having a feature of relatively high initial investment costs per MWh based on the installed capacity and very low running costs (Hvelplund, 2006; Owen, 2006; Adaramola, Agelin-Chaab, and Paul, 2014). Due to the high sunk costs, promoting renewable energy may not help economic growth in the short-run. However, recent studies show that renewable energy resources, particularly wind and solar, increase their competitiveness by reducing the cost of electricity generation (Blum, Wakeling, and Schmidt, 2013; Choi et al., 2015; Brown and Foley, 2015; MacDonald et al., 2016). In other words, the negative impact of high investment costs on economic growth would be offset by the effect of very low variable costs, which are close to zero, in the long-run.

Table 2.1 represents the selected historical mean unsubsidized levelized costs of energy (LCOE) by types which includes cost of capital, fixed and variable maintenance and operations costs, and fuel costs.[1] Apparently, LCOE values of renewable energy, including wind and solar PV, have dramatically decreased since 2009 as increasing the share of those in power generation. These decreasing trends illustrate the price characteristics of renewable resources. That is, high initial investment costs of renewable energy would be offset by very low operating costs in the long-run. With regard to non-renewable energy, LCOE values of nuclear have increased since 2013 whereas those of gas have been decreased over time. Overall, using fossil fuels is more costly to generate electricity compared to renewable energy resources.

The required high investment in development of renewable resources tends to generate economic gains in local areas since promoting renewable energy leads to not only additional investments into generation facilities, distribution grid, and transportation, but modifications in the structure of the existing power plant fleet (Hillebrand et al., 2006). This implies that the investment impulse can cause a positive labor demand shock in the energy industry and create spillover effects to other sectors, which induce increasing in sectoral output and wages. For instance, wind energy projects help to boost local economy by creating local jobs and increasing

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[1] Source: Lazard's levelized cost of energy analysis, version 14.0

total economic output during the construction period for wind turbines due to the relatively high investment costs (Carlson, Loomis, and Payne, 2010; Slattery, Lantz, and Johnson, 2011; Brown et al., 2012; Mauritzen, 2020).

TABLE 2.1: Levelized Cost of Energy by types

Year	Gas	Nuclear	Coal	Wind	Solar PV
2009	179	123	111	135	359
2010	172	96	111	124	248
2011	161	95	104	71	157
2012	145.5	96	102	72	125
2013	139.5	105	105	70	104
2014	139.5	112	109	59	79
2015	128	117	108	55	65
2016	127	117	102	47	55
2017	121.5	148	102	45	50
2018	118.5	151	102	42	43
2019	115.5	155	107	41	40
2020	117	163	112	40	37

Note: Levelized Cost of Energy measures in $/MWh.

In addition to these employment benefits, development of renewable energy can create a positive impact on economic growth with zero emissions. Khoshnevis Yazdi and Khanalizadeh (2017) describe that air pollution caused by fossil fuels adversely affects human health which has a negative impact on labor productivity. This productivity damage affects the industrial and domestic output; thus, affecting the growth of the economy. From an environmental perspective, the fundamental advantage in the use of renewable energy is reducing emissions from the electricity industry (Al-Mulali, Ozturk, and Solarin, 2016; Alvarez-Herranz et al., 2017; Dong, Sun, and Hochman, 2017). Under this circumstance, promoting renewable energy can induce a positive impact on economic growth as the main contributor of emissions reduction.

2.2.2 Non-renewable energy

At the theoretical level, a neoclassical growth model presents that exhaustible resources could play critical roles by putting a burden on economic growth (Stiglitz, 1974; Dasgupta and Heal, 1974; Solow, 1974). In reality, most countries now face the problem of energy security due to an increase in energy demand and a decrease in fossil fuels reserves. Borenstein (2012) argues that if the costs of imported fossil fuels rise, this commonwealth shock could potentially disrupt the macroeconomy in countries which highly rely on imported fossil fuels. Because the energy security problem leads to inefficient and unsustainable paths for energy production (Prado Jr et al., 2016) and the threat of a fundamental need for energy to boost economic growth (Yergin, 2006). Without a doubt, replacement of non-renewable by renewable energy resources is necessary to offset the limitations of economic growth, which imposed by exhaustible natural resources.

Regarding critics of non-renewable energy resources, the existing relevant literature emphasizes that fossil fuels generate externalities, which cause direct and indirect effects on both the environment and the economy in a negative way. A recent report by EPA (2019) presents that about 76% of the total U.S. greenhouse gas emissions came from fossil fuels combustion in 2017. In addition to directly affecting climate change, fossil fuel-fired electricity generation might lower productivity by causing damages on both physical, human, and natural capital, which are the main tools for promoting economic growth. For instance, outdoor air pollution leads to an increase in depreciation of capital equipment (Schou, 2000), and a decrease in farm workers' productivity (Graff Zivin and Neidell, 2012; Chang et al., 2016; Aragón and Rud, 2016). Furthermore, carbon emissions and toxic pollutants generated from burning fossil fuels cause ecological hazard, hence depleting local natural capital stocks (Wackernagel et al., 1999). Even though non-renewable energy generation accounts for more than 80% of total energy generation as of 2018, it may hurt economic growth due to the negative externalities in the long-run.

When it comes to resource extraction, however, it cannot be ignored that development of non-renewable energy can create financial benefits in local economy. Recently, case studies in the U.S. provide empirical evidence that oil and gas development have positive regional economic effects in employment, wages, and poverty rates (Weber, 2012; Wrenn, Kelsey, and Jaenicke, 2015; Munasib and Rickman, 2015; Agerton et al., 2017). Additionally, resource owners have opportunities to earn additional revenues created by a given parcel through larger endowments of oil and gas, which called Ricardian rents (Brown, Fitzgerald, and Weber, 2016). Overall, growing non-renewable extractive sector has not only its largest economic effects on employment and wages but economic stimulus effects through rents paid to public and private entities (Weber, 2012).

2.2.3 Energy-economic growth nexus

Table 2.2 describes the most recent evidence on the energy-economic growth nexus which employed panel data techniques. As Ahmad et al. (2020) point out, previous studies provide generally inconclusive results, with conflicting policy implications. When focusing on only renewable energy, most papers reach the consistent conclusion that renewable energy consumption leads to increased economic output (Sadorsky, 2009; Apergis and Payne, 2010; Magnani and Vaona, 2013; Inglesi-Lotz, 2016; Amri, 2017). In an early study, Sadorsky (2009) examines the relationship between renewable energy consumption and GDP for 18 emerging countries from 1994 to 2003 by using ordinary least squares (OLS), fully modified OLS (FMOLS), and dynamic OLS (DOLS) panel approaches. The author argues that renewable energy can help an emerging country to grow economy through reducing energy import dependence and greenhouse gas emissions. Under the two-step GMM approach, Amri (2017) offers evidence that renewable energy consumption has a positive impact on GDP in the selected 72 countries over the period 1990-2012. The key finding is that the benefits from using renewables are more significant in developed countries than in the developing ones. At the regional level, Magnani and Vaona (2013) use a panel data for the 20 Italian regions over the period from 1997 to 2007 and adopt a multivariate framework in Apergis and Payne (2010). The result of DOLS indicates that a 1% increase in renewable energy production is significantly associated with a 0.02% increase in output in the long-run. The authors assert that renewable energy generation helps to reduce the risk from fossil fuels price volatility and negative health and environmental externalities driving from burning fossil fuels. On the other hand, Maji, Sulaiman, and Abdul-Rahim (2019) confirm that renewable energy consumption hampers economic growth in 15 West African countries by using DOLS method during the period 1995-2014. Based on the results, they explain that the main source of renewable energy is wood biomass in West Africa, which has a side effect on the environment and human health. Thus, renewable energy consumption can hurt economic growth by reducing productivity when inefficient and unclean sources are used.

By considering both renewable and non-renewable energy consumption simultaneously, a major part of existing literature provides the conclusive empirical findings that both types of renewable and non-renewable energy consumption have positive impacts on economic growth (Apergis and Payne, 2012; Gozgor, Lau, and Lu, 2018; Bhattacharya et al., 2016; Ntanos et al., 2018; Adams, Klobodu, and Apio, 2018; Shahbaz et al., 2020). However, the comparison results between the effects of renewable and non-renewable energy on economic growth are different. For instance, Adams, Klobodu, and Apio (2018) use a panel of 30 Sub-Saharan African countries for the period from 1980 to 2012. The authors reveal that non-renewable energy has more significant effect on economic growth than renewable energy. One of the possible reasons is that many of Sub-Saharan African countries only recently have started investing in renewable energy development. In addition, the time-series analysis for each country confirms that the country-specific effects of energy consumption on economic growth varies across countries: only a few countries have positive coefficients on both types of energy consumption. Furthermore, Shahbaz et al. (2020) provide similar results of Adams, Klobodu, and Apio (2018) with the panel of 38 countries under FMOLS and DOLS framework during the period 1990-2018. However, the results of dynamic effects of renewable and non-renewable energy consumption on economic growth for each country indicate that not all countries have both positive coefficients. Given the results, Shahbaz et al. (2020) argue that individual nations have different effects from consumption of renewable and non-renewable energy due to the different levels of renewable energy development. On the contrary, Marques and Fuinhas (2012) find that renewable energy consumption slows down economic growth as increased its contribution to the total energy supply in 24 European countries covering 1990–2007 period. They insist that the high costs of renewable energy development may be placed excessively upon the economy through increasing electricity tariffs; thus, the intensive use of renewable energy seems to be hurting economic growth.

Overall, the existing literature on the energy-economic growth nexus provides mixed empirical findings. And these mixed results may arise from a lack of an appropriate economic/environmental theory (Ahmad et al., 2020). To my knowledge, there is little literature to date has paid attention to recognize the environmental impact from energy use on economic growth, which affects factor productivities in production. Stern (2010) confirms the role of energy in enabling growth with a modified Solow (1956)'s model by adding an energy factor. But the paper considers neither the types of energy nor carbon emissions associated with energy consumption. Schou (2000) introduces pollution as a negative external effect of non-renewable resources in an endogenous growth model. Despite the analysis of the negative productivity effects from pollution, the study does not include the positive external effect from using renewable energy resources on pollution. Since both energy types are typically used simultaneously (Tahvonen and Kuuluvainen, 1993), it is worthwhile to try to get a basic understanding of a mechanism that links between energy, both renewable and non-renewable energy, pollution, and economic growth simultaneously.

TABLE 2.2: Energy-economic growth nexus

Study	Dataset	Time period	Variables	Methodology
Shahbaz et al. (2020)	38 countries	1990-2018	Y, RE, NRE, K, L	DOLS, FMOLS
Maji, Sulaiman, and Abdul-Rahim (2019)	15 West African countries	1995-2014	Y, RE, K, L	DOLS
Adams, Klobodu, and Apio (2018)	30 SSA countries	1980-2012	Y, RE, NRE, K, L, POL	DOLS, FMOLS
Ntanos et al. (2018)	25 European countries	2007-2016	Y, RE, NRE, L	ARDL
Gozgor, Lau, and Lu (2018)	29 OECD countries	1990-2013	Y, RE, NRE, EC	PQR, ARDL
Amri (2017)	72 countries	1990-2012	Y, RE, K, L, T	GMM
Bhattacharya et al. (2016)	38 countries	1991-2012	Y, RE, NRE, K, L	DOLS, FMOLS
Inglesi-Lotz (2016)	34 countries	1990-2010	Y, RE, K, L, R&D	Fixed-effects
Magnani and Vaona (2013)	20 Italian regions	1997-2007	Y, RE, K, L	DOLS, GMM
Marques and Fuinhas (2012)	24 European countries	1990-2007	Y, RE, NRE, EC, IM	OLS, PCSE
Apergis and Payne (2012)	80 countries	1990-2007	Y, RE, NRE, K, L	FMOLS
Apergis and Payne (2010)	13 countries within Eurasia	1992–2007	Y, RE, K, L	FMOLS
Sadorsky (2009)	18 emerging countries	1994-2003	Y, RE	OLS, FMOLS, DOLS

Note : Y is GDP or GDP per capita; RE is renewable energy; NRE is non-renewable energy; K is capital stock; L is employment or labor force; POL is regime type, EC is economic complexity index; T is trade; R&D is Research and Development expenditure; EC is energy consumption; IM is import dependency of energy; SSA is Sub-Saharan African; ARDL is Auto Regressive Distributed Lag; PQR is Panel quantile regression; GMM is Generalized Methods of Moments; FMOLS is Fully Modified OLS; DOLS is Dynamic OLS; OLS is Ordinary Least Squares regression; PCSE is Panel Corrected Standard Errors.

2.3 Theoretical framework

In this section, I discuss how energy generation is linked to economic growth with a theoretical model. To develop a growth model with renewable and non-renewable energy resources, I adopt the consideration of pollution from non-renewable resources in Schou (2000). The aggregate output of an economy can be defined by the following a Cobb-Douglas production function with the property of constant returns to scale:

$$Y = f(K, E(R, N), P, L) = AK^{\alpha}E^{\beta}P^{-\delta}L^{1-\alpha-\beta} = AK^{\alpha}(R^{\gamma}N^{1-\gamma})^{\beta}P^{-\delta}L^{1-\alpha-\beta} \quad (2.1)$$

where A is technology parameter, K is capital, E is energy, R is renewable energy, N is non-renewable energy, P is pollution comes from energy use, L is labor, $A > 0$, $0 < \alpha, \beta < 1$, and $\alpha + \beta < 1$, γ is a factor share, which is between 0 and 1. This model considers the negative impact of pollution on productivity. For feasible balanced growth paths, the pollution function must have the constant elasticity. Therefore, I adopt the specification by Schou (2000) and develop by adding the positive effect from renewable energy resources on pollution as follows:

$$P = DR^{-\lambda_R}N^{\lambda_N} \quad (2.2)$$

where D is pollution parameter, λ_R and λ_N, reflect possible effects from renewable energy and non-renewable energy, respectively, where $D, \lambda_R, \lambda_N > 0$. In addition, $\lambda_R \leq \lambda_N$ by assuming that renewable energy is emission free, thus renewable energy consumption offsets pollution generated from non-renewable energy. If the positive impact of non-renewable energy on production outweighs its negative impact from increased pollution, it is equivalent to assuming that $(1-\gamma)\beta > \delta\lambda_N$. This can be a case where expansion of low-carbon technological innovations promotes a reduction in pollution levels (Balsalobre, Álvarez, and Cantos, 2015). The equation (2.1) can be re-written as following:

$$Y = AK^{\alpha}R^{(\gamma\beta+\delta\lambda_R)}N^{((1-\gamma)\beta-\delta\lambda_N)}D^{-\delta}L^{1-\alpha-\beta} \quad (2.3)$$

Note that along a balanced growth path, the growth rate of Y/L and K/L are constant and equal. In other words, $\frac{K/L}{Y/L} = \frac{K}{Y}$ should be constant. Dividing both sides by Y^{α} produces the following expressions:

$$Y = A^{\frac{1}{1-\alpha}}(\frac{K}{Y})^{\frac{1}{1-\alpha}}R^{\frac{\gamma\beta+\delta\lambda_R}{1-\alpha}}N^{\frac{(1-\gamma)\beta-\delta\lambda_N}{1-\alpha}}D^{\frac{-\delta}{1-\alpha}}L^{\frac{1-\alpha-\beta}{1-\alpha}} \tag{2.4}$$

Then, the growth rate of the economy is written as:

$$\frac{\dot{Y}}{Y} = \frac{1}{1-\alpha}\frac{\dot{A}}{A} + \frac{\gamma\beta+\delta\lambda_R}{1-\alpha}\frac{\dot{R}}{R} + \frac{(1-\gamma)\beta-\delta\lambda_N}{1-\alpha}\frac{\dot{N}}{N} + \frac{1-\alpha-\beta}{1-\alpha}\frac{\dot{L}}{L} \tag{2.5}$$

Let $\frac{\dot{Y}}{Y} = g_Y$, $\frac{\dot{A}}{A} = g_A$, $\frac{\dot{R}}{R} = g_R$, $\frac{\dot{N}}{N} = g_N$, and $\frac{\dot{L}}{L} = g_L$. Along the balanced growth path, the long-run growth rate is as follows:

$$g_Y = \frac{1}{1-\alpha}g_A + \frac{\gamma\beta+\delta\lambda_R}{1-\alpha}g_R + \frac{(1-\gamma)\beta-\delta\lambda_N}{1-\alpha}g_N + \frac{1-\alpha-\beta}{1-\alpha}g_L \tag{2.5}$$

Overall, the long-run growth rate of the economy depends on technological progress, g_A, energy development from both renewable and non-renewable resources, g_R and g_N, respectively, population growth, g_L, the importance of renewable energy in production, $\gamma\beta$, the importance of non-renewable energy in production, $(1-\gamma)\beta$, and the effects of pollution from renewable and non-renewable energy, $\delta\lambda_R$ and $\delta\lambda_N$, respectively.

Given non-negative g_A, g_R, and g_L, the long-run economic growth rate relies on the effect of non-renewable energy. Particularly, there are four unique cases:

i) $(1-\gamma)\beta > \delta\lambda_N$ and $g_N > 0$, the economy continues to grow. This is the situation where the positive contribution of non-renewable energy resources to production, $(1-\gamma)\beta$, outweighs the negative environmental externalities in the form of pollution, $\delta\lambda_N$. Therefore, development of non-renewable energy, $g_N > 0$, boosts economic activities as a vital factor in production;

ii) $(1-\gamma)\beta < \delta\lambda_N$ and $g_N < 0$, the economy grows continuously. In this case, the gains of non-renewable energy in production, $(1-\gamma)\beta$, do not exceed the negative impact of increased pollution from burning fossil fuels, $\delta\lambda_N$. In other words, using non-renewable energy resources causes severe economic damages while hurting productivity in production. Thus, diminishing non-renewable energy in production, $g_N < 0$, helps to grow the economy;

iii) $(1-\gamma)\beta < \delta\lambda_N$ and $g_N > 0$, economic growth is threatened. This is the case where the benefits of non-renewable energy resources in production, $(1-\gamma)\beta$, cannot exceed the negative contribution of pollution, $\delta\lambda_N$. This implies that development of non-renewable energy, $g_N > 0$, hurts economic growth due to a reduction in productivity caused by pollution;

iv) $(1-\gamma)\beta > \delta\lambda_N$ and $g_N < 0$, the economy does not grow. In this case, the positive influence of non-renewable energy in production, $(1-\gamma)\beta$, outweighs productivity damages from pollution, $\delta\lambda_N$. Therefore, a decrease in non-renewable energy in production, $g_N < 0$, threats economic growth since the benefits of non-renewable energy can offset the negative influence from pollution.

In this model, I do not consider any price effects of each energy resource on economic growth such as investment cost for renewable energy and extraction cost for non-renewable energy. Therefore, this theoretical framework is limited to account for the potential effects of each type of energy on economic growth, which associated with its price.

2.4 Data and descriptive statistics

To estimate the effects of renewable and non-renewable energy generation on economic growth, I create a panel data of 47 states in the U.S. for the period from 1999 to 2017. Delaware is excluded in this study since there is insufficient data on renewable energy generation. Alaska and Hawaii are also excluded due to the geographic separation from the other states.

By following the previous studies, Deller, Stallmann, and Amiel (2012), Papyrakis and Gerlagh (2007), and Akai and Sakata (2002), the empirical model considers state per capita real GDP (GSP) in chained in 2012 dollars as a proxy for state economic growth which is available from the U.S. Bureau of Economic Analysis (BEA). State-level electricity generation data includes net electricity generation in thousand MWh by renewable and non-renewable energy resources which is the amount of total generation less the electrical energy used at the generating stations for auxiliaries or station service. According to the U.S. Energy Information Administration (EIA), renewable energy includes wind, biomass, hydropower, geothermal, and solar, whereas non-renewable energy covers crude oil (petroleum), gas, coal, and uranium (nuclear energy). As a proxy for endogenous technological progress, Research and experimental development (R&D) expenditure in thousands of dollars is added which available from the National Center for Science and Engineering Statistics (NCSES). The R&D expenditure is deflated by the U.S. consumer price index (2015=100). Additionally, this paper includes labor force obtained from the U.S. Bureau of Labor Statistics. Table 2.3 summarizes the measurement and sources of the data. Sample statistics of the data are detailed in Table 2.4.

TABLE 2.3: Data Summary

Variable	Description	Source
Y	Per capita real GSP - Per capita real GSP is total GDP by state divided by the resident population of the area (in chained 2012 dollars)	BEA (1999-2017)
RE	Utility scale facility net generation by renewable resources – wind, biomass, hydroelectric, geothermal, solar (in thousand MWh)	EIA (1999-2017)
NRE	Utility scale facility net generation by non-renewable resources – coal, petroleum, natural and other gases, nuclear (in thousand MWh)	EIA (1999-2017)
R&D	Real Research and Development expenditure (in thousands of dollars)	NCSES (1999-2017)
LF	Number of all people age 16 and older who are either working or actively looking for work	BLS (1999-2017)

TABLE 2.4: Sample Statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
GDP	893	47899	8709	30564	78075
RE	893	9131182	1.59E+07	6734	9.99E+07
NRE	893	7.53E+07	6.95E+07	4.55E+03	4.03E+08
R&D	893	2610051	4202970	39734	3.21e+07
LF	893	3181718	3313866	262758	1.92E+07

Table 2.5 shows the average annual growth rates for per capita real GSP, renewable energy generation, and non-renewable energy generation in each state. Based on the results, it is indicated that there is heterogeneity across states. For instance, the highest average annual per capita real GSP growth is recorded for North Dakota (3.58%) whereas the lowest is recorded for Nevada (- 0.37%). The highest average annual growth of renewable energy generation is 131.86% in Rhode Island, followed by Kansas (81.32%), Missouri (44.24%), and New Mexico (21.48%). In terms of non-renewable energy, the variation of annual growth rates compared to renewable energy are relatively small. Negative annual growth rates on non-renewable energy generation are recorded for 20 states including Maryland (-2.47%), Kentucky (-1.4%), and Kansas (-1.35%). On the other hand, the rest 27 states have positive annual growth rates on non-renewable energy generation as the highest for Idaho (28.17%), Oregon (4.81%), and Mississippi (3.87%).

TABLE 2.5: Average annual growth of each of variable in the model: 1999-2017 (%)

State	Y	RE	NRE	State	Y	RE	NRE
Alabama	0.74	3.57	0.94	Nevada	-0.37	5.31	0.96
Arizona	0.46	1.85	1.45	New Hampshire	1.33	2.27	0.78
Arkansas	0.75	1.92	1.83	New Jersey	0.74	3.86	1.68
California	1.94	3.65	-0.45	New Mexico	0.63	21.48	-0.7
Colorado	0.79	13.99	0.64	New York	1.51	1.98	-1.35
Connecticut	0.78	-2.23	1.62	North Carolina	0.51	7.45	0.3
Florida	0.53	0.96	1.39	North Dakota	3.58	12.27	-0.18
Georgia	0.33	4.17	0.52	Ohio	0.84	7.83	-0.91
Idaho	1	1.78	28.17	Oklahoma	1.91	16.54	-0.19
Illinois	0.94	19.28	0.32	Oregon	1.7	0.91	4.81
Indiana	0.82	18.6	-1.34	Pennsylvania	1.35	5.46	0.45
Iowa	1.68	17.92	-0.14	Rhode Island	1.08	131.86	1.79
Kansas	1.29	81.32	-1.35	South Carolina	0.5	10	0.19
Kentucky	0.37	6.48	-1.4	South Dakota	2.03	3.75	-0.74
Louisiana	0.26	0.28	0.6	Tennessee	0.77	4.86	-0.85
Maine	0.79	0.96	-0.47	Texas	1.21	21.18	0.41
Maryland	1.5	5.12	-2.47	Utah	1.13	11.31	-0.3
Massachusetts	1.75	3.33	-1.14	Vermont	1.5	3.93	0.57
Michigan	0.38	6.52	0.39	Virginia	0.83	12.16	1.22
Minnesota	1.2	10.47	-0.1	Washington	1.17	0.81	3.65
Mississippi	0.53	1.59	3.87	West Virginia	0.64	8.63	-1.18
Missouri	0.35	44.24	0.75	Wisconsin	1.03	3.77	0.47
Montana	1.29	1.31	-0.44	Wyoming	1.11	10.88	-0.09
Nebraska	1.74	12.42	0.21				

2.5 Econometric approach

The main advantage of using state-level data to investigate economic growth is that there are relatively smaller differences in dimensions compared to county-level data; for instance, cultural characteristics, the quality of institutions, and languages (Barro, 1995). Also, using state-level data allows us to consider the potential spatial interactions across states. Ojede, Atems, and Yamarik (2018) argue that there is a correlation between "a certain level of geographic proximity to neighboring states and the economic growth process" since a policy shock in one state can influence economic activities in neighboring states through movements of labor, goods, services, technology, and firms. This implies that the potential spatial linkages can cause cross-sectional dependence across states because a shock in one state easily creates spillovers to another states. At the same time, however, institutional differences and state-specific geography are likely to generate heterogeneity issues (Ojede, Atems, and Yamarik, 2018). For the main purpose of this study, analyzing the effects of renewable energy generation and non-renewable energy generation on state economic growth, therefore, it is required to check cross-sectional dependence across the states. Breusch and Pagan (1980) propose a Lagrange Multipler statistic (LM hereafter) to examine cross-sectional dependence of the following equation;

$$y_{it} = \alpha_i + \beta_i x_{it} + u_{it} \text{ for } i = 1, \ldots, N;\ t = 1, \ldots, T \tag{2.7}$$

where i is the cross section dimension, t is the time dimension. In the LM test, the null hypothesis, $H_o : Cov(u_{it}, u_{ij}) = 0$ for all t and $i \neq j$, indicates that there is no cross-sectional dependence, whereas, alternative hypothesis, $H_1 : Cov(u_{it}, u_{ij}) \neq 0$ for at least of pair of $i \neq j$, states the cross-sectional dependence between at least one pair of cross-sections. The calculation of LM test is as follows;

$$\text{LM} = \text{T} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho_{ij}^{2}} \tag{2.8}$$

where $\widehat{\rho_{ij}}$ is the sample estimate of the pairwise correlation of the residuals from equation (2.7) for each cross section. The LM test is likely to be suitable for panels when the cross-sectional size (N) is relatively small and time dimension (T) is sufficiently large. This paper uses a balanced panel data set with the variables, Y, RE, NRE, $R\&D$, and LF which has larger N and small T. Therefore, it is required to employ alternative cross-sectional dependence test (CD hereafter) developed by Pesaran (2021), which is specified as follows:

$$\text{CD} = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho_{ij}^{2}}\right) \tag{2.9}$$

Given both state specific heterogeneity and cross-sectional dependence, it is necessary to examine the time series properties of the variables. For this purpose, first Im, Pesaran and Shin (IPS) panel unit root test is executed. IPS test developed by Im et al. (2003) allows heterogeneity in the dynamics of the autoregressive coefficients. It is assumed that with given initial values, y_{i0}, the stochastic process, y_{it}, is generated by the first-order autoregressive process as follows:

$$y_{it} = (1-\emptyset_i)\mu_i + \emptyset_i y_{i,t-1} + u_{it} \text{ for } i = 1, \ldots, N;\ t = 1, \ldots, T \tag{2.10}$$

In testing, the null hypothesis of unit roots, $\emptyset_i = 1$ for all i. Eq. (5) can be rewritten as:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{2.11}$$

where $\alpha_i = (1-\emptyset_i)\mu_i$, $\beta_i = -(1-\emptyset_i)$, $\Delta y_{it} = y_{it} - y_{i,t-1}$, β_i shows the panel-specific autoregressive coefficients, and u_{it} signifies the stationary error term which have heterogeneous variances across panels. The null hypothesis is that the variable has a unit root whereas the alternative hypothesis is the variable has no unit root:

$H_o: \beta_i = 0$ for all i

$$H_1: \begin{cases} \beta_i < 0 \text{ for } i = 1, 2, \ldots, N_1 \\ \beta_i = 0 \text{ for } i = N_1 + 1, N_1 + 2, \ldots, \text{N} \end{cases}$$

Additionally, Augmented Dickey-Fuller (ADF) unit root test is employed for robustness check.

If the variables are integrated of order one, the next step will be conducting panel cointegration test to confirm whether there is a long-run equilibrium relationship between the variables. The heterogeneous panel cointegration test, developed by Pedroni (1999) and Pedroni (2004), permits for cross-sectional interdependence with different individual effects, which considers the following type of a regression model:

$$Y_{it} = \gamma_i + \delta_i t + \beta_{1i} RE_{it} + \beta_{2i} NRE_{it} + \beta_{3i} R\&D_{it} + \beta_{4i} LF_{it} + e_{it} \text{ for } i = 1, \dots, N;\ t = 1, \dots, T \quad (2.12)$$

where γ_i shows panel-specific fixed effects, δ_i describes panel-specific linear trends, and β_{ji} indicate panel-specific cointegration parameters. In order to test the null hypothesis of no cointegration, $\varphi_i = 1$, the unit root test on the residuals is required as follows:

$$e_{it} = \varphi_i e_{it-1} + \omega_{it} \quad (2.13)$$

Pedroni (1999) and Pedroni (2004) introduce seven test statistics, which asymptotically distributed as standard normal. These statistics are grouped into two categories: panel and group- mean statistics. The penal statistics are based on pooling along the within-dimension, which includes panel v, panel ρ, panel PP, and panel ADF statistics. These statistics pool the autoregressive coefficients across different states for the unit root tests on the estimated residuals, e_{it}. The group-mean statistics are based on the between dimension, which includes group ρ, group PP, and group ADF statistics. These statistics are based on averages of the individual autoregressive coefficients, associated with the unit root tests of the residuals for each state in the panel:

$$\text{Panel } v - \text{statistic: } Z_v = \left(\sum_{i=1}^{N} \sum_{t=1}^{T} \hat{L}_{11i}^{-2}\, \hat{e}_{it-1}^{2} \right)^{-1} \quad (2.14a)$$

$$\text{Panel } \rho - \text{statistic: } Z_\rho = \left(\sum_{i=1}^{N} \sum_{t=1}^{T} \hat{L}_{11i}^{-2}\, \hat{e}_{it-1}^{2} \right)^{-1} \sum_{i=1}^{N} \sum_{t=1}^{T} \hat{L}_{11i}^{-2} \left(\hat{e}_{it-1}^{2} \Delta \hat{e}_{it} - \hat{\lambda}_i \right) \quad (2.14b)$$

$$\text{Panel PP} - \text{statistic: } Z_t = \left(\hat{\sigma}^2 \sum_{i=1}^{N}\sum_{t=1}^{T} \hat{L}_{11i}^{-2}\, \hat{e}_{it-1}^{2}\right)^{-\frac{1}{2}} \sum_{i=1}^{N}\sum_{t=1}^{T} \hat{L}_{11i}^{-2}\left(\hat{e}_{it-1}\Delta\hat{e}_{it} - \hat{\lambda}_i\right) \tag{2.14c}$$

$$\text{Panel ADF} - \text{statistic: } Z_t^{*} = \left(\hat{s}^{*2} \sum_{i=1}^{N}\sum_{t=1}^{T} \hat{L}_{11i}^{-2}\, \hat{e}_{it-1}^{*}{}^{2}\right)^{-\frac{1}{2}} \sum_{i=1}^{N}\sum_{t=1}^{T} \hat{L}_{11i}^{-2}\, \hat{e}_{it-1}^{*}\Delta\hat{e}_{it}^{*}) \tag{2.14d}$$

$$\text{Group } \rho - \text{ statistic: } \tilde{Z}_\rho = \sum_{i=1}^{N}\left(\sum_{t=1}^{T} \hat{e}_{it-1}^{2}\right)^{-1} \sum_{t=1}^{T}\left(\hat{e}_{it-1}\Delta\hat{e}_{it} - \hat{\lambda}_i\right) \tag{2.14e}$$

$$\text{Group PP} - \text{ statistic: } \tilde{Z}_t = \sum_{i=1}^{N}\left(\hat{\sigma}^2 \sum_{t=1}^{T} \hat{e}_{it-1}^{2}\right)^{-\frac{1}{2}} \sum_{t=1}^{T}\left(\hat{e}_{it-1}\Delta\hat{e}_{it} - \hat{\lambda}_i\right) \tag{2.14f}$$

$$\text{Group ADF} - \text{statistic: } \tilde{Z}_t^{*} = \sum_{i=1}^{N}\left(\sum_{t=1}^{T} \hat{s}_i^{2}\hat{e}_{it-1}^{*}{}^{2}\right)^{-\frac{1}{2}} \sum_{t=1}^{T}(\hat{e}_{it-1}^{*}\Delta\hat{e}_{it}^{*}) \tag{2.14g}$$

where $\hat{e}_{it}$ is the estimated residual from equation (2.12) and $\hat{L}_{11i}^{2}$ is the estimated long-run covariance matrix for $\Delta\hat{e}_{it}$. The null hypothesis is that all of the individuals of the panel are not cointegrated whereas the alternative hypothesis is all of the individuals are cointegrated:

$H_o\colon \hat{\rho}_i = 1$ for all i

$$H_1\colon \begin{cases} \hat{\rho}_i = \hat{\rho} < 1 \\ \hat{\rho}_i < 1 \text{ for all } i \end{cases}$$

In response to the possible simultaneity bias and endogeneity between energy generation and economic growth, the conventional OLS regression is not suitable for this paper. Because this endogeneity issue violates the assumption of the model, which describes independent variables are not correlated with the error term. To eliminate the individual effects, Arellano and Bond (1991) propose a consistent Generalized Methods of Moments (GMM) technique by using lag variables as instruments. Since this method has the problem of weak instrumental variables, however, the estimation results could be biased. In order to solve this issue, Arellano and Bover (1995) and Blundell and Bond (1998) propose the system GMM estimator, which combines the original equation and the transformed equation as a systematic equation for the generalized moment estimation. This procedure assumes that first differences of instrumental variables are not correlated with the individual specific fixed effects. In other words, using first differences allows to eliminate the state-specific heterogeneity. Therefore, I use the two-step GMM model to investigate the effects of renewable and non-renewable energy generation on economic growth. In order to capture trends in the changes in the relationship between energy generation and economic activities, this paper employs a rolling regression framework with the following dynamic panel model:

$$lnY_{s,t} = \beta_0 + \beta_1 lnY_{s,t-1} + \beta_2 lnRE_{s,t} + \beta_3 lnNRE_{s,t} + \beta_4 lnR\&D_{s,t} + \beta_5 lnLF_{s,t} + \alpha_s + \varepsilon_{s,t} \quad (2.15)$$

where s and t stand for state and year, respectively. $lnY_{s,t}$ is the dependent variable representing logarithm of per capital real GSP of state s at time t. The lagged dependent variable is included as an explanatory variable to consider the persistence of economic growth over time. The variables $lnRE_{s,t}$ and $lnNRE_{s,t}$ are the main independent variables, indicating the logarithm of net electricity generation from renewable and non-renewable energy resources, respectively. The independent variables; $lnR\&D_{s,t}$ measures logarithm of Research and Development expenditure, and $lnLF_{s,t}$ represents logarithm of labor force. α_s is the time-invariant unobserved state-specific effects that capture individual state heterogeneity, β_i is parameter, and $\varepsilon_{s,t}$ is the error term with the assumption of normal distribution. This paper uses the lags of the variables as instrumental variables in the difference equation and standard errors are clustered at the state level.

Moreover, this model specification assumes that no serial correlation of the residual, and no correlation between the residual and the independent variables. The consistency of the GMM results depends on the proper instruments employed in the first-differenced equations and the level equations. To examine the validity of the instruments, I use the Hansen test for over-identifying restrictions, under the null hypothesis that the instrument variables are uncorrelated with the error term. In addition, the Arellano–Bond AR (2) test allows to check for the existence of second-order autocorrelation in the first-differenced residuals with the null hypothesis, indicating that there is no second-order serial correlation of differenced residuals. Therefore, failure to reject those two null hypotheses supports for the validation of the model.

2.6 Results

Table 2.6 describes the results of cross-sectional dependence test, Pesaran CD test, with the null hypothesis of no cross-sectional dependence of the panel data. The statistics for the test reject the null hypothesis at the 1% level of significance, suggesting the existence of strong cross-sectional dependence. To reduce the possibility of the wrong regression, this paper performs the panel unit root tests which include the IPS and ADF tests. Table 2.7 confirms that the null hypothesis of the existence of a unit root is rejected for most of the variables. This implies that each variable may be integrated of order one so that the variables are stationary. These findings support to use the panel cointegration test to examine the long-run linkage between all the variables. Table 2.8 reports the statistics for heterogeneous panel cointegration tests by Pedroni (1999) and Pedroni (2004), showing five of them reject the null hypothesis of no cointegration at the 1% significance level in most cases. In other words, those results indicate that the variables may have a long-run equilibrium relationship. Therefore, these results confirm that the two-step GMM is a suitable method for this analysis to control for the endogeneity and the presence of serial correlation.

TABLE 2.6: Test for cross-sectional dependence

Variables	Y	RE	NRE	R&D	LF
Pesaran CD test	96.188***	67.913***	28.013***	42.847***	89.765***
p-value	0.000	0.000	0.000	0.000	0.000

Note : *** $p<0.01$.

TABLE 2.7: Results of panel unit root tests

Variables	Form	Method	Statistic
Y	Individual intercept	IPS	-0.3706
		ADF	237.6***
	Individual intercept and trend	IPS	0.0185
		ADF	85.721
RE	Individual intercept	IPS	0.4282
		ADF	246.42***
	Individual intercept and trend	IPS	-5.731***
		ADF	195.746***
NRE	Individual intercept	IPS	-0.2657
		ADF	240.131***
	Individual intercept and trend	IPS	-3.2579***
		ADF	125.2**
R&D	Individual intercept	IPS	-6.4351***
		ADF	349.54***
	Individual intercept and trend	IPS	-7.5422***
		ADF	209.16***
LF	Individual intercept	IPS	2.2214
		ADF	217.79***
	Individual intercept and trend	IPS	-2.9442***
		ADF	174.03***

Note: IPS is Im, Pesaran and Shin; ADF is Augmented Dickey-Fuller; The null hypothesis for these tests is the variable has a unit root. To control for cross-sectional dependence, cross-sectional means are removed.

TABLE 2.8: Results of panel cointegration test

	Within Dimension					
	Individual Intercept		Individual Intercept and Individual Trend		No Intercept or Trend	
	Statistic	Weighted Statistic	Statistic	Weighted Statistic	Statistic	Weighted Statistic
Panel v	-5.7055***	-4.6955***	-5.5874***	-5.2544***	-4.8418***	-4.03***
Panel ρ	4.9156***	3.5308***	6.2342***	5.0942***	3.3088***	2.5417***
Panel PP	1.9932**	-1.7803**	1.8961**	-0.5092	-1.2841*	-2.3258**
Panel ADF	2.5769***	-1.8841**	2.5939***	0.3172	-0.9739	-1.6339*
	Between Dimension					
	Statistic		Statistic		Statistic	
Group ρ	7.8142***		8.1219***		6.2346***	
Group PP	3.9548***		2.2276**		-0.0531	
Group ADF	4.5414***		2.5577***		1.0284	

Note: Variables: Y, RE, NRE, R&D, LF
*** Denote rejection of null hypothesis of no cointegration at 1% significance level.
** Denote rejection of null hypothesis of no cointegration at 5% significance level.
* Denote rejection of null hypothesis of no cointegration at 10% significance level.

The whole sample is divided into 7 overlapping subperiods and each subsequent subperiod is moved by one year. In other words, the regression data were rolled from 1999 forward by adding one additional year to the front. The first regression covers data between 1999 and 2011 and the second one covers from 1999 to 2012. The same stepwise rolling approach is applied to the aforementioned 7 subperiods. The main purpose of this paper is to evaluate the influences of both renewable and non-renewable energy generation on sustainable state economic growth. The results of the rolling regressions with the two-step GMM dynamic panel models are described in Table 2.9 and Table 2.10. Both Table 2.9 and Table 2.10 indicate that the lagged per capita real GSP appears significant and positively correlated to the current real GSP in all models. Also, both the AR(2) test and the Hansen test cannot reject the null hypothesis by suggesting: there is no evidence of second-order autocorrelation, and the used instrument variables are valid.

The key finding is that renewable energy generation has different impact on state economic activities whereas non-renewable energy production has a significantly negative impact on state economic activities over the whole period. At the early stage of renewable energy development, which associated with higher levelized cost (LCOE) of renewable energy, electricity generation from renewable resources may not lead to boosting economic activities shown in Table 2.9. On the other hand, renewable energy production enhances economic activities at the advanced stage of its development, which associated with lower LCOE of renewables, illustrated in Table 2.10. These results support that renewable energy development requires high initial investment costs and thus, renewable energy generation may not lead to economic growth in the short-run. In particular, wind and solar power paid high LCOE even though these resources accounted for less than 5% of total electricity generation during the early stage. As Wüstenhagen and Menichetti (2012) point out that improvement in renewable energy technologies leads to increased reliability and reduced production costs, however, renewable energy has increased its competitiveness over time. Therefore, the economic gains from using renewable resources outweigh the initial fixed costs. In short, this result support that development of renewable energy can promote economic activities which enhance economic growth in the long-run. The result, the positive effect of renewable electricity generation on economic activities in the long-run, is consistent with the findings of previous studies discussed in Section 2.2.3. In other words, investment in renewable energy resources can create a positive shock in local economy through increasing job opportunities and wages. Additionally, development of renewable energy can generate spillover effects to other sectors via structural changes in the electricity industry. From an environmental perspective, furthermore, renewable energy development contributes to not only lowering social costs stemming from emissions but also enhancing productivity as a key contributor of pollution reduction.

With respect to the effect of non-renewable energy generation, electricity generation from non-renewable sources may not create substantial economic benefits due to the negative environmental externalities. In other words, economic gains from using non-renewable energy may not offset productivity losses from the emissions. A report from the International Renewable Energy Agency[2], shows the estimated external costs of fossil fuels between 4.8% and 16.8% of the world GDP. This supports that non-renewable energy generation may pay substantial costs due to pollution, thus the productivity effect of non-renewable energy, $(1-\gamma)\beta$, may not exceed the environmental effect, $\delta\lambda_N$, which argued in Section 2.3. Also, the LCOE of fossil fuels, illustrated in Section 2.2.1 indicates that using non-renewable resources to generate electricity is

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[2] Source: The true cost of fossil fuels: saving on the externalities of air pollution and climate change, 2016

more costly than renewable resources. Overall, this empirical result is consistent with Shahbaz et al. (2020), showing the negative impacts of non-renewable energy consumption on economic growth in a few countries. Furthermore, the empirical results highlight that non-renewable energy generation may become less harmful to economic growth over the period. This supports that development of cleaner technology helps in lowering pollution levels so that the negative effects of pollution caused by fossil fuels can be reduced.

Regard to the other factors of production, the coefficients for the R&D expenditures are positive and statistically significant, consistent with Inglesi-Lotz (2016). One possible reason of positive impact of R&D expenditures on per capita real GSP is that the R&D expenditures are highly associated with technological improvement, which can be defined a process to reduce production costs (Gozgor, Lau, and Lu, 2018). As an important factor in production, labor force has significantly negative impacts on state economic growth, in line with Armeanu, Vintilă, and Gherghina (2017). This result may address that labor force itself can slow down economic growth in advanced economies like the U.S. due to changes in the composition of output.

TABLE 2.9: Results of the rolling regressions with the two-step generalized method of moments

Variables	1999-2011		1999-2012		1999-2013		1999-2014	
L.Y	0.905***	0.933***	0.896***	0.937***	0.918***	0.947***	0.918***	0.936***
	(0.0079)	(0.0082)	(0.0045)	(0.0023)	(0.004)	(0.00462)	(0.0062)	(0.0061)
RE	-0.0014	-0.0002	-0.0003	0.0005	-0.0014**	0.0005	-0.0007	0.0019***
	(0.0009)	(0.001)	(0.0007)	(0.0008)	(0.0006)	(0.0008)	(0.0008)	(0.0007)
NRE	-0.0177***	-0.0053***	-0.0279***	-0.007***	-0.0228***	-0.0053***	-0.0171***	-0.0035**
	(0.0024)	(0.0018)	(0.002)	(0.0022)	(0.0017)	(0.0017)	(0.0016)	(0.0013)
R&D		0.00136		0.0008		0.0007		0.00146**
		(0.001)		(0.0006)		(0.0007)		(0.0006)
LF		0.0034*		0.0049*		0.0033		0.00077
		(0.002)		(0.0026)		(0.0023)		(0.0021)
Constant	1.369***	0.763***	1.626***	0.719***	1.311***	0.608***	1.202***	0.695***
	(0.0768)	(0.0762)	(0.065)	(0.023)	(0.0446)	(0.0412)	(0.0393)	(0.0589)
Observation	564	564	611	611	658	658	705	705
Num. of State	47	47	47	47	47	47	47	47
AR(2)	-0.68	-0.81	-0.58	-0.81	-0.64	-0.85	-0.70	-0.84
	(0.495)	(0.416)	(0.559)	(0.415)	(0.520)	(0.397)	(0.481)	(0.399)
Instr.	40	42	43	45	46	48	49	51
Hansen test	46.21	46.04	46.32	46.27	46.68	46.32	46.61	46.61
	(0.119)	(0.122)	(0.196)	(0.197)	(0.286)	(0.299)	(0.406)	(0.406)

Note: Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

TABLE 2.10: Results of the rolling regressions with the two-step generalized method of moments (Continued)

Variables	1999-2015		1999-2016		1999-2017	
L.Y	0.922***	0.937***	0.918***	0.935***	0.911***	0.924***
	(0.0062)	(0.0057)	(0.0052)	-0.0066	(0.0059)	(0.0081)
RE	-0.0011***	0.0027***	0.0029***	0.0035***	0.0032***	0.0037***
	(0.0004)	(0.0006)	(0.0005)	(0.0007)	(0.0005)	(0.0011)
NRE	-0.0179***	-0.0007	-0.0051***	-0.0005	-0.006***	-0.0025
	(0.0021)	(0.0005)	(0.0011)	(0.0005)	(0.0006)	(0.0017)
R&D		0.0026***		0.0032***		0.0032***
		(0.0009)		(0.0011)		(0.0009)
LF		-0.0031**		-0.0035*		-0.0011
		(0.0012)		(0.002)		(0.0027)
Constant	1.186***	0.664***	0.943***	0.669***	1.019***	0.788***
	(0.0595)	-0.0533	(0.0544)	-0.0693	(0.0624)	-0.0791
Observation	752	752	799	799	846	846
Num. of State	47	47	47	47	47	47
AR(2)	-0.69	-0.84	-0.88	-0.82	-0.87	-0.80
	(0.488)	(0.400)	(0.377)	(0.412)	(0.382)	(0.427)
Instr.	52	54	55	57	55	57
Hansen test	46.59	46.66	46.40	46.51	46.64	46.53
	(0.531)	(0.528)	(0.657)	(0.652)	(0.647)	(0.652)

Note: Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

2.7 Conclusion and policy implications

This paper is inspired by the current increasing trends in both electricity generation from renewable energy resources and government expenditures to promote renewable energy development in the U.S. The main goal of this paper is examining the effects of electricity generation from both renewable and non-renewable energy resources on economic growth for 47 U.S. states over the period 1999-2017. Even though there is a growing literature that investigates the relationship between energy and economic growth, most of studies focus on empirical analysis at aggregated country-level with weak intuitive explanation on the results. Therefore, this study contributes to the literature by providing a theoretical framework where pollution is formally internalized and offering empirical results with a disaggregated state-level data. The theory model helps to get a grip on the role of non-renewable energy in production by considering the positive impact as a vital factor and the negative impact as a polluter. In other words, the effects of non-renewable energy on economic growth can be different based on the magnitude of those impacts. Furthermore, the empirical model produces more robust results since a state-level analysis has a smaller variation in economic structure and environmental policies compared to a country-level analysis.

For empirical analysis, this paper uses the two-step GMM model which controls for heterogeneity, endogeneity, and serial correlation issues. The key finding of the GMM estimation is that renewable energy generation positively affects state economic growth while non-renewable energy generation negatively influence economic growth. This implies that using more renewable resources to generate electricity would create economically and environmentally positive effects in the economy. Because development of renewable energy resources helps not only reducing average costs to generate electricity but improving environmental quality as zero emission resources, which enhances productivity. Even though non-renewable energy can create economic benefits as a main factor of production, burning fossil fuels generates air pollution, which directly threatened labor and capital productivities. As shown in the theoretical framework, non-renewable energy generation does not help sustainable economic development, unless the economic gains exceed the productivity losses arose from the negative environmental externalities.

Moreover, this paper finds that the effects of renewable energy generation on economic growth are different at a level of development stage: at the early stage, electricity generation from renewable energy resources hampers economic growth, while renewable energy generation helps to grow the economy at the advanced-stage. This confirms that the very low operating costs could offset the huge financial burden of the high initial investment costs in the long-run. Another finding is that the increasing replacement of conventional resources with renewable can make renewable energy to become a more important factor in the economy. It could be interpreted that non-renewable energy generation pays more costs because environmental policies and renewable energy support scheme charge higher social costs on pollution.

Throughout the analysis, this paper provides critical implications for energy policy. Most importantly, the findings of this paper provide evidence that using renewable energy resources allows to take more benefits than costs by creating economic and environmental benefits. At the same time, the economy may take a burden from using non-renewable energy resources by paying external costs of negative environmental externalities. As an alternative to replace with fossil fuels, development of renewable energy helps to reduce concerns over climate change, energy security, and depleting natural resources, which not compromising the ability of future generations to meet their needs (Turner, 1999). Therefore, it is expected that the findings of this paper will provide important implications to policy makers with appropriate directions to achieve sustainable economic growth.

Chapter 3

CO_2 emissions, renewable energy and economic growth in the U.S.

3.1 Introduction

Even though the use of energy is an essential factor to boost economic activities, it creates remarkable environmental damages due to its large consumption of fossil fuels such as coal and natural gas. As a consequence, burning fossil fuels generates the vast majority of conventional air pollutants such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are major sources of greenhouse gas emissions. These pollutants from the traditional energy consumption affect both local air quality and human health as generating external costs. According to Greenstone and Looney (2011), coal-generated electricity creates an additional 5.6 cents/kWh costs, which include 3.4 cents/kWh for health damages and 2.2 cents/kWh for damage from climate change. Additionally, the estimated external cost for the life cycle of coal, which considers damages from human health and environment, ranges from 9.42 to 26.89 cents/kWh (Epstein et al., 2011) and the evaluated average economic cost of fossil fuels, associated with health impact ranges from 14 to 35 cents/kWh (Machol and Rizk, 2013).

Since 2005, the United States has been recorded as the second largest greenhouse gas contributor as accounting for more than 11% of global greenhouse gas emissions (Ritchie and Roser, 2020). In particular, around 81% of U.S. greenhouse gases originated from CO_2 emissions, and 93.1% of the total U.S. CO_2 emissions was caused by fossil fuel combustion in 2018, which is equivalent to 5,023.1 million metric tons[3]. In addition, transportation and electric power sectors are the largest source of CO_2 emissions[4]. To reduce emissions from fossil fuel,

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[3] Source: Inventory of US greenhouse gas emissions and sinks from U.S. Environmental Protection Agency

[4] Source: U.S. Energy Information Administration

both federal and state governments have implemented environmental policies. For example, the Clean Air Interstate Rule and the Cross-State Air Pollution Rule target to limit SO_2 and NO_x emissions by instituting tradable permit systems; the Mercury and Air Toxics Standards focus on mercury and other hazardous pollutants from coal and oil-fired power plants; the Renewable Portfolio Standards require electricity supply companies to increase energy production from renewable energy sources, which have zero emissions, and the Clean Power Plan aims for reduction in CO_2 emissions of existing fuel-fired power plants.

Overall, the need to reduce emissions causes dramatic changes in the energy sector by replacing conventional energy sources with renewables; as a result, recent trends in the renewable energy consumption in the U.S. are striking. According to the U.S. Energy Information Administration, the total energy consumption from renewable sources has increased from 14,023 trillion to 22,094 trillion British thermal units between 1997 and 2017, which account for about 7.4% and 11.3% of the total U.S. energy consumption, respectively. Over the period, the energy-related CO_2 emissions have declined by 8.7%, down from 5,581 million metric tons in 1997 to 5,133.4 million metric tons in 2017. Figure 3.1 describes these trends in energy consumption and energy-related CO_2 emissions in the U.S. over 1997-2017.

To contribute to the existing literature, this paper investigates the linkages between energy-related CO2 emissions, economic growth, and renewable energy consumption for the 48 U.S. states over the period 1997-2017. Furthermore, this study employs the panel fixed-effects and the Method of Moments Quantile Regression with fixed effects developed by Machado and Silva (2019) for controlling cross-sectional dependence and state-specific heterogeneity. Additionally, this paper considers other major determinants of emissions such as climate variables and energy prices which help to avoid omitted variable bias.

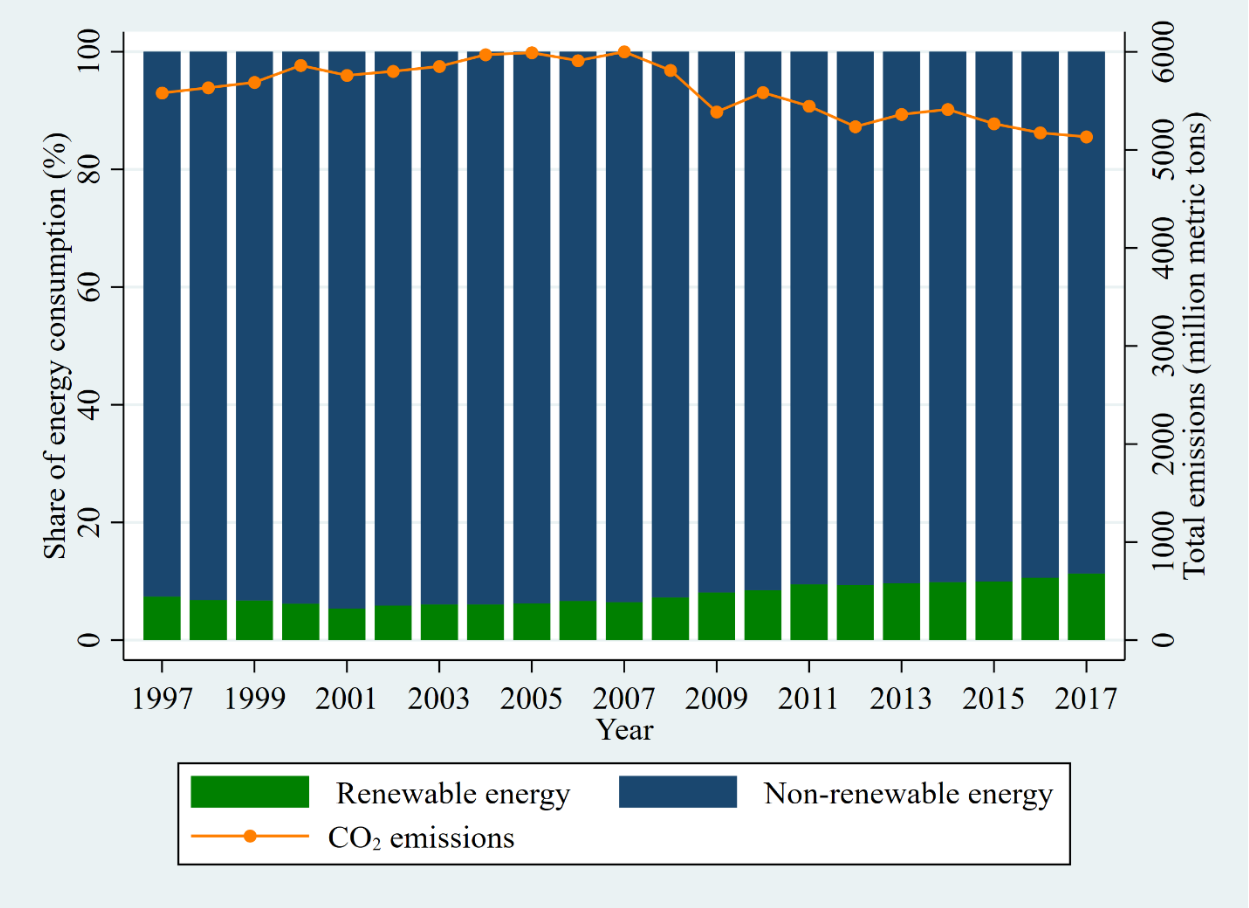

FIGURE 3.1: Trends in energy consumption and energy-related CO2 emissions

The remaining of the paper is structured as follows. Section 2 discusses the existing literature. Section 3 describes the used data and descriptive statistics of variables. The econometric methodology is presented in Section 4. The empirical findings are discussed in Section 5. Finally, in Section 6, I conclude the analysis and provide policy implications.

3.2 Literature review

One famous argument is that economic growth can bring greater harm to the environment since exhaustible resources serve as the main factors in the production, resulting in environmental degradation. In early 1990, a set of empirical studies attempted to investigate the link between environmental degradation and economic growth (Grossman and Krueger, 1991; Panayotou et al., 1993; Selden and Song, 1994; Shafik, 1994; Holtz-Eakin and Selden, 1995). In the first pioneering work, Grossman and Krueger (1991) suggest an inverted U-shaped relationship between income level and environmental degradation. This theory describes that environmental pollution first increases until reaching a threshold and then decrease over the course of economic growth, known as the Environmental Kuznets Curve (EKC). Theoretically, it has been argued that the economic growth affects environment through three separate effects: scale, composition, and technique. According to the scale effect, expanding the scale of economic activities is a driver of environmental degradation. This is because, as economic growth accelerates with the intensification of resource extraction or the pollution intensity, production processes induce increasing waste generation in quantity and toxicity (Torras and Boyce, 1998; Dinda, 2004). The composition effect states that as countries develop, nations begin to import pollution-intensive products from other countries with less stringent environmental standards, and their citizens have considerable attention to the non-economic aspects to improve their living conditions. In other words, changes in preferences for cleaner goods can cause a shift in the composition of economic output towards light manufacturing and services industries, which improve environmental quality (Jebli and Youssef, 2015). The technique effect demonstrates that a wealthy nation can substitute cleaner technologies for polluting ones, which reducing emissions. Since technological innovations in newer and cleaner technologies through greater investment in research and development (R&D) improve environmental quality (Dinda, 2004; Churchill et al., 2020). Overall, Dinda (2004) describes that the positive impact of both the composition and technique effects on environmental quality will compensate for the negative impact from the scale effect, resulting in a downward turn in EKC trend.

Additionally, Panayotou et al. (1993) argues that as an economy grows, environmental pollution accumulates. At the same time, more people can become environmentally conscious, and environmental protection policies are more strictly enforced. Because environmental quality becomes a 'normal' good as income rises, thus the demand for environmental quality rises (Rothman, 1998). Later, Shafik (1994) points out that the relationship between income and the associated costs and benefits with any given level of environmental quality may differ based on economic structure, preferences, and technology within a country. For instance, local institutional reforms, such as market-based incentives and environmental legislation can be significant roles to reduce environmental damages (Arrow et al., 1996). Selden and Song (1994) also suggest that while agricultural modernization and industrialization may hurt environmental quality in the early stages of economic development, this trend reverses due to other factors: positive income elasticities of demand for environmental quality; changes in the composition of emissions-intensity production and consumption; increasing environmental awareness and education levels, and more responsive political systems.

From an empirical perspective, most earlier studies on EKC have mainly focused on the relationship between economic growth and pollution emissions without taking into account other factors that affect environmental degradation. Furthermore, in most cases, the used data sets in EKC models have been unbalanced and incomplete time series, which have employed pooled cross-sectional econometric techniques (Moomaw and Unruh, 1997). Therefore, the literature provides mixed findings by using large sets of countries; resulting supporting the existence of the EKC hypothesis (Grossman and Krueger, 1991; Panayotou et al., 1993; Selden and Song, 1994;

Grossman and Krueger, 1995; Cole, Rayner, and Bates, 1997; Torras and Boyce, 1998) and no evidence for the EKC hypothesis (Shafik, 1994; Holtz-Eakin and Selden, 1995; Roberts and Grimes, 1997; Galeotti and Lanza, 1999) have been reported. As Schmalensee, Stoker, and Judson (1998) and Stern (2004) argue, this disparity in the initial results may arise from the misspecification due to the lack of proper explanatory variables.

Following these earlier studies, the mainstream literature on EKC has started to consider the impact of energy consumption on environmental quality as a new main factor. Because the energy consumption associated with fossil fuels is directly related to emissions, which is an essential input in boosting economic growth, both for production and consumption (Lotfalipour, Falahi, and Ashena, 2010; Saboori and Sulaiman, 2013). Particularly, renewable energy has received increasing attention during the last decade since renewable energy, a creditable replacement of fossil fuels, helps lower emissions by increasing its proportion in the total energy consumption (Chiu and Chang, 2009; Qi, Zhang, and Karplus, 2014; Aliprandi, Stoppato, and Mirandola, 2016). In other words, renewable energy is expected to reduce the energy dependency on fossil fuel which induces the structural modifications in the electricity sector (Sadorsky, 2009; Hillebrand et al., 2006). Therefore, considering renewable energy in an analysis allows to capture the composition and technique effects. As a composition effect, increases in renewable energy can reduce pollution levels in energy-intensive-polluted sectors such as transportation and electricity industries by replacing conventional energy sources. Technique effect implies that increases in renewable energy consumption require to adopt new and environmental-friendly technologies in production, which leads to environmental improvement.

At the national-level, recent empirical studies agree on the negative impact from using renewable energy on CO2 emissions but provide mixed results in the validation of the EKC: i) confirming the existence of an inverted U-shaped relationship between income and pollution for 29 OECD countries (Shafiei and Salim, 2014), 27 EU countries (López-Menéndez, Pérez, and Moreno, 2014), 25 OECD countries (Jebli, Youssef, and Ozturk, 2016), 17 OECD countries (Bilgili, Koçak, and Bulut, 2016), the European Union (Dogan and Seker, 2016), 27 advanced economics (Al-Mulali and Ozturk, 2016), 173 countries (Balado-Naves, Baños-Pino, and Mayor, 2018), 74 nations (Sharif et al., 2019), 27 EU Members (Baležentis et al., 2019), BRIGS countries (Ulucak, Khan, et al., 2020) and 66 developing countries (Akram et al., 2020); ii) supporting for the non-existence of the EKC in the North Africa, Sub-Saharan Africa and Golf States (Al-Mulali, Ozturk, and Solarin, 2016), and the selected 25 African countries (Zoundi, 2017); iii) suggesting the N-shaped EKC in 74 countries (Allard et al., 2018).

On the other hand, few studies show that electricity consumption associated with renewable sources leads to increase CO_2 emissions while confirming the existence of the EKC in 10 Middle East and North Africa countries (Farhani and Shahbaz, 2014) and 28 Sub-Sahara African countries (Adams and Nsiah, 2019). Given the results, authors suggest that renewable energy generation has not reached the required certain threshold to gain positive benefits on the environment due to the inadequate storage technology and intermittent nature of renewable sources (Adams and Nsiah, 2019). In other words, renewable energy has been less developed, being costly and economically less competitive in those regions (Farhani and Shahbaz, 2014).

In the last decade, it has been perceived that the EKC hypothesis has been investigated by the importance of renewable energy in different areas of the world. However, these empirical verifications, similar to the earlier EKC studies, mostly employ transversality data or panel data in national level, assuming the coincidence of individuals in development path and environmental evolvement level (Bo, 2011). As List and Gallet (1999) argue, a 'one size fits all' reduced-form regression analysis may present statistically biased results by ignoring the differences of economic development path, existing in different regions.

Carson, Jeon, and McCubbin (1997) notice that the earlier EKC studies have run into inevitable data issues on comparability and quality by concentrating on a wide range of countries. To avoid these issues, they first use seven types of state-level air pollutants over the time period 1988-1994 for the analysis of the income-emissions relationship. The results of the cross-sectional regression models offer support for the EKC hypothesis at the state-level. At the same time, they provide strong evidence of heteroscedasticity as showing that there is larger variability in per capita pollutant levels in higher-income states. After that, List and Gallet (1999) examine the relationship between income and per capita emissions for SO_2 and NO_x at state-level by using the panel of 48 states over 1929-1994, which excluded Alaska and Hawaii. The estimates generated by the Ordinary Least Square (OLS) model provide evidence in favor of the EKC hypothesis. However, the OLS estimators for the individual states are substantially different across states in terms of parameter significance levels and turning points. Since this confirms an existence of state-level heterogeneity, the results of the whole panel, which employed the OLS method, may be biased. Millimet, List, and Stengos (2003) replicate estimates according to List and Gallet (1999) with both parametric and nonparametric methodologies. Given the results, the authors address that there is a state-level inverted U-shaped relationship between pollution levels and income, regardless of modeling assumptions. Additionally, Flores, et al. (2014) also produce consistent findings with Millimet, List, and

Stengos (2003) by using a panel quantile regression fixed effects model on the panel data of List and Gallet (1999).

Later, Aldy (2005) has also noticed the importance of state-level analysis. The author asserts that with a state's dataset, the analysis provides better evidence of the EKC hypothesis at high-income levels since the U.S. is "a set of economies that have achieved advanced stages of economic development." This paper uses state-level CO_2 emissions associated with fossil fuel combustion across the 48 states over the period 1960-1999. Particularly, the author compares the estimations between production-based and consumption-based CO_2 emissions because a state's emissions-intensity of production may differ from its intensity of consumption. Based on the estimations of OLS and Feasible Generalized Least Squares, the results support the validation of the state-level EKC hypothesis. Furthermore, the analysis finds that the consumption-based EKCs are associated with higher income levels at emissions levels than production-based EKCs. Given this result, the author argues that higher income states may have the downward trend in CO_2 emissions because individuals in those states consume more imported carbon-based goods such as electricity, and lower income states may export more carbon-based goods.

In the recognition of linkages between emissions and commerce within a state, Burnett, Bergstrom, and Dorfman (2013) argue that there is potential spatial dependence between state-level energy consumption and state-level economic activities, which in turn leads to generate CO2 emissions. To account for spatial dependence, they employ spatial autoregressive models for the 48 contiguous states over 1970-2009. This study provides evidence in favor of the EKC hypothesis and finds that economic distance between states leads an increase in inter- and intra-state emission levels. In addition, the results show that economic activity has positive spatial spillovers and prices of oil and electricity have negative spatial spillovers to state-level energy-related CO_2 emissions.

At state-level, there are very few studies on analyzing the inter-relationship between pollutant emissions, economic growth, and renewable energy consumption within the Environmental Kuznets Curve (EKC) framework. Isik, Ongan, and Özdemir (2019) investigate the underlying association between CO_2 emissions, economic development, population, and renewable and fossil energy consumptions for the 50 U.S. states and Washington, D.C. between 1980 and 2015. After applying the common correlated effects and the augmented mean group estimation procedures, this paper provides inconclusive results for the validation of the EKC hypothesis and the effect of renewable energy consumption on CO_2 emissions. Additionally, they find that both fossil fuel consumption and population have positive and statistically significant effects on CO_2 emissions. The most recent study by Salari, Javid, and Noghanibehambari (2021) examines the elements affecting CO_2 emissions for 50 U.S. states and the District of Columbia during 1997-2016 by employing OLS as static models and generalized method of moments as dynamic estimators. Both static and dynamic models reveal that non-renewable, residential and industrial energy consumption tend to increase per capita CO_2 emissions, while renewable energy consumption tends to decrease emissions. Also, the results support the validation of the EKC hypothesis across states. However, they limit to account for other variables correlated with emission levels; therefore, they may produce bias estimates due to omitted variables.

3.3 Data and descriptive statistics

In order to study the influences of economic growth and renewable energy consumption on CO_2 emissions, this paper constructs a balanced panel of 48 U.S. states over the period 1997-2017. Following the previous literature on U.S. state-level analysis, I drop both Alaska and Hawaii due to geographic isolation from the other states. As environmental degradation indicator, the energy-related CO_2 emissions data is obtained from the U.S. Energy Information Administration (EIA). The EIA estimates the state-level energy-related CO_2 emissions by including direct fossil fuel use across all sectors, including industrial, residential, commercial, and transportation, as well as fossil fuels consumed for electricity generation at the location where primary fuels are consumed. In order to control for population growth within a state, I converted to its per capita form; thus, the estimates are offered in units of thousand metric tons per person. The state per capita real gross domestic product (GDP) in chained in 2012 dollars is used as a measure of economic growth which obtained from the U.S. Bureau of Economic Analysis (BEA). The EIA offers energy consumption by resource types in billion British thermal units. Renewable energy consumption is defined as energy consumption from renewable resources such as wind, biomass, hydroelectric, geothermal, and solar. For the empirical analysis, I use the share of renewable energy in total energy consumption to capture the structural effect from energy sector.

Furthermore, this paper includes both climate and energy price variables to reduce the possibility of omitted variable bias. In order to control climatic influences on energy demand, I use Heating Degree Days (HDD) and Cooling Degree Days (CDD), which are units of measure to relate the day’s temperature to the energy demand of heating (or cooling) at a residence or place of business. These climate variables are obtained from the National Climatic Data Center within the National Oceanic and Atmospheric Administration’s National Environmental

Satellite, Data, and Information Services. To control energy demand, I also include average electricity price in dollars per MMBtu[5]. Additionally, I include average primary energy price in dollars per MMBtu to control energy production. To obtain real values of electricity price and primary energy price, I deflated the annual nominal data using the Consumer Price Index (2015=100). Table 3.1 presents a detailed description, measurements, supporting references, and sources of the data. Table 3.2 describes the main descriptive statistics associated with the actual values of variables over the period from 1997 to 2017.

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[5] Notes: MMBtu represents for 1,000,000 British thermal units. British thermal unit means the quantity of heat required to increase the temperature of 1 pound of liquid water by 1°F at the temperature at which water has its greatest density (EIA).

TABLE 3.1: Data Summary

Variable	Description	Supporting references	Source
CO2	Per capita energy-related CO2 emissions (thousand metric tons)	Aldy (2005), Burnett, Bergstrom, and Dorfman (2013), Apergis, Christou, and Gupta (2017), Atasoy (2017), Salari, Javid, and Noghanibehambari (2021)	EIA
GDP	Per capita real gross domestic product by state (chained in 2012 dollars)	Burnett, Bergstrom, and Dorfman (2013), Apergis, Christou, and Gupta (2017), Atasoy (2017), Isik, Ongan, and Özdemir (2019)	BEA
S_RE	Share of renewable energy in total energy consumption (%)	Isik, Ongan, and Özdemir (2019), Salari, Javid, and Noghanibehambari (2021)	EIA
HDD	A unit of measure to relate the day's temperature to the energy demand of heating at a residence or place of business	Aldy (2005), Burnett, Bergstrom, and Dorfman (2013)	NCDC
CDD	A unit of measure to relate the day's temperature to the energy demand of cooling at a residence or place of business	Aldy (2005), Burnett, Bergstrom, and Dorfman (2013)	NCDC
E_PRICE	Real average electricity price (dollars per MMBtu)	Burnett, Bergstrom, and Dorfman (2013)	EIA
F_PRICE	Real average primary energy price (dollars per MMBtu)	Burnett, Bergstrom, and Dorfman (2013)	EIA

TABLE 3.2: Summary statistics of U.S. state-level data, 1997-2017

Variable	Mean	Std. Dev.	Min	Max	Obs.
CO_2	23.638	18.957	7.999	129.18	1,008
GDP	47,689	9,188	29,959	78,075	1,008
S_RE	0.105	0.108	0.0043	0.54	1,008
HDD	5,075	1,998	341	9,845	1,008
CDD	1,123	785	94	3,836	1,008
E_PRICE	29.053	8.127	16.524	58.509	1,008
F_PRICE	15.423	4.593	5.554	27.576	1,008

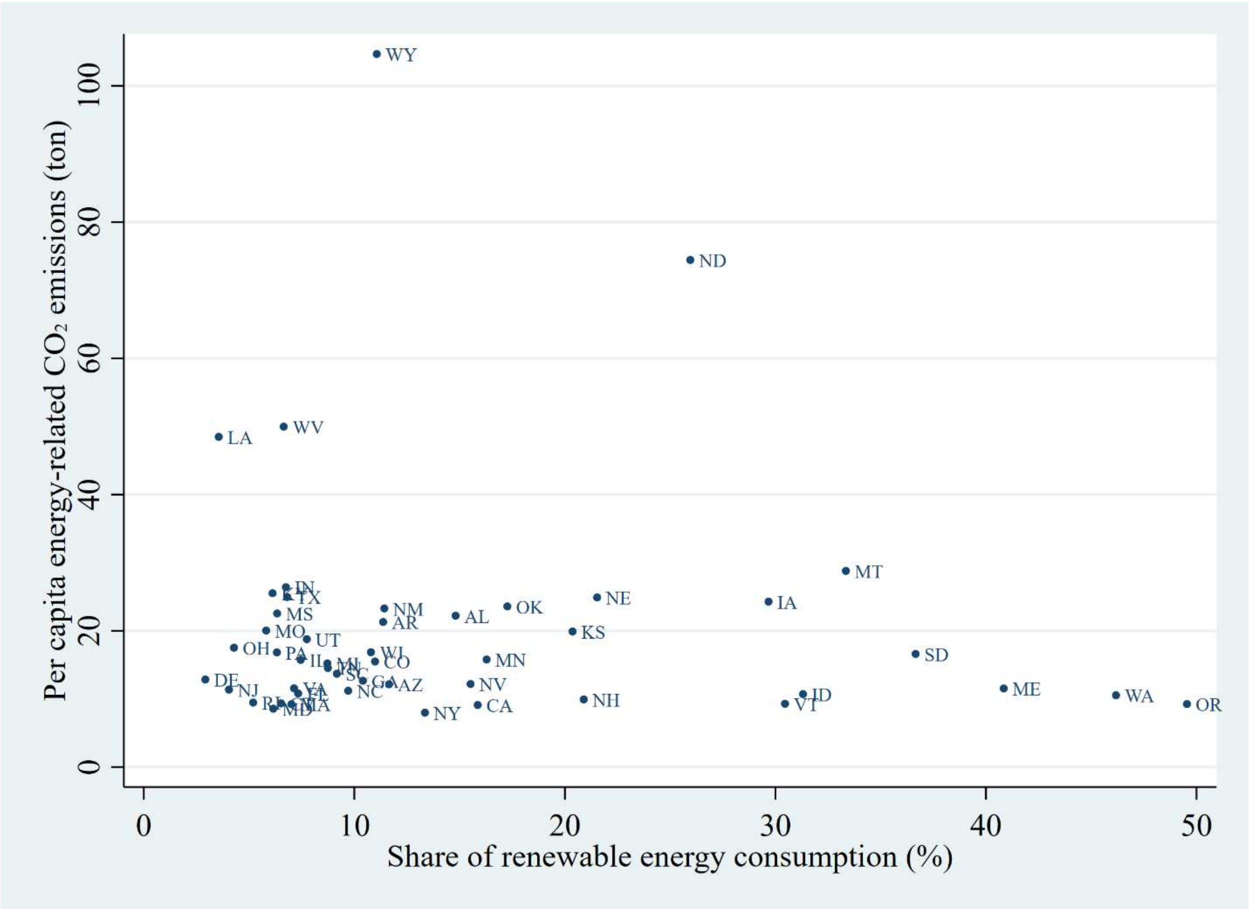

FIGURE 3.2: Relationship between share of renewable energy consumption and per capita energy-related CO2 emission across 48 U.S. states in 2017.

3.4 Econometric approach

This paper employs panel data regression models, starting with panel fixed-effects (FE) model. In the presence of heteroscedasticity, OLS estimations are not suitable since disturbances have different variances, which violates the assumption of spherical disturbances in traditional models. As a better alternative, the FE approach allows to mitigate heterogeneity across states and helps to avoid the concerns about the presence of multicollinearity problems between independent variables (Wooldridge, 2010). To estimate the model, I take the logarithm of all the variables to better interpret the results in terms of changes in those variables. The following regression model is proposed:

$$lnCO2_{s,t} = \beta_0 + \beta_1 lnGDP_{s,t} + \beta_2 lnGDP^2{}_{s,t} + \beta_3 S\_RE_{s,t} + \beta_4 lnHDD_{s,t} + \beta_5 lnCDD_{s,t}$$
$$+\beta_6 lnE\_PRICE_{s,t} + \beta_7 lnF\_PRICE_{s,t} + \theta_s + e_{s,t} \tag{3.1}$$

where the subscripts *s* and *t* denote the state and time periods, respectively. $CO2$ are per capita energy-related CO_2 emissions; GDP denotes per capita real gross domestic product by state; S_RE denotes share of renewable energy in total energy consumption; *HDD* denotes heating degree days; *CDD* denotes cooling degree days; *E_PRICE* denotes electricity price; *F_PRICE* denotes primary energy price; θ_s denotes state-specific fixed effect; $e_{s,t}$ denotes error term. The observations are available in the 48 states from 1997 to 2017 so that s=48 and t=21.

For the additional robustness analysis, I use the Method of Moments Quantile Regression (MMQR) with fixed effects developed by Machado and Silva (2019). In general, quantile regression approaches are used when the variables have different effects based on the conditional distribution of the dependent variable. Because, the conventional mean regression models such as OLS method cannot prove these heterogeneous effects since those analyses primarily investigate the effect of explanatory variables on the conditional means of the dependent variable. Therefore, the mean regression tends to emphasize the central tendency of the conditional distribution, which ignores the influence of independent variables for the entire distribution of the variables (Padhan et al., 2020). In contrast to the conventional mean regression, the MMQR estimation technique allows to control for distributional heterogeneity and consider the potential effects of the independent variables across the conditional distribution of dependent variable, which providing relatively more robust results. The MMQR approach particularly makes it possible to capture the conditional heterogeneous covariance effects of the influences of CO_2 emissions by considering the individual effects, which affect the whole distribution, rather than just shifting means as in the other panel quantile regression approaches (Ike, Usman, and Sarkodie, 2020). In other words, this method estimates conditional quantile effects through known location and scale functions, both of these estimates identified by conditional expectations of appropriately defined variables (Machado and Silva, 2019).

The estimation of the conditional quantiles of CO_2 emissions, $Q_{CO_2}(\tau|X)$, for a location-scale model takes the following form:

$$\mathrm{CO2}_{s,t} = \alpha_s + X'_{s,t}\rho + (\delta_s + Z'_{s,t}\gamma)U_{s,t} \tag{3.2}$$

where the probability, $P\{\delta_s + Z'_{s,t}\gamma > 0\} = 1$. The parameters $(\alpha_s, \delta_s), s = 1, \dots, 48$, capture the individual state fixed effects and *Z* is known differentiable transformations of the components of *X*. $X_{s,t}$ is independently and identically distributed for any fixed state s and independent across time t. ρ represents a vector of estimated parameters in the equation, which vary on different quantile τ of CO_2. $U_{s,t}$ is an unobserved random variable and independently and identically distributed across individual state *s* at time *t*. And $U_{s,t}$ is statistically independent of $X_{s,t}$ and normalized to prove the moment conditions in Machado and Santos Silva (2019):

$$E(U) = 0 \text{ and } E(|U|) = 1. \tag{3.3}$$

Thus, Equation (3.2) implies the following:

$$\begin{aligned} Q_{\mathrm{lnCO2}_{s,t}}(\tau|X_{s,t}) = (\alpha_s + \delta_s q(\tau)) + \rho_1 lnGDP_{s,t} + \rho_2 lnGDP^2{}_{s,t} + \rho_3 S\_RE_{s,t} + \rho_4 lnHDD_{s,t} + \\ \rho_5 lnCDD_{s,t} + \rho_6 lnE\_PRICE_{s,t} + \rho_7 lnF\_PRICE_{s,t} + \varepsilon_t \end{aligned} \quad (3.4)$$

where $Q_{\mathrm{lnCO2}_{s,t}}(\tau|X_{s,t})$ represents the quantile distribution of the dependent variable CO2 (natural logarithm of energy-related CO2 emissions per capita) which is conditional on the location of independent variable $X_{s,t}$. Scalar coefficient $\alpha_s(\tau) \equiv \alpha_s + \delta_s q(\tau)$ is the quantile- τ fixed effect for state *s*, or the distributional effect at τ. Unlike the usual fixed effects, the distributional effect indicates the heterogenous impacts of time-invariant characteristics, which allowed to capture different effects on different states of the conditional distribution on CO2. $q(\tau)$ indicates the τ-th sample quantile which satisfies the condition, $\int_0^1 q(\tau)\, d\tau = 0$, which implies that α_s can be interpreted as the average effect for state *s*.

The EKC hypothesis indicates that the expected signs of per capita GDP (GDP) and per capita GDP square (GDP^2) are positive and negative respectively, to postulate an inverted U-shape relationship between economic growth and environmental degradation. As an increase in scale of economic activity, CO$_2$ emissions tend to rise, which called a scale effect; however, as the economy shifts to towards services industries and light manufacturing with cleaner technologies, environmental quality gets improved, which are called composition and technique effects, respectively. The expected sign of share of renewable energy consumption (*S_RE*) would be negative. Since renewable energy consumption has been expected to reduce emissions and promote environmental quality when renewable energy consumption yields lowering fossil fuels consumptions and adopting environmental-friendly technologies, which considered as composition and technique effects, respectively. The expected signs of heating degree days

(*HDD*) and cooling degree days (*CDD*) are positive because HDD and CDD reflect the effects of high temperatures in summer and lower temperature in winter on energy demand. In other words, these weather fluctuations can cause more energy consumption, and consequently increase CO_2 emissions. Following the law of demand, the expected signs of average electricity price (*E_PRICE*) and average primary energy price (*F _PRICE*) are negative.

3.5 Results

Table 3.3 shows the estimation results of panel fixed effects (FE) and MMQR with fixed effects by the Machado and Silva (2019). Both estimations have the expected signs which discussed in the previous section. The results of FE provides strong evidence of an inverted U-shaped relationship between economic growth and environmental degradation. This supports that boosting economic activities requires more energy consumption and consequently, generates CO_2 emissions. Also, it confirms that increasing share of renewable energy in total energy consumption and higher electricity prices and primary energy prices tend to mitigate CO_2 emissions whereas increasing heating degree days induces CO_2 emissions through increasing energy demand.

With regard to the MMQR, the results are respectively reported for the 5th-95th quantiles of the conditional distribution of CO_2 emissions. More importantly, the MMQR results do not provide statistically significant evidence of the existence of the EKC hypothesis in 48 U.S. states across all quantiles. Another key finding is that renewable energy consumption has negative effect on CO_2 emissions throughout the conditional distribution, a 1% increase in share of renewable energy reduces emissions by 0.99%-1.271%. But this mitigating effect of renewable energy on CO_2 is stronger at the lower quantiles. One possible explanation is that low-CO_2

emission states may have more stringent environmental regulation compared to high-CO_2 emission states. For instance, a stricter regional environmental regulation may result in substitution toward less pollution-intensive industries with cleaner technologies. Thus, low-CO_2 emission states tend to have substantial marginal effects from renewable energy consumption on emission reduction as showing the greater magnitudes of the estimated effect of a 1% increase in share of renewable energy in total energy consumption. This finding agrees with the research conclusions of Isik, Ongan, and Özdemir (2019).

Moreover, the results explain that an increase in heating degree days tends to generate more CO_2 emissions at all quantiles, ranging 0.235%-0.369%, while the impact of electricity price on emissions shows a decreasing trend at all selected quantiles, ranging from -0.227% to -0.367%, which is consisted with Aldy (2005) and Burnett, Bergstrom, and Dorfman (2013). These findings could be attributed to the positive correlation between residential energy consumption and colder days, and negative correlation between energy demand and electricity price. Specifically, MMQR results indicate that both heating degree days and electricity price have a stronger impact at the lower quantiles, implying that residential energy consumption may account for a larger proportion of total energy consumption in low-CO_2 emission states. Finally, in agreement with Burnett, Bergstrom, and Dorfman (2013), the MMQR estimates find that the influence of primary energy price on CO_2 emission is negative: a 1% increase in primary energy price decreases emissions by 0.1%-0.126%. Specifically, energy prices have stronger mitigation effects at the higher quantiles. This result may stem from the different sectoral energy demand across states as mentioned above. That is, industrial or electric power sector might be a main driver of energy consumption rather than residential sector in high-CO_2 emission states. Overall, the MMQR results are quite robust for the results from FE model.

TABLE 3.3: Results of panel fixed-effect and panel quantile regression

Variables	FE	Quantiles									
		0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
lnGDP	3.846*	5.322	4.861	4.546	4.257	3.936	3.634	3.391	3.188	2.928	2.542
	(2.252)	(6.167)	(4.760)	(3.869)	(3.148)	(2.561)	(2.361)	(2.511)	(2.821)	(3.386)	(4.421)
GDP^2	-0.173*	-0.248	-0.225	-0.209	-0.194	-0.178	-0.162	-0.150	-0.140	-0.126	-0.107
	(0.105)	(0.287)	(0.221)	(0.180)	(0.146)	(0.119)	(0.110)	(0.117)	(0.131)	(0.158)	(0.206)
S_RE	-1.122***	-1.271***	-1.224***	-1.192***	-1.163***	-1.131***	-1.100***	-1.076***	-1.055***	-1.029***	-0.990***
	(0.109)	(0.294)	(0.227)	(0.184)	(0.150)	(0.122)	(0.112)	(0.120)	(0.134)	(0.161)	(0.210)
lnHDD	0.298***	0.369***	0.347***	0.332***	0.318***	0.302***	0.288***	0.276***	0.266***	0.254***	0.235***
	(0.0375)	(0.0904)	(0.0698)	(0.0567)	(0.0462)	(0.0376)	(0.0347)	(0.0368)	(0.0414)	(0.0496)	(0.0648)
lnCDD	-0.0203	-0.0536	-0.0432	-0.0361	-0.0296	-0.0223	-0.0156	-0.0101	-0.00551	0.000355	0.00905
	(0.0127)	(0.0363)	(0.0280)	(0.0228)	(0.0185)	(0.0151)	(0.0139)	(0.0148)	(0.0166)	(0.0199)	(0.0260)
lnE_PRICE	-0.292***	-0.367***	-0.343***	-0.328***	-0.313***	-0.297***	-0.282***	-0.270***	-0.259***	-0.246***	-0.227***
	(0.0351)	(0.104)	(0.0805)	(0.0655)	(0.0533)	(0.0434)	(0.0400)	(0.0425)	(0.0477)	(0.0573)	(0.0748)
lnF_PRICE	-0.114***	-0.100**	-0.105***	-0.107***	-0.110***	-0.113***	-0.116***	-0.118***	-0.120***	-0.122***	-0.126***
	(0.0128)	(0.0392)	(0.0303)	(0.0246)	(0.0200)	(0.0163)	(0.0150)	(0.0160)	(0.0179)	(0.0215)	(0.0281)
State FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
R-squared	0.976										
Obs.	1,008	1,008	1,008	1,008	1,008	1,008	1,008	1,008	1,008	1,008	1,008

Note: Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

3.6 Conclusion and policy implications

As a contribution to the EKC-related literature in the light of renewable energy consumption, this paper examines the empirical linkages between energy-related CO_2 emissions, GDP, and renewable energy consumption while validating the EKC hypothesis at state-level. The EKC hypothesis posits that environmental degradation first increases until it reaches a threshold point of income and then declines over the later stages of economic growth because economic growth affects environment quality via three effects: scale, composition, and technique. In other words, at the early stage of economic development, expansion in the scale of economic activities accelerates with the pollution intensity; or, the intensification of resource extraction induces increasing waste generation and boosting environmental degradation. At higher levels of economic development, on the other hand, the economy experiences structural and technological change towards services and information-intensive industries along with stringent environmental regulations, raised environmental recognition, and cleaner technology, which result in environmental improvement. Given the great importance of achieving sustainable economic growth, however, it has been suggested that replacement for fossil fuels by renewable energy sources can reduce environmental pollution. Because renewable energy can decrease emissions caused by economic activities through an increasing in renewable energy consumption in energy-intensive-polluted sectors and adopting environmental-friendly technologies in production.

For the empirical analysis, this paper uses panel data of 48 contiguous U.S. states from 1997 to 2017 by employing FE and the MMQR. Additionally, this paper includes heating degree days, cooling degree days, electricity price, and primary energy price as explanatory variables to obtain the robust findings. Several findings are highlighted. First, the coefficients of all variables, except cooling degree days, have the expected signs and mostly strongly significant across various estimation techniques. That is, the baseline results indicate: 1) an inverted-U shape relationship between economic growth and CO_2 emissions, supporting the EKC hypothesis at state-level particularly in FE estimation; 2) increases in renewable energy consumption, electricity prices, and primary energy prices help to mitigate CO_2 emissions, and 3) an increase in heating degree days tends to cause more CO_2 emissions. Second, using the MMQR models allows to produce relatively robust results by considering the effects of outliers and reducing the possible covariates and heterogeneity. Third, the MMQR results illustrate the impacts from renewable energy consumption is gradually decreasing while moving from lower to higher quantiles. This result implies that states at lower quantiles (low-CO_2 emission states) may have more stricter environmental regulations than those at higher quantiles (high-CO_2 emission states). Fourth, heating degree days and electricity prices have stronger impacts on CO_2 emissions at lower quantiles while primary energy prices have more significant effect on CO_2 emissions at higher quantiles. It can be interpreted that residential sector is the main driver of total energy consumption in low-CO_2 emission states while transportation or electric power sector account for greater proportions of energy consumption in high-CO_2 emission states.

Throughout the empirical analysis, this paper provides important implications for national and state environmental policies to energy-related emission abatement. Apparently, policymakers need to consider states' individual characteristics such as their economic development level, energy intensity and energy consumption patterns in their economic sectors to implement different regional policy tools rather than a single policy recommendation. Moreover, the existence of an inverted U-shaped relationship between GDP and CO_2 emissions suggests that after a certain threshold point, the economic activities and economic growth lead to reduced environmental pollutions without any government intervention. However, environmental policies promoting renewable energy development or adopting cleaner technologies can further contribute to the reduction of environmental emissions originated from the use of fossil fuels. Furthermore, energy-related emissions will be reduced by a larger amount when electricity prices and fossil fuel prices increase. In other words, energy demand related to traditional resources can be reduced through price mechanisms for energy resources such as providing subsidies for environment friendly technologies and levying taxes on emissions.

Chapter 4

The Impact of Renewable Energy on Residential Electricity Prices in the U.S.

4.1 Introduction

As a replacement for conventional sources of energy, it is well known that renewable energy contributes to achieve the mitigation of greenhouse gas emissions target with zero emission technologies. In addition to the environmental benefits, it also provides economic benefits as avoiding high costs of fossil fuel, which reduces dependence on energy imports, and increasing green job opportunities through the high investment in the renewable energy projects (Carlson, Loomis, and Payne, 2010; Slattery, Lantz, and Johnson, 2011; Armeanu, Vintilă, and Gherghina, 2017). Given the environmental and socioeconomic advantages stemming from renewable energy sources, electricity from renewable energy has been supported by government policies such as investment tax credits, production tax credits, the Clean Power Plan, Renewable Portfolio Standards, and loan guarantees. As a result, the electric power sector became the main driver of renewable energy consumption among the five major sectors, including residential, commercial, industrial, transportation, and electric power, in the U.S, which accounted for approximate 56% in 2019[6].

Despite of the benefits from using renewable energy sources, a debate has arisen about its effects on electricity prices. In general, renewable energy is characterized as having high capital investment and very low marginal operation costs. Due to the financial burden of renewable

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[6] Source: EIA's Monthly Energy Review (April, 2020). Retrieved from https://www.eia.gov/totalenergy/data/monthly/

energy installation, supportive government policies play important roles in making renewable energy cost-competitive (Wiser, Bolinger, and Barbose, 2007; Cox, 2016; Ciarreta, Espinosa, and Pizarro-Irizar, 2017). The U.S. electricity production subsidy for renewable energy resources has been increased from $0.8 billion in 2010 to $10.2 billion in 2016, which accounted for 10.9% and 12% of total energy production subsidies, respectively (EIA, 2018). A production subsidy is usually provided above the wholesale electricity prices to cover the costs of renewable energy generation, which were above the conventional electricity costs (Trujillo-Baute, Río, and Mir-Artigues, 2018). And these financial supports are reflected in the wholesale electricity prices and then translated into electricity bills, which paid by consumers. In other words, expansion of renewable energy generation can cause an excessive cost burden to consumers as increasing retail electricity prices (Sisodia et al., 2015; Trujillo-Baute, Río, and Mir-Artigues, 2018).

Given the characteristics of the price formation in the electricity market and low marginal costs, however, it is expected that the use of renewable energy can reduce the retail electricity prices by the so-called merit-order effect. In the wholesale electricity market, conventional power plants with the highest marginal cost set the price which called the merit order. Since renewable energy has very low marginal costs to generate electricity, once renewable energy generation projects have been constructed (Bell et al., 2017), substituting fossil fuels with renewable resources can exert a downward pressure on the wholesale market prices (Costa-Campi and Trujillo-Baute, 2015). In turn, the reduction in wholesale electricity prices can be relieved an increase in the retail prices resulting from financial supports for renewable energy development (Jensen and Skytte, 2003; Bell et al., 2017).

Further, many of renewable energy sources for electricity generation, such as wind, solar, wave, and tidal, are intermittent and sometimes unpredictable. Therefore, it cannot offer the same level of electricity service that can be obtained by using conventional fossil fuels. Because of the presence of uncertainties, the forecasting errors of renewable energy generation must be replaced elsewhere in the demand/supply loop (Jacobsen and Zvingilaite, 2010; Finn and Fitzpatrick, 2014). The intermittent nature of renewables causes an increase in the wholesale market price volatility (Hagemann, 2015; Gürtler and Paulsen, 2018; Kulakov and Ziel, 2019), and the effect of this variation on the retail prices is not clear.

Despite of the concerns about the potential impact on consumers' welfare, there are very few studies provide empirical support for the argument, especially in the U.S. The main objective of this paper is to empirically examine the impact of renewable energy generation on residential electricity prices to evaluate the distributive welfare impact of support schemes for renewable energy generation. In order to pursue this goal, this study proposes the empirical models with the following economic variables related to renewable energy generation in the U.S. electricity market: electricity price in the residential sector, share of renewable energy in total electricity generation, electricity consumed by the residential sector, primary energy price in the residential sector, climate variables, and policy influences from renewable portfolio standard. The consideration of all these variables allows to take into account the possible relationship between renewable energy generation and the retail electricity price. For the empirical analysis, this paper uses dataset of 48 U.S. states from 2001 to 2018 with employing the feasible generalized least squares and the two-step generalized method of moments.

Accordingly, the rest of this paper is organized as follows. The next section describes background information on the U.S. electricity generation and Section 3 offers an overview of existing literature. Section 4 presents the dataset with the explanation of the variable selection and trends of renewable energy generation in the U.S. Section 5 describes empirical modeling strategy. Section 6 illustrates the empirical findings. Finally, Section 7 provides discussion for further research.

4.2 Background of the U.S. electricity market

According to the U.S. Energy Information Administration (EIA), the primary energy sources have dominated in generating electricity. Fig.4.1 illustrates the trends in net electricity generation by resource types and average day ahead wholesale electricity prices[7] from 2001 to 2018. Remarkably, coal and natural gas have comprised more than 60% of total energy generation during the period. In detail, electricity generation from coal has been declined from 51% to 27.4% whereas electric power generation from gas has been increased from 17.3% to 35.4%. The share of renewable energy, such as hydropower and wind, in the total electricity generation has been increased from 7.8% to 17.8%. Particularly, hydro is the major renewable power source, accounting for 5.57% and 6.84% of total electricity generation in 2001 and 2018, respectively. Also, electricity generation from wind has been significantly increased from 0.18% to 6.6%. Regard to the wholesale electricity price, it has been fluctuated as showing the highest price, \$76.52/MWh, in 2008 and the lowest price, \$30.31/MWh, in 2016. However, the wholesale price appears to be less volatile since 2008 and overall, it shows a decreasing trend.

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[7] The weighted-average prices posted under EIA's agreement with the Intercontinental Exchange represent eight major electricity hubs including Mid–C, PJM West, SP15-1 (SP15-2), Palo Verde, Mass Hub, Indiana Hub, NP15, and ERCOT North. Source: https://www.eia.gov/electricity/wholesale/

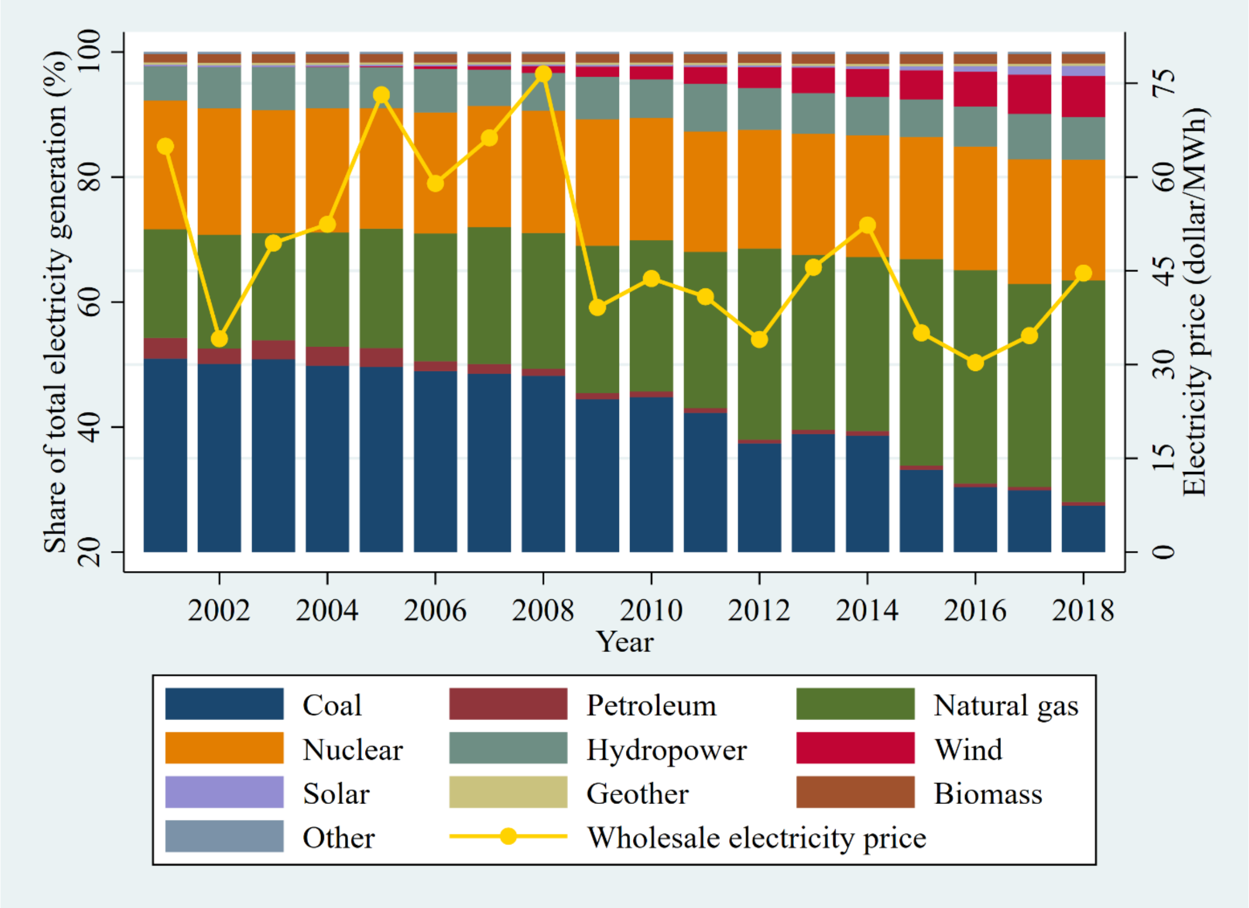
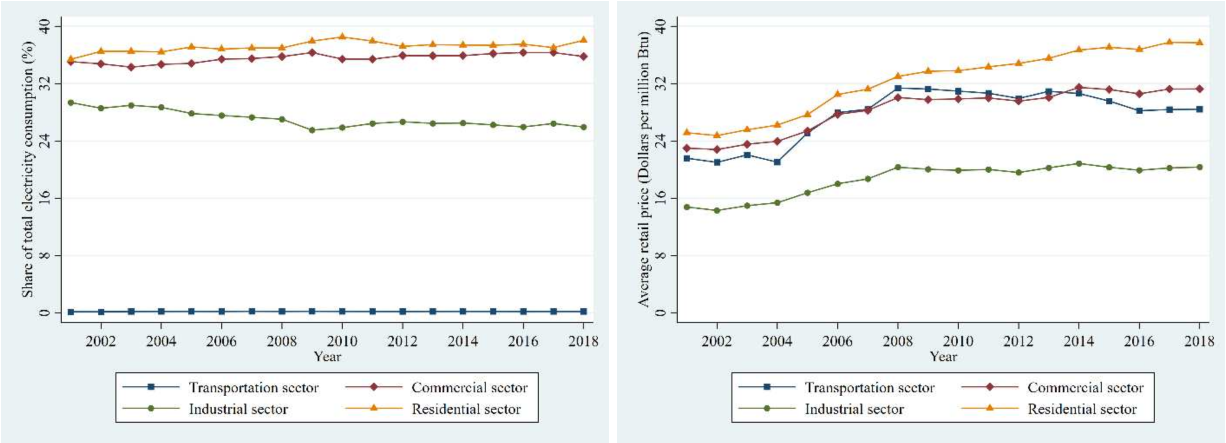


FIGURE 4.1: Trends in net electricity generation by resource types and wholesale electricity price.

Fig.4.2 describes the historical changes in the sectoral retail electricity consumption (Fig. 4.2.A) and sectoral retail electricity prices (Fig. 4.2.B) in the U.S. between 2001 and 2018. With regard to retail electricity consumption, residential sector accounts for the largest proportion of total electricity consumption with an increasing trend: for instance, residential sector accounts for 38% of the total retail electricity sales in 2018, followed by commercial (35.8%), industrial (25.9%), and transportation (0.2%) sectors. At the same time, residential consumers of electricity have paid higher rates than other sectoral consumers: for instance, residential, industrial, and commercial electricity consumers paid an average $37.71, $31.27, and $20.36 per MMBtu3 in 2018, respectively. Additionally, residential electricity prices rapidly increased by 49.9% during the period, from $25.16/MMBtu in 2001 to $37.71/MMBtu in 2018. As Iimura and Cross (2018) point out, the industrial electricity prices may be set by contract and impacted by economic policy to ensure international competitiveness and protect energy-intensive domestic sectors from transferring production overseas. Therefore, the residential electricity prices are suitable to be integrated a development of renewable energy generation in electricity markets.



(A) Electricity consumption by sector (B) Electricity prices by sectors

FIGURE 4.2: Trends in annual retail electricity market

In the U.S., one of the widely adopted state renewable energy support policies is Renewable Portfolio Standard (RPS). Under this scheme, energy suppliers are required to provide a certain amount of their energy portfolio from renewable sources. As of 2018, twenty-nine states[8] have established renewable energy targets by adopting a mandate RPS which is legally binding. Each RPS state has a unique policy design specifying allowed types of

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[8] Arizona, California, Colorado, Connecticut, Delaware, Hawaii, Illinois, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, Ohio, Oregon, Pennsylvania, Rhode Island, Texas, Vermont, Washington, Wisconsin and Washington, D.C.

renewables, required amount of energy from renewables, and deadline for the target (Rountree, 2019). Since 2000, RPS programs have been one of the main policy drivers for renewable energy development in the U.S., with more than half of additional renewable energy capacity and renewable electricity generation serving RPS requirements (Barbose, 2017). According to Barbose (2019), the total RPS compliance cost is $4.7 billion in 2018 which is equivalent to 2.6% of average retail electricity price in RPS states and those states continue to revise and refine their RPS policies as increasing RPS requirement in most cases. Fig.4.3 illustrates trends in average residential electricity prices and the share of renewable in the total electricity generation for states that do and do not adopt an RPS, which is regally binding. It shows that states that RPS enacted face a considerably rapid increase both in residential prices and renewable generation. For instance, the average residential electricity price in RPS states has been increased from $27.4 in 2001 to $42.43 in 2018 whereas the average residential price in non-RPS states has been increased from $20.77 in 2001 to $32.63 in 2018. The average share of renewable energy in the total electricity generation in RPS states has recorded 9.4% in 2001 and 20.5% in 2018 while those in non-RPS states have indicated 4.35% in 2001 and 10.74% in 2018.

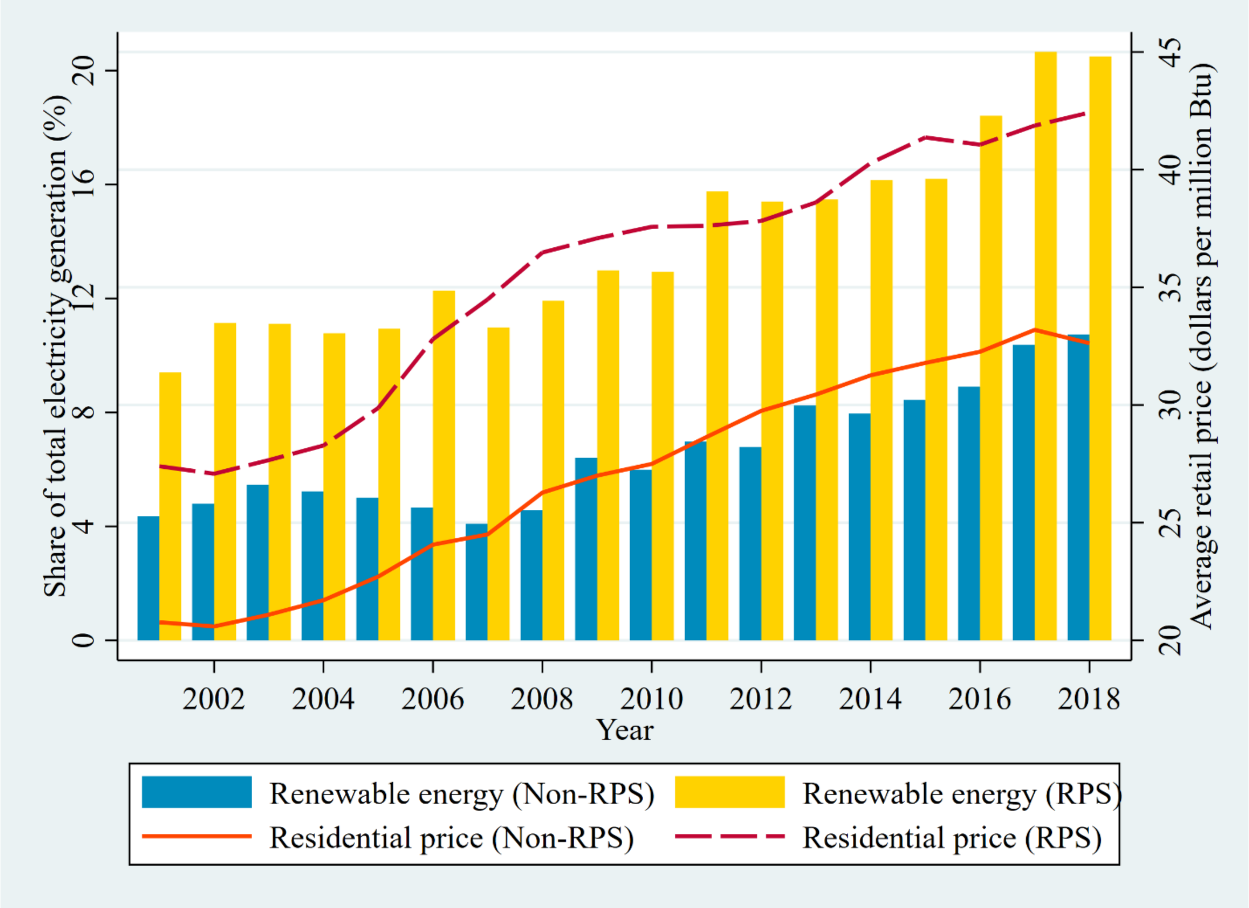

FIGURE 4.3: U.S. Average residential retail electricity prices and trend in the share of renewable energy in the total electricity generation for RPS versus non-RPS states.

4.3 Literature review

Depending on the evaluation of public renewable energy support schemes, existing studies have mixed results. One of the earlier studies, De Miera, Río González, and Vizcaíno (2008), examines the impact of wind electricity generation on electricity prices in Spain. This paper indicates that wind electricity provides both direct and indirect effects on electricity prices. Since the conventional electricity has a higher marginal operation costs than wind electricity, wind generation caused by the displacement of conventional technology tends to lower wholesale electricity prices compared with the lack of wind as a direct effect. On the other hand, wind generation creates less demand for conventional electricity, this yields lower demand for CO2 allowances to comply with the environmental-energy targets such as an emissions trading scheme (ETS) in EU, which is an indirect effect. Therefore, this indirect effect would reduce wholesale electricity prices in the long-term. By considering those two effects, the empirical results show that wind electricity generation in Spain leads to reduced wholesale market prices in range of 8.6—25.1%. In terms of consumer's perspective, the authors provide evidence that the calculated total cost savings for consumers is larger than the net costs of wind electricity promotion. This implies that the increase in the cost of renewable energy support scheme may be offset by the reduction in the wholesale market price, leading to a reduction in the retail electricity price. Similarly, Rathmann (2007) estimates the effect of renewable electricity support system, a CO2 Emission Trading Scheme (ETS), on German retail electricity prices in the first trading period of 2005-2007. The simulation results describe that an increase of renewable energy generation decreases the wholesale prices and, consequently, reduces retail prices for consumers due to additional ETS.

On the other hand, Moreno, López, and García-Álvarez (2012) argue that the public renewable energy support schemes are financed through the electricity market by increasing the retail prices paid by consumers. In the paper, the authors estimate the effect of renewable energy on the household retail electricity prices in 27 European Union countries for the period 1998-2009 by using fixed effects model. The results show that the introduction of the renewable energy sources into the electricity market creates a small final effect on household electricity prices: 1% increasing in renewable electricity causes an increase in the household electricity prices by 0.018%. Regarding electricity power generated from wind, the household electricity prices were increased by 0.031%. In addition, Traber and Kemfert (2009) clearly indicate that there are two competing effects of renewable support policy, the German Feed-in Tariff (FIT), on electricity prices through an oligopolistic German electricity market model including an endogenous emission price determination. As a substitution effect, FIT tends to increase the prices triggered by switching to renewable sources from fossil fuels. As a price effect, FIT reduces the emission permit price, leads to lower consumer prices. They find that the total effect of the support policy decreases the German producer price by 8%, while the consumer price increases by 3%. According to Munksgaard and Morthorst (2008), an increase in the level of wind penetration causes a decline in consumer electricity prices in Denmark. However, taking the subsidy effects, which paid by consumers to the wind electricity producers, into account indicates that consumer prices are higher as compared to a scenario without wind power production.

More recently, Silva and Cerqueira (2017) perform a much more detailed analysis than the previous ones discussed above by examining the main factors of household electricity prices in 23 EU countries from 2000 to 2014. Under the system Generalized Method of Moments (GMM), this paper offers evidence that an increase of the share of renewable sources leads to increased in the household electricity prices, ranged between 0.965% and 1.73%. Furthermore, the gas price and the household electricity consumption per capita have significantly increased household electricity prices whereas market liberalization or deregulation has significantly reduced the prices. Similarly, Iimura and Cross (2018) investigate the effect of renewable energy generation on residential electricity prices in liberalized electricity markets with a panel of seven selected OECD countries over the period 1991-2014. The results using random effects model shows that higher share of renewable energy in electricity generation, higher energy dependency, and higher GDP per capita are clearly associated with increasing household electricity prices.

Moreover, they paper provides that electricity market reform tends to increase household electricity prices, which is in contrast to the results reported in Silva and Cerqueira (2017).

To date, there are few studies that have focused on the effects of renewable generation on the U.S. residential prices. Swadley and Yücel (2011) investigates the effect of deregulation of electricity markets and hydro electricity generation on the real residential electricity price by using a monthly panel of 16 states and the District of Columbia from January 1990 to May 2010. From the results of the GMM dynamic panel model, they show that an increase in the level of market participation by residential customers, price controls, market size, and shares of hydro in total electricity generation tend to reduce retail prices, while increases in coal and natural gas increase rates. Similarly, Kury (2013) confirms that hydro power helps to reduce residential electricity prices by utilizing a panel data of the 48 contiguous states over the period from 1990 to 2008.

As mentioned in the previous section, one of the most widely enacted polices to promote the use of renewable energy in the U.S. is Renewable Portfolio Standards (RPS). The main goals of this policy are reducing greenhouse gas emissions and generating more stable electricity prices in the long-run. Under RPS, electricity retailers are required to generate a certain percentage of their electricity production from renewables, such as solar, wind, geothermal, and biomass. Because of the required extra investments or costs of renewable energy use, it is argued that RPS tends to increase retail electricity prices at least in the short-run (Lesser, 2013). Morey and Kirsch (2013) find that the introduction of an RPS has significantly increased in residential retail prices by 0.451 cent/kWh for the period from 1990 to 2011 by applying ordinary least squares regression with adjustments for conditional heteroscedastic errors. In addition, Tra (2016) uses dataset of electric utilities over 2001-2012 to examine the effect of a RPS mandate on the retail residential and commercial rates. Under the difference-in-difference (DID) framework, the empirical results illustrate that the implementation of RPS causes electric utilities to charge a higher electricity rate but marginal increases in RPS requirements do not translate into higher retail electricity rates. These findings imply that an RPS mandate may require a costly constraint on the utilities and the costs affected by the RPS mandate may tend to be fixed costs. Specifically, Wang (2016) estimates the effect of RPS on residential electricity prices by distinguishing between enactment year, effective year, and the first binding year. For the analysis, the author uses panel data across 47 states over 1990-2011 and the DID analysis. One unique finding is that the RPS mandate leads to increased residential retail electricity prices in the short-run and this change was captured by the first binding mandate of the PRS. Later, Maguire and Munasib (2018) find that no statistically significant evidence that RPS is a contributing factor in increasing electricity price in Texas by utilizing the Synthetic Control Method. The authors argue that this result can arise from the simultaneous adoption of the RPS and market deregulation policies in Texas. In other words, it is necessary to consider other potential determinants of electricity prices such as market structure, availability of renewable energy resources, and energy costs, to identify the effect of RPS on electricity price accurately.

4.4 Data and descriptive statistics

The empirical assessment of the impact of the renewable energy generation on residential electricity prices in the U.S. is conducted through a panel data analysis for 48 states from 2001 to 2018. The used key variables are the electricity prices in the residential sector (*P_RESI*) measured in dollars/ MMBtu, which are not adjusted for inflation, and the share of renewable energy in the overall gross electricity generation (*S_RE*) measured in a percentage of net renewable electricity generation, i.e., generated electricity from renewable sources such as hydro and wind in thousand MWh. Additionally, this paper examines the effect of renewable energy by type, particularly hydro and wind, on residential price, which measured in a percentage of net hydro (*S_HYDRO*) and wind power generation (*S_WIND*), respectively. The share of renewable electricity would be expected to be either positively or negatively associated with residential electricity prices. Because the renewable electricity captures the initial endowment of technically and economically exploitable renewable sources and government support schemes (Iimura and Cross, 2018). On the other hand, the renewable energy electricity creates the long-term price reduction effect (merit-order effect) with the low marginal costs.

This paper also includes a number of control variables that would reasonably be expected to influence residential electricity prices. The cost of energy source is a main factor of electricity prices, thus, average primary energy price in the electric power sector (*F_PRICE*) is included, which measured in $/million Btu. The expected sign of the coefficient would be positive since higher input costs are associated with higher final prices. In addition to that, the electricity consumed by the residential sector (*E_CONS*) in billion Btu is considered. The expected sign of the coefficient would be either positive or negative. Because it is assumed that electricity demand is associated with economic development, it might increase electricity prices. But at the same time, the quantity represents the size of the electricity market therefore, the scale effect might reduce prices (Trujillo-Baute, Río, and Mir-Artigues, 2018).

Additionally, this paper considers climatic effects on residential electricity price by including Heating Degree Days (*HDD*) and Cooling Degree Days (*CDD*). HDD (or CDD) are the aggregate of daily population-weighted units of measure to related cold (or hot) temperature to the energy demand of heating (or cooling) at place of business or a residence. To access the effect of renewable energy support scheme, I include a Renewable Portfolio Standard (RPS) policy dummy variable, which is coded 1 if the policy is binding in a given year. Table 4.1 indicates the first binding years for the RPS in each state. The effect of RPS on electricity prices would be positive because an RPS mandate can be a costly constraint on the electricity generators that have to meet the requirement in the short-run (Tra, 2016), which are usually paid by end use consumers.

Annual state residential electricity prices, net electricity power generation, residential electricity consumption, and costs of fossil fuels are obtained from the U.S. Energy Information Administration (EIA). Annual aggregated HDD and CDD are obtained from the National Climatic Data Center (NCDC) within the National Oceanic and Atmospheric Administration's National Environmental Satellite, Data, and Information Services, and the state policy data is obtained from the Database for State Incentives for Renewables and Efficiency (DSIRE). Table 4.2 summarizes the variables descriptive statistics with their data sources. It illustrates significant variation on the data due to time-series characteristics of the variables and both institutional and structural differences across states.

TABLE 4.1: RPS' first binding year

State	First binding year	State	First binding year
Iowa	1991	Colorado	2007
Maine	2000	Delaware	2007
Wisconsin	2000	Pennsylvania	2007
Arizona	2001	Rhode Island	2007
Connecticut	2001	Montana	2008
New Jersey	2001	New Hampshire	2008
Texas	2002	Illinois	2008
Massachusetts	2003	Ohio	2009
Nevada	2003	North Carolina	2010
California	2004	Missouri	2011
Hawaii	2004	Oregon	2011
Minnesota	2005	Michigan	2012
New Mexico	2006	Washington	2012
New York	2006	Vermont	2015
Maryland	2006		

TABLE 4.2: Summary statistics of U.S. state-level data, 2001-2018

Variable	Mean	Std. Dev.	Min	Max	Obs.	Source
P_RESI	31.989	9.11	16.37	63.33	864	EIA
S_RE	0.153	0.217	0	0.999	864	EIA
S_HYDRO	0.097	0.184	-0.017	0.896	864	EIA
S_WIND	0.031	0.061	0	0.369	864	EIA
F_PRICE	2.55	1.34	0.59	10.37	864	EIA
E_CONS	96,614	92,692	6,856	536,598	864	EIA
HDD	5,086	2,009	341	9,845	864	NCDC
CDD	1,137	780	94	3,836	864	NCDC
RPS	0.411	0.492	0	1	864	DSIRE

4.5 Empirical model

The main purpose of this paper is to investigate the impact of renewable electricity generation on residential retail prices by using a sample of 48 U.S. states during the period 2001-2018. As indicated in the previous section, there is heterogeneity across states. That means, an ordinary least squares estimation violates the assumption that error term is not correlated with all independent variables due to the unobserved heterogeneity which affects residential electricity prices. In order to ensure unbiased and consistent parameter estimates, this paper first utilizes static model, the feasible generalized least squares (FGLS), to estimate the coefficients of Eq.(4.1). The FGLS approach allows to overcome issues of problems of heteroscedasticity and autocorrelation. In other words, the FGLS model specifies a heteroskedastic error structure with no cross-sectional correlation and a one-lag autoregressive, AR(1), error structure within panels. In the linear regression models, state fixed effect is included to control for time-invariant state characteristics and year fixed effect is also included to control for the time trend. The standard errors of linear regression with fixed effects allow for clustering of observations by state. The following regression model is suggested:

$$lnP\_RESI_{s,t} = \beta_0 + \beta_1 S\_RE_{s,t} + \beta_2 lnF\_PRICE_{s,t} + \beta_3 lnE\_CONS_{s,t} + \beta_4 lnP\_GDP_{s,t}$$
$$+\beta_5 lnHDD_{s,t} + \beta_6 lnCDD_{s,t} + \beta_7 RPS_{s,t} + \delta_s + \sigma_t + \varepsilon_{s,t} \qquad (4.1)$$

where the subscripts s and t denote the state, $s = 1, ..., 48$, and time periods, $t = 2001, ..., 2018$, respectively. The dependent variable *lnP_RESI* refers to the natural logarithm of residential electricity prices; *S_RE* measures the share of renewable energy in total electricity generation; *lnF_PRICE* measures the natural logarithm of primary energy price in the electric power sector; *lnE_CONS* denotes the natural logarithm of electricity consumed by the residential sector; *lnHDD* denotes the natural logarithm of heating degree days; *lnCDD* denotes the natural logarithm of cooling degree days; the dummy variable, *RPS*, takes the value one if the RPS requirement became binding; δ_s and σ_t are state and time fixed effects, respectively, and $\varepsilon_{s,t}$ denotes error term.

While the FGLS is useful, this may not well suited for addressing endogeneity problems arising from the interactions between dependent and independent variables. Therefore, to ensure that the results are robust to endogeneity, this paper employs the two-step system Generalized Method of Moments (GMM) approach by Arellano and Bover (1995) and Blundell and Bond (1998) with robust errors (Windmeijer, 2005). In general, the GMM techniques allow to demonstrate potential short-run dynamics and control for endogeneity, persistency and heteroskedasticity problems. The two-step system GMM procedure fixes: the endogeneity by incorporating lag-terms of endogenous variables as instruments; the autocorrelation properties of the residential electricity prices by introducing a lagged dependent variable as an independent variable, and the state-specific heterogeneity by using first differences. Moreover, this paper adopts the Windmeijer (2005) finite sample correction, which helps to avoid downward biased standard errors.

This model specification assumes no correlation between the residual and the independent variables and no serial correlation of the residual. Therefore, the consistency of the two-step system GMM estimator relies on the validity of the instruments and the assumption that the differenced residuals do not exhibit second-order serial correlation. This paper employs two tests to confirm these assumptions. The first test is the Hansen test for over-identifying restrictions, under the null hypothesis that the instrument variables are not correlated with the error term. The second, the Arellano–Bond AR (2) test allows to examine the existence of second-order serial correlation in the differenced residuals because the null hypothesis is that there is no second-order autocorrelation of differenced residuals. Thus, failure to reject those two null hypotheses provides strong evidence that the two-step system GMM estimator are valid. Eq.(4.2) represents the dynamic panel analysis model:

$$lnP\_RESI_{s,t} = \alpha_0 + \alpha_2 lnP\_RESI_{s,t-1} + \alpha_2 S\_RE_{s,t} + \alpha_3 lnF\_PRICE_{s,t} + \alpha_4 RPS_t + \alpha_5 lnE\_CONS_{s,t}$$
$$+\alpha_6 lnP\_GDP_{s,t} + \alpha_7 lnHDD_{s,t} + \alpha_8 lnCDD_{s,t} + \rho_s + e_{s,t} \tag{4.2}$$

where ρ_s and $e_{s,t}$ are the disturbance terms of this model, which indicate ρs for time invariant and es,t for time variant variables. ρ_s and $e_{s,t}$are not cross-correlated and assumed to be mutually independent and identically distributed with mean zero and variance σ^2, which clustered at the state level.

For the empirical analysis, this paper first uses the full sample to confirm the expected effects of independent variables. Then, I divide the whole sample into two subgroups based on the adaptation of RPS. As discussed in Section 4.2, states that enacted RPS have experienced significant development in renewable energy generation compared to the states that do not adopt an RPS: the average share of renewable energy in the total electricity generation in RPS states has recorded 20.5% in 2018 while that in non-RPS states has indicated 10.74% in 2018. The analysis based on these two subgroups can help to capture differential effects of renewable energy generation on residential prices at different level of its development. Additionally, I estimate the effects of hydro and wind electricity generation on residential electricity prices in order to confirm the robustness of the main results.

4.6 Results

In terms of the specification tests for the two-step system GMM, all models show that the probability value of AR (2) is higher than 0.1, indicating that the disturbance term has no second-order autocorrelation. Furthermore, the probability value of the Hansen test is higher than 0.1, suggesting that the selected instrument variables are valid.

Table 4.3 presents the estimation results of the FGLS and the two-step GMM. The empirical results confirm that the estimation results are consistent with the expectations which described in Section 4.4. By using the whole sample, I find that a higher percentage of renewable electricity generation results in a lower residential electricity prices: a 1% increase in the share of renewable energy generation reduces residential electricity prices by in the range 0.098% - 0.28%, described in columns (1) and (2). This result implies that the very low marginal costs of renewable electricity generation create the merit-order effect so that it leads to a reduction in wholesale electricity prices. In turn, lowering wholesale market prices decreases residential electricity prices. In order to confirm the effect of renewable energy generation and RPS on residential prices, this paper provides additional evidence of those effects by considering individually. These additional estimations confirm that both renewable energy and RPS are significant and robust across regressions, illustrated in columns (3)-(6).

The findings based on the analysis with subgroups support this explanation which shown in Table 4.4: a 1% increase in the share of renewable energy generation decreases residential prices by in the range 0.0653% - 0.115% in non-RPS states, illustrated in columns (1) and (2), whereas a 1% increase in the share of renewable energy generation decreases residential prices by in the range 0.0786% - 0.266% in RPS states, indicated in columns (3) and (4). In short, the results support that development of renewable energy generation has negative impact on residential electricity prices and this financial benefit would be more significant as increasing renewable energy generation.

As for the primary energy price, the results highlight that an increasing in fossil fuels price leads to an increase in the residential price: a 1% increase in the primary energy price increases residential electricity price by in the range 0.0666% - 0.116%. Since the primary energy resources are still dominant inputs to generate electricity, increasing primary energy price results in increasing costs of electricity generation, which is associated with higher consumer prices. This is consistent with Swadley and Yücel (2011) and Silva and Cerqueira (2017). As for the residential electricity consumption, the results suggest the existence of a scale effect in the U.S. electricity market, which is consistent findings with Trujillo-Baute, Río, and Mir-Artigues (2018): a 1% increase in the electricity consumption decreases residential electricity price by in the range 0.047% - 0.054%. The results of both heating and cooling degree days are consistent with this finding. In other words, increasing heating and cooling degree days can lower residential electricity price through increasing electricity demand.

With regard to the effect of RPS, the results indicate that RPS has a significantly positive impact on residential electricity price in the range 0.027% - 0.057%, shown in columns (1) and (2). This implies that implementation of RPS requires additional fixed costs, which reflected in the higher electricity price. This finding agrees with the conclusions of Morey and Kirsch (2013), Tra (2016), and Wang (2016). However, one argument is that the increased costs from rising RPS requirements have been offset by reducing costs of renewable electricity generation (Barbose, 2019). This suggests that as increasing renewable energy generation, the cost savings from using renewable resources will exceed the fixed costs occurred from RPS.

Table 4.5 describes the results of the effects of hydro and wind power generation on residential electricity prices. Similar to the results in Table 4.3, the results of AR(2) and Hansen tests confirm no second-order autocorrelation in disturbance term and the validity of the selected instruments. The remarkable finding is that hydro power leads to a reduction in residential electricity price: a 1% increase in the share of hydro in total electricity generation decreases residential electricity price by in the range 0.241% - 0.419%, illustrated in columns (1) and (2). It is in line with previous studies from Swadley and Yücel (2011) and Kury (2013). The results also show that wind power generation may reduce residential price: a 1% increase in the share of wind in total electricity generation reduces residential price by 0.188%, described in column (3). Based on the results, it is indicated that hydro power tends to have substantial marginal effects on residential price reduction. One possible explanation is that a sizable hydro electricity generation could offset the huge financial burden of initial investment costs of hydro power.

TABLE 4.3: Results of the regressions of renewable energy generation on residential electricity prices

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	FGLS	GMM	FGLS	GMM	FGLS	GMM
$L.lnP\_RESI$		0.895***		0.923***		0.858***
		(0.0242)		(0.014)		(0.026)
S_RE	-0.28***	-0.098**	-0.236***	-0.095**		
	(0.033)	(0.046)	(0.035)	(0.044)		
lnF_PRICE	0.116***	0.066***	0.104***	0.068***	0.089***	0.068***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.011)	(0.012)
lnE_CONS	-0.054***	-0.047***	-0.04***	-0.045**	-0.026***	-0.064***
	(0.008)	(0.014)	(0.008)	(0.017)	(0.008)	(0.016)
$lnHDD$	-0.001	-0.029*	-0.004	-0.025	-0.002	-0.028
	(0.011)	(0.015)	(0.01)	(0.016)	(0.012)	(0.02)
$lnCDD$	-0.013*	-0.002	-0.005	-0.004	-0.015**	0.025*
	(0.007)	(0.013)	(0.006)	(0.013)	(0.007)	(0.014)
RPS	0.057***	0.027*			0.047***	0.047**
	(0.008)	(0.016)			(0.008)	(0.019)
Constant	3.819***	1.114***	3.65***	0.979***	3.514***	1.201***
	(0.161)	(0.25)	(0.161)	(0.301)	(0.154)	(0.324)
AR(2)		0.05		0.02		-0.05
		(0.957)		(0.981)		(0.957)
Instr.		67		66		51
Hansen test		44.59		45.46		46.79
		(0.918)		(0.902)		(0.359)
State FE	Yes		Yes		Yes	
Year FE	Yes		Yes		Yes	
Observations	864	864	864	864	864	864
Number of State	48	48	48	48	48	48

Note: Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

TABLE 4.4: Results of the regressions of renewable energy generation on residential electricity prices based on the subgroups

Variables	(1) FGLS	(2) GMM	(3) FGLS	(4) GMM
$L.lnP\_RESI$		0.919***		0.913***
		(0.021)		(0.04)
S_RE	-0.115**	-0.065*	-0.266***	-0.079**
	(0.045)	(0.033)	(0.041)	(0.036)
lnF_PRICE	0.08***	0.058***	0.088***	0.052***
	(0.014)	(0.017)	(0.014)	(0.017)
lnE_CONS	-0.008	-0.004	-0.058***	-0.015
	(0.012)	(0.023)	(0.012)	(0.026)
$lnHDD$	-0.062***	-0.013	0.028	-0.018
	(0.016)	(0.032)	(0.017)	(0.029)
$lnCDD$	0.007	-0.029	-0.002	-0.014
	(0.007)	(0.02)	(0.009)	(0.015)
RPS			0.007	0.0122
			(0.009)	(0.018)
Constant	3.552***	0.609	3.643***	0.696
	(0.231)	(0.585)	(0.242)	(0.503)
AR(2)		-0.88		0.36
		(0.379)		(0.72)
Instr.		51		52
Hansen test		16.81		25.58
		(1.000)		(0.988)
State FE	Yes		Yes	
Year FE	Yes		Yes	
Observations	360	360	504	504
Number of State	20	20	28	28

Note: Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

TABLE 4.5: Results of the regressions of hydro and wind power generation on residential electricity prices

	(1)	(2)	(3)	(4)
Variables	FGLS	GMM	FGLS	GMM
$L.lnP\_RESI$		0.896***		0.881***
		(0.018)		(0.032)
S_HYDRO	-0.419***	-0.241***		
	(0.0338)	(0.081)		
S_WIND			-0.188**	-0.1
			(0.077)	(0.117)
lnF_PRICE	0.114***	0.074***	0.093***	0.065***
	(0.0106)	(0.013)	(0.011)	(0.012)
lnE_CONS	-0.057***	-0.032	-0.035***	-0.061***
	(0.008)	(0.022)	(0.008)	(0.016)
$lnHDD$	0.003	-0.03	-0.004	-0.024
	(0.011)	(0.021)	(0.012)	(0.02)
$lnCDD$	-0.0159**	-0.029***	-0.014**	0.023*
	(0.007)	(0.01)	(0.007)	(0.014)
RPS	0.057***	0.01	0.054***	0.039**
	(0.008)	(0.014)	(0.008)	(0.019)
Constant	3.853***	1.144***	3.619***	1.079***
	(0.157)	(0.404)	(0.160)	(0.315)
AR(2)		0.04		-0.04
		(0.966)		(0.97)
Instr.		71		67
Hansen test		45.96		46.73
		(0.947)		(0.876)
State FE	Yes		Yes	
Year FE	Yes		Yes	
Observations	864	864	864	864
Number of State	48	48	48	48

Note: Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

4.7 Conclusion and policy implications

In general, renewable energy is characterized as having high initial investment and very low marginal operation costs. Due to the financial burden of renewable energy installation, government support schemes play important roles in making renewable energy cost-competitive. And these financial supports are reflected in the wholesale electricity prices and then translated into electricity bills, which paid by consumers. At the same time, it is expected that the use of renewable energy can reduce the retail electricity prices by the so-called merit-order effect. Given these different aspects, the effects of renewable energy generation on residential electricity price are not clear. The main goal of this paper is empirically examining the impact of renewable energy generation on residential prices by using the dataset of 48 U.S. states over the period 2001-2018.

For the empirical analysis, this paper utilizes the feasible generalized least squares (FGLS) and two-step Generalized Method of Moments (GMM). This paper also considers economic and climatic variables related to renewable energy generation in the U.S. electricity market: residential electricity consumption, primary energy price, heating degree days, cooling degree days, and policy influences from renewable portfolio standard (RPS). The main finding is that increases in the share of renewable energy generation help to reduce residential electricity prices. The results based on the analysis with subgroups show that RPS states have more significant effect of renewable energy on residential prices than non-RPS states. From the robustness check, it is confirmed that both hydro and wind power generation can lead to a reduction in residential prices, which support the main findings. Additionally, the findings show that increases in the primary energy prices and implementation of RPS lead to an increase in the residential prices whereas increases in the residential electricity consumption, heating degree days, and cooling degree days decrease residential electricity prices.

Throughout the analysis, this paper provides important public policy implications. Most importantly, the findings of this paper suggest that the current trend of increased renewable energy generation may increase consumer's welfare by paying less electricity bills. At the same time, producers may take advantages from using renewable energy resources with the very low operating costs. Once the initial financial burden would be offset, arising from renewable energy installation, it is expected that both consumers and producers enjoy cost savings by utilizing more renewable energy in the long-run. Overall, the findings of this paper will provide critical implication to policy makers to improve long-run social welfare.

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