DENİZ EGE BOZ ANALYSING THE EFFECTS OF CROSS-BORDER ELECTRICITY TRADE ON POWER PRODUCTION FROM DIFFERENT ENERGY SOURCES Bilkent University 2020

# ANALYSING THE EFFECTS OF CROSS-BORDER ELECTRICITY TRADE ON POWER PRODUCTION FROM DIFFERENT ENERGY SOURCES

A Master's Thesis

by

DENİZ EGE BOZ

Graduate Program in

Energy Economics, Policy and Security

İhsan Doğramacı Bilkent University

Ankara

April 2020

*To my dear family*

**ANALYSING THE EFFECTS OF CROSS-BORDER ELECTRICITY TRADE ON POWER PRODUCTION FROM DIFFERENT ENERGY SOURCES**

The Graduate School of Economics and Social Sciences

of

İhsan Doğramacı Bilkent University

by

Deniz Ege Boz

In Partial Fulfillment of the Requirements for the Degree of MASTER OF ARTS IN ENERGY ECONOMICS, POLICY AND SECURITY

Graduate Program in Energy Economics, Policy and Security

İhsan Doğramacı Bilkent
University Ankara

April 2020

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Arts in Energy Economics, Policy and Security.

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Supervisor: Prof. Dr. M. Hakan Berument

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Arts in Energy Economics, Policy and Security.

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ABSTRACT

ANALYSING THE EFFECTS OF CROSS-BORDER ELECTRICITY TRADE ON POWER PRODUCTION FROM DIFFERENT ENERGY SOURCES

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M.A. Program in Energy Economics, Policy and Security

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This thesis provides empirical evidence to emphasize the crucial role of cross-border electricity trade for decreasing the use of fossil fuels in power industries and attaining higher electricity supply from solar and wind energy sources. We collected data for 48 countries across three continents (the Americas, Europe and Asia) from 1991 to 2018 to create a world sample that would reflect the diversity of various energy mixes in different electricity markets. We showed the existence of long-term relationships between power production from natural gas, solar, wind and the level of cross-border electricity trade through panel unit root and panel cointegration tests. Later on, we conducted panel data analyses that utilize the fixed-effect approach with interactive variables. The empirical evidence reveals that when electricity production from solar and wind energy sources interacts with cross-border electricity trade, power production from natural gas decreases statistically significantly. Furthermore, we created efficiency indices for solar and wind energy sources and provide evidence for the increased utilization of solar and wind electricity production in the presence of cross-border electricity trade.

Key Words: Electricity Markets, Electricity Trade, Panel Data Analysis, Renewable and Non-Renewable Sources.

# ÖZET

ULUSLARASI ELEKTRİK TİCARETİNİN FARKLI ENERJİ KAYNAKLARINDAN ELEKTRİK ÜRETİMİNE ETKİLERİNİN ANALİZİ

Boz, Deniz Ege

Yüksek Lisans, Enerji Ekonomisi ve Enerji Güvenliği Politikaları Programı

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Nisan 2020

Bu tez, enerji endüstrilerinde fosil yakıtların kullanımını azaltmak, güneş ve rüzgar enerjisi kaynaklarından daha yüksek elektrik tedariki elde etmek için uluslararası elektrik ticaretinin önemli rolünü vurgulamak adına ampirik kanıtlar sunmaktadır. Dünyada farklı elektrik piyasalarındaki kurulu güçlerin sahip olduğu enerji çeşitliliğini yansıtabilmek adına, üç kıtadan (Amerika, Avrupa ve Asya) 48 ülke seçilmiş ve 1991'den 2018'e yılları için veri toplanmıştır. Panel birim kök testi ve panel eşbütünleşme (koentegrasyon) testleri ile doğal gaz, güneş, rüzgardan enerji üretimi uluslararası elektrik ticareti seviyesi arasında uzun vadeli ilişkilerin varlığını gösterilmiştir. Daha sonra, etkileşimli değişkenlerle sabit etkili yaklaşımı kullanan panel veri analizleri yapılmıştır. Ampirik kanıtlar, bir ülkede güneş ve rüzgar enerjisi kaynaklarından elektrik üretiminin uluslararası elektrik ticareti ile etkileşime girmesinin, doğal gazdan elektrik üretiminin istatistiksel olarak manalı ölçüde azalttığını ortaya koymaktadır. Ayrıca, güneş ve rüzgar enerjisi kaynakları için verimlilik endeksleri oluşturulmuştur ve uluslararası elektrik ticareti yapan ülkelerde güneş ve rüzgar enerjisinden elektrik üretiminin kullanımının arttığını dair ampirik kanıtlarla gösterilmiştir.

Anahtar kelimeler: Elektrik Piyasaları, Elektrik Ticareti, Panel Veri Analizi, Yenilenebilir ve Yenilenebilir olmayan Kaynaklar

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# CHAPTER I

# INTRODUCTION

The power industry is one of the most carbon-emitting industries on the global level since the majority of power plants in the world still use carbon-based fossil fuels to generate electricity. Amid rising concerns over climate crisis and decreasing costs of renewable technologies, a number of countries have been increasing their uptake of solar and wind energy applications to attain sustainable, low-carbon economies in the long-run. However, replacing fossil-fuel based power plants completely with renewable energy sources is a challenging task, especially from a technical perspective. It is well known that rising shares of solar and wind energy sources put technical constraints on grid operations by increasing short-term volatility in power production due to their intermittent nature. Also, their capacities cannot be utilized to the full extent in the presence of high demand fluctuations and in the absence of high response baseload power plants. For instance, on the island of Cyprus, wind capacities stay idle because baseload is only provided by fuel oil power plants (Özden, 2019). In this thesis, we argue that besides helping to solve technical constraints and gaining economic benefits from trade, increasing the levels of cross-border electricity trade is crucial for decreasing the use of fossil fuels in power industries and attaining higher electricity supply from solar and wind energy sources.

By providing empirical evidence using annual data from 1991 to 2018 over a world sample containing 48 countries across three continents (Americas, Europe, and Asia);

we assessed the effects of the levels of cross-border electricity trade on electricity markets using various econometric specifications. First, we showed that there exist long-run relationships among electricity production from natural gas, solar, wind energy sources, and the level of cross-border electricity trade. Afterward, we conducted panel data analyses using the fixed effects approach by utilizing interactive variables containing cross-border electricity trade. As a result, we were able to demonstrate that as the level of cross-border electricity trade of a country increases together along with electricity production from solar and wind energy sources; electricity production from natural gas power plants decreases statistically significantly. Furthermore, we provided evidence that for countries with positive economic growth, rising levels of cross-border electricity trade leads to more efficient electricity production from solar and wind energy sources. Our results emphasize the importance of increasing interconnection capacities and integration among electricity markets in terms of completing a global energy transition in the long-run and accelerate the transition process.

The energy mix of installed capacities all around the world is quite diverse and after the electricity is produced and ready to be transmitted, there is no certainty which type of energy source has been used for it. It is possible that most of the electricity traded across borders has been produced from carbon-based coal or natural gas. Hence, it is critical to have a detailed analysis of the effects of such a beneficial tool for creating flexibility[1] in power systems (cross-border electricity trade) on an

[1] According to the International Energy Agency, the flexibility of a power system refers to "the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise" (IEA, 2019).

aggregate level. Theoretically, considering the priorities solar and wind energy sources have in the merit orders of many electricity markets; we expect that co-existence of cross-border electricity trade and growing shares of solar and wind energy sources in total electricity production to create diminishing effects on the usage of fossil fuels in power industry relative to these two types of energy. Hence, we hypothesize that in the existence of adequate flexibility in the system, more units of produced electricity from solar and wind energy sources can be supplied to the end consumers.

As investments on solar and wind energy sources increase, trading electricity more across borders can create the required additional flexibility to better accommodate existing power supply. For many countries around the world (especially in the European Union), cross-border trade of electricity and market integration have started to be considered as a favorable option to alleviate the adverse effects on grid operations caused by high growth rates of renewable deployment. Nonetheless, the full potential of benefits is far from being realized in most of the countries. Currently, electricity is still one of the least traded types of energy by far compared to liquid global markets of oil, natural gas, and coal. Global exports of electricity are around 3% of total production, in contrast to 64% for oil and 31% for gas and 16% for coal (Pollitt & Oseni, 2014).

The rest of the thesis is organized as follows. Section 2 presents the review of previous studies analyzing different aspects of cross-border electricity trade and points out the contribution of this thesis to the existing literature. Section 3 describes the data. Section 4 provides empirical analyses, including panel unit root and panel cointegration tests, and the estimations. Finally, Section 5 gives the concluding remarks and policy implications of the findings.

# CHAPTER II

# LITERATURE REVIEW

Physical laws governing the electromagnetic activity of photons necessitates overall electricity supply and demand to be synchronized at all times on the transmission lines, within a very small range of frequency. Electricity grid operators have to deal with serious instability issues as shares of solar and wind energies increase in overall installed capacity. Unlike any other fossil fuel-based or nuclear power plants, the production of electricity from solar and wind energy sources are not continuous and fluctuate according to weather conditions, which is not an estimable phenomenon with high accuracy. Hence, it becomes very challenging to reinforce congestion management, frequency balancing and optimization of economic dispatch[2] for system operators. Consequentially, the overall capacity factor and efficiency of the entire power system may decrease which results in both financial losses and physical losses of generated power.

Countries in the electricity network zones of North America and European Network of Transmission System Operators for Electricity (ENTSO-E) demonstrated collective efforts to achieve sustainable cross-border trade policies and build more efficient and dynamic generation and transmission capacities. The successful development

[2] Economic dispatch is the short-term determination of the optimal output of a number of electricity generation facilities, to meet the system load, at the lowest possible cost, subject to transmission and operational constraints.

and functioning of the Nord Pool Network[3] provided a good demonstration of the laudable outcomes that can arise from cross-border electricity trade. Clark, Zipkin, Bobo & Rong argue in their 2017 paper that the Nord Pool Network exhibits a good model of an integrated system that enables increases of aggregate efficiency and capacity factors of intermittent renewable energy sources. Thus, many scholars such as Li and Kimura (2015), Rose, McBennett, Palchak and Cochran (2018) and Martinez- Anidoa, Migliavaccab, Sorannob, and Vriesc (2013) identified electricity markets with high potential to procure aggregate efficiency gains in both economic and technical terms as a result of increased cross-border transmission network capacities. They developed corresponding economic, regulatory and institutional models within theoretical and real market conditions that will facilitate cross-border electricity trade. These models aimed to invoke the necessary conditions in each state's electricity market and regulatory structures which would enable adaptation to more integrated electricity markets and transmission networks.

Bahar and Sauvage (2013) developed a theoretical model for measuring the effects of relative electricity prices and net transfer capacity on electricity exports. By using Samuelson (1954)'s iceberg specification, they incorporated the effects of different regulatory policies on electricity prices. Later, they simulated scenarios within the European Power Markets to assess the effects of price differences and net transfer capacity on the level of cross-border electricity trade. By assuming that exporters face trade costs when sending electricity to an interconnected country, they concluded that differences in relative prices and to less extent relative net transfer

[3] Nord Pool Network is established in 2001. As of today 7 countries is part of the Nord Pool Network: Austria, Belgium, Denmark, Estonia, Finland, France, Germany.

capacity do have a significant and positive impact on the level of cross-border electricity trade. Hence, their results suggest that price differentials in interconnected electricity markets in Europe are the main driver of electricity trade.

Agostini, Shahriyar, and Silva (2017) identified political, regulatory and infrastructural obstacles for the short-term electricity exchanges among countries in South America. Since most countries in South America lack well-established regulatory frameworks to facilitate the integration of large electricity grids; Agostini et al. (2017) proposed a regulatory model that allows short-term electricity exchanges between countries by utilizing the production surpluses in local markets that were going to waste in the absence of demand. Based on the empirical analysis of simulations which considered international trade of electricity centering Chile and its neighboring countries; they supported the argument that market integration among South American countries is economically feasible in the long run. Rose et al. (2018) created a highly detailed thesis supported by the National Renewable Energy Laboratory (NREL) of the United States Department of Energy to examine the potential cross-border electricity trade and market integration between India and Sri Lanka which would be initiated in 2025. One of the prominent conclusions they have attained was that a 500-MW high voltage direct current transmission link would generate annual production cost savings of USD 180 million and improve power system operations between these countries.

Similar studies were undertaken by Martinez-Anido et al. (2013) as well as Li and Kamura (2016) by analyzing costs and benefits of increased power grid interconnections between North Africa and Europe, and in Northern Asia, respectively. Furthermore, Ji, Jia, Chiu, and Xu (2016) examined the global grid as a network by defining nations as nodes and international electricity trade as links. Their work revealed the existing physical connections among grid networks on a global level and identified sub-groups of networks. In which, they argued that adequate capacity of transmission technologies in strategic geographical locations can significantly facilitate cross-border electricity trade of an entire identified network. On the other hand, Oseni and Pollitt (2014) focused on the institutional arrangements needed for facilitating regional electricity cooperation while Clark et al. (2017) argued that government, private sector, and public interests are inclined to have contradicting interest within electricity markets and provided investigation of some noteworthy cases.

Such empirical findings deliberated on the effective expansion of cross-border electricity trade all over the world with specific case-studies. Nonetheless, there is a lack of a large-scale empirical analysis focusing on the overall effects of cross-border electricity trade on electricity production from fossil fuels and renewable energy sources. How the interaction of cross-border electricity trade and increasing shares of solar and wind technologies have affected the overall electricity production from fossil fuels and how cross-border electricity trade has affected production from solar and wind energy sources emerge as important questions to be answered. This thesis aims to fill this gap by breaking down and assessing the endogenous relationship among cross-border electricity trade and electricity production output from natural gas, solar and wind energy sources on a global level.

# CHAPTER III

# DATA

In our sample, annual panel data covering 28 years from 1991 to 2018, including 48 countries (15 countries from Americas, 15 from Asia and 18 countries from Europe) are used for the empirical analyses in this thesis (list of countries are presented in the Appendix). International electricity data of Energy Information Administration (EIA) is the main source of our data where all sample countries are selected from. However, the additional data has been gathered from multiple resources to eliminate existing gaps as much as possible. Electricity production data of fossil fuel-based power plants (coal and natural gas) has been gathered from the United Nations Database and the World Bank Data since EIA only reports joint electricity production data for fossil fuels. Electricity production data of renewable technologies (solar and wind) are taken from the International Renewable Agency database for the 2017-2018 period since the EIA data ends in 2016. Unavailable electricity export and import data of European countries have been supplemented from the ENTSOE Database. Unavailable data of electricity export and imports for non-European OECD countries have been gathered from the International Energy Agency Monthly Electricity Statistics by being converted to annual data. Table 1 gives the variable names and labels used in estimations as well as their respective data source. Descriptive statistics are presented in Table 2.

Electricity markets around the world can exhibit profoundly different characteristics due to various reasons. Existing natural resources, available technology and infrastructure, and regulations in the market are some of the straightforward examples which result in such diversity. In order to create a sample that will incorporate the extent of this diversity; we have selected countries with different levels of market interconnections from all around the world. The variables used in the analyses include electricity production from coal, natural gas, solar and wind energy sources. Among these variables, electricity production from coal is excluded from the estimations because panel cointegration tests suggest that it does not have long-run relationships with electricity production from solar and wind energy sources in our world sample of 48 countries for the last 28 years.[4]

The series used in this thesis for the electricity production from natural gas, solar and wind sources are in their logarithmic forms to investigate the relationship between the rates of production rather than in levels. Levels of cross-border electricity trade and GDP growth rate are other variables included in the analyses designated as 'trade', and 'GDP'. The cross-border electricity trade is the sum of electricity exports and imports of country *i* in absolute values, denominated by the first lag of total electricity production of country *i*. The division is made with the lag of total electricity production to prevent the endogeneity problem since electricity exports are correlated with electricity production. Solar and wind efficiency indices which are discussed in section 4.3 are created to assess the effects of cross-border electricity trade on the production efficiency from Variable Renewable Energy Sources (VREs)[5]. The indices measure the productiveness of solar and wind capacities of a sample

[4] This makes sense because high carbon emissions and other environmental concerns force countries to make use of more environmentally friendly alternatives.
[5] The abbreviation is used by (IEA, 2019) to designate solar and wind energy sources.

country by taking into account the share of solar and wind in total electricity production and comparing it to the share of solar and wind in total installed capacity. GDP growth rate is formulated as the first difference of the logarithm of GDP. The unit of measurement for all variables concerning production or trade of electricity production is billion kWh. The unit of measurement for installed capacities is billion kW. GDP is a real measure and measured at $2010 Purchasing Power Parity.

**Table 1. Variable Names and Labels Used in Estimation Tables**

| Variable Name | Variable Label | Source of Data |
| --- | --- | --- |
| Logarithm of electricity production from natural gas | Natural Gas | World Bank Data, UN Data |
| Logarithm of electricity production from solar PV | Solar | EIA, IRENA |
| Logarithm of electricity production from wind turbines | Wind | EIA, IRENA |
| Level of Cross-Border Electricity Trade as a Ratio of Previous Year's Total Electricity Production | Trade | EIA, IEA |
| GDP growth rate | GDP | EIA |
| Efficiency of Solar Capacity as a Ratio of the Efficiency of Overall Installed Capacity | Solar Efficiency | EIA, IRENA |
| Efficiency of Wind Capacity as a Ratio of the Efficiency of Overall Installed Capacity | Wind Efficiency | EIA, IRENA |

**Table 2. Descriptive Statistics**

| Variables in Levels | Whole Sample | | | | | 2010-2016 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Standard Dev. | Min | Max | Number of Observations | Mean | Standard Dev. | Min | Max | Number of Observations |
| Natural gas (billion kWh) | 56.02 | 149.19 | 0.00 | 1454.22 | 1282 | 80.29 | 196.13 | 0.00 | 1418.10 | 320 |
| Solar (billion kWh) | 1.58 | 8.66 | 0.00 | 175.86 | 1295 | 3.26 | 8.68 | 0.00 | 66.52 | 336 |
| Wind (billion kWh) | 5.77 | 24.77 | 0.00 | 358.96 | 1296 | 12.48 | 32.67 | 0 | 237.07 | 336 |
| Trade | 0.13 | 0.21 | 0.00 | 1.20 | 1340 | 0.15 | 0.23 | 0.00 | 1.07 | 336 |
| GDP | 1277.4 | 2600.2 | 8.27 | 22051.7 | 1340 | 1659.4 | 3270.2 | 20.5 | 19400.2 | 336 |
| Solar efficiency | 0.25 | 0.33 | 0.00 | 5.89 | 610 | 0.28 | 0.37 | 0.00 | 5.89 | 322 |
| Wind efficiency | 0.47 | 0.25 | 0.00 | 1.56 | 830 | 0.57 | 0.26 | 0.00 | 1.56 | 306 |

# CHAPTER IV

# EMPIRICAL ANALYSIS

## 4.1 Initial Analysis

In order to assess any long-run relationship among fossil fuels and solar, wind-generated electricity, and how these relationships altered with cross-border electricity trade; we perform panel unit and panel cointegration tests and estimation of models allowing the assessments.

### 4.1.1 Panel Unit Root Tests

Table 3 reports Paseran (2007)'s panel unit root test with constant and with constant & time trend for the rates of power production from different natural resources and cross-border electricity trade over the span of 28 years (1991 to 2018)[6] and relates to the estimations of models (1) and (2). On the other hand, Table 4 reports the results of the same test with the same conditions but relates to the variables used in models (3) and (4) which have the same sample countries but are estimated for the period 2010 to 2016. The reason behind this preference is elaborated in sub-section 4.3.

Baltagi (2005) argues that the information contained in cross-section data would enhance the power of the unit-root tests in contrast to univariate unit root tests. In

[6] The data availability for electricity production from natural gas and coal for 2017 and 2018 is very low.

this thesis, the estimates from a second-generation panel unit root test are used for multivariate time series' unit root processes. The first generation of panel unit root tests such as Levin and Lin (1992, 1993), Levin et al. (2002) Maddala and Wu (1999), Choi (1999, 2001) are based on the cross-sectional independence hypothesis. Yet, the data used in this thesis have cross-sectional dependence since many of the energy sources used in electricity production as well as the technological commodities used in production are subject to international trade among countries in our data set. On the other hand, the cross-sectional independence hypothesis is rather restrictive and somewhat unrealistic in the majority of macroeconomic applications of unit root tests (Hurlin & Mignon, 2007).

Pesaran (2007) Panel Unit Root Test in the Presence of Cross-section Dependence (CIPS) test allows for heterogeneity in the autoregressive coefficient of the Dickey-Fuller(DF) regression and the presence of a single unobserved common factor with heterogeneous factor loadings in the data. The statistic is constructed from the results of panel-member-specific (A)DF regressions where cross-section averages of the dependent and independent variables (including the lagged differences to account for serial correlation) are included in the model. The averaging of the group-specific results follow the procedure in the Im, Pesaran, and Shin (2003) test. Under the null hypothesis of non-stationarity at the order of (1), the test statistic has a non-standard distribution which uses $\overline{Zt}$ statistics.

The main goal of carrying out this test is to assess the order of integration of all variables under thesis and conduct a co-integration analysis among them later on. The precondition for a cointegration analysis requires all the variables of interest to be integrated of order one, I (1). The null hypotheses of all tests are the presence of a unit root; hence, the desired results would be not to reject the null hypothesis.

Obtained results indicate that the existence of a unit root process of I (1) for the logarithm of power production from coal, natural gas, solar and wind, as well as the efficiency indices for the electricity production from solar and wind, cross-border electricity trade and GDP growth rate, cannot be rejected for all cases without trend and with trend. Hence, all the variables used in the models (1) to (4) can have cointegrated relationships among themselves depending on the results of reported cointegration tests in the next section and Appendix.

**Table 3: Pesaran's Panel Unit Root Test (1991 – 2018)**

| Variables/ Tests | | Pesaran (2007) (Levels) | Pesaran (2007) ($1^{st}$ difference) |
|---|---|---|---|
| Logarithm of Power Production from Coal | No Trend | 9.227 [ 1.000] | -3.255*** [0.001] |
| | With Trend | 10.794 [1.000] | -4.287*** [0.000] |
| Logarithm of Power Production from Natural Gas | No Trend | 4.032 [1.000] | -5.276*** [0.000] |
| | With Trend | 5.629 [1.000] | -4.214*** [0.000] |
| Logarithm of Power Production from Solar PV | No Trend | 2.356 [0.991] | -5.126*** [0.000] |
| | With Trend | 2.987 [0.999] | -2.144** [0.016] |
| Logarithm of Power Production from Wind | No Trend | 1.291 [0.902] | -9.716*** [0.000] |
| | With Trend | 0.869 [0.808] | -7.011*** [0.000] |
| Trade | No Trend | 5.345 [1.000] | -5.115*** [0.000] |
| | With Trend | 5.048 [1.000] | -3.569*** [0.000] |

Notes: Null Hypothesis: Series is I (1). Pesaran (2007) uses $\overline{Zt}$ statistics. All Lag Lengths are set at (0). (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

**Table 4: Pesaran's Panel Unit Root Test (2010 – 2016)**

| Variables/ Tests | | Pesaran (2007) (Levels) | Pesaran (2007) (1st difference) |
|---|---|---|---|
| Solar Efficiency | No Trend | 3.603 | 1.367 |
| | | [ 1.000] | [0.914] |
| | With Trend | 3.990 | 1.697 |
| | | [1.000] | [0.955] |
| Wind Efficiency | No Trend | -0.787 | -3.747*** |
| | | [0.216] | [0.000] |
| | With Trend | -0.627 | -3.182*** |
| | | [0.265] | [0.001] |
| GDP Growth Rate | No Trend | 0.206 | -6.066*** |
| | | [0.582] | [0.000] |
| | With Trend | -0.107 | 16.740 |
| | | [0.457] | [1.000] |
| Trade | No Trend | 2.575 | 2.587 |
| | | [0.995] | [0.995] |
| | With Trend | 3.675 | 3.465 |
| | | [1.000] | [1.000] |

Notes: Null Hypothesis: Series is I (1). Pesaran (2007) uses $\overline{Zt}$ statistics. All Lag Lengths are set at (2). (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

### 4.1.2 Panel Cointegration Analysis

Pedroni's panel cointegration test is employed in order to provide evidence for the existence of any long-run relationship between electricity production from fossil fuels (coal and natural gas) and electricity production renewable energy sources (solar and wind). Several tests have been proposed in the literature for panel cointegration like (Pedroni,2004) and (Kao, 1999). They are both based on (Engle & Granger, 1987)'s methodology which is two-step (residual-based) cointegration tests. On the other hand, Fisher-type tests are using an underlying Johansen methodology (Wu & Maddala, 1999) which relaxes the assumption of a unique cointegrating vector among variables. The focus of our thesis requires analyzing the cointegrating properties of a two-dimensional vector of I(1) variables. The trade variable we included in our estimation is a sheer exogenous variable which we expect to observe the effects of, on the long-run relationship between fossil fuel-based and renewable-based electricity production. In addition, Pedroni's panel cointegration test is residual-based and the estimated slope coefficients are permitted to vary across individual members of the panel (Pedroni, 2004). The test is appropriate for various cases of heterogeneous dynamics, endogenous regressors, and individual-specific constants and trends (Westerlund, 2007).

Pedroni's panel cointegration test includes seven test statistics. These test statistics are panel-v, o, group-rho, panel-t (non-parametric), group-t (non-parametric), panel-adf (parametric), and group-adf (parametric). All test statistics are normalized to be distributed under N (0,1) and diverge to negative infinity as the p-value converges to 0, except for panel-v. Hence, it is considered as a comprehensive panel cointegration test. Four or more test statistics out of seven having p-values less than 0.10 enables us to reject the null of cointegration and conclude that the variables of interest have a cointegrated relationship (Pedroni, 2004). The optimal lag length is chosen based on Schwarz Information criteria.

Before analyzing how cross-border electricity trade may affect the relationship between the methods of electricity production from different energy sources, we assessed if there is a pair-wise long-run relationship among the chosen energy sources. Test results tabulated in Table 5 indicate that there exists a cointegrated relationship between the logarithm of electricity production from natural gas and logarithm of electricity production from renewable energy sources (solar and wind). In the relationship between natural gas and solar; four out of seven test statistics reject the null of no cointegration at the 10% level of significance while in the relationship between natural gas and wind; six out of seven statistics reject no cointegration. Considering the relationship with the combination of solar and wind; six test statistics reject the null at 5%. On the other hand, the logarithm of electricity production from coal does not seem to have a cointegrated relationship with any of the renewable energy sources or their combination. Only one out twenty-one test statistics reject the null of no cointegration. As a result, we can claim that only natural gas has long-term relationships with VREs. Correspondingly, we have selected these variables to be used in our model.

Next, we tested for panel cointegration among logarithms of power production from natural gas, the logarithm of power production from solar and wind energy sources and level cross-border trade of electricity by using Pedroni's panel cointegration test

(See Appendix Table A.2 and A.3). At least four out of seven test statistics rejected the null of no cointegration, thus, we can claim that there also exists a long-run relationship among the level of cross-border electricity trade, logarithm of power production from natural gas, solar and wind energy sources.

**Table 5. Pedroni's Panel Cointegration Test Among Electricity Production from Different Natural Resources (1991-2018)**

| Series | Panel v-statistics | | Panel rho-statistics | | Panel PP-statistics | | Panel ADF-statistics | |
|---|---|---|---|---|---|---|---|---|
| | Statistic | Prob | Statistic | Prob | Statistic | Prob | Statistic | Prob |
| log(N.gas) - log(Wind) | 2.73*** | 0.00 | -4.89*** | 0.00 | -6.12*** | 0.00 | -6.32*** | 0.00 |
| log(N.gas) - log(Solar) | 0.47 | 0.32 | 0.46 | 0.32 | -4.31*** | 0.00 | -4.44*** | 0.00 |
| log(N.gas) - log(Solar+Wind) | 2.73*** | 0.00 | -4.90*** | 0.00 | -6.12*** | 0.00 | -6.32*** | 0.00 |
| log (Coal) - log(Wind) | -0.78 | 0.78 | -0.33 | 0.36 | -1.89 | 0.03 | -0.37 | 0.35 |
| log (Coal) - log(Solar) | -1.40 | 0.92 | 0.82 | 0.79 | -0.13 | 0.44 | 0.81 | 0.79 |
| log(Coal) - log(Solar+Wind) | -0.64 | 0.74 | 0.11 | 0.54 | -0.93 | 0.17 | 0.04 | 0.51 |

| | Group rho-statistics | | Group PP-statistics | | Group ADF-statistics | |
|---|---|---|---|---|---|---|
| | Statistic | Prob | Statistic | Prob | Statistic | Prob |
| log (N.gas) - log(Wind) | -0.93 | 0.82 | -1.47* | 0.07 | 2.36*** | 0.00 |
| log (N.gas) - log (Solar) | 2.29 | 0.98 | -1.52* | 0.06 | -2.05** | 0.02 |
| log(N.gas) - log(Solar+Wind) | 0.89 | 0.81 | -1.72 | 0.04 | -2.18*** | 0.01 |
| log (Coal) - log (Wind) | 1.77 | 0.96 | 0.98 | 0.83 | 0.82 | 0.79 |
| log (Coal) - log (Solar) | 2.81 | 0.99 | 1.64 | 0.94 | 1.39 | 0.91 |
| log(Coal) - log(Solar+Wind) | 1.48 | 0.93 | 0.63 | 0.73 | 0.81 | 0.79 |

**Null Hypothesis**: No cointegration
**Distribution**: All test statistics are normalized to be distributed under N (0,1)
**Trend and Lag Assumptions**: No deterministic trend - Automatic lag length selection based on SIC
**Rejection Criteria**: Following (Pedroni, 2004), if at least four out of seven test statistics have p-values less than 0.10, we reject the null of no cointegration and consider selected variables cointegrated. . (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

## 4.2 Empirical Evidence

Tables 6 and 7 below reports the estimates of panel data analyses reporting the separate and integrated effects of VREs and cross-border electricity trade on the logarithm of electricity production from natural gas in our world sample over 28 years. Panel A and Panel B in both tables present the estimates obtained from fixed-effects and random-effects models. Hausman Test is used for the selection between fixed and random effects. Also, heteroskedasticity corrections are applied to all estimates using Huber-White covariances and standard errors. In retrospect, the extent to which electricity is traded across borders varied significantly both within and across countries. This feature allowed us to assess the effect of electricity trade on the orientation of the relationship among natural gas and VREs by using the fixed effects approach as suggested by the Hausman Test. In the models (1) and (2):

$$y_{it}^{ng} = \beta_{11}.log(solar)_{it} + \beta_{12}(trade)_{it} + \beta_{13}\,[(trade)_{it} \times log(solar)_{it}\,] + \varepsilon_{1it} \qquad (1)$$

$$y_{it}^{ng} = \beta_{21}.log(wind)_{it} + \beta_{22}(trade)_{it} + \beta_{23}\,[(trade)_{it} \times log(wind)_{it}] + \varepsilon_{2it} \qquad (2)$$

We have created interactive variables comprising of the combination of electricity traded across borders and electricity produced using solar PV and wind turbines to assess their integrated effects on the rate of electricity production from natural gas. Since the sample size is large with 1,219 observations and encompasses countries from multiple continents, the unobserved variables that are constant over time such as geographical disposition are not statistically independent from the included variables in the model. These time-independent effects are prone to create inefficient estimates, which is also suggested by the results of the Hausman test. Thus, we estimate our model using the fixed effects approach which mainly evaluates the within variation of included cross-section units in the sample. By employing the fixed effect model, regressors' time-independent characteristics related to geographical disposition are excluded from the analysis. This exclusion causes our models to mainly capture the effects of the dynamic features among countries. The estimates of Random Effects which consider time-independent factors in the idiosyncratic error term were also posted to add robustness to the results, yet they are statistically insignificant. The effects of existing regulations and policies regarding the exchange of electricity produced in the electricity markets could have also been subject to elimination from the results. Since changes in direct or indirect financial support dramatically affect new installments of VREs, this would have been uncaptured information that could have affected the outcome of the results in an undesired way. Yet, this is not the case for the specified models in Tables 6 and 7 where time period covers 28 years in which regulatory policies regarding power markets have been on a dynamic path in the world. For instance, Germany reduced its solar subsidy, a feed-in tariff for photovoltaic roof systems, from 55 Eurocents per kilowatt-hour in 2005 to 12 Eurocents per kilowatt-hour in 2016 (Paltsey, 2016). The new installation of solar photovoltaic capacity in Spain declined from 2700 MW in 2008, before the government changed its support structure for solar energy, to 160 MW in 2012. In Turkey, since feed-in tariffs for solar energy started in 2015, solar generation has increased by 700 fold in 4 years.

As reported in Tables 6 and 7, there are positive relationships among electricity production from natural gas and VREs. Overall electricity demand, hence, production has been growing in the world for the past 28 years. When the sample time period started in 1991, electricity production levels from VREs were almost nonexistent and we know that they have only been increasing until today. Thus, the positive relationship indicates that the overall usage of natural gas for electricity production in the world has been increasing as well together along VREs. On the other hand, the signs of the interactive variables' parameters are negative for both models which means that the orientation of the relationship between natural gas and VREs reverses when coupled with cross-border trade of electricity. The estimated coefficient of β3 is -0.031 for the model with solar electricity and -0.010 for the model with wind electricity. Both coefficients are significant at 5% in both models. These estimates indicate that for any country *i*; if increasing rates of electricity production from solar and wind sources co-exist with cross-border electricity trade, the rate of electricity production from natural gas has decreased for that country *i*. This result is plausible considering the economic differences between natural gas power plants and VREs within the changing market conditions of power industries going through energy transition. VREs attract financial and technical incentives through implementations of regulatory policies. For instance, feed-in tariffs can offer both financial and technical incentives through guaranteed purchase price over a certain time period plus priority of dispatch by the grid operator in day-ahead and intra-day markets. Besides, VREs have really low marginal costs in production because they do not use any additional input of relatively expensive raw material as in the case of natural gas power plants. Consequentially, VREs exert downward pressure in the long run on wholesale market prices both domestically and internationally and pushed high marginal cost power plants out of the market. Hence, it can be inferred that cross-border electricity trade has a supportive function in the fulfillment of an energy transition in favor of VREs by exerting downward pressure on the rates of production from natural gas power plants.

**Table 6: Interactive Effects of Electricity Production from Solar PV and Cross-Border Trade on Natural Gas (1991-2018)**

**Dependent Variable:** Logarithm of electricity production from natural gas

| | **Panel A: With-in group Fixed Effect** Panel EGLS (Cross Section Weights) | | **Panel B: Random Effects (RE)** Panel EGLS (Cross Section Random Effects) | |
|---|---|---|---|---|
| Explanatory Variables | Coefficient | t-Statistic | Coefficient | t-Statistic |
| solar | 0.019*** | 9.22 | 0.043*** | 3.98 |
| trade | -0.217 | -0.96 | -1.513 | -0.48 |
| solar* trade | -0.031*** | -6.75 | -0.069 | -0.84 |
| $R^2$ | 0.999 | | 0.013 | |
| $\bar{R}^2$ | 0.999 | | 0.010 | |
| Prob (F-statistic) | 0.000 | | 0.000 | |
| Hausman $c^2$ | Fixed Effects | | | |
| Number of Observations of Unbalanced Panel | | 1219 | | |

**Notes**: ‘solar’ is the logarithm of electricity production from solar PV. Regressor ‘trade’ is (electricity exports + imports)/1st lag of total electricity production. Cross section units consists of 48 countries and specified time period is 1991 to 2018. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

**Table 7: Interactive Effects of Electricity Production from Wind and Cross-Border Trade on Natural Gas (1991-2018)**

**Dependent Variable:** Logarithm of electricity production from natural gas

| | **Panel A: With-in group Fixed Effect** Panel EGLS (Cross Section Weights) | | **Panel B: Random Effects (RE)** Panel EGLS (Cross Section Random Effects) | |
|---|---|---|---|---|
| Explanatory Variables | Coefficient | t-Statistic | Coefficient | t-Statistic |
| wind | 0.033*** | 14.19 | 0.080*** | 5.49 |
| trade | -0.074 | -0.35 | -1.150 | -0.39 |
| wind* trade | -0.010*** | -3.98 | -0.024 | -0.43 |
| $R^2$ | 0.999 | | 0.047 | |
| $\bar{R}^2$ | 0.999 | | 0.045 | |
| Prob (F-statistic) | 0.000 | | 0.000 | |
| Hausman $c^2$ | Fixed Effects | | | |
| Number of observations of Unbalanced Panel | | 1,219 | | |

**Notes**: 'wind' is the logarithm of electricity production from wind turbines. Regressor 'trade' is (electricity exports + imports)/1st lag of total electricity production. Cross section units consists of 48 countries and specified time period is 1991 to 2018. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

### 4.3 Analyses of Efficiency Indices

A further investigation of the relationship among cross border electricity trade and VREs are conducted through the models (3) and (4):

$$y_{it}^{se} = \beta_{31}.(trade)_{it} + \beta_{32}\,[\,\Delta log(GDP)_{it}\,] + \beta_{33}\,[(trade)_{it} \times \Delta log(GDP)_{it}\,] + \varepsilon_{3it} \qquad (3)$$ [7]

$$y_{it}^{we} = \beta_{41}.(trade)_{it} + \beta_{42}\,[\,\Delta log(GDP)_{it}\,] + \beta_{43}\,[(trade)_{it} \times \Delta log(GDP)_{it}] + \varepsilon_{4it} \qquad (4)$$ [8]

Models (3) and (4) consider the effects of cross-border electricity trade and GDP growth rate on the effective efficiency of electricity production from VREs, and add robustness to the suggested results from models (1) and (2). Solar and wind efficiency indices are created with the purpose of capturing the share of VREs in total electricity production given their existing share in the overall installed capacity for country *i* at time *t*. It is claimed that the effective efficiency of electricity production increases as the index gets bigger.[9] Furthermore, additional panel cointegration tests are conducted to assess if there exist long term relationships among cross-border electricity trade, GDP growth rate and each of our solar and wind efficiency indices (See Appendix Table A.4). In all the cases, 4 out of 7 test statistics rejected the null hypothesis of no cointegration. Hence, within the 2010-2016 period, we claim there

[7] 'se' is abbreviation for solar efficiency.
[8] 'we' is abbreviation for wind efficiency
[9] The mathematical formula of the index is the following:

$$(solar;\ wind)\ efficiency = \frac{electricity\ production\ from\ (solar\ PV;\ wind)\ /total\ electricity\ production}{capacity\ of\ (solar\ PV;\ wind)\ /total\ installed\ capacity}$$

existed a long term relationship between solar, wind efficiency indices and cross border trade as well as between solar, wind efficiency indices and GDP growth rate.

In Table 8 and Table 9 below, we report the estimates of specification (3) and (4) using panel data analysis with the fixed effects approach; to capture the integrated effects of cross-border electricity trade and economic development on the effective efficiencies of electricity production from VREs. We have chosen the time period 2010 to 2016 resulting in a smaller size of 329 observations for this analysis. The reason behind this is to have a more balanced panel in which a relatively vast majority of the countries in our sample have started producing electricity using solar and wind energy sources. Prior to 2010 many countries had zero solar and/or wind capacities, and this has caused our efficiency indices to be mathematically incalculable for those countries. Considering the time period 2016 – 2018, even though IRENA offers access to data of solar and wind capacities and generations of all countries, electricity export and import data of the majority of countries in Asia and the Americas are unavailable. Hence, it would not be possible to capture the effects of cross-border trade in our world sample while including the 2016-2018 period.

Electricity demand is one of the dynamically decisive factors determining the level of electricity production utilized from solar and wind energy sources. Yet, we cannot use electricity demand in our regression equation directly. Since our efficiency indices involve total electricity production in its numerator, using electricity demand as a regressor would not be appropriate due to the high correlation between electricity production and consumption. By employing electricity demand as a regressor, we would introduce endogeneity to our model and cause our estimators to be less efficient. Hence, we have employed the GDP growth rate as an indicator of economic development which would be reflective of electricity demand growth.

The Hausman tests for selecting between Fixed Effects and Random Effects in these models do not give a clear answer. Nonetheless, we have chosen to employ the Fixed Effects approach in specifications of (3) and (4) for an underlying reason. In order to employ Random Effects in the specified models, we have to be able to claim that $cov(\alpha_i, trade_{it}) = 0$ ; which means that cross-border electricity trade is uncorrelated with $\alpha_i$ (the time-independent part of idiosyncratic error term $\varepsilon_{it}$ ). This is unlikely to hold true since the geographical disposition of any country *i* in the sample can play a big part in the amount of cross-border electricity trade occurring at time *t*. A simple illustration of this can be given over isolated countries in the sample such as Australia and Japan where the ocean surrounds all land and these countries do not have any border with other countries that enable interconnected transmission lines. Hence, the cross-border trade of electricity is bound to be zero for them. On the other hand, losing the information coming from the time-independent geographical disposition is tolerable since we are not interested in capturing the overall efficiency of VREs through these indices. The overall efficiency of VREs would capture how many hours they produce electricity in a year under dynamic weather conditions compared to how many hours they do not. Yet, we are trying to find out the effects of cross-border trade on the effective efficiency levels of VREs which only capture how much of the electricity they produce is supplied to the system and consumed.

The empirical evidence we report supports that the rate of growth in the share of capacities of VREs may not result in an equivalent growth in the share of VREs in total electricity production. Even though continuously investing in solar and wind capacities would definitely increase the level of electricity production from these energy sources; significant differences can occur between the increases in the share of capacity and in the share of electricity production. Three factors prominent in creating this difference are the intermittent nature of VREs, physical constraints on transmission and distribution capacities and fluctuations in load. All these can either lead to potential curtailments in electricity supply or excess electricity production from VREs that cannot be supplied to the system and going to waste. The likelihood of potential curtailments and excess production increases significantly as the share of VREs increase in the overall installed capacity of countries and when power systems do not have enough flexibility to accommodate the production coming from VREs. For power systems with relatively weak and small grids, or with ambitious VREs deployment targets; it is very beneficial to proactively initiate reforms and investments in the market that will provide additional flexibility to the system, even at the early deployment stages of VREs (IEA, 2019). Within this context, we expect to see that cross-border trade of electricity has positively affected the effective efficiency of electricity production from VREs by providing additional flexibility to the electricity supply systems of countries.

As can be seen from Fixed Effects columns in Tables 8 and 9, the interactive term of cross-border electricity trade and GDP growth rate have positive relations with our efficiency indices for solar and wind electricity production, at the 1% significance level. Hence, it can be asserted that when a country's economic growth increases with rising levels of cross-border trade, the amount of electricity utilized by solar and wind power generation rises. Cross-border trade of electricity enables countries to gain access to a more diversified portfolio of power plants, producing electricity over a wider geographic area. By exploiting time and load differences among integrated international markets, the excess power production of solar PV and wind turbines that would have gone to waste otherwise can be utilized through exports. Also, ancillary services that comprise the balancing mechanism of the electrical system can be supported by electricity imports when unexpected curtailments occur in VREs. The benefit of electricity imports would be realized to a greater extent as the share of VREs increases in total installed capacity and electricity production from high response fossil fuel-based power generation (natural gas power plants) declines. Therefore, cross-border electricity trade fosters the effective production efficiency of VREs, paving the way for the accelerated growth of renewable share in overall electricity production. The results depicted in Table 8 and 9 provide the necessary empirical evidence that cross-border trade of electricity adds significant flexibility to the power system to better accommodate existing electricity production from VREs. Even though it cannot be precisely known that which energy source produces the electricity that is traded across borders; as cross-border electricity trade increases, electricity production from VREs has an increased chance of being utilized either in domestic or international markets. Further thesis can investigate these indices for sub-Saharan African countries with rising levels of economic growth and a high potential for solar energy.

**Table 8: Effects of Cross-Border Trade on the Efficiency of Electricity Production from Solar PV (2010-2016)**

**Dependent Variable:** Solar Efficiency

| | **Panel A: With-in group Fixed Effect** | | **Panel B: Random Effects (RE)** | |
|---|---|---|---|---|
| | Panel EGLS (Cross Section Weights) | | Panel EGLS (Cross Section Random Effects) | |
| Explanatory Variables | Coefficient | t-Statistic | Coefficient | t-Statistic |
| trade | 0.196** | 2.58 | -0.027* | -1.68 |
| GDP | -0.755*** | -4.80 | -2.915 | -3.57 |
| trade*GDP | 3.186*** | 3.97 | 9.518 | 3.38 |
| $R^2$ | 0.960 | | 0.019 | |
| $\bar{R}^2$ | 0.953 | | 0.010 | |
| Prob (F-statistic) | 0.000 | | 0.098 | |
| Number of Observations | 329 | | | |

**Notes**: 'Solar Efficiency' is an index created to capture efficiency of electricity production solar PV given its existing capacity. The index gives the overall ratio of the respective share of solar PV in total electricity production and in total installed capacity. Efficiency increases as the ratio gets higher. Regressor 'GDP' is GDP growth rate. Cross section units consists of 47 countries and specified time period is 2010 to 2016. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

**Table 9: Effects of Cross-Border Trade on the Efficiency of Electricity Production from Wind (2010-2016)**

**Dependent Variable:** Wind Efficiency

| | **Panel A: With-in group Fixed Effect** Panel EGLS (Cross Section Weights) | | **Panel B: Random Effects (RE)** Panel EGLS (Cross Section Random Effects) | |
|---|---|---|---|---|
| Explanatory Variables | Coefficient | t-Statistic | Coefficient | t-Statistic |
| trade | 0.760*** | 4.37 | 0.253** | 2.52 |
| GDP | -1.568*** | -6.31 | -1.873*** | -3.57 |
| trade*GDP | 4.167*** | 2.92 | 4.436 | 1.42 |
| $R^2$ | 0.930 | | 0.019 | |
| $\bar{R}^2$ | 0.917 | | 0.010 | |
| Prob (F-statistic) | 0.000 | | 0.098 | |
| Number of Observations | 329 | | | |

**Notes:** : ‘Wind Efficiency’ is an index created to capture efficiency of electricity production from wind turbines given its existing capacity. The index gives the overall ratio of the respective shares of wind in total electricity production and in total installed capacity. Efficiency increases as the ratio gets higher. Regressor ‘GDP’ is GDP growth rate. Cross section units consists of 47 countries and specified time period is 2010 to 2016. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

## CHAPTER V

## CONCLUSION

In this thesis, we measured the integrated effects of cross-border electricity trade and electricity production from solar and wind energy sources; on the electricity production from carbon-based natural gas power plants over the 1991-2018 period for 48 countries. The empirical evidence reveals that the overall electricity production from natural gas, solar and wind energy sources are in an increasing path in our world sample over the specified time period. However, we also found that when solar and wind electricity production increases in interconnected energy markets where electricity is traded across borders, electricity production from natural gas power plants decrease statistically significantly.

Under the circumstances created by climate emergency, many of the countries in the world and their respective institutions pledged to an energy transition process to renewable energy sources. Transformation in the power industries carries a vital role in this process. Hence, pointing out the long-term relationship among carbon-based and renewable energy sources in electricity production within a techno-economic framework including cross-border trade is very important for long-term planning in power industries. Considering the current amounts of electricity trade happening across markets and the anticipated increases in the future with the interconnection expansion plans of states like China and India; there exist an uncertainty about the origin energy source of the traded electricity. In other words, it is ambiguous that which type of energy source benefits (in terms of production rates) from the additional demand/supply flexibility cross-border trade creates within interconnected markets. Our results demonstrated that among different types of energy sources with long term relationships in electricity production, solar and wind benefits from cross-border trade and electricity production from carbon-based natural gas power plants are exposed to curtailment effects. It can be anticipated from our results that increasing levels of cross-border trade together along increasing solar and wind capacities will benefit the energy transformation process in the long run.

Furthermore, we created an efficiency index both for solar and wind energy-based electricity production. We conducted panel data analysis using the fixed effects approach on 48 countries but this time over the 2010-2016 period where most of the sample countries have started generating power from these renewable energy sources. This time, we examined the integrated effects of cross-border electricity trade with economic growth (as an indicator of growing electricity demand). Our results showed that cross-border trade increases the chance of electricity produced from intermittent solar and wind energy sources to be utilized either in domestic or international markets. Hence, cross-border trade contributes significantly to their effective efficiency levels of solar and wind electricity production. These findings also add robustness to our inferences in the first model where it is argued that cross-border trade benefits the transformation to low-carbon economies.

## APPENDIX

**Table A.1: List of Sample Countries by Continent**

| **Americas** | **Asia** | **Europe** |
|---|---|---|
| Bolivia | Australia | Austria |
| Brazil | Bangladesh | Belgium |
| Canada | China | Czech Rep. |
| Chile | India | Denmark |
| Colombia | Indonesia | Finland |
| Costa Rica | Israel | France |
| El Salvador | Japan | Germany |
| Guatemala | Jordan | Greece |
| Mexico | Lebanon | Italy |
| Nicaragua | Mongolia | Netherlands |
| Panama | New Zealand | Norway |
| Paraguay | Pakistan | Poland |
| Peru | Philippines | Russian Federation |
| United States | South Korea | Spain |
| Uruguay | Thailand | Sweden |
| | | Switzerland |
| | | Turkey |
| | | United Kingdom |

**Table A.2. Results of Panel Cointegration Test Among Variables in Model (1) (1991-2018)**

| Series | **Panel v-statistics** | **Panel rho-statistics** | **Panel PP-statistics** | **Panel ADF-statistics** |
|---|---|---|---|---|
| | Statistic | Statistic | Statistic | Statistic |
| **N.gas, Solar, Trade, Trade*Solar** | -3.05 | 3.00 | -2.34*** | -2.31*** |

| | **Group rho-statistics** | **Group PP-statistics** | **Group ADF-statistics** |
|---|---|---|---|
| | Statistic | Statistic | Statistic |
| **N.gas, Solar, Trade, Trade*Solar** | 3.57 | -2.51*** | -4.86*** |

**Null Hypothesis**: No cointegration

**Distribution**: All test statistics are normalized to be distributed under N (0,1)

**Trend and Lag Assumptions**: No deterministic trend - Automatic lag length selection based on SIC

**Rejection Criteria**: Following (Pedroni, 2004), if at least four out of seven test statistics have p-values less than 0.10, we reject the null of no cointegration and consider selected variables cointegrated. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

**Notes:** 'N.gas' and 'Solar' are the logarithm of electricity production from natural gas power plants and solar PV. Trade' is (electricity exports + imports)/1$^{st}$ lag of total electricity production. Cross section units consists of 48 countries and specified time period is 1991 to 2018

**Table A.3. Results of Panel Cointegration Test Among Variables in Model (2) (1991-2018)**

| Series | **Panel v-statistics** | **Panel rho-statistics** | **Panel PP-statistics** | **Panel ADF-statistics** |
|---|---|---|---|---|
| | Statistic | Statistic | Statistic | Statistic |
| **N.gas, Wind, Trade, Trade*Wind** | 0.20 | -0.91 | -4.16*** | -4.02*** |

| | **Group rho-statistics** | **Group PP-statistics** | **Group ADF-statistics** |
|---|---|---|---|
| | Statistic | Statistic | Statistic |
| **N.gas, Wind, Trade, Trade*Wind** | 1.58 | -4.67*** | -7.58*** |

**Null Hypothesis**: No cointegration
**Distribution**: All test statistics are normalized to be distributed under N (0,1)
**Trend and Lag Assumptions**: No deterministic trend - Automatic lag length selection based on SIC
**Rejection Criteria**: Following (Pedroni, 2004), if at least four out of seven test statistics have p-values less than 0.10, we reject the null of no cointegration and consider selected variables cointegrated. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.
**Notes:** 'N.gas' and 'Wind are the logarithm of electricity production from natural gas power plants and wind turbines. Trade' is (electricity exports + imports)/1$^{st}$ lag of total electricity production. Cross section units consists of 48 countries and specified time period is 1991 to 2018.

**Table A.4. Results of Panel Cointegration Test Among Variables in Model (3) and (4) (2010-2016)**

| Series | Panel v-statistics | Panel rho-statistics | Panel PP-statistics | Panel ADF-statistics |
|---|---|---|---|---|
| | Statistic | Statistic | Statistic | Statistic |
| **Solar Efficiency, Trade, GDP, Trade*GDP** | 0.33 | 4.54 | -2.33*** | -1.74** |
| **Wind Efficiency, Trade, GDP, Trade*GDP** | -2.46 | 4.32 | -7.43*** | -4.46*** |

| | Group rho-statistics | Group PP-statistics | Group ADF-statistics |
|---|---|---|---|
| | Statistic | Statistic | Statistic |
| **Solar Efficiency, Trade, GDP, Trade*GDP** | 7.01 | -13.16*** | -7.98*** |
| **Wind Efficiency, Trade, GDP, Trade*GDP** | 6.82 | -9.54*** | -6.66*** |

**Null Hypothesis**: No cointegration
**Distribution**: All test statistics are normalized to be distributed under N (0,1)
**Trend and Lag Assumptions**: No deterministic trend - Automatic lag length selection based on SIC
**Rejection Criteria**: Following (Pedroni, 2004), if at least four out of seven test statistics have p-values less than 0.10, we reject the null of no cointegration and consider selected variables cointegrated. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%. **Notes:** 'GDP' is GDP growth rate. Trade' is (electricity exports + imports)/1st lag of total electricity production. Cross section units consists of 47 countries and specified time period is 2010 to 2016.

**Table A.5. Results of Panel Cointegration Test Among Variables in Model (1) with Coal (1991-2018)**

| Series | **Panel v-statistics** | **Panel rho-statistics** | **Panel PP-statistics** | **Panel ADF-statistics** |
|---|---|---|---|---|
| | Statistic | Statistic | Statistic | Statistic |
| **Coal, Solar, Trade, Trade*Solar** | -3.17 | 3.73 | 2.35 | 2.98 |

| | **Group rho-statistics** | **Group PP-statistics** | **Group ADF-statistics** |
|---|---|---|---|
| | Statistic | Statistic | Statistic |
| **Coal, Solar, Trade, Trade*Solar** | 3.26 | -0.49 | 1.15 |

**Null Hypothesis**: No cointegration
**Distribution**: All test statistics are normalized to be distributed under N (0,1)
**Trend and Lag Assumptions**: No deterministic trend - Automatic lag length selection based on SIC
**Rejection Criteria**: Following (Pedroni, 2004), if at least four out of seven test statistics have p-values less than 0.10, we reject the null of no cointegration and consider selected variables cointegrated. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.
**Notes:** 'Coal' and 'Solar' are the logarithm of electricity production from coal power plants and solar PV. Trade' is (electricity exports + imports)/1$^{st}$ lag of total electricity production. Cross section units consists of 48 countries and specified time period is 1991 to 2018.

**Table A.6. Results of Panel Cointegration Test Among Variables in Model (2) with Coal (1991-2018)**

| Series | **Panel v-statistics** | **Panel rho-statistics** | **Panel PP-statistics** | **Panel ADF-statistics** |
|---|---|---|---|---|
| | Statistic | Statistic | Statistic | Statistic |
| **Coal, Wind, Trade, Trade*Wind** | -1.49 | 1.61 | 0.01 | 0.18 |

| | **Group rho-statistics** | **Group PP-statistics** | **Group ADF-statistics** |
|---|---|---|---|
| | Statistic | Statistic | Statistic |
| **Coal, Wind, Trade, Trade*Wind** | 3.36 | 0.52 | 0.22 |

**Null Hypothesis**: No cointegration

**Distribution**: All test statistics are normalized to be distributed under N (0,1)

**Trend and Lag Assumptions**: No deterministic trend - Automatic lag length selection based on SIC

**Rejection Criteria**: Following (Pedroni, 2004), if at least four out of seven test statistics have p-values less than 0.10, we reject the null of no cointegration and consider selected variables cointegrated. (***) means the parameter is significant at 1%. (**) means the parameter is significant at 5%. (*) means parameter is significant at 10%.

**Notes:** 'Coal' and 'Wind are the logarithm of electricity production from coal power plants and wind turbines. Trade' is (electricity exports + imports)/1st lag of total electricity production. Cross section units consists of 48 countries and specified time period is 1991 to 2018.

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