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RESEARCH ARTICLE

# Dynamics of renewable energy consumption and economic activities across the agriculture, industry, and service sectors: evidence in the perspective of sustainable development

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**Abstract** This study aims to examine the impact of renewable and non-renewable energy consumption on the agriculture, industry, services, and overall economic activities (GDP) across a panel of G20 nations. The study makes use of annual data from 1980 to 2012 on 17 countries of the G20. To achieve the study objectives, we apply several robust panel econometric models which account for cross-sectional dependence and heterogeneity in the analysis. The empirical findings confirm the significant long-run equilibrium relationship among the variables. The long-run elasticities indicate that both renewable and non-renewable energy consumptions have significant positive effect on the economic activities across the sectors and also on the overall economic output. These results also imply that the impact is more from renewable energy on economic activities than that of non-renewable energy. Given that, our results offer significant policy implications. We suggest that the policy makers should aim to initiate effective policies to turn domestic and foreign investments into renewable energy projects. This eventually ensures low carbon emissions and sustainable economic development across the G20 nations.

**Keywords** Renewable energy consumption · Sectoral economic activities · Sustainable economic growth · Cross-sectional dependence · G20

**JEL classifications** C23 · O44 · Q01 · Q28 · Q42

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## Introduction

For the last two decades, there has been a significant growth in energy consumption across the globe. It is predicted that the world's energy use will increase about 48% by 2040, and fossil fuels will continue to dominate with 78% of the global energy mix. The consumption of fossil fuels such as coal, oil, and natural gas emits greenhouse gases which have severe impact on the environment. Given that, many countries across the world have formulated renewable energy targets by 2030 to reduce greenhouse gas emissions. According to the International Energy Outlook (IEO 2016), the renewables are the world's fastest growing energy sources, and its consumption increases an average of 2.6%/year until 2040. The global renewable energy uses has increased from 16.6 to 18.1% of total final energy consumption during 1990–2012 (IEA 2014a, b). It has been forecasted that the share of total renewable energy use will be increased to 21% of total final energy consumption with an average growth of 0.17%/year until 2030. The growth in renewable energy can be achieved through initiating effective policies by the governments and policy makers. More specifically, the policy makers have to encourage the investment from domestic and foreign investors in renewable energy projects by providing tax incentives on renewable energy production, ensuring renewable portfolio standards (RES), and the creation of new market opportunities for renewable energy (Apergis and Payne 2012; Paramati et al. 2016, 2017b).

The G20 countries consist of the world's largest advanced and emerging economies. These countries account 85% of the world's GDP and 76% of $CO_2$ emissions. These countries have 80% of renewable energy generation in the world and also they contributed 87% of the world's renewable energy in 2015 (IRENA 2016a). Further, it is estimated that the G20 countries will account 75% of total renewable energy deployment and 80% of total investments in renewable energy across the globe by 2030 (IRENA 2016b).

The consumption of renewable and non-renewable energy is the major sources of energy for economic activities and economic growth in a country. However, the use of non-renewable energy sources in economic activities increases the greenhouse gas emissions and, in turn can accelerate the climate change. Therefore, it forces the policy makers to initiate effective policies to promote the renewable energy sources to replace the conventional energy sources. The consumption of renewable energy plays an important role to address the issue of environmental degradation and sustainable economic growth. This therefore helps the policy makers to meet the increasing energy demand, and it can reduce the growth of $CO_2$ emissions that are primarily generated through the consumption of fossil fuels.

Given the significance of renewable energy use on economic activities, the previous studies have investigated the effect of renewable energy consumption on economic growth in both developed and developing economies of the world. For instance, Apergis and Payne (2010) examined on OECD countries, Apergis and Payne (2011) also investigated on the Central American countries, and Bhattacharya et al. (2016) explored on top renewable energy-consuming countries. Their results suggest that renewable energy consumption has a significant positive impact on economic growth. Some other studies (e.g., Marques et al. 2016; Salim et al. 2014) also examined the effect of renewable and non-renewable energy consumption on overall economic output and industrial production. It indicates from the prevailing literature that the previous studies have failed to examine the impact of renewable and non-renewable energy consumption on the agriculture, industry, and service sectors. Therefore, this study will address this issue by exploring the effect of renewable and non-renewable energy consumption on three major sectors of the economy.

In this regard, the aim of this study is to investigate the effect of renewable and non-renewable energy uses across the economic activities of agriculture, industry, services, and overall GDP of the G20 economies, spanning the period 1980–2012. To achieve the objectives of this study, we apply several robust panel econometric techniques which account for cross-sectional dependence and heterogeneity in the analysis. More specifically, we first identify whether the given data series is cross-sectional dependence (CD) or independent using Pesaran (2004) CD test. If we establish cross-sectional dependence in the data series then we apply cross-sectionally augmented IPS (CIPS) test to identify the order of integration of the variables using the Pesaran (2007) and Smith et al. (2004) panel unit root tests. We then investigate the long-run equilibrium relationship among the variables using the approach developed by Westerlund (2008) which accounts for cross-sectional dependence in the analysis. The long-run output elasticities across the sectors are estimated using the Pesaran's (2006) Common Correlated Effects Mean Group (CCC-MG) models. The study employs the Dumitrescu and Hurlin (2012) panel non-causality test to examine the direction of causality among the variables. Finally, we also explore the country-specific long-run output (GDP) elasticities using the fully modified ordinary least square (FMOLS) method. The estimated results from these models are expected to provide more reliable and robust results.

The present study contributes to the literature in several ways. For instance, any nation or group of states depends heavily on energy consumption for achieving their targeted economic growth rates. The general perception is that higher energy consumption leads to an adverse effect on the environment and eventually on economic growth. However, the consumption of energy may not always have a negative effect on the environment and economic growth. For instance, the energy use can be divided into two categories such as the renewable and non-renewable energy. The renewable energy consumption will have no adverse effect on the environment and also ensures sustainable economic development. On the other hand, the excessive consumption of non-renewable energy leads to both economic and environmental problems. Therefore, it is important to understand the dynamic impact of renewable and non-renewable energy uses on economic activities across the sectors of agriculture, industry, and services and also on the overall economy of the G20 nations. This understanding is very crucial for the policy makers and governments to determine the impact of renewable and non-renewable energies on economic activities across the sectors. Further, this study makes significant contribution to the empirical literature by applying several robust econometric models.

The rest of the paper is designed as follows. "Literature review" presents a brief review of the literature related to the present study. "Data and empirical methodology" describes the data, the model specification, methodology, and preliminary statistics, while "Empirical results and discussion" reports empirical results and discussion. Finally, "Conclusion and policy implications" provides both concluding remarks and policy implications.

## Literature review

### Renewable energy consumption and economic growth

Many studies have empirically explored the renewable energy-growth nexus. These studies have illustrated the four set of hypothesis to explain the nexus between these two variables. For instance, when both renewable energy consumption and economic growth drive each other then it is known as bidirectional (feedback) causality between the variables. In this case, renewable energy use plays an important role for economic growth and vice versa. If causality runs from renewable energy consumption to economic growth then any reduction in renewable energy consumption will hamper the economic output. On the other hand, if causality runs from economic growth to renewable energy consumption then any reduction in renewable energy use will have no effect on the economic output. Finally, if no causal nexus exists between these two variables then reduction in one variable will have no effect on other variable.

The empirical findings of Sadorsky (2009) revealed that increasing real-income per capita raises the consumption of renewable energy in 18 emerging market economies during 1994–2003. Apergis and Payne (2010) investigated the relationship between renewable energy and economic growth in 20 OCED countries, spanning the period 1985–2004. They found that the renewable energy consumption has a positive impact on economic growth. Further, they indicated feedback causality between two variables. The similar results are also found by Apergis and Payne (2011) and Ohler and Fetters (2014).

However, Ocal and Aslan (2013) examined the nexus between renewable energy consumption and economic growth in Turkey during 1990–2010. They found that renewable energy has a negative impact on economic growth. Further authors also reported one-way causality from renewable energy use to economic growth. Al-mulali et al. (2013) documented bidirectional causality between renewable energy consumption and economic growth for 79% of countries, unidirectional causality from economic growth to renewable energy consumption for 2% of countries, and no causality between two variables for 19% of countries across high-income, upper middle-income, lower middle-income, and low-income countries.

The recent studies have examined the nexus between renewable energy consumption and economic growth. However, their results are ambiguous. Alper and Oguz (2016) studied on eight new EU member developing countries during 1990–2008 by using the asymmetric causality approach. They found unidirectional causality from renewable energy consumption to economic growth in Bulgaria, while unidirectional causality from economic growth to renewable energy consumption in the Czech Republic, and no causality between two variables in Cyprus, Estonia, Hungary, Poland, and Slovenia. Further, they documented that the renewable energy has a positive impact on economic growth when all of these countries are put together. Inglesi-Lotz (2016) found that renewable energy consumption has a positive and significant impact on economic growth in 34 OECD countries over the period 1990–2010. Recently, Bhattacharya et al. (2016) also reported that renewable energy consumption has a positive impact on economic growth for 57% of top 38 renewable energy consuming countries in the world, spanning the period 1991–2012. Most recently, Bhattacharya et al. (2017) also found that renewable energy consumption has a positive impact on economic growth in 85 developed and developing countries, spanning the period 1991–2012.

However, there are some studies which could not establish any relationship between renewable energy consumption and economic growth. For instance, Menegaki (2011) documented no causal relationship between renewable energy consumption and economic growth in 27 European countries over the period 1997–2007. Similarly, Ben Aissa et al. (2014) also found no causality between renewable energy consumption and economic growth in 11 African countries, spanning the period 1980–2008. Finally, a very recent study by Kutan et al. (2017) document that the renewable energy consumption makes significant positive contribution to the economic growth in the major emerging market economies.

### Non-renewable energy consumption and economic growth

Some empirical studies have looked the effect of renewable and non-renewable energy consumption on economic output. For instance, Payne (2009) documented an absence of causality among the variables in the USA during 1949–2006. However, Apergis and Payne (2012) found two-way causality between renewable and non-renewable energy consumption, and economic growth in 80 countries over the period 1990–2007. Tugcu et al. (2012) reported an absence of a significant causal relationship between non-renewable energy consumption and economic growth in G7 countries except Japan over the period 1980–2009. Further, they found unidirectional causality running from non-renewable energy consumption and economic growth in Japan. Pao and Fu (2013) reported non-renewable energy consumption has no significant impact on economic growth in Brazil, while unidirectional causality running from non-renewable energy consumption to economic growth has been found. Bloch et al. (2015) examined the effect of coal, oil, and renewable energy consumption on economic growth in China. They found bidirectional causality between coal, oil, renewable energy consumption, and economic growth. They suggested that the Chinese economic growth has been driven by these three sources of energy consumptions. Ben Jebli and Ben Youssef (2015) suggested that renewable and non-renewable energy consumption has a positive impact on economic growth in 69 countries over the period 1980–2010. Recently, Paramati et al. (2017e) explored the effects of renewable and non-renewable energy consumptions on economic output in a sample of the Next-11 developing economies. Authors utilized annual data from 1990 to 2012 and employed several panel econometric techniques to achieve their objectives. Their findings revealed that both renewable and non-renewable energy consumptions positively contributed for economic development in the considered developing economies. Another recent study by Paramati et al. (2017c) also came up with similar findings in the case of the G20 nations.

**Renewable and non-renewable energy consumption and economic activities at the sector levels**

There are few studies which have examined the nexus between energy consumption and sectors' output in the literature. For example, Zachariadis (2007) examined the causal relationship between energy consumption and four sectors of the economy including industry, service, residential, and transportation in G7 countries. For the industry sector, author reported that industrial energy consumption causes output in Japan, output causes industrial energy consumption in Canada, Germany, and the UK and an absence of causality in France, Italy, and the USA. For the service sector, author documented energy consumption in service sector causes output in Italy, Japan, and the USA; output causes energy consumption in service sector in Canada and the UK, bidirectional causality in Germany, and no causality in France. However, Costantini and Martini (2010) found contrary results between 26 OECD and 45 non-OECD countries. For the industry, unidirectional causality from energy consumption to output in OECD countries whereas output causes energy consumption in non-OECD countries. For the service sector, bidirectional causality between energy consumption and output in OECD countries whereas unidirectional causality from output to energy consumption in non-OECD countries. Bowden and Payne (2009) investigated the nexus between aggregate and sectoral primary energy consumption and real output in the USA during the period 1949–2006. The results indicated the unidirectional causality from industrial primary energy consumption to real output, whereas bidirectional causality between commercial and residential primary energy consumption and real output.

Similarly, limited studies have examined the nexus between energy consumption and real output at sectors. For instance, Abbas and Choudhury (2013) examined the relationship between agriculture energy consumption and agriculture output in India and Pakistan during 1972–2008. Author documented the feedback causality between agriculture energy uses and economic growth in India, while unidirectional causality from output to energy in Pakistan. Tang and Shahbaz (2013) investigated the relationship between energy consumption and real output at the aggregate and sectoral levels in Pakistan during the 1972–2010. They found one-way causality from energy use to economic growth. At the sectoral level, they reported unidirectional one-way causality from energy consumption to manufacturing and service sectors, while no causality between energy use and agriculture sector. Further, Shahbaz et al. (2016) documented unidirectional causality from energy consumption to agriculture growth, whereas bidirectional causality between modern sectors[1] and energy consumption in Pakistan over the period 1972–2011.

Most recently, a very few studies have been conducted the impact of renewable and non-renewable energy consumption on real output at the sector level. For example, Bowden and Payne (2010) examined the sectoral causal relationship between renewable and non-renewable energy consumption and economic growth in the USA during 1949–2006. They documented an absence of causality between commercial and industrial renewable energy consumption and real output, whereas unidirectional causality from residential renewable energy consumption to real output. On the other hand, the result indicates that bidirectional causality between commercial and residential non-renewable energy consumption and real output, and unidirectional causality from industrial non-renewable energy consumption to real output. Similarly, Salim et al. (2014) examined the dynamic relationship between renewable and non-renewable energy consumption and industrial output and economic growth in 29 OECD countries, spanning the period 1908–2012. They found bidirectional causality of industrial output with both renewable and non-renewable energy consumption in the short and long runs. They also found bidirectional causality between non-renewable energy consumption and economic growth in the short-run while unidirectional causality from economic growth to renewable energy consumption in the long run. A recent study by Marques et al. (2016) reported bidirectional causality between non-renewable energy consumption and industrial output, whereas no causality between renewable energy consumption and industrial output in Greece.

In summary, most of the previous studies have examined the relationship between renewable and non-renewable energy consumption and economic growth. However, the previous studies failed to look at the impact of renewable and non-renewable energy consumption across the economic activities of agriculture, industry, service and overall GDP. Further, the previous studies mostly

[1] Authors have considered industrial and service sectors as the modern sectors.

used conventional econometric techniques which largely rely on the assumption of cross-sectional independence. Due to the increasing globalization of the economies around the world, there can be a significant cross-sectional dependence among the variables. Therefore, the application of the models which rely on the assumption of cross-sectional independence may provide misleading results. Given these limitations from the existing studies, in this paper, we aim to fill these gaps by examining the effect of renewable energy consumption on the economic activities of agriculture, industry, service, and overall GDP of the G20 nations and also will apply econometric techniques which account for cross-sectional dependence and heterogeneity in the analysis.

## Data and empirical methodology

### Nature of data and measurement

The present study uses annual data for G20 nations, spanning the period from 1980 to 2012. The selection of the sample period and countries from the G20 are based on the availability of data. The considered sample countries from the G20 include Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, South Africa, Turkey, the UK, and the USA.[2] To meet the study objectives, we collect the data on agriculture, industry, services, gross domestic product (GDP), capital, and labor from the World Development Indicators (WDI) online database, while non-renewable and renewable energy consumptions are sourced from the US Energy Information Administration (EIA) online database. Using the annual data, from 1980 to 2012, on 17 G20 countries, we construct balanced panel data set for the empirical analysis. In the following, we describe the measurement of the variables:

The total value added by the agriculture (agr), industry (ind), and services (ser) are measured in constant 2005 US dollars, while GDP (y) at market prices and gross fixed capital formation (in) are also measured in constant 2005 US dollars; labor force (l) is the total number of people available in the workforce; non-renewable energy consumption (nren) is the sum of total coal, gas, and petroleum consumption in quadrillion Btu and finally, renewable energy consumption (ren) is the total renewable electricity net consumption in billion kilowatthours. We converted all of these variables into natural logarithms before the empirical analysis begin to avoid the issues related to the data measurement.

[2] We excluded Russia and Saudi Arabia from the sample due to unavailability of the data.

### Econometric methodology

To examine the effect of renewable and non-renewable energy consumption on agriculture, industry and service sectors, and also overall GDP, we frame the following equations:

$$Model\ 1: \mathrm{agr}_{it} = a_{1i} + b_1 in_{it} + b_2 l_{it} + b_3 nren_{it} + b_4 \mathrm{ren}_{it} + e_{1it} \quad (1)$$

$$Model\ 2: \mathrm{ind}_{it} = a_{2i} + b_5 in_{it} + b_6 l_{it} + b_7 nren_{it} + b_8 \mathrm{ren}_{it} + e_{2it} \quad (2)$$

$$Model\ 3: \mathrm{ser}_{it} = a_{3i} + b_9 in_{it} + b_{10} l_{it} + b_{11} nren_{it} + b_{12} \mathrm{ren}_{it} + e_{3it} \quad (3)$$

$$Model\ 4: y_{it} = a_{4i} + b_{13} in_{it} + b_{14} l_{it} + b_{15} nren_{it} + b_{16} \mathrm{ren}_{it} + e_{4it} \quad (4)$$

where, agr, ind, ser, y, in, l, nren, and ren represent for agriculture, industry, service, GDP, capital, labor, non-renewable energy consumption, and renewable energy consumption, respectively. Similarly, countries and time period are indicated by the subscripts $i$ $(i = 1, \ldots\ldots, N)$ and $t$ $(t = 1, \ldots\ldots., T)$, respectively. The parameters $a_{1i}$, $a_{2i}$, $a_{3i}$, and $a_{4i}$ need to be estimated with respect to the independent variables, while $e_{1it}$, $e_{2it}$, $e_{3it}$, and $e_{4it}$ denote the residuals which represent deviations from the long-run equilibrium relationships.

Given the panel nature of our data, the analysis first examines panel unit root tests, simultaneously recognizing the likelihood of cross-sectional dependence. If significant degrees of positive residual cross-sectional dependence exist and are ignored, panel unit root tests of the first-generation can lead to spurious results due to size distortions. As a result, second-generation panel unit root tests are preferred only when it has been established that the panel is subject to a significant degree of residual cross-sectional dependence. Therefore, to address the issue of cross-sectional dependence (CD), the analysis applies the Pesaran (2004) cross-dependence test. This approach is based on a simple average of all pair-wise correlation coefficients of the OLS residuals obtained from standard augmented Dickey-Fuller regressions of each variable in the panel. This test assumes the null hypothesis of cross-sectional independence as against the cross-sectional dependence. The CD test statistic follows asymptotically a two-tailed standard normal distribution.

In light of the presence of cross-sectional dependence, two second-generation panel unit root tests are examined to determine the degree of integration in the respective variables. The Pesaran (2007) panel unit root test does not require the estimation of factor loading to eliminate cross-sectional dependence. Pesaran (2007) advances a statistic based on the average of the individual cross-sectional ADF statistics (CADF), which is denoted as a cross-sectional augmented (Im et al. 2003) test (CIPS). His approach provides two statistics such as CIPS and CIPS* to test the order of integration of the variables. Both of these tests assume the null hypothesis of a unit root. Similarly, the analysis also applies bootstrap panel unit root tests recommended by Smith et al. (2004). Their approach utilize a sieve sampling scheme to account for both the time series and cross-sectional dependence in the data through bootstrap blocks. The tests we consider are denoted as t-bar, LM-bar, max-bar, and min-bar. All four tests are constructed with a unit root under the null hypothesis and heterogeneous autoregressive roots under the alternative hypothesis, in which the rejection provides evidence in favor of stationarity for at least one country.

Next, the analysis employs panel cointegration methodology to investigate the long-run equilibrium relationship across the variables under study. The study makes use of the Durbin-Hausman test, recommended by Westerlund (2008), to explore the presence of cointegration. This test is applied under very general conditions, because it does not rely heavily on a priori knowledge of the integration order of the variables included in the modeling approach. Additionally, it allows for cross-sectional dependence modeled by a factor model in which the errors in Eqs. (1), (2), (3), and (4) are obtained by idiosyncratic innovations and unobservable factors that are common across units of the panel.

To examine the long-run elasticities of agriculture, industry, service and overall GDP, we apply a panel methodology, which takes into account both cross-section and time dimensions of the data. However, when the errors of a panel regression are cross-sectionally correlated then standard estimation methods can lead to inconsistent estimates and incorrect inference (Phillips and Sul, 2003). In order to take into account the cross-sectional dependence, we implement a novel econometric methodology, namely, the Common Correlated Effects (CCE) by Pesaran (2006). He suggests a new approach that takes into account cross sectional dependence. The proposed methodology allows individual specific errors to be serially correlated and heteroskedastic.

Finally, the study applies bivariate panel causality tests to explore the short-run causalities across the considered variables. We apply this test based on the Dumitrescu and Hurlin (2012) approach. This test requires all the variables to be stationary; hence, it is applied on the first differenced data series. The null hypothesis of no causality is tested against the alternative hypothesis of causality at least for a few cross-sections. The Wald statistics are computed separately for each cross-section. The panel test value is obtained by taking the cross-sectional average of individual Wald statistics.

## Empirical results and discussion

### Preliminary analysis

The first step of empirical analysis is to investigate whether the variables are cross-sectional dependent or interdependent. For this purpose, we apply CD test proposed by Pesaran (2004). This is an important issue to be looked at before applying any econometric models. Since the conventional econometric techniques assume that cross-section members are independence and if these tests are applied on the series which is cross-sectional dependence then the results will be spurious and can be misinterpreted. Therefore, it is important to establish whether there is any evidence of cross-sectional dependence among the variables. The results of CD test are reported in Table 1. The findings show that there is a significant evidence of cross-sectional dependence among the variables across the panels. More specifically, the null hypothesis of cross-sectional independence is strongly rejected across the variables with irrespective of lags (from 1 to 4). Given that, we confirm the presence of cross-sectional dependence in the series.

In this respect, the application of first generation (also known as conventional) unit root tests become invalid as they rely on the assumption of cross-sectional independence in the series. Therefore, we apply second-generation panel unit root tests developed by Pesaran (2007)[3] and Smith et al. (2004). The findings of these tests are documented in Table 2. These test results on the level data series confirm the presence of unit root (non-stationary) for all of the variables. However, when these tests are applied on the first difference data series, then it clearly indicates rejection of the null hypothesis of a unit root for all of the variables. Therefore, our results of unit root tests confirm that all of the variables have the same order of integration, i.e., I (1).

In order to provide robust evidence to the presence of unit roots across the variables under study, while linear panel unit root tests do not allow for structural breaks and may suffer from significant loss of power if data display possible breaks, we also report evidence on panel unit root tests with breaks by using the Lagrange Multiplier (LM) panel unit root test developed by Im et al. (2005). The results reported in Table 3 support evidence of all variables under consideration which confirms the findings in relevance to the linear panel unit root tests presented in Table 2. Moreover, Table 4 reports the results of a non-linear panel unit root test (i.e., the NSURADF test), recommended by Lau et al. (2012),[4] which takes into consideration the contemporaneous cross-sectional correlations across panel members. The findings also provide further statistical support to the baseline linear results reported in Table 2.[5]

[3] A number of recent studies (e.g., Alam et al. 2017; Alam and Paramati 2016; Paramati et al. 2017a) have applied the panel unit root tests which account for cross-sectional dependence in the analysis, while some other studies (e.g., Alam and Paramati 2015) did not account for cross-sectional dependence while estimating panel unit root tests.

[4] Cerrato et al. (2013) provide detailed discussion on linear and non-linear panel unit root tests.

[5] On the other hand, Gozgor (2016) and Gozgor and Demir (2017) provide detailed discussion on the structural breaks in time-series data set.

**Table 1** Cross-sectional dependence tests

| Variable | Lags | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| agr | 24.52[a] (0.00) | 25.19[a] (0.00) | 25.95[a] (0.00) | 27.10[a] (0.00) |
| ind | 27.84[a] (0.00) | 28.37[a] (0.00) | 30.16[a] (0.00) | 32.25[a] (0.00) |
| ser | 23.79[a] (0.00) | 24.36[a] (0.00) | 26.15[a] (0.00) | 28.41[a] (0.00) |
| y | 32.18[a] (0.00) | 34.36[a] (0.00) | 38.31[a] (0.00) | 39.84[a] (0.00) |
| in | 30.16[a] (0.00) | 33.52[a] (0.00) | 35.86[a] (0.00) | 36.59[a] (0.00) |
| l | 27.83[a] (0.00) | 29.16[a] (0.00) | 31.20[a] (0.00) | 32.64[a] (0.00) |
| nren | 30.94[a] (0.00) | 32.18[a] (0.01) | 35.48[a] (0.01) | 36.35[a] (0.01) |
| ren | 34.19[a] (0.00) | 36.48[a] (0.00) | 39.05[a] (0.00) | 42.14[a] (0.01) |

Notes: Under the null hypothesis of cross-sectional independence, the CD statistic is distributed as a two-tailed standard normal. Figures in brackets denote *p* values

[a] Significance level—1%

## Main results and discussion

Since unit root tests result show the same order of integration of the variables then there may be a long-run equilibrium relationship among the variables across the panels. Hence, to explore the cointegration relationship among the variables, we

**Table 3** Panel unit root test results with structural breaks

| Variable | No break | One break | Two breaks |
|---|---|---|---|
| agr | − 1.07 | − 1.09 | − 1.12 |
| Δagr | − 8.71[a] | − 8.95[a] | − 9.68[a] |
| ind | − 1.12 | − 1.16 | − 1.20 |
| Δind | − 8.95[a] | − 9.81[a] | − 11.85[a] |
| ser | − 1.02 | − 1.08 | − 1.16 |
| Δser | − 9.16[a] | − 12.43[a] | − 16.91[a] |
| y | − 0.94 | − 1.01 | − 1.12 |
| Δy | − 9.92[a] | 15.82[a] | − 19.58[a] |
| in | − 0.86 | − 0.97 | − 1.21 |
| Δin | − 8.86[a] | − 9.75[a] | − 13.76[a] |
| l | − 1.01 | − 1.06 | − 1.15 |
| Δl | − 9.63[a] | − 12.37[a] | − 18.61[a] |
| nren | − 1.03 | − 1.08 | − 1.17 |
| Δnren | − 8.92[a] | − 10.45[a] | − 16.94[a] |
| ren | − 1.05 | − 1.13 | − 1.19 |
| Δren | − 9.88[a] | − 12.35[a] | − 19.92[a] |

Notes: Δ denotes first differences. The 1, 5, and 10% critical values for the panel LM unit root tests with structural breaks are − 2.33, − 1.65, and − 1.28, respectively

[a] Rejection of the null hypothesis

**Table 2** Linear panel unit root tests

| Variable | Pesaran CIPS | Pesaran CIPS[a] | Smith et al. *t* test | Smith et al. LM test | Smith et al. max test | Smith et al. min test |
|---|---|---|---|---|---|---|
| agr | − 1.18 | − 1.25 | − 1.36 | 3.31 | − 1.38 | 1.30 |
| Δagr | − 5.57[b] | − 5.86[b] | − 5.74[b] | 22.69[b] | − 7.94[b] | 6.96[b] |
| ind | − 1.19 | − 1.25 | − 1.30 | 3.36 | − 1.44 | 1.29 |
| Δind | − 5.93[b] | − 5.82[b] | − 6.28[b] | 19.58[b] | − 7.35[b] | 7.71[b] |
| ser | − 1.25 | − 1.38 | − 1.36 | 3.11 | − 1.38 | 1.33 |
| Δser | − 5.51[b] | − 5.64[b] | − 6.92[b] | 23.98[b] | − 7.40[b] | 6.56[b] |
| y | − 1.39 | − 1.21 | − 1.32 | 3.19 | − 1.39 | 1.34 |
| Δy | − 5.94[b] | − 5.87[b] | − 6.95[b] | 24.15[b] | − 7.20[b] | 7.85[b] |
| in | − 1.42 | − 1.50 | − 1.31 | 3.23 | − 1.39 | 1.43 |
| Δin | − 5.38[b] | − 5.53[b] | − 6.47[b] | 22.15[b] | − 7.92[b] | 7.51[b] |
| l | − 1.32 | − 1.46 | − 1.35 | 3.21 | − 1.41 | 1.460 |
| Δl | − 5.64[b] | − 5.52[b] | − 6.86[b] | 22.48[b] | − 7.50[b] | 7.85[b] |
| nren | − 1.23 | − 1.32 | − 1.37 | 3.18 | − 1.33 | 1.38 |
| Δnren | − 5.39[b] | − 5.64[b] | − 6.89[b] | 22.54[b] | − 7.49[b] | 6.48[b] |
| ren | − 1.35 | − 1.23 | − 1.32 | 3.30 | − 1.41 | 1.35 |
| Δren | − 5.81[b] | − 5.77[b] | − 6.49[b] | 19.84[b] | − 7.46[b] | 7.48[b] |

Notes: Δ denotes first differences. A constant is included in the Pesaran (2007) tests. Rejection of the null hypothesis indicates stationarity in at least one country

[a] Truncated CIPS test. Critical values for the Pesaran (2007) test are − 2.57 at 1%, − 2.33 at 5%, and − 2.21 at 10%, respectively. Both a constant and a time trend are included in the Smith et al. (2004) tests. Rejection of the null hypothesis indicates stationarity in at least one country. For both tests, the results are reported at lag = 4. The null hypothesis is that of a unit root. Critical values for the Smith et al. (2004) test are: *t* test = − 3.43 at 1%, − 2.86 at 5%, and − 2.57 at 10%; LM test = 3.94 at 1%, 3.66 at 5%, and 3.57 at 10%; max test = − 3.96 at 1%, − 3.41 at 5%, and − 3.12 at 10%; min test = 2.21 at 1, 2.15 at 5%, and 2.12 at 10%

[b] Rejection of the null hypothesis

**Table 4** The NSURADF non-linear panel unit root test

| Variable | Lau et al. test |
|---|---|
| agr | − 1.95 |
| Δagr | − 8.82[a] |
| ind | − 2.36 |
| Δind | − 9.34[a] |
| ser | − 2.59 |
| Δser | − 9.48[a] |
| y | − 2.42 |
| Δy | − 9.41[a] |
| in | − 1.86 |
| Δin | − 7.94[a] |
| l | − 2.85 |
| Δl | − 9.63[a] |
| nren | − 1.99 |
| Δnren | − 7.93[a] |
| ren | − 2.57 |
| Δren | − 8.74[a] |

Notes: Δ denotes first differences. Critical values are − 4.196 at 1%, − 3.495 at 5%, and − 3.127 at 10%, respectively and were taken from Lau et al. (2012)

[a] Rejection of the null hypothesis

apply Westerlund (2008) panel cointegration methodology which relies on the assumption of the consider variables are cross-sectional dependence. The cointegration test is applied across all the panels and results displayed in Table 5. The findings confirm the rejection of the null hypothesis of no cointegration across all the panels and are statistically significant at the 1% level. Therefore, our results suggest that there is a considerable long-run equilibrium relationship among the variables of economic activities, renewable and non-renewable energy consumption. These results are uniform across the panels.

The above results confirmed the long-run equilibrium relationship among the variables. However, these results did not imply the cause and effect relationship between dependent and independent variables. Therefore, in this section we explore the impact of renewable and non-renewable energy consumption on agriculture, industry, service sector and overall GDP. The results of these models are presented in Table 6. The findings show that:

- A 1% increase in renewable energy consumption raises agriculture, industry, service and overall GDP by 0.342, 0.384, 0.328, and 0.401%, respectively.

This implies that the renewable energy consumption has a significant positive impact on economic output across the agriculture, industry, service sector, and total GDP in G20 nations. More specifically, results show that the impact of renewable energy consumption is more effective on industry and agriculture sectors and also overall economic output. These results are consistent with Apergis and Payne (2010, 2011), Ohler and Fetters (2014), and Paramati et al. (2017c, e) who documented that renewable energy consumption has a positive impact on economic growth. Further, Salim et al. (2014) also reported that renewable energy consumption has a positive impact on industrial output and economic growth in 29 OECD countries. Similarly, the effect of non-renewable energy consumption on agriculture, industry, service sector and overall GDP show that:

- A 1% raise in non-renewable energy consumption increase economic output of agriculture, industry, service and total GDP by 0.297, 0.376, 0.301, and 0.385%, respectively.

These results indicate that the consumption of non-renewable energy has a considerable positive impact on the economic activities of agriculture, industry, service sector, and also overall GDP. These results are similar to Salim et al. (2014), who found that non-renewable energy consumption

**Table 5** Panel cointegration test results

| | $DH_g$ | $DH_p$ |
|---|---|---|
| Model 1 | 6.129[a] (0.00) | 6.436[a] (0.00) |
| Model 2 | 5.783[a] (0.00) | 5.905[a] (0.00) |
| Model 3 | 7.093[a] (0.00) | 7.318[a] (0.00) |
| Model 4 | 6.538[a] (0.00) | 6.882[a] (0.00) |

*Note*: *p* values are reported in brackets. The criterion used in this paper is IC2 (K) with the maximum number of factors (K) set equal to 5. For the bandwidth selection, M was chosen to represent the largest integer less than 4(T/100)2/9, as suggested by Newey and West (1994)

[a] Rejection of no cointegration null hypothesis at the 1% level of significance

**Table 6** Panel Common Correlated Effects Mean Group (CCE-MG) long-run estimates

| | Model 1 Agricultural | Model 2 Industrial | Model 3 Services | Model 4 Total GDP |
|---|---|---|---|---|
| Constant | 0.8247 (0.03) | 0.8516 (0.04) | 0.7938 (0.05) | 0.7546 (0.04) |
| in | 0.3211 (0.00) | 0.4872 (0.00) | 0.4496 (0.00) | 0.4983 (0.00) |
| l | 0.4271 (0.00) | 0.3512 (0.00) | 0.4655 (0.00) | 0.4853 (0.00) |
| nren | 0.2974 (0.00) | 0.3758 (0.00) | 0.3013 (0.00) | 0.3851 (0.00) |
| ren | 0.3418 (0.00) | 0.3844 (0.00) | 0.3275 (0.00) | 0.4014 (0.00) |
| Wald tests | (0.01) | (0.00) | (0.00) | (0.01) |

Note: Figures in brackets denote *p* values. Wald tests investigate the validity of the null hypothesis that the coefficient of the non-renewable energy consumption is greater than that of the renewable energy consumption has a positive impact on industrial output and economic growth in 29 OECD countries. Similarly, Paramati et al. (2017e) reported that non-renewable energy uses has a positive impact on economic growth in the Next-11 developing countries. Most importantly, the results show that the renewable energy consumption has more positive effect on the economic output across the sectors and overall output than that of non-renewable energy consumption. The remaining control variables, i.e., capital and labor force, are carrying the expected theoretical (positive) signs, indicating a positive impact on output across all four models considered.

Based on these findings, the policy implications can go as follows. Our results suggested that renewable energy consumption has a more effect than non-renewable energy consumption on the economic output across the agriculture, industry, service, and total GDP. Therefore, the policy makers and government officials need to note that it is worth promoting renewable energy generation and uses across the sectors as it has a significant positive effect on the economic activities. Further, the policy makers have to frame appropriate policies to shift the conventional energy subsidies to the renewable energies so that it can further encourage the renewable energy generation and uses. The policy makers and government officials need to come up with the policies that can promote domestic and international investments into renewable energy sectors. By promoting more investments into renewable energy sector will not only increase its generation capacity but also meets the increasing energy demand by discouraging fossil fuels. Hence, the higher consumption of renewable energy will further expand the economic activities across the sectors and also reduces $CO_2$ emissions significantly which were mainly sourced from the non-renewable energy consumption (fossil fuels). Given that, the G20 countries can move towards the sustainable economic development without damaging the environment.

In the next section, we aim to explore the direction of causality among the variables in the short-run using the heterogeneous panel non-causality test of Dumitrescu and Hurlin (2012).[6] The results of causality test are displayed in Table 7. The findings show an absence of causal relationship between renewable energy consumption and total GDP, while total GDP Granger causes non-renewable energy consumption. These results are consistent with Menegaki (2011) and Ben Aissa et al. (2014), whose studies documented no causal relationship between renewable energy consumption and economic growth. Further, unidirectional causality from economic growth to non-renewable energy consumption implies that preventing non-renewable energy use will not have a negative effect on economic growth. This result suggests that the policy makers should implement effective policies to promote renewable energy to replace non-renewable energy uses, which can address the issue of environmental degradation and may lead to sustainable economic development in G20 countries.

At the sectoral level, renewable energy consumption Granger causes service sector. It indicates that the growth of renewable energy consumption causes service sector in G20 nations. Given this finding, we argue that the service sector across the G20 nations might have adopted to use more renewable energy than the non-renewable energy. This is a significant outcome as the share of service sector to the total GDP has grown significantly in the recent time. On the other hand, we could not establish any causal relationship of renewable energy or non-renewable energy consumption with respect to the agriculture and industry sectors in the short-run.

**Table 7** Results of short-run heterogeneous panel non-causality test

| Null Hypothesis: | Zbar-Stat. | Prob. |
|---|---|---|
| in does not homogeneously cause agr | − 1.399 | 0.162 |
| agr does not homogeneously cause in | − 0.111 | 0.912 |
| l does not homogeneously cause agr | − 0.263 | 0.792 |
| agr does not homogeneously cause l | 3.102*** | 0.002 |
| nrec does not homogeneously cause agr | − 1.335 | 0.182 |
| agr does not homogeneously cause nrec | 0.174 | 0.862 |
| rec does not homogeneously cause agr | 1.231 | 0.218 |
| agr does not homogeneously cause rec | 0.002 | 0.998 |
| in does not homogeneously cause ind | 2.631*** | 0.009 |
| ind does not homogeneously cause in | 2.008** | 0.045 |
| l does not homogeneously cause ind | 0.547 | 0.585 |
| ind does not homogeneously cause l | 3.070*** | 0.002 |
| nrec does not homogeneously cause ind | 0.865 | 0.387 |
| ind does not homogeneously cause nrec | 1.156 | 0.248 |
| rec does not homogeneously cause ind | − 1.360 | 0.174 |
| ind does not homogeneously cause rec | − 1.160 | 0.246 |
| in does not homogeneously cause ser | − 1.107 | 0.268 |
| ser does not homogeneously cause in | 1.008 | 0.313 |
| l does not homogeneously cause ser | − 0.626 | 0.531 |
| ser does not homogeneously cause l | 3.842*** | 0.000 |
| nrec does not homogeneously cause ser | − 0.444 | 0.657 |
| ser does not homogeneously cause nrec | − 0.825 | 0.409 |
| rec does not homogeneously cause ser | − 1.778* | 0.076 |
| ser does not homogeneously cause rec | − 0.577 | 0.564 |
| in does not homogeneously cause y | − 0.011 | 0.991 |
| y does not homogeneously cause in | 1.800* | 0.072 |
| l does not homogeneously cause y | − 0.612 | 0.541 |
| y does not homogeneously cause l | 3.912*** | 0.000 |
| nrec does not homogeneously cause y | 0.210 | 0.834 |
| y does not homogeneously cause nrec | 1.872* | 0.061 |
| rec does not homogeneously cause y | − 0.671 | 0.502 |
| y does not homogeneously cause rec | − 0.054 | 0.957 |

*10%, **5%, and ***1% significance levels—rejection of the null hypothesis of no causality

[6] A number of recent empirical studies (Alam et al. 2015; Alam and Paramati 2017; Paramati et al. 2017d) have used heterogeneous panel no-causality test to explore the direction of causality between the variables.

Finally, we explore the long-run output (GDP) elasticities across the individual countries of the G20. This is particularly important as the panel analysis of long-run elasticities did not indicate the sign and scale of renewable and non-renewable energy consumption on the economic output for the individual countries. These findings will be more specific to the individual countries so it can be a crucial for the policy makers and government officials to take appropriate strategies with regard to the renewable energy generation and uses. For this purpose, we make use of FMOLS models. This is a robust technique as it accounts for endogeneity and serial correlation that present in the model. The results of these models are reported in Table 8.

The empirical findings of country specific long-run output elasticities show that the renewable energy consumption has a significant positive impact on the economic output. More specifically, the renewable energy consumption has a positive and statistically significant effect on the output growth in 12 countries out of the 17. On the other hand, the renewable energy consumption seems to adversely influence economic growth in India and the USA and has no significant effect on growth in Australia, Indonesia, and Mexico. Among the sample countries, the renewable energy consumption has more positive effect on the economic output in Japan, Brazil, Canada, and China. Based on these findings, we argue that the countries that have positive effect of renewable energy consumption on economic output should focus on promoting more renewable energy generation and uses across the economic activities while the countries that have negative impact should increase the share of renewable energy consumption in total energy use so that it can also positively influence the growth. However, if a country is in the transition, in terms of shifting the energy sources from conventional to renewables then there can be a positive or negative impact on economic output. Given these results, we suggest the policy makers of those countries to frame appropriate policies to convent the domestic and foreign investments into the renewable energy sectors by ensuring strong institutional set up.

## Conclusion and policy implications

Given the significance of renewable energy consumption for sustainable economic development and low carbon environment, the recent literature has paid considerable attention in exploring the relationship between renewable energy consumption and economic output across the developed and developing economies around the world. The main drawback of the previous studies is that they only looked at the impact of renewable energy consumption on overall economic output and failed to look at sectoral level such as agriculture, industry and service sectors. Further, the previous studies mostly used econometric models which largely rely on the assumption of cross-sectional independence among the variables. In reality, due to increasing globalization, the countries around the world become more interdependent and hence there is a considerable cross-sectional dependence among the variables. Therefore, choosing an appropriate econometric model for the analysis has become an important issue to be looked at carefully. Given that, in this study, we aimed to examine the effect of renewable energy consumption on economic output across the major sectors such as the agriculture, industry, service, and overall GDP of the G20 nations. For this purpose, we used annual data from 1980 to 2012 and applied several robust panel econometric models which account for cross-sectional dependence in the analysis.

The empirical results of our study confirmed the significant long-run equilibrium relationship among the variables. Further, our results of long-run elasticities showed that the consumption of renewable energy has a significant positive impact on the economic output across the sectors. More importantly, our findings indicated that the renewable energy consumption has more effect on the economic activities across the sectors than that of non-renewable energy consumption. The short-run causality test results showed unidirectional causality that runs from renewable energy consumption to service sector. However, we could not establish any causal relationship between renewable energy consumption and overall economic output in the short run. Finally, our study also established significant linkage between renewable energy consumption and economic out across the individual countries.

Given these findings, the study makes significant contributions to the body of knowledge on the relationship between renewable energy consumption and economic output across the major sectors. Further, study also adds value to the empirical literature on selecting the appropriate econometric models when there is any evidence of cross-sectional dependence in the series. The policy implications of our study go as follows: (i) our results showed that the consumption of renewable energy has more positive effect on the economic output of agriculture, industry, service, and overall GDP than that of non-renewable energy consumption; (ii) therefore, we suggest that the policy makers need to realize the potentiality of the renewable energy use in promoting the economic activities across the sectors; (iii) given that the policy makers and government officials need to frame appropriate policies to promote the renewable energy sources by encouraging domestic and foreign investors to investment more money into renewable energy projects; (iv) the policy makers also need to provide lucrative incentives in terms of tax exceptions and assured above the market average returns to the investors. Further, the policy makers have to ensure no discrimination but equal opportunities for the domestic and foreign investors. These incentives will encourage both domestic and foreign investors to invest more money into renewable and clean energy projects; finally, (v) this increasing renewable energy generation

**Table 8** Results of country-specific long-run output elasticities

| Country | Constant | ln | l | nrec | rec | $R$-squared | Adj. $R$-squared |
|---|---|---|---|---|---|---|---|
| Argentina | | | | | | | |
| Coefficient | 16.378** | 0.315*** | 0.081 | 0.504** | 0.078* | 0.988 | 0.986 |
| Prob. | 0.010 | 0.000 | 0.806 | 0.027 | 0.084 | | |
| Australia | | | | | | | |
| Coefficient | 15.263*** | 0.150*** | 0.419** | 0.634*** | 0.088 | 0.997 | 0.997 |
| Prob. | 0.000 | 0.001 | 0.023 | 0.000 | 0.213 | | |
| Brazil | | | | | | | |
| Coefficient | 5.173 | 0.440*** | 0.522 | − 0.270 | 0.321* | 0.990 | 0.989 |
| Prob. | 0.445 | 0.000 | 0.115 | 0.216 | 0.076 | | |
| Canada | | | | | | | |
| Coefficient | 7.342*** | 0.254*** | 0.700*** | 0.332*** | 0.227* | 0.995 | 0.994 |
| Prob. | 0.001 | 0.002 | 0.006 | 0.002 | 0.058 | | |
| China | | | | | | | |
| Coefficient | − 12.488*** | 0.506*** | 1.249*** | 0.066 | 0.204** | 0.999 | 0.999 |
| Prob. | 0.003 | 0.000 | 0.000 | 0.542 | 0.024 | | |
| France | | | | | | | |
| Coefficient | − 5.931*** | 0.594*** | 1.069*** | − 0.051 | 0.024* | 0.980 | 0.977 |
| Prob. | 0.000 | 0.000 | 0.000 | 0.108 | 0.060 | | |
| Germany | | | | | | | |
| Coefficient | − 11.312** | 0.419*** | 1.563*** | 0.372 | 0.078*** | 0.988 | 0.986 |
| Prob. | 0.043 | 0.002 | 0.001 | 0.186 | 0.000 | | |
| India | | | | | | | |
| Coefficient | 10.454*** | 0.605*** | 0.041 | 0.292*** | − 0.096* | 0.998 | 0.998 |
| Prob. | 0.001 | 0.000 | 0.774 | 0.001 | 0.089 | | |
| Indonesia | | | | | | | |
| Coefficient | 9.689*** | 0.295*** | 0.473*** | 0.444*** | − 0.024 | 0.998 | 0.998 |
| Prob. | 0.009 | 0.000 | 0.010 | 0.000 | 0.435 | | |
| Italy | | | | | | | |
| Coefficient | 20.639*** | − 0.159 | 0.502 | 1.304*** | 0.191*** | 0.973 | 0.969 |
| Prob. | 0.000 | 0.286 | 0.128 | 0.000 | 0.000 | | |
| Japan | | | | | | | |
| Coefficient | − 7.001 | − 0.017 | 1.843** | 0.513** | 0.407** | 0.954 | 0.947 |
| Prob. | 0.536 | 0.897 | 0.023 | 0.047 | 0.011 | | |
| Korea | | | | | | | |
| Coefficient | − 52.727*** | − 0.090 | 4.888*** | − 0.274 | 0.084* | 0.994 | 0.993 |
| Prob. | 0.000 | 0.321 | 0.000 | 0.164 | 0.077 | | |
| Mexico | | | | | | | |
| Coefficient | 16.266*** | 0.252*** | 0.207* | 0.532*** | 0.019 | 0.995 | 0.994 |
| Prob. | 0.000 | 0.000 | 0.087 | 0.002 | 0.634 | | |
| South Africa | | | | | | | |
| Coefficient | 14.525*** | 0.317*** | 0.206*** | 0.335** | 0.020** | 0.983 | 0.981 |
| Prob. | 0.000 | 0.000 | 0.003 | 0.014 | 0.032 | | |
| Turkey | | | | | | | |
| Coefficient | 14.901*** | 0.203*** | 0.363*** | 0.529*** | 0.016** | 0.997 | 0.996 |
| Prob. | 0.000 | 0.000 | 0.000 | 0.000 | 0.021 | | |
| UK | | | | | | | |
| Coefficient | 15.311*** | 0.440*** | 0.021 | 0.262* | 0.161*** | 0.996 | 0.995 |
| Prob. | 0.000 | 0.000 | 0.925 | 0.075 | 0.000 | | |
| USA | | | | | | | |
| Coefficient | 9.246*** | 0.187*** | 0.779*** | 0.177*** | − 0.033*** | 0.999 | 0.999 |
| Prob. | 0.004 | 0.000 | 0.000 | 0.002 | 0.006 | | |

Note: The county-specific long-run output elasticities are estimated using FMOLS models

*10%, **5% and ***1% levels of statistical significance

not only meets the increasing demand for energy but also replaces the use of conventional energy sources such as coal, gas and oil. The reduction of conventional energy uses will also ensure low $CO_2$ emissions and makes path towards the sustainable economic development.

Given the significant role of renewable energy consumption across the economic activities, the future studies may investigate the effect of renewable energy consumption on economic activities across the sectors of developed, emerging, and least-developed economies. These findings will be more useful for the policy makers and government officials to initiate appropriate policies to promote sustainable economic development across the economies.

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