UNIVERSIDADE CATÓLICA PORTUGUESA

Renewable Energy and Economic Growth in Major Renewable Energy Consuming Countries: An Empirical Analysis

by

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Julho, 2022

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Renewable Energy and Economic Growth in Major Renewable Energy Consuming Countries: An Empirical Analysis

Final work in the form of Dissertation presented at Universidade Católica Portuguesa - Católica Porto Business School – to obtain a Master's degree in Business Analytics

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Julho, 2022

Resumo

Este estudo tem como objetivo investigar os efeitos do consumo de energia renovável no crescimento económico dos principais países consumidores de energia renovável em todo o mundo. É utilizado o Renewable Energy Country Attractiveness Index desenvolvido pela Ernst & Young Global Limited, e foram escolhidos os 31 principais países consumidores de energia renovável para explicar o processo de crescimento entre 1990 e 2019. Empregam-se técnicas de estimação em painel para lidar com a heterogeneidade entre os países e a cointegração das variáveis. Os resultados confirmam a existência de uma dinâmica de longo prazo entre inputs tradicionais e energéticos e crescimento econômico. Os resultados para o país médio indicam que o consumo de energia renovável tem um impacto significativo e positivo na produção económica. Também foi realizada uma análise das elasticidades do produto de longo prazo para cada país e confirma-se a hipótese de crescimento para 14 dos 31 países, sugerindo que, na maioria destas economias, governos, conselheiros políticos, planeadores de energia e órgãos associados devem promover investimentos em fontes de energia renovável.

Palavras-chave: Consumo de energia renovável; Crescimento económico;
Dados em painel; Dinâmico OLS; Hipótese do crescimento.

Número de palavras: 9475

Abstract

This study aims to investigate the effects of renewable energy consumption on economic growth of major renewable energy consuming countries across the globe. It is used the Renewable Energy Country Attractiveness Index developed by Ernst & Young Global Limited, and were chosen 31 top renewable energy consuming countries to explain the growth process between 1990 and 2019. Panel estimation techniques are employed to cope with heterogeneity between countries and cointegration between variables. The results confirm the existence of long-run dynamics between traditional and energy inputs to economic growth. The findings from the average country indicate that renewable energy consumption has a significative and positive impact on economic output. It was also carried out a analysis of long-run output elasticities for each country. The findings confirm the growth hypothesis for 14 out of 31 countries, suggesting that, in most of these economies, governments, policy advisers, energy planners and associated bodies should promote investments in renewable energy sources.

Keywords: Renewable energy consumption; Economic growth; Panel data; DOLS model; Growth hypothesis.

Number of words: 9475

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Introduction

Today's society relies heavily on fossil energy, with around 81% of primary energy coming from fossil fuels (IEA, 2021). The depletion of these sources due to their high consumption and emissions in terms of greenhouse gases (GHG) (see Figure A 3 in the Appendix) such as carbon dioxide (CO2) resulting from their use, require alternatives and the focus is now on renewable energies. The environmental degradation that has been verified at a global level and the awareness of the implications of its consequences has demanded the concertation of strategies to be implemented and goals to be achieved by several countries (IEA, 2021). According to Ma and Jiang (2019) global warming and energy security are worldwide concerns. The growing concern about global warming and energy security has activated the idea of renewable energy as the most appropriate option to meet the needs of the present without compromising the ability of future generations to meet their own needs. Several countries have made efforts to implement renewable energy practices (production and consumption) and therefore contribute to sustainable growth (UNFCC, 2020). Dedicated to this cause, developed and developing economies have increased renewable energy production and consumption in absolute terms (see Figure A 1 and Figure A 4 in the appendix). Hereupon, it is important to know if the consumption of renewable energies leads to the economic growth of a country.

Hall et al. (2014) and Weibbach et al. (2013) found that with the level of technology at the time of their analysis, the energy returns on investment for renewable energy were much lower than fossil fuel energy. Painuly (2000) finds that a highly controlled energy sector may lead to lack of investment in renewable energy. Restricted access to technology implicates technology not available or available at high costs, consequently, the high investments required constitute entry barriers for entrepreneurs and may affect economic viability as there's less number of producers hence competition and the market may suffer. On the other hand, Pirlogea and Cicea (2012) argue that renewable energy sources can favor the creation of new jobs in new sectors, also promote regional development as they can be used in less developed areas without conventional energy sources and could reduce costs associated with climate change. Kaygusuz et al. (2007) and Kaygusuz (2007) also mention that the choice to promote renewable energies will lead not only to further modernization of the energy sector but also support the various countries' goals for economic development and sustainability.

As this topic is so relevant, there are different studies by different authors regarding this relationship. Sebri (2015) conducted the first meta-analysis of the link between renewable energy consumption (REC) and economic growth based on 40 empirical studies and found that most studies validate the growth hypothesis, a unidirectional relationship from renewable energy consumption to economic output. This hypothesis is also validated for all OECD countries by Inglesi-Lotz (2016). On the other hand, Apergis and Payne (2010) found for the same panel of countries that the feedback hypothesis was validated. Battacharya et al. (2016) and Shahbaz et al. (2020) studied the relationship between renewable energy consumption and economic growth for the same major renewable energy consuming countries, following the renewable energy country attractiveness index, through DOLS and FMOLS models and reached different results regarding statistical significance and magnitude of the impact. For example, Battacharya et al (2016) validated the growth hypothesis in Canada, France, Norway, Spain and UK, yet the same countries in the analysis covered by Shahbaz et al. (2020) were not validated according to the growth hypothesis, due to negative elasticities of renewable energy consumption with respect to economic output. Beyond that, Battacharya et al. (2016) for Israel, Italy, Morocco, United States and Portugal validated the growth hypothesis, however, years later in a study by Shahbaz et al. (2020) the same countries did not validate the growth hypothesis due to statistical insignificance of renewable energy consumption. Furthermore, Battacharya et al. (2016) and Saidi and Omri (2020) validated the growth hypothesis in Portugal, United States and Italy however, in the analysis by Shahbaz et al. (2020) for these three countries the hypothesis could not be validated due to statistical insignificance. Lastly, Spain is the only country with positive and statistically significant results in the studies performed by these three authors. Even within each analysis the results are different depending on the country.

Several studies have tested the growth hypothesis. Results have been mixed so far and seem sensitive to the sample period, data, methods and countries under study. Thus, whether the growth hypothesis holds is still a matter of debate.

In this sense, this study resumes the growth hypothesis and tries to determine, for major renewable energy consuming countries in the world, what is the impact of renewable energy consumption on economic growth. This leads to the question: Can renewable energy be a driver of economic growth in major renewable energy consuming countries?

We seek a complete answer to the question with the latest data available on major energy-consuming economies identified by the 2019 Renewable Energy Country Attractiveness Index (RECAI). Answering this question, we hope to contribute to the solution of this puzzle.

In order to understand the dynamic relationship between renewable energy use and economic growth, almost all studies in the literature have used panels of countries. The panel selection is a major point of contention in this research. Countries in the panel under consideration have a high degree of heterogeneity, and the variables might be cointegrated. This study uses contemporary heterogeneous panel estimate approaches to treat heterogeneity and cointegration.

The methodology used in this work makes it possible to know the evolution of the dynamic relationship between the consumption of renewable energies and economic growth, through an econometric analysis using a dynamic Ordinary Least Squares model (DOLS).

The 2019 RECAI by Ernst & Young Global Limited was utilized for this purpose. Each market's RECAI ranking is based on macroeconomic, technological, and energy-specific variables.[1] For the panel, it was selected 31 out of 40 major renewable energy consuming countries based on the RECAI ranking.[2] Both renewable and non-renewable energy consumption were chosen alongside traditional inputs (capital and labor) so that the relative effect of each of these in the economic growth process could be determined. Long-run

[1] https://assets.ey.com/content/dam/ey-sites/ey-com/en_ro/news/2019/12/ey-recai-country-index-and-chart.pdf

[2] Explanations regarding the selected 31 countries are provided in sub chapter 3.1.Data Description.

dynamics are used to calculate the long-run output elasticities for the average country and individual countries for each form of energy.

The average country elasticity of renewable energy consumption (REC) with respect to economic output (GDP) was 0.110, this means that, a 1% increase in renewable energy consumption increased GDP in 0.110%, ceteris paribus.

For 14 out of 31 countries in the panel, the growth hypothesis was validated, renewable energy consumption was considered to be a driver of economic growth. These projections are significant for policy makers because they reflect the long-term demand for renewable and non-renewable energy sources in these countries' growth processes.

The rest of the study is structured as follows. Chapter 1 gives an overview of the renewable energy consumption-growth hypotheses with a focus on the literature that supports the growth hypothesis, which is the hypothesis tested in this study. Chapter 2 describes the theoretical hypothesis and econometric method used. Chapter 3 discusses empirical application and findings. Finally, the last chapter presents the conclusions that can be drawn from this study.

Chapter 1
Literature Review

In the literature there is no agreement on the links between energy consumption and economic growth because of the structural features of the analyzed countries, their development stage, econometric methods used and time frames analyzed are different. However, some researchers, such as Payne (2010), Ozturk (2010) and Omri (2014) have made a synthesis of the main results of the literature, highlighting that the literature on the relationship between energy consumption and economic growth rests upon four testable hypotheses.

Firstly, the growth hypothesis which assumes a unidirectional relationship from renewable energy consumption (REC) to economic growth [REC→GDP]. An increase in renewable energy consumption fosters higher economic growth.

Sebri (2015) conducted the first meta-analysis of the link between renewable energy consumption and economic growth based on 40 empirical studies concluding that the probability of validating the neutrality hypothesis is greater on the short run than on the long run, while the probability of validating the conservation hypothesis is similarly distributed according to the timeframe. In terms of feedback and growth hypotheses, representing the majority among the results obtained, the relationship between the two variables was validated rather on the long run.

The study carried out for European and Eurasian countries by Tiwari (2011) from 1990-2009, through a structural Vector Autoregressive approach concluded that the growth rate of renewable energy consumption has a positive impact on the growth of GDP per capita while the growth rate of non-renewable energy consumption has a negative impact.

Also, the impact of renewable energy consumption on economic well-being was estimated by Inglesi-Lotz (2016) through panel data techniques for all OECD countries from 1990-2010 and found that the impact of renewable energy on the energy mix on economic growth was positive, i.e, a positive and statistically significant impact of total renewable energy consumption or share of total renewable energy consumption from total energy consumption on GDP.

Dogan and Seker (2016) studied the impact of renewable energy consumption on economic growth during the period 1985-2011 for 38 top listed countries following the 2011 RECAI, through FMOLS and DOLS models and unit root tests and recommended that EU decision makers should make further progress in reducing non-renewable energy and developing other sources of the energy, because the alternative sources will boost economic growth.

Ito (2017) has empirically estimated the link between CO2 emissions, renewable energy and non-renewable energy and economic growth, from 2002-2011 through an ARDL model, concluding that the heightened renewable energy consumption had positively influenced economic growth, while conventional energy had no positive impact on real GDP, especially in developed countries.

Bhattacharya et al. (2016) found through a Dynamic Ordinary Least Squares model ranging from 1991-2012 for the top 38 major renewable energy consuming countries, following the 2015 RECAI, that, in the long-run renewable energy consumption has a significant and positive impact on economic growth for Austria, Bulgaria, Canada, Chile, China, the Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Kenya, Korea Republic, Morocco, the Netherlands, Norway, Peru, Poland, Portugal, Romania, Spain and the United Kingdom, confirming the growth hypothesis.

More recently, Saidi and Omri (2020) studied the impact of renewable energy consumption on economic growth for 15 major renewable energy consuming countries from 1990-2014 through a FMOLS model and found that renewable energy consumption has a statistically positive impact on economic growth.

Shahbaz et al. (2020) studied the impact of renewable energy consumption on 38 major renewable energy consuming countries, following the 2018 RECAI, during the period 1990-2018 through a DOLS and FMOLS models and heterogeneous panel non-causality approaches and found that the growth hypothesis is validated for 22 countries of the panel, namely Australia, Austria, Brazil, Bulgaria, Chile, China, Czech Republic, Denmark, Finland, Germany, Greece, Ireland, Japan, Kenya, Korea Republic, Mexico, Netherlands, Peru, Poland, Slovenia, Sweden and Ukraine.

Studies that also support the growth hypothesis and justify EU policies regarding the need to increase renewable energy consumption are supported by

Soava et al (2018) based on a sample of 28 EU countries from 1995-2015. They found evidence that renewable energy consumption has a positive impact on economic growth.

Secondly, the conservation hypothesis assumes a unidirectional relationship from economic growth to renewable energy consumption [GDP→REC]. Renewable energy consumption increases as a result of higher economic growth.

Tugcu (2012) validated this hypothesis for Germany during the period 1980-2009 through an ARDL model and panel causality tests; Sadorsky (2009) for 18 emerging countries from 1994-2003 through OLS, FMOLS and DOLS models; Marinas et al. (2018) for Czech Republic and Romania during the period 1990-2014 through an ARDL model; Smolovic et al. (2020) for traditional EU member states through and ARDL model during the period 2004-2018; Usman et al. (2020) for 15 highest emitting countries during the period from 1990 to 2017 through multivariate structure techniques (Augmented Mean Group, panel causality tests); Simionescu et al. (2020) for Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Netherlands, Italy, UK, Sweden, Ireland, Spain, Bulgaria, Croatia, Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Slovakia, Slovenia, Romania, Luxembourg during the period 2007-2017 through a fixed-effects, random-effects models, and a model based on generalized estimating equation.

Thirdly, the feedback hypothesis which assumes a bi-directional causal relationship between renewable energy consumption and economic growth and assumes that the two are interrelated and complement each other [REC↔GDP].

This hypothesis is validated by Apergis and Payne (2010) during the period 1985-2005, through a Fully Modified Ordinary Least Squares model and panel causality tests; Apergis and Danuletiu (2014) for a panel of 80 countries, from 1990-2012, including countries from the European Union, Weastern Europe, Asia, Latin America and Africa under the Cannig and Pedroni long-run causality test; by Tugcu (2012) for England and Japan during the period 1980-2009 through an ARDL model and panel causality tests; Inglesi-Lotz (2016) for OECD countries during the period 1990-2010 through Pedroni's panel cointegration and unit root tests; by Amri (2017) for different income groups of countries during the period 1990-2012 through the dynamic simultaneous-equation panel data approach; by Marinas et al. (2018) for Bulgaria, Estonia, Latvia, Lithuania, Poland, Slovakia, Slovenia during the period 1990-2014 through an ARDL model; by Radmehr (2021) for Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Ireland, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden, and the United Kingdom during the period 1995-2014 through a spatial simultaneous equation model; by Ntanos et al. (2018) for 25 European countries ranging the period 2007-2016 through a cluster analysis and an ARDL model; by Smolovic et al. (2020) for new EU member states during the period 2004-2018 though an ARDL model.

Lastly, the neutrality hypothesis assumes that there is no relationship between renewable energy consumption and economic growth, they are independent and do not affect each other [REC-GDP].

This hypothesis is validated by Menegaki (2011) for 27 European countries during the period 1997-2007 through a random effect model; by Tugcu (2012) for France, Italy, Canada and USA during the period 1980-2009 through an ARDL model and panel causality tests; by Marinas et al. (2018) for Hungary during 1990-2014 through an ARDL model; by Chica-Olmo (2020) for Austria, Belarus, Belgium, Bulgaria, the Czech Republic, Denmark , Finland, France, Germany, Greece, Hungary, Ireland, Italy, the Netherlands, Norway, Poland , Portugal, Romania, the Russian Federation, Slovakia, Spain, Sweden, Switzerland, Turkey, Ukraine and the United Kingdom during the period 1991-2015 through panel pool and fixed-effects model and panel unit root and cointegration tests.

However, studies with the same countries validate different hypotheses, as is the case of studies carried out by Radmehr (2021), Chica-Olmo (2020) and Simionescu (2020), in which they use 22 common European countries. For these 22 countries, the first author validates the feedback hypothesis, the second, the neutrality hypothesis, and the third, the conservation hypothesis. For OECD countries different results are also found by Inglesi-Lotz (2016) and Apergis and Payne (2010), who validate the growth and feedback hypothesis respectively.

There is a wide range of results across countries, years and each hypothesis and no consensus has emerged.

With this said, it will be tested the growth hypothesis in a panel study. Country selection follows the RECAI index and heterogeneous panel estimation techniques are employed to provide new findings in the literature.

Chapter 2
Theoretical Hypothesis and Method

The aim of this analysis will be to test the growth hypothesis. According to Apergis and Payne (2010) the growth hypothesis asserts that energy consumption affects the growth process both directly and indirectly as a complement to labor and capital inputs. The growth hypothesis is supported if there is unidirectional causality from energy consumption to economic growth. According to Painuly (2000) a highly controlled energy sector may lead to lack of investment in renewable energies, restricted access to technology implicates technology not available or available at high costs, which is an entry barrier for entrepreneurs. On the contrary, as mentioned before, the employment of renewable energy sources can create jobs, promote development in less developed areas or countries, reduce costs associated with climate change (Pirlogea and Cicea 2013) and reduce the risk of high price volatility of fossil fuels for oil-importing countries (Shahbaz et al. 2016).

For that, it is proposed a simple production function where, along with traditional inputs, renewable and non-renewable energy are used into the production process. The conventional neo-classical one-sector aggregate production technology is employed according to Solow (1957), where labor, capital, and energy are treated as separate inputs.

(1) $GDP_{it} = f(\ GCFC_{it}, LF_{it}, REC_{it}, NREC_{it}, U_{it})$,

where, GDP_{it} denotes the gross domestic product (GDP) as a measure of economic output in country *i* in year *t*, $GCFC_{it}$ denotes the gross fixed capital formation as a proxy for capital stock in country *i* in year *t*, LF_{it} denotes the labor force as a measure of available labor in the market in country *i* in year *t*, REC_{it} denotes the total of renewable energy consumption in country *i* in year *t* and $NREC_{it}$ denotes the total non-renewable energy consumption in country *i* in year *t*, and U_{it} denotes the error term associated to country *i* in year *t*.

The data used in this analysis is panel data. The panel is large both in cross-section (N) and time (T) dimensions and due to this, two problems arise, namely, the need for slope coefficients to be heterogeneous and the concern for non-stationarity. The need for slope coefficients to be heterogeneous is eminent as the dataset has different countries, each one with different characteristics, so it would be wrong to assume they all have the same production technology function. To correct that, the coefficient estimates were allowed to change from country to country. The equation (1) above is assumed to be a Cobb-Douglas function as follows:

(2) $GDP_{it} = \alpha_i GCFC_{it}^{\beta_{1i}} LF_{it}^{\beta_{2i}} REC_{it}^{\beta_{3i}} NREC_{it}^{\beta_{4i}} U_{it}$.

The relationship between renewable energy consumption and economic output can be represented as a linear regression model, that is, a linear approach for modeling the relationship between a scalar response (Gross Domestic Product) and one or more explanatory variables (renewables, non-renewables, labor, capital). The transformation of the data series into logarithms assures linearity and results in each coefficient being interpreted as an elasticity.

(3) $\log(GDP_{it}) = \alpha_i + \beta_{1i}\log(GCFC_{it}) + \beta_{2i}\log(LF_{it}) + \beta_{3i}\log(REC_{it}) + \beta_{4i}\log(NREC_{it}) + \varepsilon_{it}$,

where β_{1i}, β_{2i}, β_{3i} and β_{4i} are elasticities of output with respect to gross fixed capital formation, labor, renewables, and non-renewables, respectively, for country *i* and ε_{it} is the logarithm of the error term for country *i* in year *t*.

The purpose of this analysis is to determine if renewable energy consumption can be considered a driver of economic growth, for this the growth hypothesis will be tested, i.e., a unidirectional relationship from renewable energy consumption to economic growth. To assess this, special attention will be given to the renewable energy consumption coefficient estimator (β_3). The coefficient estimator β_3 will give the impact of renewable energy consumption on economic growth. If renewable energy consumption (β_3) fosters economic growth (GDP), $\beta_{3i} > 0$ if it doesn't, $\beta_{3i} \leq 0$.

Non-stationary time series data are data points that often have mean, variance and covariance that changes over time. An example of this behavior are trends or cycles. Time series data have long periods of time (large T) and as the data only varies in time, the variables may be cointegrated, that is, have a common trend. For example, two variables might be increasing or decreasing in the same direction and the model may find that this trend, that is purely common, is a relationship between the variables and will capture this relation which is not true. This is called the spurious regression problem. Due to this, the model cannot be estimated through an OLS method because this method doesn't include trend functions as explanatory variables to eliminate this common trend.

To cope with the spurious regression problem there are different approaches, in this study it will be used the method developed by Stock and Watson (1993), the DOLS. The DOLS method is a way of obtaining estimates for variables that are cointegrated, i.e., that have a common trend. This is an alternative parametric approach that consists in a simple robust equation which corrects for endogeneity by including ρ lags and leads of the explanatory variables in the model. The leads and lags are used to shift one variable ahead or back in time so that the movements of two variables are more closely aligned if there is a time lag between a change in one variable and its impact on another. The trend is included in the model through a vector of the variations of the explanatory variables and if this trend is not included, the model might be capturing a relationship that only occurs due to a common trend in the variables, what would lead to spurious estimates. The variations have no interpretation, although, they are in the model to capture the long-run relationship, the common trend. For example, the meaning of a lead and lag of 1 is that the GDP_{it} is being explained by the vector of explanatory variables $\boldsymbol{X}_{it}$, by the vector of variations of the explanatory variables $\boldsymbol{X}_{it-1}$ and $\boldsymbol{X}_{it+1}$, so, this year's GDP_{it} is explained by the current year $\boldsymbol{X}$, by the variation of $\boldsymbol{X}$ from $\boldsymbol{X}_{it-2}$ to the following year ($\boldsymbol{X}_{it-1}$) and by the variation of $\boldsymbol{X}$ from the current year to the following one ($\boldsymbol{X}_{it+1}$). For comparison purposes the model was also calculated using a lead and lag of 0, meaning GDP_{it} is being explained by $\mathbf{X}_{it}$, and by the variation of $\mathbf{X}_{it}$, so today's GDP is explained by today's $\mathbf{X}$ and by the variation of $\mathbf{X}$ from the previous year to this year. Thus, the equation is as follows:

$$(4)\ \log(GDP_{it}) = \alpha_i + \boldsymbol{\beta}_i \log(\mathbf{X}_{it}) + \sum_{j=-\rho}^{\rho} \gamma_{\mathrm{ij}} \bigtriangleup \log(\mathbf{X}_{it-j}) + \varepsilon_{it},$$

where $\bigtriangleup \mathbf{X}_{it-j}$ denotes the vector of the variations of the explanatory variables for country *i* according to the ρ lags and leads.

Equation (4) will be regressed using the OLS estimator. OLS is a linear regression estimation method that chooses the parameters of a linear function of a set of explanatory variables by the principle of least squares, this is, minimizing the sum of the squares of the difference between the observed dependent variable in the given dataset and those predicted by the linear function of the independent variable. The classical regression model specifies a set of assumptions on the joint distribution of the explained and explanatory variables. Special attention will be given to spherical errors assumption. The spherical errors assumption is divided in two parts, namely, heteroskedasticity and no autocorrelation. The homoscedasticity assumption implies that the error term has the same variance in each observation. If this is violated it is called heteroskedasticity. The no autocorrelation, also called no serial correlation, implies that the errors must be uncorrelated between observations, which may fail in the context of time series as mentioned before. In the presence of autocorrelation and heteroskedasticity the coefficient estimators are still unbiased and consistent but are not efficient, that is, they are not the minimum variance estimates, the usual estimator of the variance of the coefficients is biased and consequently the statistical inference is not valid (t-test, F-test).

Autocorrelation and heteroskedasticity are addressed with the use of the estimator developed by Newey and West (1987). The Newey-West estimator corrects the variation formula by specifying the number of lags to be used in the Bartlett Kernel for the Newey-West long-run variance, allowing a certain degree of autocorrelation between error terms, correcting the standard errors and consequently validating the statistic inference.

Chapter 3
Empirical Application
3.1. Data Description

Data regarding gross domestic product, gross fixed capital formation and labor force were retrieved from the World Bank. The required data on renewable and non-renewable energy consumption was collected from the U.S Energy Information Administration (EIA).

It is used GDP in constant 2015 US dollars as a measure of economic output, gross fixed capital formation (GCFC) in constant 2015 US dollars as a proxy for capital stock and labor force (LF) in number of people as a measure of available labor in the market. Two energy sources are used in the production function, being renewable energy consumption (REC) and non-renewable energy consumption (NREC). It is used REC measured in quadrillion BTU[3] as a measure of the total renewable energy consumption and NREC measured also in quadrillion BTU as a measure of the aggregate of the total consumption of coal, natural gas, nuclear, petroleum and other liquids.

The selection of the sample countries is based on the RECAI prepared by the Ernst & Young. This index is constituted by 40 countries. However, one of the countries is Taiwan and the World Bank database does not have data regarding Taiwan only, Taiwan statistics are included in China's. With this, it was only extracted data for 39 countries.

While regressing this model, some adversities were encountered, namely, most countries had missing data from 1980 to 1989 and some had at least one year missing in the period 1990-2019 what made the estimation not possible. In this sense, the years from 1980-1989 (included) were dropped for all countries and the countries that had missing data between years were also dropped, which included China, Denmark, Indonesia, Israel, Pakistan, Peru, Philippines and Thailand. Out of the first 40 ranked countries were left 31: Argentina, Australia, Belgium, Brazil, Canada, Chile, Egypt, Finland, France, Germany, Greece, India,

[3] British Termal Units

Ireland, Italy, Japan, Jordan, Kazakhstan, Kenya, Korea, Mexico, Morocco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, UK, US, Vietnam. The analysis was then carried out with a balanced panel of 31 countries covering the period from 1990-2019, the longest time period for which data is available for all the variables.

Table 1- Descriptive Statistics

	Mean	Median	S.D.	Min	Max
GDP (trillion US dollars)	1.340	0.499	2.720	0.012	20.000
GCFC (trillion US dollars)	0.288	0.108	0.561	0.002	4.250
LF (million people)	37.600	16.300	77.600	0.850	495.000
REC (quadrillion BTU)	0.834	0.300	1.550	0.001	11.436
NREC (quadrillion BTU)	7.487	3.213	15.777	0.079	94.867
Number of observations = 950					

The average country in the panel has a GDP of 1.34 trillion UD dollars, a gross fixed capital formation (GCFC) of 0.288 trillion US dollars, a labor force (LF) of 37.6 million people, a renewable energy consumption (REC) of 0.834 quadrillion BTU and a non-renewable energy consumption of 7.487 quadrillion BTU.

3.2. Estimation Results

Here are regressed three models. All models are corrected for serial correlation, with the use of Newey-West, allowing a correlation of the error term between observations up to 3 periods.

Firstly, it is regressed the OLS model, where non-stationarity is not treated.

Then the dynamic OLS corrected for non-stationarity and jointly with Newey-West estimator corrected for serial correlation and heteroskedasticity. Therefore, the DOLS model is regressed, where non-stationarity and endogeneity are treated with the inclusion of leads and lags (ρ) in the model.[4]

Thus, secondly, is regressed the DOLS model with a lead and lag of 0.

Thirdly, and lastly, the DOLS model with a lead and lag of 1.

The coefficient estimates displayed below in Table 2 are an average of the coefficients estimates obtained for each country, the test statistics are the sum of the test statistics obtained for each country divided by √N, where N is the number of countries in the panel, and the adjusted R^2 is the average of the adjusted R^2 obtained for each country.

Table 2- Panel data analysis of long-run output elasticities.

	OLS		DOLS			
Variable			ρ = 0		ρ = 1	
	Coefficient	t-Statistic*	Coefficient	t-Statistic	Coefficient	t-Statistic
GCFC	0.268	23.843***	0.252	23.650***	0.287	25.229***
LF	0.780	24.092***	0.820	20.121***	0.839	14.720***
REC	0.099	14.717***	0.110	17.465***	0.104	15.742***
NREC	0.260	13.993***	0.264	15.523***	0.159	12.565***
Adjusted R^2	0.976		0.985		0.994	

* T-test performed for the null hypothesis that the elasticity of the coefficients (β_i) is 0.

*** Denotes the significance level at 1%.

Note: The estimation includes a constant not reported in the table.

[4] The default number of leads and lags is 2, however, computations with this value were not possible as the number of explanatory variables would be greater than the number of observations. Thus, the result found for leads and lags was 1 lead and lag. In this way the DOLS model is calculated for a lead and lag of 1 and for comparison purposes was also calculated using a lead and lag of 0

The long run output elasticities are estimated using Ordinary Least Squares (OLS) and Dynamic OLS models. The empirical findings of these models are presented above in Table 2. The three approaches produce very similar results for each variable in terms of sign and significance, however in terms of magnitude they vary. All variables are statistically significant at a 1% level for all models, this is, the t-statistic is higher than the critical value at a 1% significance level for each of the variables for all models. It can also be argued that non-renewable energy consumption has a higher impact on economic growth than renewable energy consumption for all models.

The OLS results show that all variables had a positive significant impact on economic output. A 1% increase in renewable energy consumption increased output by 0.099%, while an increase in non-renewable energy consumption increased output by 0,260%. Therefore, the growth hypothesis is validated in this model.

Let's keep in mind that this model is only corrected for autocorrelation, thus, a possible common trend that might exist between explanatory variables might be getting captured by the model, what is undesirable and leads to spurious regression results. The adjusted R^2, a measure of fit, tells us the percentage of variation of the logarithm of GDP that is being explained by the logarithm of the explanatory variables. In this model, 97.6% of the variation of the logarithm of GDP is being explained by the logarithm of the explanatory variables.

With this said, the next step would be to estimate the model taking into account this possible common trend, what is achieved through the Dynamic OLS model. Firstly, it is computed the dynamic OLS model for a lead and lag of 0. All variables had a positive significant impact on economic output. The results showed that, a 1% increase in renewable energy consumption increased output 0.110%, while a 1% increase in non-renewable energy consumption increased output by 0.264%. Thus, the growth hypothesis is also validated in this model. So, it can be seen an increase in the coefficient estimates from the OLS to the DOLS model with a lead and lag of 0 when non-stationarity is addressed with the inclusion of the common trend in the model. As it is observable, there is a change in the coefficient estimates, so it can be said that the latter model, the DOLS model with $\rho = 0$, produces less biased estimates. The percentage of the variation of the logarithm of GDP that is being explained by the logarithm of the explanatory variables in this model is 98.5%.

Then, it is computed the DOLS model with a lead and lag of 1. All variables had a positive impact on economic output. The results for a lead and lag of 1 show that, a 1% increase in renewable energy consumption increased output by 0.104%, validating the growth hypothesis, while a 1% increase in non-renewable energy consumption increased output by 0.159%. As more variations of the explanatory variables are included in the model to treat non-stationarity, it can be noticed a change in the coefficient estimates from the DOLS model with $\rho = 0$ to the DOLS model with $\rho = 1$, meaning the last model, the DOLS model with $\rho = 1$ produces even less biased estimates. Regarding the adjusted R^2, the model presented a value of 99.4%.

The findings on the long run output elasticities suggest that along with traditional inputs such as capital and labor, both renewables and non-renewables had a significant role in the process of economic development in the selected sample countries, though based on these facts it can be said that non-renewable energy plays a bigger role in promoting economic growth.

These conclusions are valid for the average country, therefore now the aim is to examine the long-run output elasticities for each individual country (see Table 3). This is very important to understand the dynamic impact of renewable energy consumption on output across the sample countries. The long-run output elasticities are estimated using DOLS model with one lead and lag and results are displayed below.

Table 3- Long-run output elasticities using DOLS Model (Dependent variable: Output).

	GCFC	LF	REC	NREC	Adjusted R^2
Argentina	-0.265	0.307***	0.060	0.671***	0.998
Australia	0.367**	0.114	0.151***	0.940***	0.999
Belgium	0.291	0.511***	0.048	0.265**	0.992
Brazil	0.574	0.473***	-0.283	0.261	0.994
Canada	1.938***	0.085	0.316	-0.193	0.997
Chile	0.884***	0.158***	-0.014	0.367***	0.999
Egypt	0.639	0.222***	0.217***	0.265	0.997
Finland	3.711***	0.326*	0.030	0.243*	0.991
France	1.089***	0.381***	0.097**	0.190	0.998
Germany	0.441*	0.326***	0.153***	0.409***	0.995
Greece	-1.659	0.302***	0.247***	0.753**	0.993
India	0.108	0.114	0.434***	0.725***	0.999
Ireland	-0.111	0.304***	0.189	0.813*	0.995
Italy	0.285	0.268**	0.169*	0.325*	0.980
Japan	0.426	-0.515	0.350***	0.623*	0.971
Jordan	0.665**	0.247***	0.019	0.327*	0.997
Kazakhstan	6.855***	0.804***	0.160**	-3.183	0.999
Kenya	-0.497**	0.437***	0.213*	0.381***	0.999
Korea	2.748**	-0.090	-0.0561	0.684**	0.994
Mexico	0.617	0.114	0.265*	0.271	0.980
Morocco	0.753***	-0.040	0.099	0.487**	0.996
Netherlands	0.599	0.403***	0.063	-0.166	0.998
Norway	0.924***	0.180**	0.532***	0.433***	0.997
Portugal	-0.860	0.040	0.201***	0.870***	0.979
Spain	0.554**	0.612***	0.081	-0.332	0.995
Sweden	-0.641	0.797***	-0.287	-0.634	0.994
Switzerland	1.128***	0.422***	-0.047	0.265***	0.997
Turkey	0.753***	0.287***	-0.032	0.362***	0.999
UK	1.129***	0.730***	-0.199	-0.806	0.994
US	1.882***	0.409***	-0.090	-0.839	0.999
Vietnam	0.695*	0.164***	0.146***	0.155***	0.999

*** denotes statistical significance level at 1%.

**denotes statistical significance level at 5%.

*denotes statistical significance level at 10%.

Note: The estimation includes a constant not reported in the table.

The long-run elasticities of output with respect to renewable energy were statistically significant and had a positive impact for 14 out of the 31 countries. For these 14 countries, the growth hypothesis is validated. These results are consistent with the results found by Bhattacharya et al. (2016), whom validated the growth hypothesis for 23 out of 38 top renewable energy consuming countries, by Saidi and Omri (2020) whom also validated the growth hypothesis for 8 out of 15 major renewable energy consuming countries and by Shahbaz et al. (2020) whom also validated the growth hypothesis for 22 out of 38 major renewable energy consuming countries.

The long-run elasticities of output with respect to renewable energy were statistically significant and had a positive greater magnitude for India (0.434), Japan (0.350) and Norway (0.532). These values might be due to innumerous reasons. For example, India has a lot of sun (+10h/day), a large geographic area (2 973 190 km^2),[5] accounts for 18% of world population, has a high population density (459.5 inhabitant/km^2), many poor rural areas, little developed economically, not industrialized as their primary activity is agriculture what does not have a high need for energy,[6] thus a small increase in renewables might have a significant impact in output. Japan has a population of 126 264 931 people with a geographic area of 364 500 km^2, making it a high population density country (346.4 people/km^2). It is a highly urbanized and industrialized country, highly developed technologically,[7] making it easier to implement technology in hydrogen, solar, wind, biomass and geothermal sources (ITA, 2022). Norway has a geographical area of 365 107.85 km^2 with a population of 5 347 896 people making it a low population density country (14.6 people/km^2). This is a sloping country, in contrast to Sweden, highly urbanized, that has industry and technology, which can be invested in wind and hydropower sources (The Explorer, 2021).

Beyond that, in countries such as Australia (0.151), Egypt (0.216), France (0.096), Germany (0.152), Greece (0.247), Italy (0.168), Kazakhstan (0.159),

[5] Data regarding total population, land area, population density and urbanization rate were retrieved from World Bank-World Development Indicators. https://databank.worldbank.org/source/world-development-indicators#

[6] Data regarding the level of industrialization was obtained from United Nation Industrial Development Organization – UNIDO's Competitive Industrial Performance Index 2020: Country Profiles (report)

[7] Data regarding technological development was retrieved from United Nations Conference on Trade and Development – Technology and Innovation report 2021

Kenya (0.213), Mexico (0.265), Portugal (0.200) and Vietnam (0.164) renewable energy consumption showed to be statistically significant with a positive magnitude. As it is observable this is also a heterogeneous group, thus, it'll be presented possible explanations only for European countries. Germany has 83 092 962 people for 357.022 km^2 of geographic area making it a high population density country (237.8 people/km^2) and highly urbanized. It is highly industrialized and highly developed technologically. Its focus was on nuclear energy, but since the disaster in Fukushima, German government decided to initiate the process of shutting down all nuclear stations (IAEA, 2021). An alternative to this may have been the bet on renewables, namely, solar and wind turbines, which can be seen by a more significant increase in production and consumption compared to previous years (see Figure A 1 and Figure A 2 in the Appendix). Similarly, Italy has 59 729 081 people for 297 730 km^2 of geographical area counting 200.6 people/km^2. It is highly urbanized, industrialized and technologically developed in the north making it easier to implement technology in renewables. France in terms of population density is similar to Greece and Portugal with 122 habitants per km^2. In terms of the rate of industrialization and technological development, it is similar to Italy and Germany, which are highly developed. However, of these five countries it is the country with the highest urbanization rate. Usually, more urbanized countries consume more energy, consequently, due to the low energy density of renewables, they may not meet the needs of the population, what might be a possible explanation for the result obtained for France being lower than that of Germany and Italy. The remaining European Union countries in this group have similar characteristics in terms of geographic area, namely Greece with 128 900 km^2 and Portugal with 91 605.6 km^2. The population density is respectively 83 persons/km^2 and 112 persons/km^2. The urbanization rate for these countries is lower than the average urbanization rate of the four groups of countries. At a technological level these two countries are highly developed. Regarding industrialization, Portugal and Greece have lower values in contrast with the other European Union countries in the group. Low urbanization and population density mean that there are fewer energy needs, which facilitates the use of renewable energies. In addition, they are produced within the country itself, with no need to import them. It should be noted that all these countries have the need to import non-renewables (CIA, 2018). These countries have favorable conditions to produce renewable energy, for example, Greece, which has solar, wind, and geothermal (Energy Industry Review, 2021) and Portugal wind, an extensive hydrographic basin, biomass and sun (APREN, 2019).

These findings suggest that higher renewable energy consumption in these two groups of countries will generate greater economic output. Policy advisers should take measures to increase the share of renewable energy in the energy mix.

Yet the opposite also happens. Countries such as Argentina (0.060) Brazil (-0.283), Belgium (0.047), Canada (0.316), Chile (-0.014), Finland (0.029), Ireland (0.188), Jordan (0.019), Korea Republic (-0.056), Morocco (0.098), Netherlands (0.062), Sweden (-0.287), Spain (0.081), Switzerland (-0.047), Turkey (-0.032), United Kingdom (-0.199) and United States (-0.089) renewable energy consumption wasn't statistically significant, therefore, for these 17 countries renewable energy consumption could not be established as a driver of economic growth. Similar results were also found by Bhattacharya et al. (2016) for 11 out of 38 major renewable energy consuming countries, by Saidi and Omri (2020) for 7 out of 15 major renewable energy consuming countries and by Shahbaz et al. (2020) for 9 out of 38 major renewable energy consuming countries.

This could be explained by the fact that these countries have non-renewable sources of their own (USA, Brazil) or in neighboring countries (Korea, Turkey). Although most of the countries in this group have a high technological and industrial development, investment in renewable energy competes with investment in non-renewable ones, not being advantageous for countries, such as these, producers or transformers of non-renewable energy (CIA, 2018).

According to Barrington-Leigh and Ouliaris (2016) Canada has an extensive hydrographic basin, wind farms (on shore and offshore), farms to transform biomass into bioenergy, large geographic area (8 965 590 km^2), a low population density (4.1 inhabitant/km^2), highly urbanized, highly developed technologically and industrially what might make easier for renewable energy to reach and supply populations. For European countries, Belgium and the Netherlands have high population density, Finland and Spain have a lower one compared to the two previous mentioned countries. This group of countries is commonly characterized by high urbanization rates, highly developed technologically and industrially where due to the low energy density of renewables it is difficult for this type of energy sources to supply all population, what might explain the relationship between renewable energy consumption and economic growth. Ireland, on the other hand, although it is technologically and industrially highly developed like the four previous countries, in terms of population density is low and in terms of urbanization rate it has the second lowest urbanization rate in the study. These lower values for Ireland may explain why there’s no impact of renewable energy consumption on economic growth. These findings suggest that both these two latter groups of countries, where renewable energy consumption was not statistically significant, may continue to use non-renewable energy sources to promote growth.

Conclusion

Since the 1997 Kyoto Protocol (*Kyoto Protocol,* n.d.), several countries have strived to implement renewable energy practices and thus contribute to sustainable growth. The worldwide attention towards sustainable development has accelerated renewable energy consumption in recent years (see Figure A 1 in the Appendix).

This study evaluates the impact of renewable energy consumption on economic growth, testing the growth hypothesis, i.e., a unidirectional relationship between renewable energy consumption and economic growth.

Using heterogenous panel estimation techniques such as DOLS model, it was established the long-run dynamics of GDP in constant 2015 US dollars with traditional and energy related inputs for 31 major renewable energy consuming countries following the RECAI index developed by Ernst & Young Global Limited in 2019. The time period chosen was 1990-2019, the longest time period for which data was available.

This analysis covers heterogeneity across countries, cointegration between variables, heteroskedasticity and serial correlation and after analyzing long-run output elasticities it was possible to segregate the selected countries in two groups according to the statistical significance of renewable energy consumption on economic growth.

In three of the countries under study, Japan, India and Norway, renewable energy consumption was found to have a significant and positive impact on economic growth. In these countries, renewable energy consumption has established itself as an engine of economic growth, validating the growth hypothesis.

Despite a lower magnitude impact value, the consumption of renewable energy had a statistical positive impact on economic growth for Australia, Egypt, Germany, Greece, France, Italy, Kazakhstan, Kenya, Mexico, Portugal and Vietnam, also validating the growth hypothesis.

In the second group of countries, made up of Argentina, Brazil, Belgium, Canada, Chile, Finland, Ireland, Jordan, Korea Republic, Morocco, Netherlands, Sweden, Spain, Switzerland, Turkey, United Kingdom and United States it can be seen that renewable energy consumption had no statistical significance on economic growth, so for this group of countries, renewable energy consumption could not be established as a driver of economic growth, therefore the growth hypothesis could not be validated.

Thus, the growth hypothesis is validated for 14 of the 31 countries.

In an attempt to explain the relationship between renewable energy consumption and economic growth, factors such as land area, population density, urbanization rate, state of technological development, industrialization rate and availability of renewable and non-renewable energy sources were analyzed for some of the countries. In the hope of finding common explanatory aspects and given the heterogeneity of the characteristics of the countries under study for countries with statistically positive results, only the characteristics of European countries were analyzed and of the rest only those in which the impact of renewable energy consumption was higher. For countries in which renewable energy consumption was not considered a driver of economic growth, possible explanations were given for some European countries and others with higher GDP.

It can be seen that in countries with similar values, regarding the factors analyzed, different results were obtained regarding the impact and magnitude of the impact of renewable energy consumption on economic growth. On the other hand, countries where the results obtained in terms of impact on economic growth were similar, being, therefore, in the same group, present diversity in relation to the factors analyzed. High industrialization and high technological development seem to be promoters of investment in renewable energy, provided that a supply of the population is achieved, a situation dependent on population density and urbanization. On the contrary, the ability of the country, or neighboring countries, to produce non-renewable energy seems to be an obstacle to the use of renewable energy. Although there are groups of countries that indicate the validation of these relationships, there are always countries where these relationships are contradicted, and therefore, conclusive explanations cannot be made.

We can indeed conclude that there’s a variety of factors influencing the energy sector, form the very particular characteristics of each country (climate conditions, technological development, energy needs), to global geopolitics and to international and local measures adopted with a view to certain ends, for example environmental, will influence the target relationship of this study.

Given the impossibility of carrying out an in-depth analysis of all these factors in a study like this one, it is suggested that in future investigations this analysis can be carried out, so that there is greater knowledge of the conditions that lead different countries to implement the use of renewable energies.

On a final note, it is important to emphasize that the increment in renewable energies arises from the need to mitigate environmental degradation (climate change, global warming, etc.) and aims at the ability to not compromise future generations. Global targets are being set in this direction, and this study gives some comfort to governmental policy makers, as it proves that economic growth can be promoted by renewable energy.

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Appendix

Figure A 1- REC(Absolute, quadrillion BTU)

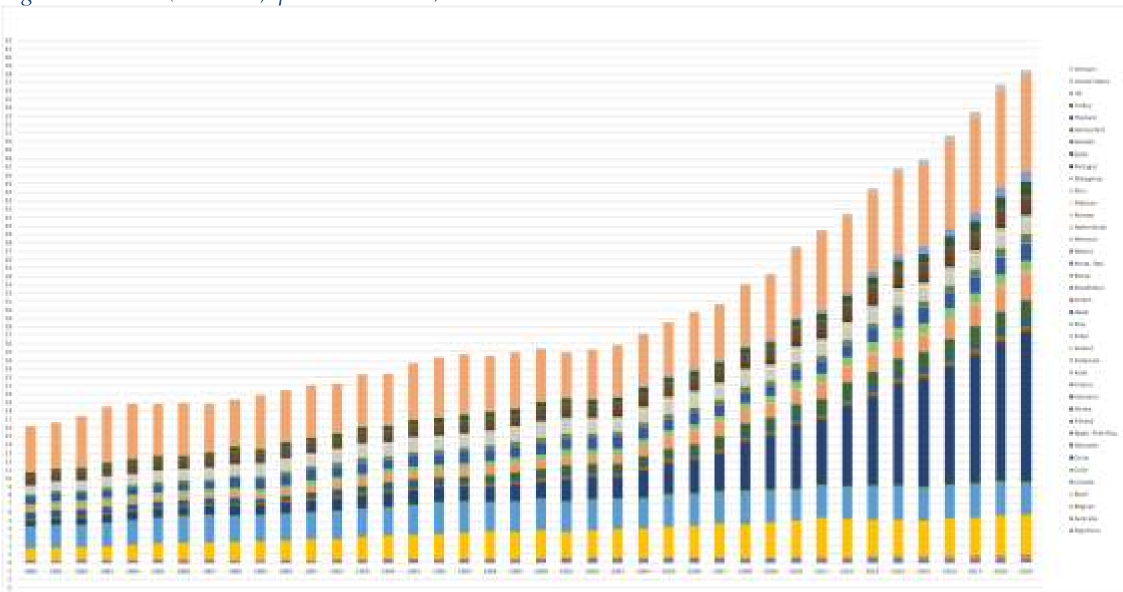

Figure A 2-NREC (Absolute, quadrillion BTU)

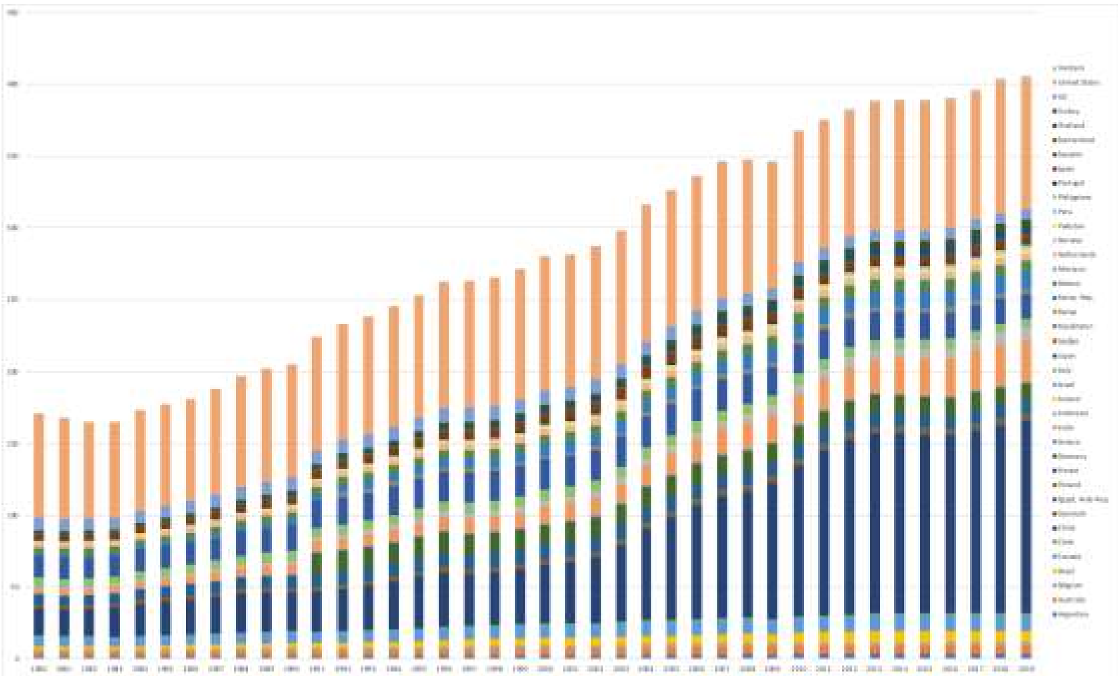

Figure A 3- GHG Emissions (Absolute, quadrillion BTU)

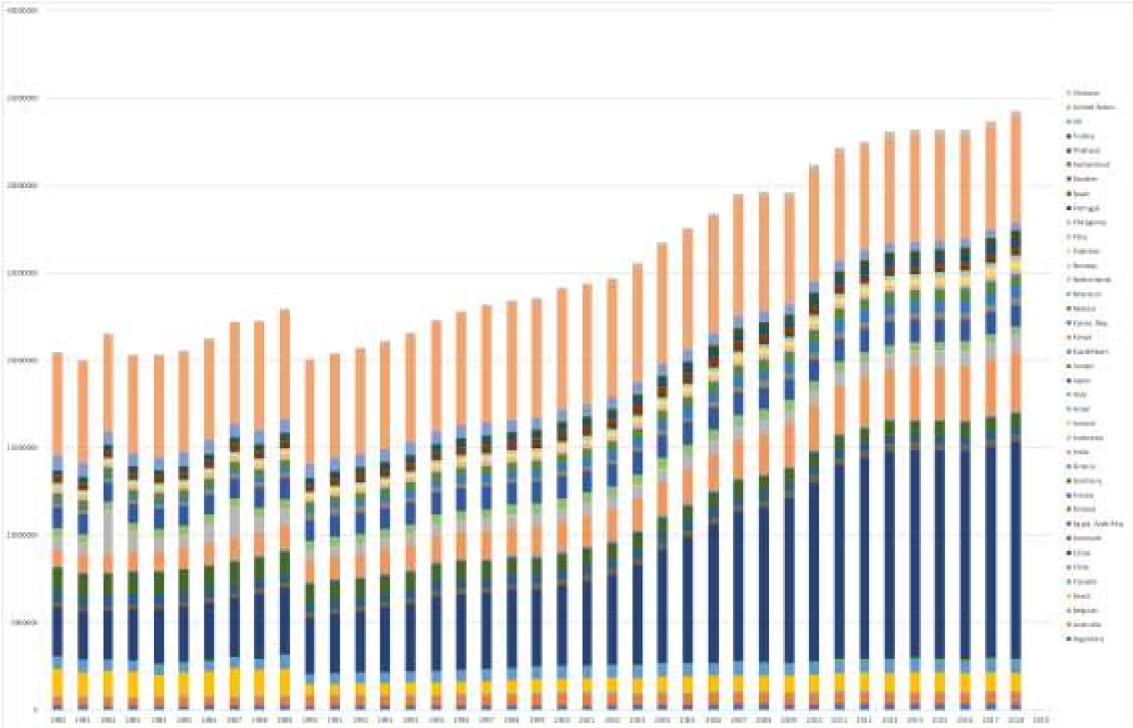

Figure A 4-NREP (Absolute, quadrillion BTU)

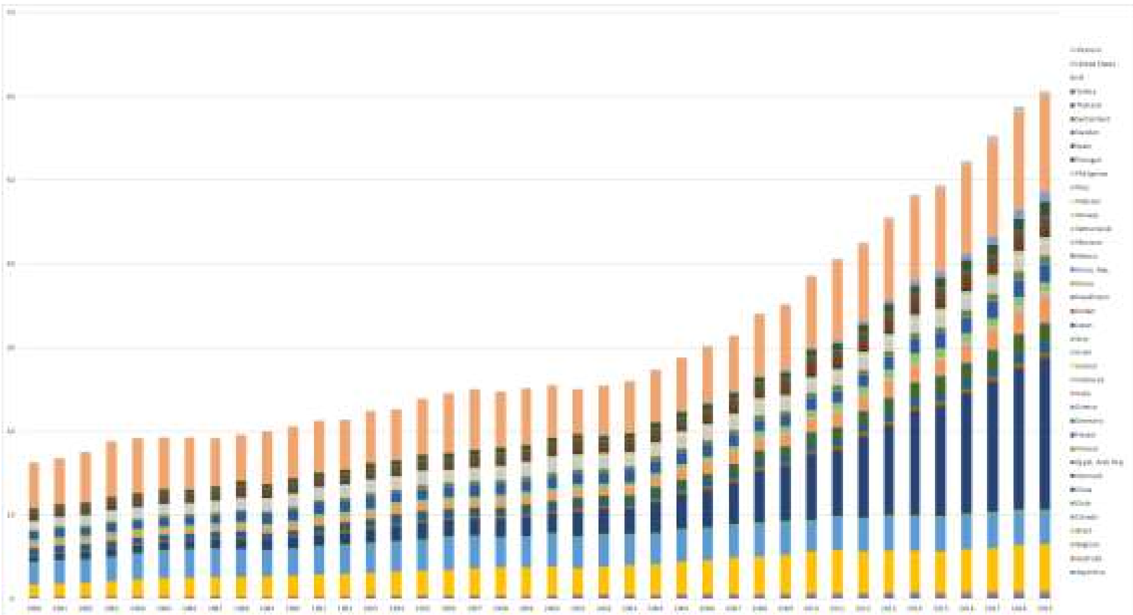

Figure A 5-REC (% of total final energy consumption)