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Does economic growth promote electric power consumption? Implications for electricity conservation, expansive, and security policies

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ABSTRACT

The purpose of this study is to determine the relationship between electric power consumption per capita (kWh) and real GDP per capita (PEN, constant 2007 prices), in Peru, during the period 1971–2014. The four theoretical hypotheses behind this relationship are the growth hypothesis –electricity consumption explains economic growth–, the conservation hypothesis –economic growth explains electricity consumption–, the feedback hypothesis –mutually affecting explanation between electricity consumption and economic growth–, and neutrality hypothesis –electricity consumption does not explain economic growth and vice versa–. Empirically, we initially conclude that the conservation hypothesis can be confirmed using the Granger Causality test, after estimating the dynamic impacts of the long-run equilibrium and short-run models. We highlight the inelastic behavior of electric power consumption per capita with regard to real GDP per capita. These results have implications for electricity conservation, expansive and security policies. We also discussed investments in electricity generation, transmission and distribution from renewable energy sources such as hydro, wind and solar. These eco-sustainable energies also called green and clean energies, are necessary for the sustainability of the electric power demand and the level of national electrification.

1. Introduction

Energy is the capacity to do work or produce heat (United Nations, 1982). Energy is classified, according to the source, into primary and secondary energy. Primary energy sources allow for it to be extracted or captured to be then turned into heat or mechanical work, while secondary energy sources are derived from the transformation of primary energy (United Nations, 1982). Under this classification, electrical energy is considered a type of secondary energy. The sources of electric power generation come from two types of energies: renewable energy (hydro, solar, wind, biomass waste, geothermal, tidal, wave, and marine) and non-renewable energy (coal, oil, natural gas, nuclear, chemical heat, non-renewable biomass waste, and biofuels) (United Nations, 2021). Over the last five decades, there has been an upward trend in the international oil price; OPEP (2022) published the dramatic change in crude oil spot prices, which in the period between June 2021 and July 2022 increased by 100 % on average. The World Bank, (2022a) recorded that between 1960 and 2015, global carbon dioxide (CO_2) emissions from the global consumption of liquid fuels (oil and liquid derivatives) increased by 257.08 %, and in 2016 the share of total global carbon dioxide (CO_2) emissions from the global consumption of natural gas is 32.48 % less than the share of total world emissions from oil and liquid derivatives. The latter percentage constitutes evidence that natural gas is a less polluting fuel (ecologically cleaner) than oil. The scenarios presented in which oil is a non-renewable energy source for electricity generation and the existence of some deregulated electricity markets lead to the design, implementation, execution, supervision, and evaluation of economic, environmental, and social policies to achieve what Ciarreta and Zarraga (2009) indicated as solutions to mitigate the potential negative effect on economic growth —including efficient energy use, infrastructure improvement, R&D investments, and competition laws— which ensure the reliability and efficiency of the electricity market Ciarreta and Zarraga (2010).

The electricity sector of a developed or developing economy has

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three policies that regulate its market: conservation policies, expansive policies, and security policies. Conservationist policies are aimed at reducing electricity consumption, the savings of which will enable environmental sustainability (Chouaïbi and Abdessalem, 2011; Ciarreta and Zarraga, 2010, 2009; Majewski et al., 2022; Mighri and Ragoubi, 2020; Mutumba et al., 2021; Nazlioglu et al., 2014; Ozturk, 2010; Pata and Yurtkuran, 2017; Payne, 2010; Sekantsi and Okot, 2016; Squalli, 2007; Tamba et al., 2017; Yoo, 2006; Zhao et al., 2016). Expansionary policies, including investment policies, constitute the counterpart of conservation policies. They promote the increase of electricity consumption for two reasons: first, the substitution of polluting energies (with high greenhouse gas (GHG) emissions) by non-polluting electric energy and second, increase of satisfied family needs (Bildirici, 2016; Chouaïbi and Abdessalem, 2011; Ciarreta and Zarraga, 2009; Hwang and Yoo, 2016; Mighri and Ragoubi, 2020; Mutumba et al., 2021; Ozturk, 2010; Pata and Yurtkuran, 2017; Sekantsi and Okot, 2016; Tamba et al., 2017; Yoo, 2006; Yoo and Kwak, 2010; Zhao et al., 2016). Security policies ensure the sustainability of electricity consumption through optimal distribution mechanisms, avoiding power outages (Ciarreta and Zarraga, 2009; Ho and Siu, 2007; Hwang and Yoo, 2016).

In the modelling of the relationship between the real GDP and electricity consumption variables, there are positive or negative impacts according to the dependent variable set (Mutumba et al., 2021; Squalli, 2007). Akinlo (2009) investigated the causality relationship between electricity consumption (billions of kWh) and real GDP (constant 2000 prices) for Nigeria between 1980 and 2006. These variables expressed in natural logarithm are non-stationary series as they achieve their stationarity with their transformation to the first difference, which show a long-run equilibrium relationship at a 5 % significance level according to Johansen's cointegration test. Thus, he concludes that the income elasticity of electricity consumption is equal to −0.77 at a 1 % significance level. This negative dependence produces divergent interpretations (Squalli, 2007). We state that a negative income elasticity of electricity consumption indicates that the growing economy is less and less intensive regarding electricity consumption.

The positive impacts estimated in models in which the dependent variable can be real GDP or electricity consumption and the independent variable can be electricity consumption or real GDP, respectively, allow us to find the causal effect in four theoretical hypotheses (Squalli, 2007). The direction of causality between the real GDP and electricity consumption variables allows to design and implement environmental and energy policies (Payne, 2010). Squalli (2007), Ozturk (2010), Payne (2010), Bildirici (2016), Kumari and Sharma (2016), Sekantsi and Okot (2016), Zhao et al. (2016), Pata and Yurtkuran (2017), Tamba et al. (2017), Mighri and Ragoubi (2020) and Majewski et al. (2022) cite the four theoretical hypotheses used to empirically test the direction of the causal effect between economic growth and electricity consumption: First, the growth hypothesis (GH), which suggest a unidirectional causal relationship from electricity consumption to economic growth. According to Ozturk (2010) and Mutumba et al. (2021), the above approach is based on the idea that energy consumption [electricity] can directly or indirectly stimulate economic growth by complementing the capital and labor factors in the production process. Moreover, Squalli (2007) highlights the theoretical dependence of an economy on energy [electricity] making it clear that economic growth will be reduced if there is a reduction in energy consumption [electricity], and Payne (2010) points out that conservation policies—aimed at reducing electricity consumption—could have negative effects on economic growth. Empirical evidence regarding this hypothesis can be found in (Chouaïbi and Abdessalem, 2011; Ho and Siu, 2007; Pata and Yurtkuran, 2017; Yoo and Kwak, 2010). Second, the conservation hypothesis (CH) states that economic growth influences the demand for energy consumption [electricity]; therefore, there is a unidirectional causal relationship from economic growth to energy consumption [electricity] (Nazlioglu et al., 2014). Furthermore, as Squalli (2007), Ozturk (2010) and Payne (2010), indicate, CH establishes that conservationist policies aimed at reducing electricity consumption would have little or no effect on economic growth. Yoo (2006), Ciarreta and Zarraga (2010), and Sekantsi and Okot (2016) show empirical evidence supporting this hypothesis. Third, the feedback hypothesis (FH),which suggests there is a bidirectional causal relationship between electricity consumption and economic growth, establishes that electricity consumption and economic growth complement each other (Sekantsi and Okot, 2016). As Payne (2010) states, under this hypothesis, conservation policies designed to improve the efficiency of electricity consumption might not have negative effects on economic growth. Yoo (2006), Yoo and Kwak (2010), Nazlioglu et al. (2014), Hwang and Yoo (2016), Bildirici (2016), and Sekantsi and Okot (2016) obtained empirical results supporting the FH. Finally, the neutrality hypothesis (NH) states that there is no causal relationship between electricity consumption and economic growth. Consequently, electricity consumption should not affect a country's economic growth because it represents a small share of GDP (Squalli, 2007) and it explains that policies to preserve or expand electricity consumption would not affect economic growth and vice versa (Mighri and Ragoubi, 2020; Ozturk, 2010). Ciarreta and Zarraga (2010), Yoo and Kwak (2010), Nazlioglu et al. (2014) and Tamba et al. (2017) find empirical evidence supporting this hypothesis.

Bazán (2011) explains the existence in Peru of the National Interconnected Electric System (SEIN), which started in 2000 and should be understood as a set of electricity transmission lines without considering some isolated systems. He also showed, for the period between 2001 and 2008, the upward trend in the percentage variation of real GDP, while the percentage variation of the maximum electricity demand in the SEIN only presented an upward trend in the period between 2003 and 2007, since there was a drop in the demand for electricity due to the financial crisis in 2008. According to the Ministry of Energy and Mines (MINEM), (Ministerio de Energía y Minas, 2020) the maximum demand has shown a sustained upward trend between 2009 and 2019, growing from 4322 MW to 6991 MW. The maximum demand in 2020 was 7125.30 MW while in 2021, it was 7113.03 MW (COES, 2022). Bazán (2011) presented the structure of energy sources for electricity production in 2008: hydraulic (60.93 %) and thermal (39.07 %: natural gas, 31.53 %, D2-Residual, 4.47 %, and coal 3.07 %). In the SEIN, the percentages of electricity production in 2021 were 56.80 %, 38.38 %, 1.49 %, and 3.34 % for hydroelectric, thermoelectric, solar, and wind type of generation, respectively. The percentages in 2020 are as follows: hydroelectric, 59.60 %; thermoelectric, 35.15 %; solar, 1.58 %; and wind, 3.67 % (COES, 2022). The percentage variation of electric energy production with respect to hydroelectric energy in 2021 compared to that of 2020 was 4.59 %. Similarly, it was 19.8 %, 3.09 %, and −0.14 % through thermoelectric energy, solar energy, and wind energy, respectively (COES, 2022).

In 2008, as Bazán (2011) explains, the Peruvian electricity sector had the following problems: lack of price signals to provide adequate incentives for investment in generation, lack of investment in electricity transmission (congestion in transmission lines), and distribution companies did not have electricity supply contracts. As of 2021, the Peruvian Association of Engineers (Colegio de Ingenieros del Perú, 2021) identified the following four problems in the Peruvian electricity sector: SEIN has generation oversupply; it is geographically unbalanced due to the large concentration of electricity generation capacity by natural gas in the capital of Peru; electricity transmission congestion may occur in certain areas of SEIN due to the massive entry of renewable energy resources (RER) plants far from the system, especially in areas of greater availability of wind and solar energy; and the long period of almost three years between the approval of the transmission plan by MINEM and the call for the respective international bidding for the infrastructure concession contracts in electricity transmission, which caused transmission shortages that resulted in high costs and electric power rationing. The latter problem has also been highlighted by (Pacific Credit Rating, 2022).

Peru's MINEM created the energy efficiency policy within the framework of the national energy policy (Ministerio de Energía y Minas, 2000). Thus, the following conservation policies have been implemented: Law for the promotion of efficient energy use (Law No. 27345, enacted in September 2000), which seeks to reduce the negative environmental impact of the use and consumption of different types of energy (Ministerio de Energía y Minas, 2000); Supreme Decree approving the regulations of the law for the promotion of efficient energy use (D.S. No. 053–2007-EM, enacted in October 2007), and whose purpose is to reduce environmental impact and raise public awareness on the importance of efficient energy use (Ministerio de Energía y Minas, 2007); Supreme Decree ordering measures for energy saving in the public sector (D.S. No. 034–08-EM, enacted in June 2008), which requires public sector entities to replace in-candescent lamps with fluorescent lamps and energy-saving light bulbs and to purchase lighting equipment with the energy efficiency label (Ministerio de Energía y Minas, 2008a); Legislative Decree promoting investment in electricity generation using renewable energies (D.L. No. 1002, enacted in May 2008), to promote the utilization of RER improving the quality of life of the population and protecting the environment by promoting investment in the production of electricity, in addition, it provides that the Supervising Agency of Investments in Energy and Mining (OSINERGMIN) will auction the allocation of premiums to each project with RER generation, within the National Energy Plan (Ministerio de Energía y Minas, 2014) it also orders the MINEM to prepare the National Plan of Renewable Energies in accordance with the regional plans of renewable energies (OSINERGMIN, 2008); Regulation for environmental protection in electrical activities (D.S. No. 014–2019-EM, enacted in July 2019), seeks to promote and regulate environmental management —in a sustainable development framework— of electric power activities (generation, transmission and distribution) with the purpose of preventing, minimizing, rehabilitating (recovering altered elements or functions of the ecosystem) and compensating (to keep biodiversity and the operation of affected or lost ecosystems) the negative environmental impacts deriving from such activities in their different stages (construction, operation, or abandonment). In addition, the most important guidelines for the environmental management of electricity activities are to encourage the reuse of solid and liquid waste for the production of electricity and to adopt measures to mitigate and adapt to climate change in the electricity sub-sector, to ensure semi-annual monitoring of upstream and downstream hydroelectric power plants operations (turbine water not considered waste or effluent), the discharge of cooling water [increase in temperature after its purpose is fulfilled] should not affect the quality of water ecosystems or the use of hydro biological resources, requires lifting (through dispersion models) of the effect of atmospheric emissions generated during the operations of electrical activities, it requires controlling unforeseen fugitive emissions in the environmental study of electrical activities, and requires an annual environmental report on the execution of projects or operation of electrical activities (Ministerio del Ambiente, 2019); and, Ministerial Resolution (R.M. No. 285–2022-MINEM/DM, enacted in August 2022) approving the terms of reference for the preparation of the annual environmental report of electrical activities, in accordance to the previous decree the reference terms are approved to develop the annual environmental report including the estimated amount of chemical inputs used during electrical activities, indicating the source of water use and final disposal of effluents, indicating the registration code for the presentation of the annual declaration on the minimization and management of solid waste and presenting the matrix of compliance with environmental undertakings with references and means of verification (description, photographic records, among others) (El Peruano, 2022; Ministerio de Energía y Minas, 2022).

As regards expansive policies applied in Peru, we cite the following regulations: Law creating the electric social compensation fund (Law No. 27510, enacted in August 2001) (OSINERGMIN, 2001), favoring access of residential users to the public electricity service whose monthly consumption is less than 100 kWh, with a fee reduction based on the allocation of resources from the electric social compensation fund (FOSE), this fund will be financed by means of a surcharge in the billing of the fee charges of power, energy, and monthly fixed charge of the users of the public electricity service with residential and low voltage fees up to 20KW, the percentage of such surcharge is determined by the Energy Investment Supervising Agency OSINERGMIN (2022b); General Rural Electrification Law (Law No. 28749, enacted in May 2006), establishing rules for the promotion and sustainable efficient development of electrification in rural areas, isolated and border communities of the country for the purpose of contributing to sustainable socioeconomic development, of improving the life quality of the population, fighting poverty, and discouraging rural-urban migration, the resources for rural electrification constitute non-seizable assets that come mainly from annual transfers from the public treasury, from the total amount of penalties imposed on electric activity companies (with concession or authorization) by the OSINERG, and from resources obtained from the privatization of electric companies of up to 25 %, the creation of the national rural electrification plan with a 10-year term, it also creates the special system of rural electric concessions incorporating incentives for the development of private investment in rural electrification, under which even the State may grant subsidies (not subject to taxes) to ensure the economic sustainability of rural electrification services (OSINERMIN, 2006); Legislative Decree promoting investment in the activity of electricity generation with water resources and other renewable resources (D.L. No. 1058, enacted in June 2008), which provides for the special accelerated depreciation system (maximum annual depreciation rate of 20 %) applicable to machinery, equipment and civil works necessary for the installation and operation of power plants for income tax purposes applied to electricity generation activities based on RER (Ministerio de Energía y Minas, 2008b); Supreme Decree approving the Regulations of Law No. 28749, General Law of Rural Electrification (D.S. No. 018–2020-EM, enacted in July 2020) (El Peruano, 2020); and Law No. 27510 modifying articles 1, 2 and 3, and incorporating article 3-A (Law No. 31429, enacted in February 2022), regarding fees reduction, this law extends the monthly consumption up to 140 kWh excluding users located in blocks stratified by socioeconomic level as high and medium-high, the surcharge percentage is determined by the Supervisory Body for Investment in Energy and Mining (OSINERGMIN, formerly OSINERG) calculated based on the sales projection for the following period (El Peruano, 2001).

In the third and last group of policies applied to the electric power sector in Peru, we consider the following security policies: First, Law No. 28832 (enacted in July 2006) which ensures the sufficient and efficient generation of electricity to reduce exposure to price volatility and the risks of prolonged rationing due to lack of energy whose consequence is the most competitive electricity fee ensured for the final consumer. It also seeks market solutions for the determination of electricity generation prices, promotes effective competition in the electricity generation market, and introduces a compensation mechanism between the SEIN and the isolated systems (not electrically connected to the SEIN) so that bar prices —electricity sales price from generators aimed at the public electricity service (Campodónico, 1999)— of the latter incorporate the benefits of natural gas and reduce their exposure to the fuels market volatility (OSINERGMIN, 2002). Second, Emergency Decree (D.U. No. 037, enacted in August 2008) ordering the necessary measures to ensure the timely supply of electric energy to the SEIN, states that the MINEM will declare the situations of temporary restriction of electric energy generation, calculate the magnitude of the necessary additional generation capacity, and will request from companies with the biggest State share to perform procurement and contracting of the necessary works, goods, and services in order to ensure the timely supply of electric energy in SEIN (Ministerio de Energía y Finanzas, 2008). Third, Law No. 29970 (enacted in December 2012), which strengthens energy security and promotes the development of a petrochemical pole in the south of the country, implements measures to strengthen the country's energy security through the diversification of energy sources, reducing external dependency, and enhancing the reliability of the energy supply chain; thus, MINEM in order to increase the reliability of energy production and transportation, uses the following principles: Geographical decentralization of energy production; defining a portfolio of projects; maintaining the energy reserve margin; exploitation through several production units and/or the use of alternative fuels in the production units; defining a compensation mechanism for natural gas costs that favors installing electric generators to decentralize electric generation in the central area of the country; a compensation mechanism —due to the difference between the bar prices of the isolated systems and the bar prices of the SEIN— for the generation of electric energy in the isolated systems, financed by OSINERGMIN with an additional use charge of the main transmission system; inclusion of greater energy storage and promotion of the efficient and/or sustainable use of renewable energy. In addition, Electroperú S. A. a State-owned company dedicated to the generation, transmission, and commercialization of electric energy participates in the Southern Energy Complex Project by procuring natural gas as an energy source to increase the reliability of the electrical system (OSINERGMIN, 2012).

In the context of the conservationist, expansionary, and security policies described in Table 1, in relation to electric energy activities in Peru, the MINEM also designed the National Energy Plan which analyses sectoral policy measures and highlights investment projects in order to have a competitive energy supply, thus achieving universal access to energy supply and the development of energy projects with minimum environmental impact and low carbon emissions within a sustainable development framework. (Ministerio de Energía y Minas, 2014).

Under the definitions of the four theoretical hypotheses, the purpose of this study is to empirically differentiate whether or not economic growth precedes electricity consumption and/or vice versa, and show whether or not economic growth impact electricity consumption and/or vice versa, in Peru between 1971 and 2014, by analyzing stationarity, causality in the Granger sense, cointegration of the annual series of GDP per capita (S/, constant 2007 prices), and electricity consumption (kWh per capita).

Table 1
Electric Energy Policy in Peru.

Electric policies	Number	Year	Act
Conservation Policies	Law 27345	2000	Law for the promotion of efficient energy use.
	D.S. 053–2007-EM	2007	Decree for the Law Regulation of the promotion of efficient energy use.
	D.S. 034–08-EM	2008	Decree on measures for energy saving in the public sector.
	D.L. 1002	2008	Decree on investment in electricity generation with renewable energies.
	D.S. 014–2019-EM	2019	Regulation for environmental protection in electrical activities.
	R.M. 285–2022-MINEM/DM	2022	Resolution of the environmental report of electrical activities.
Expansive policies	Law 27510	2001	Law creating the electric social compensation fund.
	Law 28749	2006	General rural electrification law.
	D.L. 1058	2008	Decree for investment in electricity generation with water and renewable resources.
	D.S. 018–2020-EM	2020	Decree approving the Regulations of Law 28749.
	Law 31429	2022	Law modifying articles 1, 2, and 3 and including article 3-A in Law 27510.
Security policies	Law 28832	2006	Law ensuring the efficient development of electric generation.
	D.U. 037	2008	Decree ensuring the timely supply of electric energy to the SEIN.
	Law 29970	2012	Law ensuring energy security and the petrochemical pole in the south of the country.

Developed by authors.

This paper is divided into five sections: After the introduction, Section 2 describes the materials and methods used in this research, while Sections 3 and 4 present and discuss the results, respectively. Finally, some conclusions and implications for economic and energy policy are outlined in Section 5.

Below is a brief literature review of articles that use time series models and have found empirical evidence supporting some of the theoretical hypotheses used to analyze the direction of causality between electricity consumption and economic growth. Likewise, the theoretical model on which the functional relationship between the research variables is based is presented.

1.1. *Empirical evidences of the hypotheses*

According to the previous section, we must take into account the following four theoretical hypotheses: the growth hypothesis (GH) consists of the causality or impact from electricity consumption to economic growth; when the economic growth causes or impacts the electricity consumption, it is called the conservation hypothesis (CH); both previous hypotheses can be confirmed at the same time producing the feedback hypothesis (FH); and, finally, the electricity consumption may not cause or impact economic growth and vice versa, then this situation corresponds to the neutrality hypothesis (NH).

1.1.1. *Growth hypothesis (GH)*

Ho and Siu (2007) sought to establish the statistical relationship between electricity consumption (TJ) and real GDP (millions of HKD) in Hong Kong. The variables present annual time series data over the period between 1966 and 2002. The variables were transformed into natural logarithms and the results of the Dicky–Fuller and Phillips–Perron unit root tests —considering the Akaike information criteria (AIC)— yielded that the series are non-stationary behaving as first-order integrated processes $I(1)$. By applying Johansen's cointegration test, both the trace test and the maximum eigenvalue test found the presence of a cointegration vector between the series expressed in logarithms, with a significance level of 5 %. The estimation of the vector error correction model (VECM) presents the long-run equilibrium elasticity of real GDP with respect to electricity consumption equal to 0.94 verified through a negative and significant coefficient of the error correction term for the equation of the logarithm of real GDP and for the equation of the logarithm of electricity consumption at 10 % and 5 % significance level, respectively. The elasticity of the contemporaneous real GDP with respect to the electricity consumption of the previous year is equal to 0.65 and significant at a 5 % significance level. The results of the causality test indicate that the first difference in the logarithm of electricity consumption causes the first difference in the logarithm of real GDP.

Yoo and Kwak (2010) sought to investigate the causality between the variables (USD, constant 2000 prices, PPP Exchange rates are used) for seven South American countries (Argentina, Brazil, Chile, Colombia, Ecuador, Peru, and Venezuela) in the period between 1975 and 2006. The variables present annual data and the Phillips–Perron unit root test results indicate that both series are non-stationary $I(1)$ in all countries at a 5 % significance level, except in Chile, Colombia, and Peru where real GDP per capita is a non-stationary series $I(1)$ at 10 % significance level. They detected the existence of a long-run equilibrium relationship for Venezuela between the two variables through the Johansen cointegration test with likelihood-ratio statistic at a 5 % significance level; cointegration for Argentina, Brazil, Chile, Ecuador, and Peru was not identified. In Argentina, Brazil, Chile, and Ecuador, the GH is verified at a 10 % significance level through the Granger causality test.

Chouaïbi and Abdessalem (2011) verified the relationship between electricity consumption (Billion kWh) and real GDP (billions of USD, constant 2000 prices) in Tunisia between 1971 and 2007. The variables were transformed into logarithms and behaved as non-stationary $I(1)$

processes according to the Dickey–Fuller and Phillips–Perron unit root tests at a 1 % significance level. The absence of cointegration between the series is supported by the application of Engle–Granger cointegration test and Johansen cointegration test. In a $VAR(4)$ with series in first differences, whose order was determined through the Akaike and Bayesian Schwartz information criterion, the Granger causality test was applied where the GH is verified at the 10 % significance level.

Pata and Yurtkuran (2017) investigated the relationship between electricity consumption (kWh) and real GDP (USD, constant 2010 prices) for five countries (Belgium, Spain, Turkey, UK, and USA) belonging to the International Energy Agency (IEA) between 1964 and 2014. The variables present annual data. In Spain and Belgium, the variables behave as stationary series $I(0)$ according to the application of the Phillips–Perron and Dickey–Fuller unit root tests, respectively. In Turkey, USA, and UK, the real GDP variable behaves as a non-stationary $I(1)$ series; while the electricity consumption series behaves as a stationary $I(0)$ series under the application of both unit root tests. They applied the cointegration bound test on the following models with real GDP dependent variable: $ARDL(1,4)$, $ARDL(2,1)$, $ARDL(2,1)$, $ARDL(1,2)$ and $ARDL(4,1)$ for Turkey, USA, UK, Belgium, and Spain, respectively, and found long-run equilibrium relationships at the 5 % significance level. At the 5 % level, the long-run equilibrium impacts of electricity consumption on real GDP are significant and equal to 0.15, 0.41, 0.37, 1.10, and 0.38 for the five countries in the above-mentioned order. The results of ECM indicate at the 5 % level that the short-run impacts of electricity consumption on real GDP are significant and equal to 0.75, 0.56, 0.50, 0.39 and 0.41, for the five countries in the order detailed above.

Hossen and Hasan (2018) uncovered the relationship between electricity consumption per capita (kWh), real GDP (US$) and carbon dioxide emissions from electricity and head production (percentage of total fuel combustion) in Bangladesh for the period 1972–2011. The three time-series are non-stationary $I(1)$ according to Dickey-Fuller and Phillips-Perron unit root tests. The Johansen cointegration test using the trace and maximum eigenvalue statistics indicated the long-run equilibrium relationship between the three variables. The Granger causality test verified the GH.

Bekun and Agboola (2019) explored the interaction between the electricity consumption per capita (kWh) and real GDP per capita (US$, constant 2010 prices), with the incorporation of the third variable (omitted variable) carbon dioxide emission (Kt) in India for the period 1990–2016. The variables were transformed into natural logarithms. The Toda-Yamamoto causality test verified the GH, thus the logarithm of electricity consumption per capita causes the logarithm of real GDP per capita at 5 % significance level.

Samu et al. (2019) studied the causality relationship between electricity consumption per capita (kWh), real GDP (US$, constant 2010 prices) and carbon dioxide emission (Kt) in Zimbabwe for the period 1971–2014. The three series was expressed in natural logarithms and follow a behavior of non-stationary $I(1)$ time series according to Zivot-Andrews unit root test. The Toda-Yamamoto causality test verified GH.

Zhong et al. (2019) investigate the relationship among electricity consumption (kWh), real GDP (constant 2000 prices) and total employment for China during the period of 1971–2009. All variables were transformed into the natural logarithms, being non-stationary $I(1)$ time series as a result of the Dickey-Fuller, Phillips-Perron, Kwiatkowski-Phillips-Schmidt-Shin, and Zivot-Andrews unit root tests. The $ARDL(4,4,1)$ cointegration test with dependent variable $\ln GDP$ determined the long-run equilibrium relationship between the three research variables, the real GDP presents a significant long-run equilibrium unit elasticity with respect electricity consumption at 5 % significant level, also the error correction model based on $ARDL(4,4,1)$ provides a significant short-run elasticity from GDP relative to electricity consumption equals to 0.77 at 5 % significant level, both results verified the GH.

Mighri and Ragoubi (2020) examined the long-run relationship and directional causality between electricity consumption per capita (kWh) and real GDP per capita (US$, constant 2010 prices) for Tunisia during the period 1971–2013. Both series were transformed in natural logarithm, the Phillips-Perron unit root test expressed that the log-series are non-stationary $I(1)$ at 1 % significance level. The VECM Granger causality test verified the GH in the short-run at 1 % significance level.

Ha and Ngoc (2021) investigated the potential nonlinear impact of electricity consumption on economic growth in Vietnam for 1971–2017. The research variables involved were electricity consumption per capita (kWh), real GDP per capita (US$, constant 2010 prices), foreign direct investment per capita (US$) and the rate of urbanization (percentage). The three first variables were transformed in natural logarithm, which together with the fourth variable are non-stationary $I(1)$ time series. The cointegration bound test applied in the $NARDL(3,2)$ model with logarithm of real GDP per capita as dependent variable, the logarithm of electricity consumption per capita is a dynamic regressor, and logarithm of foreign direct investment per capita and rate of urbanization are the fixed regressors, the finding was the long-run equilibrium relationship between variables, the error correction model indicated significant short- and long-run elasticities of the real GDP per capita relative to the electricity consumption per capita, this result verified the GH.

1.1.2. *Conservation hypothesis (CH)*

Yoo (2006) conducted a research work in four Asian countries (Indonesia, Malaysia, Singapore, and Thailand) in order to find a causal relationship between their electricity consumption per capita (kWh) and real GDP per capita (USD, constant 1995 prices) from 1971 to 2002. The variables were expressed in natural logarithms and the results of Dickey–Fuller and Phillips–Perron unit root tests indicate that these series are non-stationary $I(1)$, except for Thailand where they behave as non-stationary $I(2)$ series. The results of the Granger causality test applied to stationary series as a result of the transformation of the series expressed in logarithms confirm the CH for Indonesia and Thailand; the absence of cointegration between the series —according to Engle–-Granger and Johansen cointegration tests— does not strengthen this hypothesis.

Ciarreta and Zarraga (2010) first sought to analyze the dynamic linear relationship between the variables electricity consumption (GWh) and real GDP (€, constant 1986 prices) for Spain between 1971 and 2005. The variables were transformed into natural logarithms and resulted in non-stationary series $I(1)$ through the application of Dickey–Fuller and Phillips–Perron unit root tests. The CH is verified at a 10 % significance level by the Granger causality test in the Dolado–Lütkepohl approach applied in an unrestricted vector autoregressive (VAR) model of second order considering the information criteria of Akaike, Schwartz, and Hannan-Quinn. Moreover, the CH is verified by the Granger causality test in the traditional approach in a first-order VAR model according to the three information criteria described (maximum lag equal to 4), at the 10 % significance level.

Sekantsi and Okot (2016) sought to test the link between electricity consumption per capita (thousands of kWh) and real GDP per capita (USD, 2005 constant prices) in Uganda from 1981 to 2013. The variables were transformed into natural logarithms and through the Dickey–Fuller, and Phillips–Perron unit root tests, both series behave as $I(1)$ processes at the 10 % significance level. Both series cointegrate, alternating the dependent variable under the ARDL cointegration bound test methodology, at the 1 % significance level. They identified unidirectional Granger causality in the short run at the 1 % significance level, thus confirming the CH.

Balcilar et al. (2019) sought to determine the long- and short-run relationships between electricity consumption per capita (kWh) and real GDP (US$, constant 2010 prices) ascertaining how carbon dioxide emissions (Kt) affect to such relationships for Pakistan during the period 1971–2014. The three variables were transformed in natural logarithms. The Toda-Yamamoto causality test verified the CH at the 5 %

significance level.

Bekun and Agboola (2019) explored the interaction between the electricity consumption per capita (kWh) and real GDP per capita (US$, constant 2010 prices), with the incorporation of the third variable (omitted variable) carbon dioxide emission (Kt) in Nigeria for the period 1971–2014. The variables were transformed into natural logarithms, the Zivot-Andrews unit root test indicated that all the variables are non-stationary $I(1)$ time series. The Maki cointegration test reflected existence of a long-run equilibrium relationship between the variables. The long-run equilibrium elasticities were estimated by dynamic ordinary least squares (DOLS) and fully modified ordinary least squares (FMOLS) methods, considering the logarithm of the electricity consumption per capita as the dependent variable, the long-run equilibrium income elasticity of electricity consumption per capita is 0.20 at 10 % significance level and 0.70 at 5 % significance level with each method, respectively. Hence the CH is verified.

Samu et al. (2019) studied the causality relationship between electricity consumption per capita (kWh), real GDP (US$, constant 2010 prices) and carbon dioxide emission (Kt) in Zimbabwe for the period 1971–2014. As the second methodology, the cointegration test of Maki verified the CH, the long-run equilibrium income elasticity of electricity consumption was estimated equal to 0.78 significantly at 5 % level, the electricity consumption is significant inelastic to carbon dioxide emission.

Mighri and Ragoubi (2020) examined the long-run relationship and directional causality between electricity consumption per capita (kWh) and real GDP per capita (US$, constant 2010 prices) for Tunisia during the period 1971–2013. Both series were transformed in natural logarithm, the Phillips-Perron unit root test expressed that the log-series are non-stationary $I(1)$ at 1 % significance level. The *ARDL* cointegration bound test considered to electricity consumption per capita as dependent variable, the result was the presence of the long-run equilibrium relationship with the real GDP per capita. Then, the CH was verified. The VECM Granger causality test also verified the CH in the long-run at 1 % significance level.

1.1.3. Feedback hypothesis (FH)

In his research on the four Asian countries (Indonesia, Malaysia, Singapore, and Thailand), Yoo (2006) also confirmed the FH for Malaysia, and Singapore as per the results of the Granger causality test applied to stationary series; the absence of cointegration between the series —according to Engle-Granger and Johansen cointegration tests— does not support this hypothesis.

Yoo and Kwak (2010) sought to investigate the causality between electricity consumption per capita (kWh) and real GDP per capita (USD, constant 2000 prices, PPP Exchange rates) for seven South American countries (Argentina, Brazil, Chile, Colombia, Ecuador, Peru, and Venezuela) between 1975 and 2006. In Venezuela, the FH is verified both in the short run and in the long run at a 10 % significance level through the Granger causality test in the VECM.

Nazlioglu et al. (2014) analyzed the causal relationships between electricity consumption (kWh) and GDP (index, 2000 = 100, as a proxy for the real income) in Turkey between 1967 and 2007. The variables present annual data and they were then turned into natural logarithm; the results of the Dickey–Fuller and Phillips–Perron unit root tests yield the non-stationary behavior $I(1)$ of the series expressed in logarithms at the 5 % significance level. The Akaike and Schwartz Bayesian information criteria indicated the optimal order in the $ARDL(1,1)$ model with a dependent variable logarithm of GDP and absence of autocorrelation of residuals according to the Breusch–Godfrey test, and the cointegration bound test indicated the existence of a long-run equilibrium relationship between the two series at the 5 % significance level. The ECM allowed verifying the FH through long- and short-run Granger causality.

Hwang and Yoo (2016) investigated the causality between electricity consumption per capita (kWh) and real GDP per capita (local currency unit, constant 2000 prices) in Nicaragua for the period between 1971 and 2010. The data are annual and the variables were transformed into logarithms. The variables behave as non-stationary series $I(1)$ at the 10 % significance level according to the Phillips–Perron unit root test. The Engle–Granger cointegration test indicates the absence of cointegration between the series expressed in logarithms. The Granger causality test applied between stationary series (series with first order of differentiation) verifies the FH at the 10 % significance level.

Bildirici (2016) studied the relationship between electricity consumption and GDP for five countries in America (Dominican Republic, Ecuador, El-Salvador, Guatemala, and Nicaragua) between 1970 and 2010. The variables were transformed into logarithms and in each country, both series have a non-stationary behavior $I(1)$ which was obtained by means of the Elliott–Rothemberg-Stock and Ng–Perron unit root tests. They estimated a Markov–Switching VAR model for each country, considering three business cycles systems: recession, moderate-growth, and high-growth —except for Nicaragua, for which only two systems were considered for the analysis— and it was found that the past information of both variables explains each contemporaneous variable, interpreted as a bidirectional causality supporting the FH.

Sekantsi and Okot (2016) aimed to test the link between electricity consumption per capita (thousands of kWh) and real GDP per capita (USD, 2005 constant prices) in Uganda between 1981 and 2013. They also detected bidirectional Granger causality in the long run at the 5 % significance level, thus confirming the FH.

Zhong et al. (2019) investigate the relationship among electricity consumption (kWh), real GDP (constant 2000 prices) and total employment for China during the period of 1971–2009. As the second result the Granger causality analysis verified the FH.

Ha and Ngoc (2021) investigated the potential nonlinear impact of electricity consumption on economic growth in Vietnam for 1971–2017. The research variables involved were electricity consumption per capita (kWh), real GDP per capita (US$, constant 2010 prices), petroleum consumption (barrels), foreign direct investment per capita (US$) and the rate of urbanization (percentage). As the second finding the Granger causality test verified the FH.

1.1.4. Neutrality hypothesis (NH)

The second purpose of Ciarreta and Zarraga (2010) was to analyze the possible existence of a nonlinear dynamic relationship between electricity consumption (GWh) and real GDP (€, constant 1986 prices) for Spain between 1971 and 2005. They applied the nonlinear Granger causality analysis through the Hiemstra–Jones methodology applied to the standardized residuals in a third-order VAR model with series in levels and in a first-order VAR model with series in first differences and the result of both tests is the verification of the NH.

Yoo and Kwak (2010) sought to investigate the causality between variable electricity consumption per capita (kWh) and real GDP per capita (USD, constant 2000 prices, PPP Exchange rates are used) for seven South American countries (Argentina, Brazil, Chile, Colombia, Ecuador, Peru, and Venezuela) between 1975 and 2006. In Peru, the NH is verified at 10 % significance level through the Granger causality test.

Nazlioglu et al. (2014) analyzed the causal relationships between electricity consumption (kWh) and GDP (index, 2000 = 100, as a proxy for the real income) in Turkey between 1967 and 2007. In the error correction model (ECM), the application of nonlinear Granger causality test verifies the NH.

Tamba et al. (2017) studied the causal relationship between electricity consumption (GWh) and GDP (billions Franc, FCFA) in Cameroon between 1971 and 2013. The variables were transformed into logarithms and the Dickey–Fuller unit root test indicates the existence of non-stationary series $I(1)$ at a 1 % significance level. They applied the Johansen cointegration test between the series expressed in logarithms, indicating the absence of a long-run equilibrium relationship between them at the 5 % significance level. After the transformation of the series $I(1)$ in level to series $I(0)$ in the first difference, they estimated a $VAR(1)$

model and obtained partial elasticities not statistically significant at a 5 % significance level, and, in this VAR model they applied the Granger causality test through the $\chi^2_{(1)}$ and the NH was verified at a 10 % significance level.

Balcilar et al. (2019) sought to determine the long- and short-run relationships between electricity consumption per capita (kWh) and real GDP (US$, constant 2010 prices) ascertaining how carbon dioxide emissions (Kt) affect to such relationships for Pakistan during the period 1971–2014. The three variables were transformed in natural logarithms, the Kwiatkowski-Phillips-Schmidt-Shin and Zivot-Andrews unit root tests indicated that all variables are non-stationary $I(1)$ time series. The Maki cointegration test expressed the long-run equilibrium relationship between the three series. The long-run elasticities to electricity consumption per capita were estimated by dynamic ordinary least square method, only the carbon dioxide emissions had a significant inelastic positive impact to electricity consumption per capita at 10 % significance level, but the income elasticity of electricity consumption per capita was non-significant statistically at the same significance level. Hence, the NH is verified.

Ali et al. (2020) studied the relationship between electricity consumption per capita, real income per capita and urbanization in Nigeria for the period 1971–2014. The three time-series are non-stationary $I(1)$ according to the application of Ng-Perron, Kwiatkowski-Phillips-Schmidt-Shin and Zivot-Andrews unit root tests. The Maki cointegration test established the long-run equilibrium among the three variables. The Granger causality test verified NH. It should be noted that the urbanization Granger causes to electricity consumption per capita, also the urbanization Granger causes to real income per capita.

Table 2 shows the empirical literature review on the relationship between electric energy consumption and economic growth carried out in this article.

1.2. *Theoretical framework*

Santos et al. (2018) assume that aggregate production depends on three productive factors plus technological influence:

$$Y = Y(K, L, e; t) \tag{1}$$

where K is aggregate capital, L is aggregate labor, e represents aggregate energy, and t is the time that represents the technology development in the production of goods and services in the economy.

Starting from Eq. (1), we assume the ceteris paribus application to capital and technology, considering only one type of energy in the economy such as the electric energy (E), the aggregate production function is reduced to

$$Y = F(L, E) \tag{2}$$

We also assume that all the population is economically active, starting from Eq. (2) and continuing with the developed process in the appendix, we thus obtain:

$$\ln\left(\frac{Y}{L}\right) = a + \varepsilon_E \ln\left(\frac{E}{L}\right) \tag{3}$$

Eq. (3) corresponds to the theoretical model of our research that will enable the formulation of the econometric model.

2. Materials and methods

2.1. *Materials*

We used Microsoft Excel 365 to compile and process our database, and EViews software (version 12) to carry out the econometric estimations.

Table 2
Empirical literature on electricity consumption-economic growth relationship.

Authors	Country/Period	Methodology *	Results **
Yoo (2006)	4 Asian countries (1971–2002)	• Unit root (PP) • Cointegration (Engle-Granger y Johansen) • Granger and Hsiao's Granger causality	• FH is verified (Malaysia and Singapore) • CH is verified (Indonesia and Thailand) • No cointegration in all 4 countries
Ho and Siu (2007)	Hong Kong (1966–2002)	• Unit root (ADF and PP) • Cointegration (Johansen, Shin, and Choi & Ahn) • VECM Granger causality	• GH is verified • Cointegration is verified with $\ln GDP$ as dependent variable
Ciarreta and Zarraga (2010)	Spain (1971–2005)	• Granger causality in VAR, unit root (ADF and PP) • Cointegration (ARDL bound) • Linear and nonlinear Granger causality	• CH is verified by standard linear Granger causality • NH is verified by nonlinear Granger causality
Yoo and Kwak (2010)	7 South American Countries (1975–2006)	• Unit root (PP), cointegration (Johansen) • Granger and Hsiao's Granger causality • VECM Granger causality	• GH is verified in the short-run (Argentina, Brazil, Chile, Colombia and Ecuador) • FH is verified in the short-run (Venezuela) • NH is verified in the short-run (Peru)
Chouaïbi and Abdessalem (2011)	Tunisia (1971–2007)	• Unit root (ADF and PP), VAR Granger causality • Cointegration (Engle-Granger and Johansen)	• GH is verified • No cointegration is verified
Nazlioglu et al. (2014)	Turkey (1967–2007)	• Unit root (ADF and PP) • Cointegration (ARDL bound) • ECM linear and non-linear Granger causality	• FH is verified by cointegration and linear Granger causality • NH is verified by nonlinear Granger causality
Bildirici (2016)	5 Latin-American countries (1970–2010)	• Unit root (Elliott-Rothemberg-Stock and Ng-Perron) • MS-VAR model, MS-Granger causality	• FH is verified in all 5 countries
Hwang and Yoo (2016)	Nicaragua (1971–2010)	• Unit root (PP), cointegration (Engle-Granger) • Granger causality	• FH is verified • No cointegration is verified
Sekantsi and Okot (2016)	Uganda (1981–2013)	• Unit root (ADF and PP) • Cointegration (ARDL bound) • Long- short-term Granger causality	• CH is verified in the short-run • FH is verified in the long-run • Cointegration is verified
Tamba et al. (2017)	Cameroon (1971–2013)	• Unit root (ADF), cointegration (Johansen) • VAR model, Granger causality	• No cointegration is verified • NH is verified by VAR model
Pata and Yurtkuran (2017)	Belgium, Spain, Turkey, UK and USA (1964–2014)	• Unit root (ADF and PP) • Cointegration (ARDL bound), ECM	• GH is verified by cointegration for all countries (real GDP as dependent variable)

(*continued on next page*)

Table 2 (*continued*)

Authors	Country/Period	Methodology *	Results **
Hossen and Hasan (2018)	Bangladesh (1972–2011)	• Unit root (ADF and PP) • Cointegration (Johansen) • Granger Causality	• GH is verified by Granger causality
Balcilar et al. (2019)	Pakistan (1971–2014)	• Unit root (KPSS and ZA) • Cointegration (Maki) • Dynamic ordinary least squares (DOLS) • Toda-Yamamoto causality	• NH is verified by Maki cointegration and DOLS. • CH is verified by Toda-Yamamoto causality
Bekun and Agboola (2019)	Nigeria (1971–2014)	• Unit root (ZA) • Cointegration (Maki) • Dynamic ordinary least squares (DOLS) • Fully modified ordinary least squares (FMOLS) • Toda-Yamamoto causality	• GH is verified by Toda-Yamamoto causality • CH is verified by Maki cointegration test, DOLS and FMOLS methods.
Samu et al. (2019)	Zimbabwe (1971–2014)	• Unit root (ZA) • Cointegration (Maki) • Toda-Yamamoto causality	• GH is verified through the Toda-Yamamoto causality • CH is verified by Maki cointegration
Zhong et al. (2019)	China (1971–2009)	• Unit root (ADF, PP, KPSS and ZA) • Cointegration (ARDL bound) • Granger causality	• GH is verified by *ARDL* cointegration (real GDP presents a long-run equilibrium unit elasticity with respect electricity consumption) • FH is verified by Granger causality
Ali et al. (2020)	Nigeria (1971–2014)	• Unit root (Ng-Perron, KPSS and ZA) • Cointegration (Maki) • Granger causality	• NH is verified by Granger causality
Mighri and Ragoubi (2020)	Tunisia (1971–2013)	• Unit root (PP) • Cointegration (ARDL bound) • VECM Granger causality	• GH is verified by VECM Granger causality (short-run) • CH is verified by *ARDL* cointegration and VECM Granger causality (long-run)
Ha and Ngoc (2021)	Vietnam (1971–2017)	• Unit root (ADF and PP) • Cointegration (NARDL bound) • Granger causality	• GH is verified by *NARDL* cointegration (logarithm of electricity consumption is a dynamic regressor, and logarithm of foreign direct investment and the rate of urbanization are the fixed repressors) • FH is verified by Granger causality

Developed by authors. (*) ADF: Augmented Dickey-Fuller, ARDL: Autoregressive distributed lag, ECM: Error correction model, KPSS: Kwiatkowski-Phillips-Schmidt-Shin, MS-VAR: Markov-Swiftching VAR, MS-Granger: Markov-Swiftching Granger, NARDL: Nonlinear autoregressive distributed lag, PP: Phillips-Perron, VAR: Vector autoregressive, VECM: Vector error correction model, ZA: Zivot-Andrews. (**) CH: Conservation hypothesis, EC: Electricity consumption, FH: Feedback hypothesis, GH: Growth hypothesis, NH: Neutrality hypothesis.

2.2. Variables and data

The research variables are the following:

GDP_t : real gross domestic product per capita (in local currency PEN, constant 2007 prices) (World Bank, 2022a).

EPC_t : Electric power consumption per capita (kWh, measures the production of power plants and combined heat and power plants less transmission, distribution, and transformation losses and own use by heat and power plants) (World Bank, 2022a).

The data for the variables were obtained from the World Development Indicators (World Bank, 2022a) as annual frequency time series between 1971 and 2014 in Peru. Regarding the calculation of the EPC_t using the method of The World Bank, (2022a), Bazán (2008) lists the phases of the electricity production chain: generation, transmission, distribution, and commercialization. In addition, Bazán (2008) presented the identity of the electric energy demand $D = G + P$, where G is the generated electric energy and P is the lost electric energy (with negative sign), thus supporting the EPC_t calculation method.

The sample size is 44. During the analysis period, the average value of real GDP per capita was PEN 9591.38927 and the average value of electric power consumption per capita was 673.36614 kWh. Time series GDP_t and EPC_t presented very high standard deviations: 2165.80316 and 263.87388, respectively; therefore, it was necessary to transform them into natural logarithms to reduce their dispersion. Finally, Table 3 reports a strong positive correlation between GDP_t and EPC_t.

Fig. 1 shows that the electric power consumption per capita series has an upward trend throughout the period studied, and starting in 1992, real GDP per capita showed an upward trend.

2.3. Methodology

As per Larios-Meoño et al. (2016) the high dispersion observed in the annual data of the variables will lead to their respective transformations into natural logarithms, achieving low levels of the variance of the time series. The differentiation between stationary and non-stationary time series (expressed in logarithms) will be achieved with the application of the Dickey–Fuller unit root test (Dickey and Fuller, 1979) considering the appropriate auxiliary model (with the trend and intercept, with intercept, or without trend or intercept) (Dickey and Fuller, 1981). The auxiliary models can be corrected for the presence of higher-order autocorrelation of errors by choosing the optimal lag according to the AIC, Schwarz Bayesian (SIC) and Hannan-Quinn (HQ). According to Larios-Meoño and Álvarez-Quiroz (2014), results in an augmented auxiliary model whose null hypothesis expresses the presence of unit root in the series and the hypothesis test consists of comparing the τ-statistic with the respective critical values of the Dickey–Fuller distribution. This test allows us to know the order of integration of each time series expressed in logarithms.

The series expressed in logarithms that turn out to be non-stationary will be transformed into stationary series with the difference operator according to the order of integration resulting from the previous test, for a better inference after the inclusion of the series in the models (Larios-Meoño et al., 2016). The finding of causal relationships between the stationary series will be achieved by applying the Granger causality test Granger (1969), whose unrestricted auxiliary model presents the

Table 3
Correlation Matrix * .

	GDP_t	EPC_t
GDP_t	1.00000	0.84999
EPC_t	0.84999	1.00000

(*) Development by Authors.

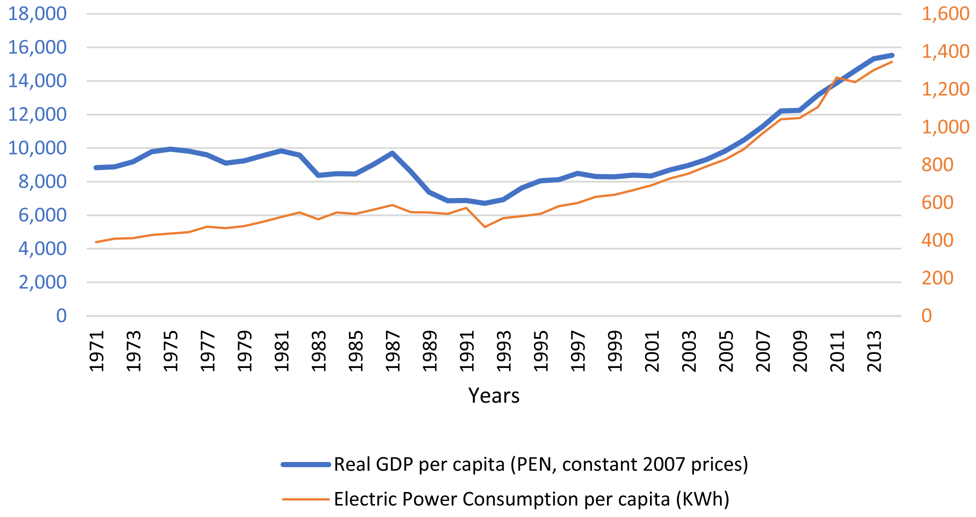

Fig. 1. Electric power consumption and GDP, per capita, 1971–2014, Peru.

caused series as its regress and variable. As regressor variables, the lags of the same order for both the caused variable and the causal variable, whose lag length will depend on the smallest value of the chosen information criterion (AIC, SIC, or HQ), the null hypothesis is the unidirectional non-causality between the stationary series. Its F-statistic with Fisher's F probability distribution allows hypothesis testing Larios-Meoño et al. (2014).

The cointegration is a quality of the time series that established their long-run equilibrium relationship. As per the methodology of Pesaran et al. (2001), when zero-order $I(0)$ and first-order $I(1)$ integrated processes are presented, it is possible to test the existence of cointegration between these non-differentiated time series in an autoregressive distributed lag model (ARDL):

$$ARDL(p,q) : Y_t = \beta + \sum_{i=1}^{p} \delta_i Y_{t-i} + \sum_{i=0}^{q} \phi_i X_{t-i} + \varepsilon_t \tag{4}$$

The advantage of the cointegration bound test is that it not only supports not only $I(1)$ time series but also $I(0)$ time series. The application of the cointegration bound test will continue, whose null hypothesis is the absence of cointegration between Y_t and X_t, which will be rejected when its F-statistic exceed the $I(0)$ and $I(1)$ bands. The existence of the long-run relationship between Y_t and X_t leads to the short-run analysis in its respective ECM from Eq. (4). The estimated ECM should comply with the assumptions of the linear regression model: non-autocorrelation, homoscedasticity, normality, stationarity, structural stability, and non-multicollinearity Larios-Meoño et al. (2016). The Durbin–Watson first-order error autocorrelation test will then be applied, and its d-statistic should approach 2 for the suspected absence of autocorrelation; the Breusch–Godfrey higher-order autocorrelation test of errors incorporates the lags of the residual as additional regressor variables —taking into account the smallest value of the chosen information criterion (AIC, SIC, or HQ)— in the auxiliary model whose regressor is the contemporaneous residual and the null hypothesis expresses the absence of autocorrelation which will be tested through the LM-statistic and this follows probability distribution χ^2 with degrees of freedom equal to the lag length. The Breusch–Pagan–Godfrey, White, Harvey and Glejser error heteroscedasticity tests present the presence of homoscedasticity of errors in the model as null hypothesis and each test estimates the LM-statistic that follows the probability distribution of χ^2 with degrees of freedom equal to the number of regressor variables in their respective auxiliary models. The Jarque–Bera normality test applied to the residuals presents the presence of normal probability distribution of residuals as null hypothesis and it will be tested through its JB-statistic with probability distribution χ^2 with degrees of freedom equal to 2. The Dickey–Fuller unit root test applied to the residuals with auxiliary model without constant or trend presents the presence of unit root in the residuals as null hypothesis and it will be tested with the τ-statistic that presents Dickey–Fuller distribution. The structural stability will be evaluated through the CUSUM and CUSUM of squares tests Larios-Meoño et al. (2014).

3. Results

This section reports the results of the hypothesis tests and econometric estimations conducted in this research.

3.1. Stationarity analysis of the series

The results of the application of the augmented Dickey–Fuller unit root test to the two series (transformed into natural logarithms) and their respective first difference transformations are presented in Table 4.

Based on Table 4, it is concluded that series $\ln GDP_t$ and $\ln EPC_t$ are non-stationary. The first difference transformed series, $\Delta\ln GDP_t$ and $\Delta\ln EPC_t$, constitute stationary series; additionally, their Jarque-Bera statistics are 17.17522 and 118.87946 respectively. Thus, it is evidenced that neither $\Delta\ln GDP_t$ nor $\Delta\ln EPC_t$ present a normal probability distribution at the 5 % significance level.

3.2. Granger causality

The causality relationship between the time series will be evaluated by means of the Granger causality test, with the prior condition of series stationarity. In our case, the first difference of the series expressed in natural logarithms are stationary series, $I(0)$. Table 5 shows the existence of one-way causality from $\Delta\ln GDP_t$ to $\Delta\ln EPC_t$, but one-way non-causality is also found from $\Delta\ln EPC_{tt}$ to $\Delta\ln GDP_t$at the 5 % significance level. Then, as for the Granger causality, we demonstrate the fulfilment of the CH in Peru. Therefore, we dismissed the GH, FH, and NH in this research, also as per Granger causality.

3.3. ARDL cointegration

The results in Table 4 result in the consideration of the non-stationary series $I(1)$ as an endogenous variable $\ln EPC_t$ and as an exogenous variable $\ln GDP_t$, in the sense of Granger causality. These integrated processes allowed us to estimate the $ARDL(2,5)$ model without constant or trend, in which $\ln EPC_t$ is the dependent variable and $\ln GDP_t$ is the independent variable. The length of lags is attributed to the Akaike

Table 4
Results of augmented Dickey-Fuller unit root test.

Series	Auxiliary model	Criteria*	Lag	τ-statistic	Probability	Integration**
$\ln GDP_t$	None***	SIC	1	0.88872	0.89670	$I(1)$
$\Delta \ln GDP_t$	None***	SIC	0	-3.69518	0.00050	$I(0)$
$\ln EPC_t$	None***	SIC	0	3.74417	0.99990	$I(1)$
$\Delta \ln EPC_t$	C&T****	SIC	0	-8.73041	0.00000	$I(0)$

Developed by authors. (*) Schwarz bayesian information criterion. (**) Integration order at 5 % significance level. (***) Without constant or trend (None). (****) With constant and trend (C&T).

Table 5
Results of Granger's causality test.

Causality *	Criteria	Lag	F-statistics	p-Value
$\Delta \ln EPC_t \nrightarrow \Delta \ln GDP_t$	SIC**	1	0.39038	0.53570
$\Delta \ln GDP_t \rightarrow \Delta \ln EPC_t$	SIC**	1	4.93831	0.03210

Developed by authors. (*) 5 % significance level. (**) Schwarz bayesian information criterion.

information criterion considering a maximum of five lags in all variables. The application of the cointegration bound test without constant or trend in the estimated $ARDL(2,5)$ model yielded F-statistic equal to 15.83052 and allowed rejecting the null hypothesis at the 5 % significance level due to the $I(0)$ and $I(1)$ band which is equal to 3.15 and 4.11, respectively. In the long-run equilibrium, $\ln GDP_t$ impacts $\ln EPC_t$ with a value of 0.76. The finding of the long-run equilibrium relationship under the Pesaran–Shin–Smith methodology between $\ln GDP_t$ and $\ln EPC_t$ led to the estimation of the respective ECM.

Table 6 shows the estimated ECM results with a significant and negative coefficient of the error correction term, strengthening the results of the long-run equilibrium relationship. A significant and positive short-run impact on $\Delta \ln EPC_t$ caused by $\Delta \ln GDP_t$, two significant and positive impacts on $\Delta \ln EPC_t$ caused by $\Delta \ln GDP_{t-3}$ and $\Delta \ln GDP_{t-4}$, and a significant and negative impact is found on $\Delta \ln EPC_t$ caused by $\Delta \ln EPC_{t-1}$. The estimated ECM shows a good adjustment sustained in R^2-adjusted greater than 0.5. It is suspected that there is no first-order autocorrelation of residuals due to the value of the Durbin–Watson D-statistic being close to 2. The results of the Breusch–Godfrey higher-order autocorrelation test of errors confirm at the 5 % significance level that the residuals of the model do not present first-order autocorrelation. According to the Schwarz bayesian information criteria, the homoscedasticity of residuals of the model is guaranteed at the 5 % significance level. According to the results of the Breusch–Pagan–Godfrey tests and White, Harvey, and Glejser tests, the residuals of the model present normal probability distribution at 5 % significance level according to the results of the Jarque-Bera normality test. The Dickey–Fuller unit root test of the residuals expresses that they constitute an $I(0)$ process at 5 % significance level with absence of autocorrelation in the auxiliary model. According to Schwarz bayesian information criteria, the structural stability is confirmed at a 5 % significance level through the CUSUM and CUSUM of squares tests.

Table 6
Estimation of error correction model.

Variables	Coefficients
Error correction term	-0.06088*
$\Delta \ln EPC_{t-1}$	-0.61788*
$\Delta \ln GDP_t$	0.66442*
$\Delta \ln GDP_{t-1}$	0.22833
$\Delta \ln GDP_{t-2}$	-0.03109
$\Delta \ln GDP_{t-3}$	0.33158*
$\Delta \ln GDP_{t-4}$	0.36105*
Regressand variable	$\Delta \ln EPC_t$
Observations	39
Number of coefficients	7
R^2-adjusted	0.65295
Durbin-Watson test d-statistic	2.294191
Breusch-Godfrey test Prob. LM-statistic**	0.10560
Breusch-Pagan-Godfrey test Prob. LM-statistic	0.54852
White cross terms test Prob. LM-statistic	0.15081
White non-cross terms test Prob. LM-statistic	0.56908
Harvey test Prob. LM-statistic	0.88364
Glejser test Prob. LM-statistic	0.90996
Jarque-Bera test Prob. JB-statistic	0.88348
Dickey-Fuller test Prob. τ-statistic***	0.00000
Cointegration bound test F-statistic****	15.83052

Developed by authors. (*) Statistically significant at 5 % level. (**) Akaike, Schwarz bayesian and Hannan-Quinn information criteria were considered for the first-order lag. (***) Non-augmented auxiliary model by Schwarz bayesian information criterion. (****) No constant and no trend.

4. Discussion

The first finding we present is the non-stationary behavior of the series expressed in natural logarithm: electric power consumption per capita and real GDP per capita, i.e., both series constitute integrated processes $I(1)$ at the 5 % significance level. After the transformation of log series to its first difference, through Granger causality with stationary series we confirmed the *conservation hypothesis* in Peru at the 5 % significance level. The results of this study differ from the results presented by Yoo and Kwak (2010) as the unique revised paper for Peru, since they first identified that real GDP per capita is an integrated process $I(1)$ at the 10 % significance level; then through the Granger causality test, they confirmed the *neutrality hypothesis* at the 10 % significance level. Applying the causality analysis, the *conservation hypothesis* was obtained in other countries according the following evidence: Yoo (2006) for Indonesia and Thailand, Ciarreta and Zarraga (2010) for Spain, Sekantsi and Okot (2016) for Uganda (in the short-run), Balcilar et al. (2019) for Pakistan, and Mighri and Ragoubi (2020) for Tunisia.

Our long-run equilibrium analysis through the Pesaran–Shin–Smith cointegration also confirms the *conservation hypothesis* in Peru at the 5 % significance level as the second finding, where the long-run equilibrium per capita income elasticity of the electric power consumption per capita is 0.76. In the corresponding ECM, we confirm the *conservation hypothesis* in a short-run analysis, where the significant statistically short-run per capita income elasticity of the electric power consumption per capita is 0.66 at the 5 % significance level. Yoo and Kwak (2010) did not find a long-run equilibrium relationship between variables electricity consumption per capita and real GDP per capita, while considering their analysis between 1975 and 2006 under Johansen cointegration. Using *ARDL* cointegration, also Mighri and Ragoubi (2020) verified the *conservation hypothesis* for Tunisia. Through another cointegration methodology (Maki test), Bekun and Agboola (2019) for Nigeria and Samu et al. (2019) for Zimbabwe, both found the *conservation hypothesis*.

5. Conclusions and policy recommendation

Our study identifies the relationship between electric power consumption per capita and real GDP per capita as confirming the *conservation hypothesis* in Peru. This hypothesis was identified by using Granger causality and showing the positive inelastic short- and long-run equilibrium behavior of electric power consumption per capita relative to real GDP per capita. Thus, *conservation policies* have a negligible effect on economic growth (Ozturk, 2010; Payne, 2010; Squalli, 2007). In Peru, *conservation policies* are oriented toward saving electricity, promoting efficient energy use, investing in electricity generation from renewable energies, and developing eco-sustainable electricity activities (El Peruano, 2022; Ministerio de Energía y Minas, 2022, 2014, 2008a, 2007; Ministerio de Energía y Minas, 2000; Ministerio del Ambiente, 2019; OSINERGMIN, 2008). The current exorbitant figures for world carbon dioxide (CO_2) emissions due to oil and liquid derivatives (World Bank, 2022a) have led countries such as Peru to design *conservation policies* (see Table 1) that introduce eco-sustainable sources of electricity generation that includes renewable energy sources. Among the green energy types (clean energy) introduced in Peru, we find the following: hydraulic energy, hydroelectric power plants, wind energy, and photovoltaic solar energy (United Nations, 2021; Ministerio de Energía y Minas, 2014; OSINERGMIN, 2008, 2022a).

On the other hand, in Peru economic activities tend to be electricity-intensive as it was the case in Pakistan discussed by Balcilar et al. (2019) where economic growth precedes electric power consumption based on the development of public electric energy *conservation, expansive and security policies* that highlight the use of renewable energies considered clean energies. We estimate that a percentage increase in real GDP per capita produces a lower percentage increase in electric power consumption. The Central Reserve Bank of Peru (2022) forecast for that the real GDP growth rate will be 3 % in 2022 and will remain constant during the next year; based on previous expression we select the baseline scenario for real GDP growth rate forecast to the period 2018–2030 by COES (2019) which will set the scenario to forecast the electric power consumption for SEIN: 66 720 GWh for the year 2022, 70 887 GWh for the year 2023, 74 764 GWh for the year 2024, 79 556 GWh for the year 2025, and 83 186 GWh for the year 2026. Ministerio de Energía y Minas del Perú (2022) presented the historical of the total investment made by generation, transmission and distribution electrical companies: 766.2 million US$ for the year 2018, 709.6 million US$ for 2019, 462.5 million US$ for 2020, and 1 197.8 million US$ for 2021. The historical investment data recorded in recent years has been growing, then the electric power consumption forecast for the following 4 years is also growing, therefore, we recommend strengthening and increasing the promotion of investment in electric power generation through green and clean energies applying the *conservation, expansive and security policies* described in Table 1, and provide other incentives to attract foreign investment or national capital for electricity generation that will allow achieving the projections and to ensure amelioration, optimization and sustainability (Zhong et al., 2019), also the increase of the national electrification coefficient, after the execution of economic policies that will allow for the country's economic growth.

The World Bank (2022b) considers Peru an upper middle-income economy —using the World Bank Atlas method, according to its gross national income per capita. This result is consistent with the national electrification coefficient which measures the percentage of the population with access to electricity supply with respect to the total population (Sociedad Nacional de Minería Petróleo y Energía, 2015). This electrification coefficient shows an upward trend due to the development of technology which triggers new needs in the population and it rose between 2017 and 1993 from 69.72 to reach 99.9 % in 2025 (OSINERGMIN, 2022b). In Table 1, we observe the *expansive* and *security policies* as a result of the concern of policymakers to achieve greater coverage and ensure electric power consumption in the population of Peru, which led to the upward trend of the national electrification coefficient. The concern and emphasis on the increase in global CO_2 emissions (World Bank, 2022a), the increase in the international price of oil (OPEP, 2022), and the focus on the *conservation policy* of incentives for investment in electricity generation activities with renewable energy sources (OSINERGMIN, 2008) has led to a lack of interest in promoting investments in electricity generation from non-renewable energy sources such as oil, natural gas, and coal for the production of thermoelectric energy (OSINERGMIN, 2022a). We also point out that the share of thermal energy in electricity generation has decreased by 0.69 % in 2021 compared to 2008 (Bazán, 2011; COES, 2022). Thus, the government of the Republic of Peru has entered into final concession and investment commitment contracts, and authorizations for power generation plants which are under execution (engineering or construction studies) through July 2022, for a total power capacity of 6089.3 MW with a total investment of USD 13,050 million. The contracts covered four types of power generation plants: 55 hydroelectric power plants, 4 wind power plants, 5 solar photovoltaic power plants, and 1 thermal power plant which contribute 76.72 %, 11.80 %, 9.80 %, and 1.68 % of the total electric power, while the investment represents 87.05 %, 8.35 %, 3.13 %, and 1.47 % of the total investment, respectively. The figures shown above highlight that the hydroelectric power plant contracts reflect the geomorphology of Peru, which runs from its northern to southern border alongside the Andes Mountains (Instituto Geográfico Nacional, 2015)— located in 13 regions, whose electrical power is 4671.8 MW with an investment of USD 11,359.5 million. In northern Peru, there are 15 hydroelectric power plants [Amazonas (5), Ancash (7), La Libertad (2), and Lambayeque (1)] whose contracts contribute 38. 55 % of the electrical power of the total contracts for hydroelectric power plants and constitutes a 39.41 % investment share. In the central area, there are 22 hydroelectric power plants [Ayacucho (1), Huánuco (8), Junín (8), and Lima (5)] whose contracts produce 22.73 % of the electrical power and constitute an investment share of 22.52 %. In the south, there are 18 hydroelectric plants [Arequipa (5), Cusco (6), Moquegua (2), Puno (4), and Tacna (1)] whose contracts contribute 38.72 % of electric power, and an investment share of 38.07 %. The wind power plant contracts reflects a different geographical distribution. They provide 718.7 MW with an investment of USD 1089.8 million. The plants are located in the south of Peru [Ica (3) and Arequipa (1)]. The solar photovoltaic power plant contracts on the other hand, generate 596.5 MW with an investment of USD 409,000 million. In the north of the country, there is only one plant [Iquitos (1)] whose contract produces a mere 3.35 % of the total electrical power of the total solar photovoltaic power plant contracts with a 3.91 % investment share. In the south, there are four solar photovoltaic power plants [Arequipa (3) and Moquegua (1)]. Finally, in the department of Piura —in the north of the country— there is only one thermal power plant whose contract provides 102.3 MW with an investment of USD 191,700 million (OSINERGMIN, 2022a).

Lastly, we consider pertinent to evaluate the identification of some additional independent variable through an omitted variable test as an extension of the present research to avoid the possible misspecification bias of the econometric model. Future research can include carbon dioxide emissions as a third variable as found in Hossen and Hasan (2018) that showed the *growth hypothesis,* Balcilar et al. (2019) that verified the *neutrality* and *conservation hypotheses*, Bekun and Agboola (2019), and Samu et al. (2019) that confirmed the *growth* and *conservation hypotheses* by including the same variable. Others such as Zhong et al., (2019) verified the *growth* and *feedback hypotheses* by including total employment as the third variable while Ali et al. (2020) verified the *neutrality hypothesis* by including urbanization as the third variable. Ha and Ngoc (2021) also verified the *growth* and *feedback hypotheses* by including three additional variables: petroleum consumption, foreign direct investment per capita and the rate of urbanization. Future research might benefit from including these variables in future specifications.

CRediT authorship contribution statement

Ciro Bazán and Víctor Josué Álvarez–Quiroz performed writing—original draft preparation, writing—review and editing, conceptualization, validation, investigation, methodology, formal analysis and project administration. James Sampi and Adolfo Arana performed validation, writing—review and editing, visualization and supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Based on Eq. (2), we suggest the production function $F(L,E)$ is a first-degree homogeneous function and presents the following non-negativity restrictions are defined: $Y \geq 0, L \geq 0, A \geq 0$..

We define the signs of the first-order and second-order partial derivatives of $F(L,E)$:

$$\frac{\partial F(L,E)}{\partial L} > 0, \frac{\partial F(L,E)}{\partial E} > 0, \frac{\partial^2 F(L,E)}{\partial L^2} < 0, \frac{\partial^2 F(L,E)}{\partial E^2} < 0 \tag{A.1}$$

To obtain the infinitesimal changes in Y, as per Simon and Blume (1994), the total differential is applied to Eq. (2) and we obtain the following:

$$dY = \frac{\partial F(L,E)}{\partial L} dL + \frac{\partial F(L,E)}{\partial E} dE \tag{A.2}$$

Dividing each part of equation (A.2) by Y, y multiplying L/L by the first term and E/E by the second member of equation (A.2) we obtain:

$$\frac{dY}{Y} = \varepsilon_L \frac{dL}{L} + \varepsilon_E \frac{dE}{E} \tag{A.3}$$

We define partial elasticities $\varepsilon_L = [\partial F(L,E)/\partial L](L/Y)$ as the population-income elasticity and $\varepsilon_E = [\partial F(L,E)/\partial E](E/Y)$ as the electric energy elasticity of income. Applying indefinite integral to equation (A.3) and considering the mentioned non-negativity constraints and constant partial elasticities, we obtain:

$$\ln Y = \ln A + \varepsilon_L \ln L + \varepsilon_E \ln E \tag{A.4}$$

where A is the arbitrary constant resulting from the integration. From equation (A.4) we subtract $\ln A$ from each member and obtain by property of the difference of logarithms according to Sydsæter et al. (2005):

$$\ln\left(\frac{Y}{A}\right) = \varepsilon_L \ln L + \varepsilon_E \ln E \tag{A.5}$$

In equation (A.5) we apply the exponent property of the argument of the logarithm and then apply the sum property of logarithms according to Sydsæter et al. (2005), and we obtain as follows:

$$\ln\left(\frac{Y}{A}\right) = \ln\left(L^{\varepsilon_L} E^{\varepsilon_E}\right) \tag{A.6}$$

Taking antilogarithm in equation (A.6) and then clearing Y we obtain the Cobb–Douglas production function (Cobb and Douglas, 1928; Douglas, 1976) including electric power as a factor and excluding capital:

$$Y = A L^{\varepsilon_L} E^{\varepsilon_E} \tag{A.7}$$

Using the first degree of homogeneity of $F(L,E)$, we recognize constant returns to scale of the factors:

$$\varepsilon_L + \varepsilon_E = 1 \tag{A.8}$$

In equation (A.7) variables Y, L, and E are turned into per capita variables by means of the method of Solow (1957) explained in Barro and Sala-i-Martin (2004) considering the restriction presented in equation (A.9):

$$\frac{Y}{L} = A\left(\frac{E}{L}\right)^{\varepsilon_E} \tag{A.9}$$

By applying the natural logarithm to equation (A.9) and defining $a = \ln A$, we thus obtain:

$$\ln\left(\frac{Y}{L}\right) = a + \varepsilon_E \ln\left(\frac{E}{L}\right) \tag{3}$$

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