RESEARCH ARTICLE

Re-estimating the interconnectedness between the demand of energy consumption, income, and sustainability indices

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Abstract
In this study, we analyze the time-varying causality linkages between energy consumption, economic growth, and environmental degradation in 33 Organization for Economic Co-operation and Development countries, spanning the period 2000 to 2013. The curve causality approach provides evidence of a significant environmental Kuznets curve in 25 countries in the case of the ecological footprint and in 23 countries in the case of the Environmental Performance Index. However, out of them, only Italy, Slovakia, and South Korea have traditional environmental Kuznets curve, in the form of an inverted U–shaped curve. For the remaining countries, different forms of curves are valid. In particular, an N-shaped curve appears to be valid between income and environmental degradation for nearly half of the sample, i.e., for Austria, Belgium, Chile, Estonia, Finland, France, Germany, Hungary, Luxembourg, Netherlands, Sweden, Switzerland, New Zealand, Turkey, and the USA. Additionally, bidirectional causality relationships are confirmed among all covariates in most countries. In view of the results, some crucial policy implications would be suggested, such as sustainable development that aims to make a balance between economic growth and environmental protection.

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Introduction

All countries have been struggling to have higher economic growth rates and better environmental performance levels as well as more energy productivity. However, it is really difficult to reach all those goals simultaneously because economic growth generally comes at the cost of the environmental quality, particularly through the exploitation of natural resources and uncontrolled industrialization (Yale University 2018). This situation might be seen as an inherent tension between environment and economy. However, as a result of the increasing awareness of upcoming environmental threats, such as global warming, climate change, deforestation, and water scarcity and pollution, human beings have been trying to ameliorate the environmental pressure that stems from their own activities over half a century. In this respect, changing quality of the environment as well as the relationship between economic development and natural resource consumption has become a subject of great interest since the 1960s (Acar and Asici 2017). In particular, the concerns about global warming gained important research interest in the

1960s when more sophisticated environmental models were used as a result of digital computers that have the ability to compute the global warming effects accurately (Thomakos and Alexopoulos 2014).

In respect of policy perspective against rising environmental problems, the Stockholm Conference in 1972 was a milestone as it emphasized the need to preserve natural habitats in order to ameliorate the living conditions for all, in a sustainable stream which calls for international cooperation across countries.[1] In the same year, the Club of Rome published a report, "The Limits to Growth," which is a reflection of pessimistic views of a group of scientists regarding the environmental effects of the economic growth and population increase. The report highlights the fact that the current exponential growth rates of population and economic activity cannot continue indefinitely on a planet with finite natural resources (Beder 2006). Finally, the concerns about environmental quality led sustainable development to become an essential discussion agenda in the world summits and conferences. For instance, in 1987, the World Commission on Environment and Development published a report entitled "Our Common Future," which is also known as the "Brundtland Report." In this report, sustainable development was defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations 1987). Since then, some other conferences and summits such as the Rio de Janeiro Conference in 1992, Johannesburg Conference in 2002, the Earth Summit in 2012, and the United Nations Sustainable Development Summit in 2015 were held to define the principles of sustainable development.

As a result of the conclusions and recommendation of such environmental conferences, policy-makers, on the one hand, and scientists, on the other hand, started searching for a reconciliation between environmental quality and economic development. For instance, energy and environmental economists have analyzed economic growth and environmental pollution nexus in the framework of the environmental Kuznets curve (EKC) hypothesis, which assumes an inverted U–shaped relationship between environmental pollution and economic development and draws its roots from the pioneering study by Grossman and Krueger (1991). The EKC postulates that as income increases, environmental pollution rises as well, until some threshold level of per capita income is reached beyond which pollution starts declining (Apergis and Payne 2010). The presence of the inverted U–shaped curve can be elucidated by three effects, namely, *scale*, *composition*, and *technique effects*, which appear during the different development stages. The scale effects coincide with the initial stage of industrialization and result in more

environmental pollution because rising level of output requires more inputs and natural resources as well as additional waste and emissions as a by-product (Grossman and Krueger 1991). The composition effects indicate a transition from an agricultural-based economy towards energy and technology intensive service economy and result in a less polluted environment (Ang 2007). Last, the technique effects, representing technological enhancements in production techniques such as cleaner technologies, will probably create a reduction in pollution (Jaunky 2011). In case that the positive environmental quality impacts of the composition and technique effects outweigh the negative impacts of scale effect, the inverted U–shaped EKC is supported.

Apart from the EKC issue, as a second research area, the nexus of energy consumption and economic growth has stimulated research curiosity with the pioneering study by Kraft and Kraft (1978).[2] Herein, energy as a vital input in the production of many commodities represents the backbone of the world's industrial development (Al-Mulali and Ozturk 2016). As such, more energy consumption leads to more economic development while simultaneously using energy in a more efficient way requires a higher economic development level as well (Ang 2007; Kourtzidis et al. 2018; Tzeremes 2018a). Therefore, the direction of causality cannot be determined a priori (Halicioglu 2009).[3] Finally, a third research area analyzing the relationships between energy consumption, economic growth, and environmental pollution has emerged as a result of the combination of the energy-growth and environment-growth nexuses. The studies by Ozcan (2013) and Tiba and Omri (2017) provide extensive literature reviews for this research area. In this research strand, reduction of energy demand appears a direct way of handling air pollution problem because pollution mainly stems from the consumption of fossil fuels (Soytas and Sari 2009). Additionally, the achievement of economic growth and the expansion of industrialization require more energy, which in turn degrades environmental quality through the discharge of greenhouse gases (GHGs) emissions into the atmosphere (Shahbaz et al. 2017). Therefore, energy consumption is accepted as a determinant of environmental pollution. To obtain environmental sustainability, using energy in a more efficient way via investments in renewable energy sector is of importance. The reason of high environmental pollution worldwide is the consumption of

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[1] See https://www.unostamps.nl/subject_united_nations_conference_human_environment.htm

[2] The study proposed by Kraft and Kraft (1978) is based on a bivariate model that includes only energy consumption and economic growth. However, recent studies have analyzed the energy consumption and economic growth issue by adding more variables into model to prevent omitted variable problem.
[3] There are four hypotheses in this research field: growth hypothesis assumes a unidirectional causality running from energy consumption to economic growth; the conservation hypothesis implies a one-way causality running from economic growth to energy consumption; the feedback hypothesis indicates a bidirectional causality between energy consumption and economic growth; and finally, the neutrality hypothesis doesn't postulate any significant causality between energy consumption and economic growth.

high-level of fossil energy sources. For instance, in 2015, OECD region and the world were in similarity regarding the share, which was equal to approximately 80% of fossil fuel energy consumption in total energy consumption.[4] In this respect, it could be asserted that energy is the engine of both economic growth and environmental sustainability.

Based on the aforementioned views, this paper aims at analyzing the nexus of economic growth, environmental quality, and energy consumption by using, for the first time, two sustainability indices[5] (hereafter, SI), the ecological footprint (EF) and the Environmental Performance Index (EPI), as proxies for environmental pollution in the framework of the time-varying causality test proposed by Ajmi et al. (2015). This pattern suggested by Sato et al. (2007) and the extension of time-varying causality suggested by Ajmi et al. (2015). The sample includes 33 OECD countries over the period 2000–2013. OECD region deserves a special research interest as it is the most energy intensive region in the world in terms of primary energy supply per capita that equals to 4.1 toe (IEA 2017). According to Energy Information Administration (EIA 2017), energy consumption level of the OECD economies, though not growing as fast as in the case of non-OECD countries, is expected to increase by 9% over the period 2015–2040. In 2016, OECD region accounted for 17% of global population, 44% of GDP, 40% of total primary energy supply, and 89% of CO_2 intensity (World Bank 2017). Moreover, analyzing the EKC issue is crucial to decide on the right energy policy for the OECD region. In this context, the shape of the curve can be accepted as a signal to decide among different energy policies. For instance, the existence of a U-shaped curve indicates that environmental pollution is a byproduct of economic development and the country has not reached yet an adequate development level that starts ameliorating pollution problems. In this case, energy policies should be transformed from fossil fuels to renewable energy sources. However, an inverted U–shaped curve signals that economic development level is high enough, which alleviates environmental pollution problems via more sophisticated energy policies. Additionally, an N-shaped curve indicates the presence of technological obsolescence effects. In this situation, OECD countries should substitute the old and exhausted technologies with the new and more sophisticated technologies and implement those technological innovations into their energy sectors. For instance, making use of information and communication technologies (ICTs) in energy markets could be a plausible solution for the environmental pollution problems.

Contributions of this study to the related literature are two-fold. First, the previous studies didn't allow for time-varying relationships during their causality analyses, likely to result in erroneous conclusions on both the EKC hypothesis and

environmental policies (Ajmi et al. 2015). The economic rationale behind employing a time-varying Granger causality test depends on the fact that the relationship between environmental degradation, economic growth, and energy use might be changing over time due to the effects of changing economic conditions, natural disasters, energy and environmental policies, as well as regulatory and new technological advancements. Consequently, implementing this time-varying Granger causality test, we have an all-inclusive picture of the dataset and not only in the conditional mean which is applied by the conventional procedures (Ajmi et al. 2015; Tzeremes 2018b). Second, the previous studies mostly utilized CO_2 emissions as a proxy for environmental degradation, whereas we utilize two different SI that gather different dimensions of environmental pollution under two indices. Given that air pollution is just one aspect of environmental pollution, the effects of human beings' activities cannot be fully accounted for using only one-dimensional pollution indicator such as CO_2 emissions (Acar and Asici 2017). Additionally, there isn't any paper aims at revealing the simultaneous causality linkages between the EPI, energy consumption, and economic growth. Therefore, we also aim at filling this void in the existing literature. Besides, there are quite few EF-based studies in the existing literature compared to CO_2-based studies.

The rest of the paper is organized as follows. In " A brief literature review," data and methodology are explained while in "Data and Methodology," the empirical results and discussion are provided. Finally, in "Empirical results and discussions," the study is concluded with some policy implications.

A brief literature review

Under this subheading, we just provide the studies using the EF or EPI as an indicator for environmental quality; however, an interested reader can read the studies of Ozcan (2013) and Tiba and Omri (2017) for an extensive literature survey for the nexus of energy, economic growth, and environment. As we expressed before, existing studies in this field mostly utilize CO_2 emissions as a proxy for environmental degradation. Therefore, we aim filling this void by utilizing two indices representing different dimensions of environmental quality. Concerning the studies using the EPI, a positive relationship was obtained for the EPI and human development index (HDI) nexus by Samimi et al. (2011) in the case of 28 developed and 86 developing countries. Thomakos and Alexopoulos (2014) for 129 countries (the effect is stronger for the high-income developed countries but insignificant for the middle-income developing countries) obtained that economic development has a positive impact on the EPI. Similarly, Neagu et al. (2017), in the case of 166 countries, found that income per capita is positively associated with the

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[4] See https://data.worldbank.org/indicator/eg.use.comm.fo.zs
[5] For more details about SI, please see Bohringer and Jochem (2007).

EPI and the causality is running from income per capita to the EPI. In contrast, Chang and Hao (2017) for 87 countries (particularly in the case of the OECD sample) and Fakher and Abedi (2017) for a group of developing countries supported that EPI has a positive effect on economic growth. However, Chowdhury and Islam (2017) found a negative relationship between economic growth and EPI in BRICS economies while Shahabadi et al. (2017) obtained that HDI had an insignificant influence on the EPI in the case of OPEC countries. Concerning the EKC issue, for a group of developed and developing countries, Kashyna (2011) between the per capita income and the EPI and Lachmann (2017) between the HDI and the EPI verified the EKC hypothesis. Besides, by using EPI and cross-section data from 2006 for a large panel of countries, Alam and Kabir (2013) supported EKC partially in the case of the East and South-East Asian countries, whereas Yoshioka (2010) didn't verify it. The existing literature indicates that there is still not a paper aims at defining the causality relationships between the EPI, energy consumption, and economic growth.

Compared to the EPI-based studies, there exist more studies using EF as an indicator for environmental quality. Out of them, using cross-sectional data, Rothman (1998) for a group of countries, York et al. (2003) for 142 countries, Gondran and Brodhag (2006) for 131 countries, Moran et al. (2008) for 93 countries, Bagliani et al. (2008) for 141 nations, and Wang et al. (2013) for 150 countries didn't support EKC type relationship between per capita income (or HDI) and the EF. Additionally, some panel data studies such as Caviglia-Harrisa et al. (2009) for 146 countries, Charfeddine and Mrabet (2017) for the case of the non-oil-exporting countries, Al-Mulali et al. (2015) and Ozturk et al. (2016) in the cases of the low- and lower middle-income countries couldn't find any supportive evidence for the EKC hypothesis. However, Asici and Acar (2016) for a panel of 116 countries (only in the case of the footprint of domestic production), Charfeddine and Mrabet (2017) in the case of oil-exporting countries, Al-Mulali et al. (2015) and Ozturk et al. (2016) in the cases of the upper middle- and high-income countries confirmed the EKC hypothesis. In this research vein, there are time series studies as well. For instance, Hervieux and Darne (2015) for seven Latin American countries, Hervieux and Darne (2016) for 11 countries, Wang (2017) for Sweden, and Charfeddine (2017) for Qatar obtained evidence against traditional form of EKC, whereas Mrabet and Alsamara (2017) for Uddin et al. (2017) for Australia, Nepal, Sri Lanka, Turkey, and UK supported the EKC hypothesis.

From the above-mentioned studies, Al-Mulali et al. (2015), Asici and Acar (2016), Charfeddine and Mrabet (2017), Mrabet and Alsamara (2017), Charfeddine (2017), and Ozturk et al. (2016) included energy consumption into their models as a determinant of environmental degradation. Of them, Charfeddine and Mrabet (2017) supported a

bidirectional causality between the EF and income, between the EF and energy consumption, and between the income and energy consumption. Charfeddine (2017) found a bidirectional causality relation between electricity consumption and income and a unidirectional causality running from electricity consumption to the EF. Additionally, Al-Mulali and Ozturk (2015), for 14 MENA countries, obtained a short-run unidirectional causality running from industrial output and energy consumption to the EF and a bidirectional causality between industrial output and energy consumption. Likewise, based on the panel data, Uddin et al. (2017), for the leading world EF contributors, found a positive and significant effect of income on the EF and a unidirectional causality running from income to the EF.

Data and methodology

Data and preliminary tests

Our practical application probes the existence of the EKC hypothesis via a time-varying Granger causality test in the 33 OECD countries[6] over the period 2000–2013 based on the data accessibility. There are four variables under consideration: (i) EPI, (EPI dataset stems from the report of Yale Center for Environmental Law and Policy, Yale University[7]), (ii) EF, (EF sample derives from the Global Footprint Network[8]), (iii) energy consumption (EC hereafter) (measured as kg of oil equivalent per capita) has been extracted from the World Bank, World Development Indicators[9], and finally, the real gross domestic product (GDP) per capita at purchasing power parity (in millions, constant 2011 international $) has been collected from the World Bank, World Development Indicators as well. Arguably and bearing in mind that a slight number of the data is missing, Latvia and Iceland are excluded from the sample. Furthermore, because our sample is small (only 14 years), we used the quadratic match-sum framework in order to transform all the annual series into quarterly data.[10] Consequently, our new sample contains 56 observations.[11]

Concerning the SI, the EF index, introduced by Rees (1992) and developed by Wackernagel and Rees (1996), is a

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concise indicator of environmental sustainability which identifies the critical natural capital requirements of a defined population in terms of the corresponding biologically productive areas (Wackernagel et al. 1999). That is to say, EF is the total area necessary to produce the resources a country (a population) consumes and to absorb the waste it generates, based on the prevailing technology (Bagliani et al. 2008). The second indicator is the EPI, produced jointly by the universities of Yale and Columbia in collaboration with the World Economic Forum and the Joint Research Center of European Commission. The EPI, an international composite environment index, identifies scores for several core environmental policy objectives and measures how close countries are to meeting them.[12] The high scores in the EPI reflect the long-standing commitments to protecting the public health, preserving natural resources, and decoupling GHGs from the economic activities (Himmelstein 2018).[13]

Giving priority to preliminary tests, we conduct three classical unit root tests—Dickey and Fuller (1979), ADF unit root test; the Phillips and Perron (1988), PP test; and the Kwiatkowski et al. (1992), KPSS test—in order to ascertain the maximum order of integration among the covariates. Furthermore, when we evaluate the stationary tests to the drift-trend and decide the lag length of the test by the Akaike information criterion (AIC) statistic, the stationary tests help us attest whether the sample contains a unit root in its time-series representations.

Time-varying vector autoregressive model

Deeming two variables (p, r) for a vector autoregressive (VAR) model, Granger (1969) developed the well-known Granger causality test. Having an unprecedented influence on the scientific discipline, the traditional Granger causality test can be written in its general form as:

$$P_t = q_0 + \sum_{i=1}^{n} q_i P_{t-i} + \sum_{i=1}^{n} x_i R_{t-i} + t_i, \tag{1}$$

and

$$R_t = l_0 + \sum_{i=1}^{n} l_i R_{t-i} + \sum_{i=1}^{n} y_i P_{t-i} + b_i, \tag{2}$$

P_t and R_t are two variables (EC, GDP, EPI, or EF) of our analysis in order to check the causality as a pair for Eqs. (1) and (2), respectively. Apart from that, Dahlhaus et al. (1999) proposed a theoretical model of locally stationary procedure. This method was adopted from Sato et al. (2007), who developed a time-varying vector autoregressive framework (or dynamic VAR as called) that have a time-smooth variation as a

contribution. The dynamic VAR can be reproduced in the following form:

$$w_{t,T} = d(t/T) + \sum_{l=1}^{k} C_l(t/T) w_{t-l,T} + u_{t,T}, \tag{3}$$

where $w_{t,T}$ and $d(t/T)$ are two variables (EC, GDP, EPI, or EF) of our analysis in order to check the causality as a pair, $C_l(t/T)$ is the autoregressive coefficients and $u_{t,T}$ is the error vector of the Eq. (3). Ajmi et al. (2015) remodeled Eq. (3) by proposing the M- and B-splines functions.[14] In particular, the new time-varying vector autoregressive pattern calculates the splines through a multiple linear regression framework by Eq. (3). Hence, the new time-varying framework takes the below form:

$$v_t = \sum_{n=0}^{H} c_n j_n(t) + \sum_{k=1}^{O} M_n^l j_n(t) v_{t-l} + a_t \tag{4}$$

c_n display the vectors and M_n^l illustrate the B-splines coefficients. Another vital characteristic of Ajmi et al. (2015) is the concept of the examination of Granger causality. Implementing the Wald test on the coefficients, we can capture the validity of the time-varying Granger causality. To clarify, having two variables, we can estimate the existence of time-varying Granger causality when the coefficients are equal to zero (or not). Moreover, when the B-spline is significant (or not) for each coefficient, this in turn means that the time-varying causality is time-varying or constant. The principal restriction of employing this pattern is that it demands the reckoning of many coefficients. Therefore, because of the lessened number of observations, we had to accede a bivariate DVAR of order 1. Consequently, we set a dynamic VAR of order $n = 1$, $k = 3$ and $lag = 1$ for a VAR model with two variables and we check the causality for each pair (see Sato et al. 2007; Ajmi et al. 2015; Shahbaz et al. 2016).

Empirical results and discussions

Beginning our analysis from to preliminary tests, stationary tests are yielded and tabulated in Table 1 for the logarithmic levels (log-levels) and logarithmic first differences (log-difference), for each of the variables. All the covariates of OECD countries are integrated in log-differences. Before probing the time-varying causality and the EKC results, notably are the outcomes of traditional, Eqs. (1) and (2), and dynamic Granger causality tests, Eq. (3). From the traditional causality point of view, as tabulated in Table 2, there are 11 feedback, 12 unidirectional, and 43 non-significant relationships in either way around between GDP and SI. Similarly, there are 4 feedback, 10 unidirectional, and 19 insignificant relationships in

Table 1 Unit root tests results

Countries	ADF test								Pperron test			
	Level				1st diff.				Level			
	EF	EPI	EC	GDP	EF	EPI	EC	GDP	EF	EPI	EC	GDP
Australia	− 1.11[3]	− 1.23[3]	− 0.93[3]	0.38[3]	− 5.98[3]***	− 3.60[3]**	− 3.72[3]**	− 3.79[3]**	− 13.88[3]	− 5.66[3]	− 4.80[3]	− 3.66[3]
Austria	− 1.10[3]	− 1.42[3]	− 2.33[3]	− 1.76[3]	− 4.56[3]***	− 3.66[3]**	− 4.17[3]***	− 3.66[3]***	− 8.86[3]	− 6.24[3]	− 9.16[3]	− 9.75[3]
Belgium	− 1.41[3]	− 1.53[3]	− 2.44[3]	− 1.71[3]	− 3.34[3]*	− 3.85[3]**	− 4.34[3]***	− 5.94[3]***	− 6.99[3]	− 8.80[3]	− 14.86[3]	− 12.61[3]
Canada	− 2.38[3]	− 1.29[3]	− 2.55[3]	− 1.39[3]	− 4.23[3]***	− 3.69[3]**	− 3.55[3]**	− 4.02[3]**	− 10.66[3]	− 5.77[3]	− 10.61[3]	− 8.35[3]
Chile	− 3.01[3]	− 1.20[3]	− 0.08[3]	− 2.77[3]	− 4.71[3]***	− 3.54[3]**	− 3.52[3]**	− 3.79[3]**	− 15.87[3]	− 5.42[3]	− 3.41[3]	− 8.55[3]
Czech Republic	− 1.69[3]	− 1.48[3]	− 1.28[3]	− 0.96[3]	− 5.61[3]***	− 3.71[3]**	− 3.87[3]**	− 3.49[3]**	− 12.03[3]	− 6.90[3]	− 5.69[3]	− 5.84[3]
Denmark	− 1.38[3]	− 1.42[3]	− 2.43[3]	− 1.53[3]	− 3.37[3]*	− 3.65[3]**	− 4.35[3]***	− 3.74[3]**	− 4.70[3]	− 6.47[3]	− 12.51[3]	− 10.25[3]
Estonia	− 2.46[3]	− 1.27[3]	− 1.37[3]	− 1.96[3]	− 3.16[3]*	− 3.64[3]**	− 3.74[3]**	− 3.21[3]*	− 6.95[3]	− 5.80[3]	− 3.90[3]	− 5.02[3]
Finland	− 1.96[3]	− 1.39[3]	− 2.40[3]	− 0.95[3]	− 3.21[3]*	− 3.72[3]**	− 3.76[3]**	− 3.19[3]*	− 5.02[3]	− 6.05[3]	− 10.76[3]	− 3.49[3]
France	− 0.88[3]	− 1.37[3]	− 2.37[3]	− 2.20[3]	− 5.13[3]***	− 3.77[3]**	− 3.86[3]***	− 3.73[3]**	− 9.63[3]	− 7.78[3]	− 10.78[3]	− 9.58[3]
Germany	− 3.03[3]	− 1.38[3]	− 2.27[3]	− 2.18[3]	− 3.69[3]**	− 3.55[3]**	− 3.94[3]**	− 3.58[3]**	− 14.12[3]	− 5.90[3]	− 12.45[3]	− 9.34[3]
Greece	− 1.16[3]	− 1.33[3]	− 1.25[3]	− 1.36[3]	− 4.72[3]***	− 3.61[3]**	− 4.12[3]***	− 3.57[3]**	− 3.02[3]	− 6.01[3]	− 5.86[3]	− 3.00[3]
Hungary	− 2.24[3]	− 1.46[3]	− 1.50[3]	− 3.19[3]*	− 5.32[3]***	− 3.59[3]**	− 3.28[3]*	− 3.84[3]***	− 12.45[3]	− 6.74[3]	− 7.05[3]	− 10.14[3]
Ireland	− 1.38[3]	− 1.34[3]	− 1.67[3]	− 2.03[3]	− 3.24[3]*	− 3.66[3]**	− 3.21[3]*	− 3.50[3]**	− 6.80[3]	− 6.35[3]	− 4.66[3]	− 2.70[3]
Israel	− 1.87[3]	− 1.32[3]	− 1.91[3]	− 1.46[3]	− 3.29[3]*	− 3.61[3]**	− 5.22[3]***	− 3.45[3]*	− 9.74[3]	− 6.10[3]	− 14.27[3]	− 3.16[3]
Italy	− 0.97[3]	− 1.43[3]	− 1.22[3]	− 2.34[3]	− 4.17[3]***	− 3.65[3]**	− 4.09[3]**	− 3.96[3]**	− 3.05[3]	− 7.66[3]	− 3.80[3]	− 5.30[3]
Japan	− 1.68[3]	− 1.43[3]	− 1.79[3]	− 1.34[3]	− 3.57[3]**	− 3.65[3]**	− 3.79[3]**	− 4.16[3]***	− 7.71[3]	− 7.66[3]	− 8.03[3]	− 7.45[3]
Luxembourg	− 1.85[3]	− 1.46[3]	− 1.98[3]	− 2.41[3]	− 5.09[3]***	− 3.42[3]*	− 3.47[3]*	− 4.68[3]***	− 13.02[3]	− 5.61[3]	− 4.19[3]	− 10.10[3]
Mexico	− 1.47[3]	− 1.35[3]	− 2.54[3]	− 1.80[3]	− 5.60[3]***	− 3.67[3]**	− 5.18[3]***	− 4.08[3]**	− 13.78[3]	− 6.49[3]	− 10.24[3]	− 7.98[3]
Netherlands	− 1.21[3]	− 1.32[3]	− 0.98[3]	0.83[3]	− 5.51[3]***	− 3.65[3]**	− 3.65[3]**	− 3.71[3]**	− 14.58[3]	− 7.03[3]	− 5.30[3]	− 4.05[3]
New Zealand	− 1.13[3]	− 1.46[3]	− 2.41[3]	− 1.65[3]	− 4.62[3]***	− 3.60[3]**	− 4.29[3]***	− 3.78[3]**	− 9.26[3]	− 8.23[3]	− 9.45[3]	− 10.66[3]
Norway	− 1.39[3]	− 1.61[3]	− 2.39[3]	− 1.66[3]	− 3.37[3]*	− 3.72[3]**	− 4.43[3]***	− 5.35[3]***	− 7.69[3]	− 9.12[3]	− 15.64[3]	− 13.13[3]
Poland	− 2.31[3]	− 1.21[3]	− 2.59[3]	− 1.45[3]	− 4.51[3]***	− 3.62[3]**	− 3.65[3]**	− 4.12[3]**	− 11.56[3]	− 6.45[3]	− 11.60[3]	− 9.55[3]
Portugal	− 3.2[3]	− 1.55[3]	− 0.19[3]	− 2.51[3]	− 4.98[3]***	− 3.60[3]**	− 3.61[3]**	− 3.75[3]**	− 14.47[3]	− 7.32[3]	− 5.60[3]	− 4.56[3]
Slovakia	− 1.59[3]	− 1.41[3]	− 1.82[3]	− 0.69[3]	− 5.72[3]***	− 3.82[3]**	− 3.81[3]**	− 3.53[3]**	− 13.13[3]	− 8.13[3]	− 6.09[3]	− 6.44[3]
Slovenia	− 1.33[3]	− 1.49[3]	− 2.34[3]	− 1.62[3]	− 3.33[3]*	− 3.56[3]**	− 4.53[3]***	− 3.66[3]***	− 5.45[3]	− 10.32[3]	− 13.98[3]	− 11.99[3]
South Korea	− 2.22[3]	− 1.31[3]	− 1.73[3]	− 1.69[3]	− 3.25[3]*	− 3.58[3]**	− 3.69[3]**	− 3.19[3]*	− 7.59[3]	− 7.06[3]	− 4.58[3]	− 6.45[3]
Spain	− 1.8[3]	− 1.29[3]	− 2.04[3]	− 0.89[3]	− 3.30[3]*	− 3.69[3]**	− 3.73[3]**	− 3.23[3]*	− 6.12[3]	− 9.12[3]	− 11.55[3]	− 7.88[3]
Sweden	− 1.23[3]	− 1.32[3]	− 0.39[3]	0.42[3]	− 6.15[3]***	− 3.72[3]**	− 3.71[3]**	− 3.71[3]**	− 12.48[3]	− 4.65[3]	− 11.55[3]	− 5.24[3]
Switzerland	− 1.26[3]	− 1.24[3]	− 2.29[3]	− 1.70[3]	− 4.87[3]***	− 3.76[3]**	− 4.26[3]***	− 3.67[3]**	− 8.56[3]	− 6.98[3]	− 10.22[3]	− 10.99[3]
Turkey	− 1.54[3]	− 1.35[3]	− 2.41[3]	− 1.65[3]	− 3.24[3]*	− 3.81[3]**	− 4.53[3]***	− 5.90[3]***	− 6.89[3]	− 7.90[3]	− 15.08[3]	− 14.56[3]
UK	− 2.41[3]	− 1.92[3]	− 2.50[3]	− 1.51[3]	− 4.29[3]***	− 3.60[3]**	− 3.69[3]**	− 4.11[3]**	− 10.45[3]	− 6.45[3]	− 10.55[3]	− 5.38[3]
USA	− 3.09[3]	− 1.29[3]	− 0.28[3]	− 2.56[3]	− 4.82[3]***	− 3.51[3]**	− 3.61[3]**	− 3.69[3]**	− 14.12[3]	− 6.56[3]	− 5.99[3]	− 5.85[3]

Table 1 (continued)

Countries	Pperron test 1st diff. EF	Pperron test 1st diff. EPI	KPSS test Level EF	KPSS test Level EPI	KPSS test Level EC	KPSS test Level GDP	KPSS test 1st diff. EF	KPSS test 1st diff. EPI	KPSS test 1st diff. EC	KPSS test 1st diff. GDP
Australia	−23.36[3]**	−18.46[3]*	0.30[1]*	1.57[1]***	2.51[1]***	2.84[1]***	0.11[1]*	0.22[1]*	0.25[1]*	0.33[1]*
Austria	−19.97[3]**	−18.30[3]*	1.31[1]***	1.79[1]***	1.67[1]***	2.77[1]***	0.13[1]*	0.22[1]*	0.27[1]*	0.18[1]*
Belgium	−18.20[3]*	−18.16[3]*	1.76[1]***	2.13[1]***	2.51[1]***	2.82[1]***	0.12[1]*	0.09[1]*	0.06[1]*	0.13[1]*
Canada	−20.79[3]**	−18.48[3]*	0.31[1]*	1.79[1]***	2.71[1]***	2.52[1]***	0.20[1]*	0.23[1]*	0.07[1]*	0.10[1]*
Chile	−19.55[3]**	−17.90[3]*	2.19[1]***	1.60[1]***	1.97[1]***	2.81[1]***	0.13[1]*	0.20[1]*	0.56[1]**	0.23[1]*
Czech Republic	−22.13[3]**	−18.48[3]*	0.52[1]**	2.01[1]***	2.76[1]***	2.74[1]***	0.11[1]*	0.19[1]*	0.22[1]*	0.20[1]*
Denmark	−18.12[3]*	−18.21[3]*	2.48[1]***	1.80[1]***	2.22[1]***	2.81[1]***	0.18[1]*	0.20[1]*	0.14[1]*	0.12[1]
Estonia	−23.99[3]**	−18.53[3]*	1.16[1]***	1.61[1]***	1.35[1]***	2.66[1]***	0.37[1]*	0.22[1]*	0.38[1]*	0.20[1]*
Finland	−19.29[3]**	−18.46[3]*	2.66[1]***	1.83[1]***	2.07[1]***	2.46[1]***	0.20[1]*	0.24[1]*	0.09[1]*	0.32[1]*
France	−22.21[3]**	−18.37[3]*	1.38[1]***	2.07[1]***	2.69[1]***	2.73[1]***	0.09[1]*	0.13[1]*	0.19[1]*	0.08[1]*
Germany	−19.35[3]**	−17.74[3]*	0.11[1]*	1.59[1]***	2.65[1]***	2.71[1]***	0.08[1]*	0.22[1]*	0.11[1]*	0.09[1]*
Greece	−19.91[3]**	−18.08[3]*	1.81[1]***	1.88[1]***	1.20[1]***	0.74[1]***	0.36[1]*	0.20[1]*	0.16[1]*	0.65[1]**
Hungary	−20.55[3]**	−18.09[3]*	1.21[1]***	1.94[1]***	2.61[1]***	2.76[1]***	0.13[1]*	0.17[1]*	0.16[1]*	0.39[1]*
Ireland	−18.35[3]*	−18.62[3]*	2.18[3]***	1.88[3]***	2.51[3]***	2.07[3]***	0.11[1]*	0.20[1]*	0.26[1]*	0.93[1]***
Israel	−17.50[3]*	−18.51[3]*	0.58[1]*	1.65[1]***	2.13[1]***	2.62[1]***	0.08[1]*	0.21[1]*	0.16[1]*	0.57[1]**
Italy	−17.57[3]*	−18.21[3]*	1.79[1]***	2.01[1]***	1.83[1]***	2.26[1]***	0.44[1]**	0.10[1]*	0.39[1]*	0.19[1]*
Japan	−16.95[3]*	−18.21[3]*	1.85[1]***	2.01[1]***	2.60[1]***	1.67[1]***	0.23[1]*	0.10[1]*	0.15[1]*	0.11[1]*
Luxembourg	−20.3[3]**	−16.78[3]*	1.26[1]***	1.67[1]***	1.87[1]***	1.73[1]***	0.07[1]*	0.24[1]*	0.53[1]**	0.27[1]*
Mexico	−21.45[3]**	−18.51[3]*	0.25[1]*	2.01[1]***	1.28[1]***	2.77[1]***	0.13[1]*	0.18[1]*	0.24[1]*	0.13[1]*
Netherlands	−24.36[3]**	−18.54[3]*	0.31[1]*	1.57[1]***	2.51[1]***	2.48[1]***	0.11[1]*	0.22[1]*	0.25[1]*	0.35[1]*
New Zealand	−18.47[3]**	−18.13[3]*	1.52[1]***	1.79[1]***	1.67[1]***	2.45[1]***	0.13[1]*	0.20[1]*	0.27[1]*	0.18[1]*
Norway	−18.02[3]*	−18.30[3]*	1.76[1]***	2.13[1]***	2.51[1]***	2.28[1]***	0.12[1]*	0.09[1]*	0.06[1]*	0.16[1]*
Poland	−20.15[3]**	−18.25[3]*	0.28[1]*	1.79[1]***	2.58[1]***	2.52[1]***	0.20[1]*	0.20[1]*	0.07[1]*	0.16[1]*
Portugal	−19.41[3]**	−17.78[3]*	2.60[1]***	1.60[1]***	1.97[1]***	2.18[1]***	0.13[1]*	0.20[1]*	0.46[1]**	0.23[1]*
Slovakia	−22.31[3]**	−18.53[3]*	0.59[1]**	2.11[1]***	2.53[1]***	2.47[1]***	0.11[1]*	0.15[1]*	0.25[1]*	0.25[1]*
Slovenia	−18.21[3]*	−18.22[3]*	2.48[1]***	1.89[1]***	2.12[1]***	2.18[1]***	0.18[1]*	0.23[1]*	0.18[1]*	0.16[1]
South Korea	−23.26[3]**	−18.66[3]*	1.11[1]***	1.61[1]***	1.26[1]***	2.56[1]***	0.37[1]*	0.20[1]*	0.38[1]*	0.28[1]*
Spain	−19.02[3]**	−18.26[3]*	2.53[1]***	1.89[1]***	2.07[1]***	2.46[1]***	0.20[1]*	0.25[1]*	0.07[1]*	0.32[1]*
Sweden	−23.63[3]**	−18.46[3]*	0.28[1]*	1.52[1]***	2.15[1]***	2.58[1]***	0.11[1]*	0.22[1]*	0.25[1]*	0.35[1]*
Switzerland	−19.90[3]**	−18.30[3]*	1.31[1]***	1.79[1]***	1.74[1]***	2.77[1]***	0.13[1]*	0.22[1]*	0.24[1]*	0.13[1]*
Turkey	−18.22[3]*	−18.16[3]*	1.76[1]***	2.15[1]***	2.16[1]***	2.18[1]***	0.12[1]*	0.12[1]*	0.06[1]*	0.18[1]*
UK	−20.75[3]*	−18.85[3]*	0.31[1]*	1.79[1]***	2.28[1]***	2.52[1]***	0.20[1]*	0.29[1]*	0.07[1]*	0.11[1]*
USA	−19.45[3]**	−17.87[3]*	2.26[1]***	1.68[1]***	1.97[1]***	2.28[1]***	0.13[1]*	0.20[1]*	0.51[1]**	0.23[1]*

***, **, and * denote significance at 1%, 5%, and 10% level. Numbers in square brackets are selected lags

Table 2   Traditional Granger causality test results

Country	H: GDP to EF	H: EF to GDP	H: GDP to EPI	H: EPI to GDP	H: GDP to EC	H: EC to GDP	H: EC to EF	H: EF to EC	H: EC to EPI	H: EPI to EC
Australia	0.79	0.708	0.01[a]	0.00[a]	0.552	0.153	0.767	0.128	0.099[c]	0.475
Austria	0.364	0.777	0.257	0.992	0.993	0.491	0.00[a]	0.00[a]	0.067[c]	0.012[b]
Belgium	0.092[c]	0.398	0.967	0.494	0.069[c]	0.042[b]	0.932	0.158	0.00[a]	0.00[a]
Canada	0.249	0.035[b]	0.116	0.00[a]	0.542	0.377	0.052[c]	0.404	0.521	0.891
Chile	0.00[a]	0.037[b]	0.627	0.21	0.18	0.037[b]	0.968	0.972	0.019[b]	0.253
Czech Republic	0.337	0.753	0.986	0.354	0.349	0.406	0.00[a]	0.028[b]	0.803	0.081[c]
Denmark	0.712	0.392	0.228	0.016[b]	0.192	0.038[b]	0.17	0.344	0.03[b]	0.028[b]
Estonia	0.072[c]	0.59	0.708	0.753	0.67	0.213	0.05[b]	0.01[a]	0.027[b]	0.022[b]
Finland	0.211	0.387	0.767	0.209	0.022[b]	0.00[a]	0.071[c]	0.00[a]	0.287	0.151
France	0.188	0.464	0.035[b]	0.162	0.493	0.524	0.674	0.986	0.352	0.046[b]
Germany	0.0[a]	0.039[b]	0.023 [b]	0.00[a]	0.126	0.026[b]	0.01[a]	0.251	0.275	0.149
Greece	0.956	0.372	0.845	0.344	0.153	0.05[b]	0.755	0.157	0.00[a]	0.199
Hungary	0.956	0.526	0.064c	0.406	0.116	0.474	0.384	0.14	0.345	0.1[c]
Ireland	0.138	0.674	0.724	0.782	0.698	0.59	0.149	0.709	0.313	0.972
Israel	0.63	0.334	0.435	0.36	0.17	0.822	0.392	0.524	0.968	0.208
Italy	0.00[a]	0.00[a]	0.471	0.543	0.515	0.073[c]	0.54	0.075[c]	0.836	0.421
Japan	0.092[c]	0.208	0.144	0.00[a]	0.04[b]	0.00[a]	0.00[a]	0.017[b]	0.049[b]	0.075[c]
Luxembourg	0.012[b]	0.045[b]	0.463	0.513	0.898	0.138	0.187	0.241	0.811	0.58
Mexico	0.326	0.303	0.05 [b]	0.00[a]	0.336	0.301	0.261	0.05[b]	0.075[c]	0.00[a]
Netherlands	0.32	0.999	0.384	0.935	0.1[c]	0.086[c]	0.00[a]	0.174	0.434	0.04[b]
New Zealand	0.1[c]	0.029[b]	0.148	0.385	0.247	0.683	0.523	0.354	0.441	0.338
Norway	0.035[b]	0.01[a]	0.574	0.119	0.603	0.233	0.079 [c]	0.301	0.059[c]	0.032[b]
Poland	0.525	0.418	0.997	0.443	0.798	0.697	0.242	0.199	0.079[c]	0.00[a]
Portugal	0.441	0.731	0.973	0.742	0.174	0.03[b]	0.768	0.989	0.505	0.042[b]
Slovakia	0.919	0.714	0.754	0.372	0.047[b]	0.964	0.53	0.946	0.086[c]	0.05[b]
Slovenia	0.00 [a]	0.00 [a]	0.548	0.443	0.085[c]	0.865	0.805	0.181	0.621	0.197
South Korea	0.442	0.401	0.06 [c]	0.014[b]	0.247	0.512	0.149	0.378	0.308	0.05[b]
Spain	0.958	0.578	0.49	0.367	0.61	0.434	0.796	0.266	0.067[c]	0.786
Sweden	0.637	0.367	0.525	0.075[c]	0.356	0.526	0.654	0.407	0.582	0.023[b]
Switzerland	0.023[b]	0.445	0.972	0.863	0.043[b]	0.363	0.307	0.262	0.523	0.136
Turkey	0.762	0.783	0.427	0.117	0.545	0.751	0.923	0.924	0.077[c]	0.218
UK	0.925	0.191	0.927	0.963	0.069[c]	0.232	0.771	0.622	0.808	0.305
USA	0.684	0.365	0.489	0.05[b]	0.99	0.486	0.979	0.997	0.027[b]	0.033[b]

Values in the table are the p values. [a] , [b] , and [c] denote significant at 1%, 5%, and 10% level. The number of lags used to implement the test is equal to one

either way around between GDP and EC. Lastly, 15 feedback, 18 unidirectional, and 33 non-significant causality linkages are confirmed between EC and SI. Table 3 displays the results of the dynamic Granger causality. Succinctly, we can notice that the majority of the results indicate two way causalities between the covariates. More specifically, there are 36 feedback, 25 unidirectional, and 5 insignificant causality relationships between GDP and SI. Between GDP and EC, 10 feedback, 18 unidirectional, and 5 neutral causalities are confirmed, whereas 36 feedback, 21 unidirectional, and 9 neutral causalities are supported between EC and SI.

Table 4 depicts the results for the time-varying Granger causality pattern, described in Eq. (4). Indisputably, the majority of the countries display two-way causalities for all the pairwise. Precisely, if we look at the relationship between the GDP and SI, in case of the EF index, almost all the pairs show two-way causality (twenty-two countries) except for Australia, Canada, Czech Republic, Denmark, Greece, Ireland, Israel, Mexico, Poland, Spain, and Turkey; when it comes to the EPI, twenty countries[15] demonstrate bidirectional causality linkages. Besides, our empirical findings reveal five (Canada, Greece, Israel, Mexico, and Poland) and eight (Estonia, Greece, Ireland, Israel, Norway, Slovenia, Sweden, and Switzerland) unidirectional time-varying causalities

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[15] Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Finland, France, Germany, Hungary, Japan, Luxembourg, Mexico, New Zealand, Slovakia, South Korea, Spain, Turkey, and USA

Table 3 Dynamic Granger causality test results

Country	H: GDP to EF	H: EF to GDP	H: GDP to EPI	H: EPI to GDP	H: GDP to EC	H: EC to GDP	H: EC to EF	H: EF to EC	H: EC to EPI	H: EPI to EC
Australia	0.083^c	0.896	0.093^c	0.00^a	0.508	0.077^c	0.00^a	0.037^b	0.00^a	0.00^a
Austria	0.01^a	0.00^a	0.00^a	0.00^a	0.01^a	0.07^c	0.296	0.222	0.207	0.00^a
Belgium	0.047^b	0.581	0.00^a	0.00^a	0.00^a	0.737	0.86	0.295	0.00^a	0.00^a
Canada	0.152	0.179	0.00^a	0.00^a	0.03^b	0.00^a	0.00^a	0.00^a	0.00^a	0.00^a
Chile	0.202	0.00^a	0.00^a	0.00^a	0.084^c	0.378	0.418	0.00^a	0.858	0.016^b
Czech Republic	0.391	0.86	0.05^b	0.026^b	0.996	0.203	0.00^a	0.00^a	0.03^b	0.00^a
Denmark	0.248	0.266	0.027^b	0.00^a	0.578	0.073^c	0.236	0.069^c	0.00^a	0.32
Estonia	0.00^a	0.00^a	0.776	0.00^a	0.01^a	0.00^a	0.168	0.213	0.067^c	0.00^a
Finland	0.00^a	0.00^a	0.00^a	0.00^a	0.00^a	0.466	0.1^c	0.00^a	0.687	0.00^a
France	0.122	0.00^a	0.00^a	0.00^a	0.05^b	0.00^a	0.096^c	0.014^b	0.00^a	0.00^a
Germany	0.627	0.496	0.03^b	0.00^a	0.51	0.222	0.151	0.779	0.029^b	0.00^a
Greece	0.668	0.00^a	0.746	0.00^a	0.64	0.124	0.637	0.00^a	0.05^b	0.024^b
Hungary	0.00^a	0.00^a	0.00^a	0.00^a	0.00^a	0.01^c	0.155	0.36	0.01^a	0.00^a
Ireland	0.077^c	0.202	0.437	0.00^a	0.018^b	0.431	0.00^a	0.00^a	0.00^a	0.00^a
Israel	0.165	0.00^a	0.677	0.00^a	0.628	0.938	0.399	0.04^b	0.00^a	0.00c^a
Italy	0.028^b	0.00^a	0.00^a	0.268	0.00^a	0.899	0.98	0.519	0.00^a	0.00^a
Japan	0.00^a	0.00^a	0.00^a	0.00^a	0.00^a	0.13	0.031^b	0.00^a	0.176	0.00^a
Luxembourg	0.00^a	0.046^b	0.00^a	0.00^a	0.183	0.00^a	0.328	0.506	0.01^a	0.00^a
Mexico	0.355	0.05^b	0.00^a	0.00^a	0.1^c	0.145	0.292	0.00^a	0.00^a	0.00^a
Netherlands	0.00^a	0.058^c	0.00^a	0.604	0.00^a	0.801	0.00^a	0.082^c	0.00^a	0.00^a
New Zealand	0.00^a	0.441	0.00^a	0.045^b	0.00^a	0.00^a	0.08^c	0.85	0.00^a	0.00^a
Norway	0.038^b	0.00^a	0.43	0.01^a	0.323	0.074^c	0.049^b	0.227	0.571	0.00^a
Poland	0.113	0.00^a	0.335	0.124	0.72	0.082^c	0.587	0.00^a	0.199	0.00^a
Portugal	0.00^a	0.00^a	0.015^b	0.131	0.71	0.545	0.038^b	0.00^a	0.017^b	0.00^a
Slovakia	0.00^a	0.00^a	0.063^c	0.00^a	0.00^a	0.019^b	0.00^a	0.00^a	0.708	0.00^a
Slovenia	0.01^a	0.076^c	0.233	0.00^a	0.00^a	0.00^a	0.117	0.266	0.192	0.00^a
South Korea	0.00^a	0.00^a	0.119	0.00^a	0.25	0.00^a	0.1^c	0.00^a	0.00^a	0.00^a
Spain	0.067^c	0.563	0.00^a	0.00^a	0.017^b	0.119	0.00^a	0.125	0.00^a	0.00^a
Sweden	0.00^a	0.00^a	0.242	0.00^a	0.00^a	0.038^b	0.00^a	0.343	0.00^a	0.00^a
Switzerland	0.00^a	0.031^b	0.242	0.04^b	0.00^a	0.066^c	0.231	0.112	0.015^b	0.00^a
Turkey	0.00^a	0.12	0.00^a	0.00^a	0.00^a	0.472	0.00^a	0.00^a	0.162	0.049^b
UK	0.073^c	0.00^a	0.1^c	0.374	0.00^a	0.515	0.00^a	0.00^a	0.00^a	0.00^a
USA	0.00^a	0.01^a	0.00^a	0.00^a	0.00^a	0.939	0.093^c	0.22^b	0.405	0.00 ^{a}

Values in the table are the p values. ^{a}, ^{b}, and ^{c} denote significant at 1%, 5%, and 10% level. The number of lags used to implement the test is equal to one

running from the EF/EPI to GDP, respectively. In contrast, one-way time-varying causalities running from the GDP to SI are obtained for Ireland, Spain, and Turkey in the case of the EF and for Italy, Netherlands, and Portugal in the case of the EPI. Furthermore, the neutrality hypothesis is supported in three countries (Australia, Czech Republic, and Denmark) for the EF and in two countries (Poland and UK) for the EPI. Now, if we look at the EC and SI nexus, surprisingly, in the case of EPI, we can observe that almost all the countries have bidirectional time-varying causality relationships except for two countries (Chile and Slovenia) which support unidirectional causality running from the EPI to EC. In a different vein, the relationship between EF and EC differs across countries. For instance, a one-way causality running from the EF to EC is found for Chile, France, Greece, Israel, and Poland. However, the opposite unidirectional relationship appears for Germany, Luxembourg, New Zealand, Norway, Slovenia, Spain, Sweden, and Switzerland. In addition, an insignificant causality is established for three countries (Belgium, Hungary, and Italy). Finally, the outcomes point to a two-way interconnectedness for the rest of the countries. Dissecting the EC and GDP nexus, the results are almost tantamount, albeit the bidirectional causality dominates. Specifically, a unidirectional causal relationship running from EC to GDP is supported for Australia, Denmark, Germany, Greece, Luxembourg, Mexico, Norway, Poland, and South

Table 4 Time-varying Granger causality test results

Country	H: GDP to EF	H: EF to GDP	H: GDP to EPI	H: EPI to GDP	H: GDP to EC	H: EC to GDP	H: EC to EF	H: EF to EC	H: EC to EPI	H: EPI to EC
Australia	0.151	0.962	0.013[b]	0.00[a]	0.421	0.061[c]	0.00[a]	0.02[b]	0.00[a]	0.00 [a]
Austria	0.027[b]	0.00[a]	0.00[a]	0.00[a]	0.022[b]	0.096[c]	0.00[a]	0.01[a]	0.00[a]	0.00 [a]
Belgium	0.018[b]	0.084[c]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.767	0.21	0.00[a]	0.00 [a]
Canada	0.162	0.00[a]	0.00[a]	0.00[a]	0.032[b]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00 [a]
Chile	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.141	0.536	0.516	0.01[a]	0.842	0.00 [a]
Czech Republic	0.437	0.944	0.019[b]	0.035[b]	0.998	0.174	0.00[a]	0.00[a]	0.00[a]	0.00 [a]
Denmark	0.369	0.27	0.03[b]	0.00[a]	0.366	0.00[a]	0.1c	0.032b	0.00[a]	0.00 [a]
Estonia	0.00[a]	0.00[a]	0.735	0.00[a]	0.026[b]	0.00[a]	0.017[b]	0.00[a]	0.00[a]	0.00 [a]
Finland	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.014[b]	0.034[b]	0.00[a]	0.04[b]	0.00 [a]
France	0.1[c]	0.00[a]	0.00[a]	0.00[a]	0.087[c]	0.00[a]	0.156	0.03[b]	0.00[a]	0.00 [a]
Germany	0.00[a]	0.06[c]	0.013[b]	0.00[a]	0.215	0.01[a]	0.014[b]	0.576	0.00[a]	0.00 [a]
Greece	0.797	0.00[a]	0.868	0.00[a]	0.758	0.022[b]	0.777	0.00[a]	0.063[c]	0.00 [a]
Hungary	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.15	0.123	0.175	0.029[b]	0.00 [a]
Ireland	0.074[c]	0.313	0.474	0.00[a]	0.00[a]	0.495	0.00[a]	0.00[a]	0.00[a]	0.00 [a]
Israel	0.278	0.00[a]	0.736	0.00[a]	0.625	0.975	0.466	0.075[c]	0.00[a]	0.00 [a]
Italy	0.00[a]	0.00[a]	0.00[a]	0.376	0.01b	0.604	0.339	0.445	0.00[a]	0.00 [a]
Japan	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.045[b]	0.00 [a]
Luxembourg	0.00[a]	0.017[b]	0.00[a]	0.00[a]	0.162	0.00[a]	0.046[b]	0.393	0.023[b]	0.00 [a]
Mexico	0.511	0.047[b]	0.00[a]	0.00[a]	0.127	0.06[c]	0.08c	0.00[a]	0.00[a]	0.00 [a]
Netherlands	0.00[a]	0.097[c]	0.00[a]	0.75	0.00[a]	0.472	0.00[a]	0.00[a]	0.00[a]	0.00 [a]
New Zealand	0.00[a]	0.00[a]	0.00[a]	0.022[b]	0.00[a]	0.00[a]	0.057[c]	0.833	0.00[a]	0.00 [a]
Norway	0.00[a]	0.00[a]	0.573	0.00[a]	0.283	0.015[b]	0.00[a]	0.194	0.00[a]	0.00 [a]
Poland	0.17	0.016[b]	0.493	0.181	0.855	0.066[c]	0.448	0.00[a]	0.039[b]	0.00 [a]
Portugal	0.00[a]	0.00[a]	0.024[b]	0.226	0.655	0.144	0.071[c]	0.00[a]	0.023[b]	0.00 [a]
Slovakia	0.00[a]	0.00[a]	0.021[b]	0.00[a]	0.00[a]	0.04[b]	0.00[a]	0.00[a]	0.038[b]	0.00 [a]
Slovenia	0.00[a]	0.00[a]	0.197	0.00[a]	0.00[a]	0.00[a]	0.063[c]	0.363	0.118	0.00 [a]
South Korea	0.00[a]	0.00[a]	0.01[a]	0.00[a]	0.22	0.00[a]	0.01[a]	0.00[a]	0.00[a]	0.00 [a]
Spain	0.00[a]	0.593	0.00[a]	0.00[a]	0.037[b]	0.148	0.00[a]	0.165	0.00[a]	0.00 [a]
Sweden	0.00[a]	0.00[a]	0.364	0.00[a]	0.00[a]	0.076[c]	0.00[a]	0.298	0.00[a]	0.00 [a]
Switzerland	0.00[a]	0.017[b]	0.242	0.056[c]	0.00[a]	0.081[c]	0.066[c]	0.114	0.031[b]	0.00 [a]
Turkey	0.00[a]	0.212	0.00[a]	0.00[a]	0.01[a]	0.638	0.012[b]	0.00[a]	0.069[c]	0.00 [a]
UK	0.044[b]	0.00[a]	0.121	0.487	0.00[a]	0.261	0.00[a]	0.00[a]	0.00[a]	0.00 [a]
USA	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.00[a]	0.236	0.082[c]	0.02[b]	0.098[c]	0.00 [a]

Values in the table are the *p* values. [a] , [b], and [c] denote significant at 1%, 5%, and 10% level. The number of lags used to implement the test is equal to one

Korea, whereas the opposite unidirectional causal relationship is yielded by the estimations for Hungary, Ireland, Italy, Netherlands, Spain, Turkey, UK, and USA. Moreover, a feedback relationship is valid between GDP and EC for Austria, Belgium, Canada, Estonia, Finland, France, Japan, New Zealand, Slovakia, Slovenia, Sweden, and Switzerland, while the neutrality hypothesis gains empirical support in Chile, Czech Republic, Israel, and Portugal.

Based on the time-varying causality results expressed above, two-way relationships appear to be the dominant case between all covariates. First, the feedback causality relationship between EC and GDP implies that the level of economic activity and energy consumption mutually affect each other, i.e., a high level of economic growth leads to a high level of energy consumption and vice versa. In this case, energy consumption and economic growth are interrelated and serve as complements to each other (Apergis and Payne 2010). Therefore, energy policy should be carefully regulated given that one-sided policy selection is harmful for economic growth and a diversified policy as sectors or energy kinds should be implemented (Narayan and Popp 2012). This result is in line with that reached by Benavides et al. (2017), Dogan et al. (2017), and Lee and Yoo (2016).

Second, the interdependency of GDP and SI suggests that while economic growth creates environmental pressure stemming from the human activities, efforts to reduce that pressure are likely to adversely affect economic growth (Magazzino
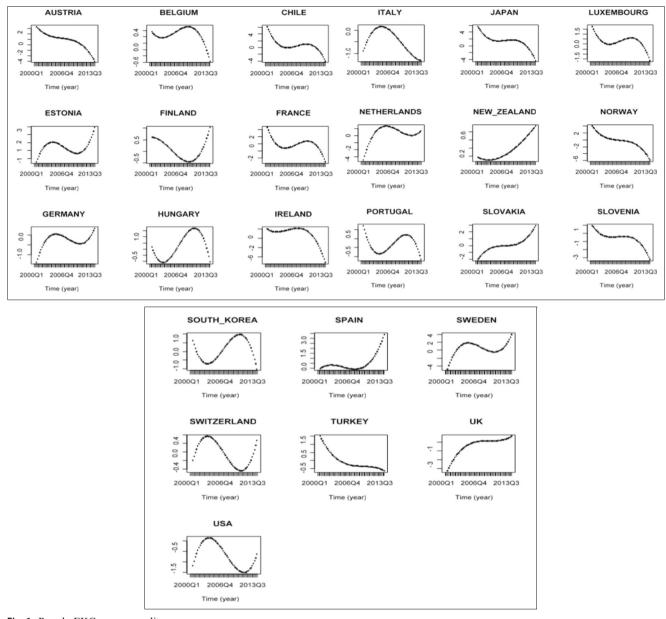
Fig. 1 Pseudo-EKC curve causality

2016). On one hand, while countries develop, they first make more pressure on the nature at the early stages of development; however, this trend starts reversing alongside the later stages of development. On the other hand, the polluted (degraded) environment negatively affects economic growth process. For instance, increased air pollution causes diseases which reduce labor productivity or polluted environment decreases agricultural productivity level, resulting in less economic growth rates. However, with the technological innovations at the later phases of development, economic growth accelerates as a result of eco-friendly technologies more energy efficient and innovative. In this context, there appears a mutual relationship between economic growth and environmental quality. This result is similar to that reached by Al-Mulali and Ozturk (2016), Dogan et al. (2017), Halicioglu

(2009), and Magazzino (2016), who used CO_2 emissions as a proxy for environmental degradation. Last, the bidirectional causality between EC and SI insinuates that higher energy consumption level leads to more environmental damage through increasing GHGs emissions level while simultaneously the worsening environmental performance causes less energy consumption, a critical input for economic growth. Besides, this reciprocal relationship might be evaluated regarding energy sources as well. In this context, increased consumption of fossil fuels pollute our environment by increasing the environmental pressure of humanity. As a response to this situation, countries begin to substitute fossil fuels with the renewable energy sources such as solar and hydro. This result is in similar with that found by Dogan et al. (2017), Dritsaki and Dritsaki (2014), and Lee and Yoo (2016).
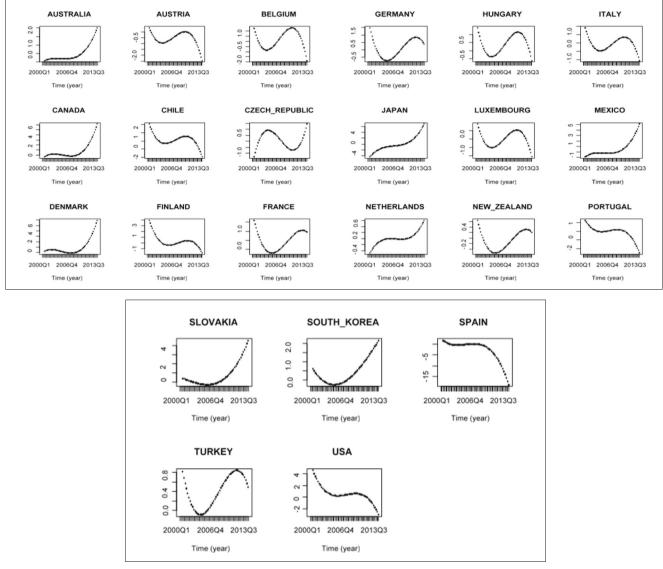
Fig. 2 Pseudo-EKC curve causality

Moreover, following the Ajmi et al.'s (2015) procedure, we conduct the "curve causality" approach for the purpose of demonstrating the validity of the traditional EKC hypothesis (presence of the inverted U–shaped curve). In addition, the authors are the first who depict the EKC as a chart. To accomplish that, they employed only the significant time-varying causality running from economic growth to air pollution. For our purpose, we will use the significant time-varying causality running from economic growth to SI. Especially, as we can clearly see from Table 4, we have 25 countries for the EF index and 23 countries for the EPI. Figures 1 and 2 describe the causality curves for the significant countries. But, before interpreting the results, we should keep in mind that an inverted U–shaped curve for the EF and a U-shaped curve for the EPI confirm the presence of the traditional EKC. Given that higher scores in the EF indicate more environmental degradation, the EKC hypothesis is valid if the EF follows

an inverted U–shaped pattern. Yet, in the case of the EPI, since higher scores signal more environmental quality, a U-shaped curve verifies the EKC hypothesis.

Based on the views above, the results in Fig. 1 (EF index) indicate that an inverted U–shaped curve is supported solely for Italy. Italy, as a sunny Mediterranean country, is rich in respect of renewable energy sources, and more than 80% of the electricity production in Italy is thermoelectric.[16] The remaining countries have different shapes of curves. For instance, a U-shaped curve is valid for Finland; an N-shaped curve is confirmed for Estonia, Germany, Netherlands, Sweden, Switzerland, and the USA; and an inverted N–shaped curve is valid for Belgium, Chile, France, Hungary, Japan, Luxembourg, South Korea, and Portugal. If we interpret country-based EKC results, for instance, Finland is one of

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[16] See https://www.climatechangepost.com/italy/energy/

the biggest carbon footprints in EU according to the map, depicting the average carbon footprints of households in 27 EU member states, [produced by] Norwegian University of Science and Technology.[17] In particular, among OECD economies, EU member countries have large ecological footprint per capita levels. For instance, the report by World Wide Fund for Nature (WWF) has listed Finland, Sweden, Denmark, Estonia, Ireland, and France as leaving the largest ecological footprint.[18] Regarding the USA, it is one of the biggest CO_2 emitters and energy consumers in the world. USA makes up 13% of the world's total footprint and has the second largest EF deficit in the world, after China.[19]

On the other hand, and in a much similar vein, the results in Fig. 2 (EPI) confirm the validity of the U-shaped curve only for Slovakia and South Korea. The remaining countries have different forms of curves. For instance, an N-shaped curve is supported for Czech Republic, while an inverted N–shaped curve is confirmed for Austria, Belgium, Chile, Finland, France, Germany, Hungary, Italy, Luxembourg, New Zealand, Turkey, and the USA. Slovakia ranked 28 in the world with its 70.60 EPI score. Slovakia aims to meet 14 percent of its gross final energy consumption with renewable energy by 2020[20] as it has a potential regarding renewable energy sources. Particularly, Slovakia is rich regarding biomass because 41% and 50% of its area are forest and agricultural land, respectively. South Korea ranked 60 in the world with its 62.30 EPI score. It has an abundant potential for using wind and solar energy to generate electricity. By 2035, the South Korean government intends to raise the energy contribution of solar stations and wind farms to 14.1% and 18.2%, respectively, of the total renewable energy production (Alsharif et al. 2018). Concerning the countries that have N-shaped curves, technological obsolescence effect which creates environmental damage in the later stages of development, appears to be dominant. Among those countries, Austria, Belgium, Chile, Finland, France, Germany, Hungary, Italy, Luxembourg, New Zealand, Turkey, and the USA ranked 8, 15, 84, 10, 2, 13, 43, 16, 7, 17, 108, and 27, respectively, regarding 2018 EPI scores. Of course, these 12 developed countries have high potential in respect of renewable energy sources, but it seems that they need more implementation of technological innovations in their energy sectors.

As sum, the curve causality results from Figs. 1 and 2 show that the traditional EKC hypothesis which assumes an inverted U–shaped relationship between economic growth and environmental degradation is valid only for Italy (for the EF), Slovakia, and South Korea (for the EPI). However, for 15 out of 33 OECD countries, namely, Austria, Belgium, Chile, Estonia, Finland, France, Germany, Hungary, Luxembourg, Netherlands, Sweden, Switzerland, New Zealand, Turkey, and the USA, an N-shaped relationship[21] is valid between income and environmental degradation. On one hand, these 15 advanced countries have developed renewable energy markets that use energy in more efficient ways via technological improvements. However, as in the world, the shares of renewable energy production in primary energy supply are still in its infancy in these countries as well. These shares in 2017 were 6.7%, 7.4%, 26%, 16.8%, 32%, 9.7%, 13.4%, 10.8%, 6.9%, 5.4%, 39%, 22%, 39%, 12%, and 7.6% for Austria, Belgium, Chile, Estonia, Finland, France, Germany, Hungary, Luxembourg, Netherlands, Sweden, Switzerland, New Zealand, Turkey, and the USA have, respectively. On the other hand, these countries have high EF per capita levels, too. For instance among them, Austria has ranked 23, Belgium has ranked 13, Estonia has ranked 10, Finland has ranked 18, France has ranked 45, Germany has ranked 38, Luxembourg has ranked 2, Netherlands has ranked 22, Sweden has ranked 15, Switzerland has ranked 40, and USA has ranked 6 in respect of EF per capita level.[22] Out of these 15 OECD countries, 10 (Austria, Belgium, Estonia, Finland, France, Germany, Hungary, Luxembourg, Netherlands, and Sweden) are the EU member countries that have local ecological deficit and are living beyond their biocapacity levels. In this context, it is stated that if everyone on the planet lived the average lifestyle of a resident of European Union, humanity would need 2.6 planet Earths to sustain our demand on nature.[23] They are advanced economies, but they have technological obsolescence effects with the later phases of their development processes. In this case, environmental destruction increases with raising income level in the initial stages of development; however, it starts declining after a threshold level of per capita income is surpassed, and this process continues until a second threshold level of per capita income, beyond which environmental degradation once again begins to

[17] See http://www.helsinkitimes.fi/finland/finland-news/domestic/14913-finns-have-one-of-the-biggest-carbon-footprints-in-eu.html
[18] See https://yle.fi/uutiset/osasto/news/wwf_finland_leaves_hefty_ecological_footprint/5217078
[19] See https://www.washingtonpost.com/graphics/world/ecologicalfootprint/?noredirect=on&utm_term=.b986769e1eaa
[20] See https://www.enercee.net/countries/country-selection/slovak-republic/latest-news/detail/?pager%5Bpage%5D=1&tx_ttnews%5Btt_news%5D=998

[21] An N-shaped relationship between economic growth and environmental degradation in the case of the EF is same with an inverted N-shaped relationship in the case of the EPI.
[22] See http://data.footprintnetwork.org/#/
[23] See http://www.yeu-international.org/en/publications/newsmail/between-the-lines/eu-countries-are-ones-with-highest-ecological-footprints-what-can-be-the-solution

rise. In this last phase of development, technological obsolescence effects appeared at reasonably high income levels is proposed as a reason of the rising environmental destruction (Lorente and Alvarez-Herranz 2016). Opschoor and Vos (1989) stated that raising income results in net environmental destruction once the potential for technological improvement has been exhausted or becomes too expensive. Torras and Boyce (1998) stated that economies might return to an upward pollution path when the margin for successive improvements in the distribution is exhausted, i.e., when there are diminishing returns in terms of technological change reducing pollution because of obsolescence.

As sum, our results indicate that scale effects outweigh the composition and technique effects in the early stages of development until the second stage in which the composition and technique effects preponderate the scale effects; and in the final stage of development, the technological obsolescence effects (see Lorente and Alvarez-Herranz 2016) create more environmental destruction. As such, OECD region appears to have a trade-off between economic growth and environmental protection. The results are in line with the findings of Barrett and Graddy (2000), Grossman and Krueger (1995), List and Gallet (1999), and Lorente and Alvarez-Herranz (2016), who supported an N-shaped relationship between economic growth and environmental pollution. However, they are in sharp contrast to those reached by Al-Mulali and Ozturk (2016), Jebli et al. (2016), and Shafiei and Salim (2014), who confirmed an inverted U–shaped relationship between growth and environmental pollution in different OECD panels.

Concluding remarks

Comprehending the nexus of governing energy consumption, economic growth, and sustainability indices is intriguing since it has substantial policy implications. It directly influences government policies on a national as well as an international level with the concomitant economic, social, and even political repercussions. Yet, not surprisingly, the energy consumption, economic growth, and sustainability indices nexus is the theme of a steadily growing body of literature that investigates the relationship among the variables. Within this strand of literature, this paper set out to readdress the nexus between the three variables, i.e., income, energy consumption, and sustainability indices (EF and EPI) used as proxies for environmental quality, in 33 OECD countries, spanning the period 2000–2013. We did so using the recent approach of time-varying interconnectedness and encompassed the illustration, for the first time, of the

validity of EKC. Then, for the purpose of comparison, the traditional Granger causality test and the dynamic Granger causality were employed. As one would intuitively expect, no empirical uniformity emerged from the findings.

Regarding the time-varying outcomes, the results for most countries provided evidence of the feedback relationships for all the covariates. In detail, regarding the relationship between GDP and SI, in case of the EF index, twenty-two countries (except for except for Australia, Canada, Czech Republic, Denmark, Greece, Ireland, Israel, Mexico, Poland, Spain, and Turkey); in case of the EPI, twenty countries (Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Finland, France, Germany, Hungary, Japan, Luxembourg, Mexico, New Zealand, Slovakia, South Korea, Spain, Turkey, and USA) show two-way causality. Concerning the EC and SI nexus, in the case of EPI, nearly all countries, except for Chile and Slovenia, have bidirectional time-varying causality relationship. In the case of the EF, a one-way causality running from the EF to EC is found for five countries (Chile, France, Greece, Israel, and Poland), the opposite unidirectional relationship appears for eight countries (Germany, Luxembourg, New Zealand, Norway, Slovenia, Spain, Sweden, and Switzerland), an insignificant causality is established for three countries (Belgium, Hungary, and Italy); and a two-way interconnectedness is valid for the rest of the countries. The EC and GDP nexus indicates that bidirectional causality is confirmed for 12 countries (Austria, Belgium, Canada, Estonia, Finland, France, Japan, New Zealand, Slovakia, Slovenia, Sweden, and Switzerland), a unidirectional causal relationship running from EC to GDP is supported for nine countries (Australia, Denmark, Germany, Greece, Luxembourg, Mexico, Norway, Poland, and South Korea), whereas the opposite unidirectional causal relationship is yielded by the estimations for eight countries (Hungary, Ireland, Italy, Netherlands, Spain, Turkey, UK, and USA), and the neutrality hypothesis is valid for four countries (Chile, Czech Republic, Israel, and Portugal).

Based on the above results, in respect of the policy perspective, development, and energy and environmental policies should be coordinated because they affect each other. Energy, as a crucial input of economic growth, seems to have effects on both economic growth and environmental quality while it is also affected from them. Therefore, energy conservation policy cannot be applied without causing adverse effects on growth process. However, in this situation, rising energy demand is likely to create more environmental pressure resulting from the human activities. In this respect, alternative energy sources (renewables) come to the forefront to

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