

Review

Towards a Global Energy-Sustainable Economy Nexus; Summing up Evidence from Recent Empirical Work

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Abstract: The recent trend in New Economics is the establishment of measures of sustainable wealth and welfare which take into account all the parameters of economic, environmental, and social life and progress, juxtaposed to the conventional and myopic GDP. This review summarizes results from a series of recent papers in the energy-growth nexus field, which have perused a proxy for the sustainable GDP instead of the conventional GDP and discusses the difference in results and policy implications. The energy-growth nexus field itself has generated a bulk of work since the seminal study of Kraft and Kraft (1978), but still the field needs new perspectives in order to generate results with a consensus. The bidirectional causality between energy consumption and sustainable economy provides evidence for the Feedback Hypothesis, a statement that essentially warns that it is too early for sustainability to be feasible without fossil energy consumption, and vice versa. The unidirectional causality reveals, on the one side, that an economy cannot grow without the plentiful consumption of energy (the Growth Hypothesis) and, on the other side, that the growth of the economy fuels energy consumption (the Conservation Hypothesis). Failure to corroborate causality between energy consumption and economic growth is evidence for the Neutrality Hypothesis.

Keywords: energy-growth nexus; sustainable economy; new economics; critical review



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1. Introduction

According to the International Energy Agency [1] the world energy consumption has increased by 45% since 1980 and will be 70% higher by 2030. Therefore, future energy policy is bound to remain focused on saving, efficiency, and renewable energy usage. European Union energy targets for 2030 have been set as follows: 40% reduction in greenhouse gas emissions (compared to 1990 levels), at least 32% share of renewable energy consumption, and 32.5% energy savings compared with the business-as-usual scenario [2]. The EU is devoting significant efforts to reduce energy consumption in the main consumption areas such as residential, tertiary, transport and industry. However, both primary and final energy consumption are slightly above their 2020 targets because not all sectors have managed to decrease their consumption. One such sector was transport and the largest increase in energy consumption was noted in the tertiary sectors (20.2%) which overshadowed the progress made in industry (−14.6%) and the households (−4.5%) [2]. Despite the applied policies, it is not an easy task to harness energy consumption given the demands for economic growth, the increasing population, the heating energy demand, the household characteristics towards single person families, and the energy prices which have not fully incorporated the incurred environmental costs pertinent to their exploitation and consumption.

Despite the need for energy conservation (with energy conservation we refer to the reduction of energy consumption in all sections of economy), energy inputs are necessary in production and thus the configuration of the impact of energy cuttings on economic growth remains important. Energy efficiency is an ongoing process, it has gone through a major

breakthrough, but there is still much structural distance to be covered until its full potential is exploited by all sectors. Thus, increases in efficiency of thermal power generation have been made, due to a shift from coal to gas, and a change in the power mix has also been achieved with a higher share of renewables [3]. The financial crisis has been acknowledged to having slowed down efficiency progress, a situation that will be prolonged with the health crisis caused by the COVID-19 pandemic. Overall, there is not a single and widely acknowledged indicator of energy efficiency and this can only be revealed through reduced energy consumption (conservation). On the other hand, we need to remember that there is not a single index to measure energy efficiency, and this can only be perceived through a combined overview of the energy intensity reduction, energy consumption reduction and energy savings [3]. Taking into account the fact that energy efficiency (through the aforementioned dimensions) is at the foreground of energy policy and the political and economic agenda worldwide, it is no doubt because the energy-growth nexus economics field remains timely despite the controversy in its results and the lack of consensus [4,5].

At the same time, the 17 sustainable development goals which were stipulated by United Nations in 2015 and have been included into the UN 2030 Agenda, do connect directly or indirectly to energy matters in at least four of the goals; the 7th goal is about affordable and clean energy, the 11th goal is about sustainable cities and communities, the 12th goal is about responsible consumption and production, and the 13th goal is about climate action. On top of that, the evolution of New Economics have introduced new perspectives in the real measurement of wellbeing which take into account all sustainability goals and many additional aspects in order to establish a measure of real wealth that could be juxtaposed to the conventional measure of the Gross Domestic Product (GDP). The usage of a sustainable GDP in place of the traditional GDP in the energy-growth nexus research field will enable comparisons between the effects of energy conservation on welfare. Societies need the knowledge of the trade-off between the reduction of energy consumption and the effect on their wellbeing.

Hypotheses encountered in the conventional energy-growth nexus are the following four:

- Growth Hypothesis: Energy consumption Granger causes GDP growth. This signifies an economy much reliant on energy consumption for its growth. It is applicable to early industrial economies which applied emphasis on their economic growth at all costs and this energy consumption has caused environmental degradation.
- Feedback Hypothesis: Energy consumption Granger causes GDP growth and vice versa. GDP growth Granger causes energy consumption. This causal relationship denotes a circle of coupling between energy consumption and economic growth. This circle cannot be interrupted unless structural changes and conservation technologies are adopted in economies.
- Conservation Hypothesis: GDP growth Granger causes energy consumption. Thus with proper structural and technological correction, conservation is feasible without interrupting economic growth.
- Neutrality Hypothesis: No causal relationship is observed between GDP growth and energy consumption. This situation can be met in either very rich and advanced economies or basic rural societies in poor countries, in which production is evolved for the maintenance of a subsistence level, but not for the sake of economic growth and wealth accumulation.

New considerations encountered in the sustainability extended energy-growth nexus are suggested as follows:

- If energy conservation affects both GDP growth and sustainable economic growth, societies should think of procrastinating energy conservation until further renewable energies penetration becomes feasible.
- If energy conservation affects GDP growth but not sustainable economic growth, the conservation adaptation will be less painful in terms of wellbeing. If societies are focused on wellbeing rather than growth, then this situation may not be problematic.

- If energy conservation affects neither conventional GDP growth, nor sustainable GDP growth, then it safely takes place with no repercussions on growth.
- If energy conservation does not affect GDP growth, but affects sustainable economic growth, then this situation needs a lot of consideration for the identification of possible rigidities that may be causing such a result.

This paper summarizes and compares results of different studies in the energy-sustainable growth nexus for various groups of countries around the world and compares the results with the respective conventional energy-growth nexus studies.

The rest of this paper is organized as follows: The current part (Section 1) is the introduction, Section 2 is the background material, Section 3 briefly refers to the employed methodologies in each paper, Section 4 summarizes and discusses the results of the different studies, while Section 5 offers the conclusion.

2. Background Material on Sustainable Economic Growth

The relationship between energy and sustainable economic development is studied with various indexes. For example Zhang and Su [6] study the rural household energy sustainable development in China with a composite indicator. Wang et al. [7] have also constructed a composite indicator for energy sustainable development in China. On the other hand, in the energy-growth nexus, Esseghir and Khouni [8] insert a focus on the discussion on sustainability, though without using a specific index in that aspect. The ISEW indicator for Europe has not been applied before within the energy-growth nexus.

The energy-growth nexus concerns the papers studying the relationship between energy consumption and economic growth and the direction of causation among the variables which best describe how an economy functions. Until recently, the literature until has not been unanimous but is rather controversial. A big picture of that situation has been provided in Kalimeris et al. [9]; Menegaki [10] and Ozturk [11]. Economic growth in most of these papers has typically been shown with GDP per capita. In different cases in which these papers performed a sector analysis rather than a country–economy as a whole, other proxies were employed for economic activity, such as industrial production which has been employed in the study by Marques et al. [12]. Overall, energy-growth studies mainly aim to discover the role of energy consumption as a factor of production in an economy. Therefore, they draw conclusions about the sensitivity of economic growth to various energy policy tools, which aim to make the economy rely less on energy consumption and consequently produce less greenhouse emissions, resulting in less fossil fuel resources depletion.

As aforementioned, these studies typically place the GDP per capita variable in the position of the dependent variable, while the independent variables are basic drivers of production, such as capital formation, labour, greenhouse gas emissions, energy consumption, electricity consumption, or production, trade etc. The elasticities of these magnitudes, with respect to GDP, constitute important information for policy making in each economy or groups of economies. However, given the principles of the so-called “New Economics” and their base of genuine progress and sustainable economic welfare and sustainable GDP, we agree that the energy-growth nexus research is rather short sighted, because it does not say anything about the genuine effect and the contribution of energy consumption on sustainable economic welfare.

In order to explain the aforementioned statement in a better way, we mean to suggest that: The GDP of each country has a different base and is generated in ways that may have different effects on human welfare. Therefore, a high-income country may have generated excessive pollution and induced extreme urbanization, accompanied by a low quality of life or family breakdown caused by the extended working hours of the working force. The list of the negative effects is rather long in this respect. Conversely, a less developed economy, usually accompanied with a lower GDP per capita, may have a cleaner natural environment, more essential human bonds, less family disintegration, and generally consist of people who enjoy their wellbeing and existence more. Furthermore, an industrialized country generates more environmental degradation than a country that produces services.

Petrochemical activities, construction, or agriculture are usually very polluting activities in an economy. Next, we provide the energy intensity of GDP for an indicative set of countries across the world (Table 1). The differences in intensity reflect the different structure of the GDP in each country with the participation of energy.

Table 1. Energy intensity of GDP across the world.

Country	Energy Intensity (koe/%15p)
Colombia	0.057
United Kingdom	0.058
Turkey	0.06
Portugal	0.064
Italy	0.064
Romania	0.066
Spain	0.067
Mexico	0.069
Germany	0.07
Egypt	0.07
Indonesia	0.071
Japan	0.076

Source: Enerdata.net [13]. Note: koe stands for kilogram of oil equivalent.

GDP does not distinguish economic activity that improves welfare from the one that reduces welfare [14]. This and other drawbacks of the GDP as a measure of wellbeing and genuine comprehensive progress, had been acknowledged from the day it was established. For instance, GDP disregards transactions performed in the unofficial and unrecorded economy. Nevertheless, these transactions are consuming energy capital and labour. These transactions are not recorded in the official accounts of the economy thus, they do not appear to generate income, but they consume energy, capital and contribute to the generation of pollution.

The same applies with market failures from environmental and social externalities that are not reflected in the GDP but contribute to the depletion of resources and formal capital. Furthermore, these externalities may inflate the GDP with much defensive expenditure, which arise from disservices generated from the externalities [15]. For example, a poor road network (this is capital) may be one of the reasons for a high number of car accidents and fatalities. The expenditure incurred to have cars repaired or people hospitalized should not be measured as GDP. This rationale of New Economics [16] that has started permeating the modern economic world, brings forward the need to re-examine the relationship of the conventional energy-growth nexus by focusing on income indicators that are as inclusive as possible.

Until today, and from what we do know from the literature, very little research has been devoted on this new promising area. For example, You [17] has employed genuine savings instead of the GDP variable and concludes that renewable energy increases China's genuine savings, while fossil energy contributes to the increase of GDP growth. Genuine savings is a variable readily available by international statistical agencies. Conversely, the ISEW explained in this paper and applied in the energy-growth nexus (in all the reviewed papers) is a more comprehensive indicator because it included data from all the three sustainability fields: economic, environmental, and societal.

The Construction of the Index for Sustainable Economy

Welfare is a controversial and multi-aspect concept. Therefore, a comprehensive indicator is needed to reflect it. Some of the aspects of welfare are the following: living standards (housing conditions, housing area, size etc.), health, the feeling of neighbourhood, education, time use, democratic engagement, leisure, culture, environment, public infrastructure, natural resources, emissions, equal access to resources and their sustainable use; corruption and transparency, waste assimilation capacity, sustainable consumption and production, demographics, recycling rates, adult literacy, mean duration of schooling,

knowledge, social relations, climate change (extreme weather phenomena), urban sprawling, commuting, noise pollution, globalization, volunteerism, criminality, unemployment costs, loss of farmland and wetland, net foreign borrowing, happiness (happy life years), peace, and safety.

As we understand, some of the above aspects are tangible and some are not. From the tangible dimensions some of them have not yet been measured. The immaterial ones are mainly psychological aspects that may lead to happiness and wellbeing. It is more difficult to calculate the value of the immaterial ones than the material or tangible ones. There are means to calculate intangibles, such as revealed or stated preference techniques. However, even if their value has been estimated for one economy, there is no institutional tool to impose or even encourage other economies to do the same. Therefore, cross country comparisons cannot be made if there is no cross-country agreement on the calculation of those values. This increases the difficulty of the calculation of a complete ISEW, which can host all possible parameters affecting human wellbeing within an economy. Countries that have made a lot of institutional progress have had more progress in advanced statistical data keeping while others with low institutional development have not managed to do this.

The convention held by the European Commission, entitled “2007 Beyond”, has presented a series of 24 similar indicators. Each one of them deals with a different and specific aspect of human welfare. However, none of them is so comprehensive and inclusive, something which would make an ideal indicator. For instance, the adjusted net savings (ANS) or genuine savings, the capability index, (according to which, the quality of life is defined by what people achieve with their resources), the ecological footprint indicator (which evaluates the balance between the demand and supply for renewable resources in a certain population or economic activity and the capacity to assimilate waste), the environmentally sustainable national income-ESNI (defined by the number of years that a certain economy with its current production capacity is away from an ideal benchmark that is considered to be sustainable), the human development index-HDI (which measures life-span and years of healthiness, together with access to education and knowledge and a decent standard of living that does not deprive one of basic facilities and goods), the Happy Planet Index- HPI, (ratio of the product of the experienced welfare and life expectancy to the ecological footprint) as well as many others. Goossens et al. [18] distinguish these indicators and place them into three categories: those replacing GDP, those supplementing GDP, and those adjusting it. The ISEW belongs to the ones which are adjusting GDP to reflect the experienced welfare.

The first version of the ISEW was generated by Daly and Cobb [19] for the US and then was further improved in 1994. There are both numerous supporters and opponents of the ISEW. The index has received a lot of criticism for measuring welfare and sustainability together within one index [20] and for the way it treats stocks and flows methodologically [21]. Responses to the former criticism state that the ISEW indicator is an aggregate indicator for both current and future wellbeing. Future welfare is an aspect of utility for the current generation. The latter receives satisfaction from knowing they will not damage the utility of their descendants [22]. This was additionally supported by Lawn [23]. He drew principles from Irving Fisher’s “net psychic income” and he explains why each component in the ISEW contributes to the psychic income. Despite the hesitations stated by the ISEW opposers, the existent ISEW is better than nothing (Lawn and Clarke, [24]). This is explained by the fact that the Index has covered a lot of distance to the measurement of sustainability but not all of that. Posed in a different way by Posner and Costanza [25], it is better to be approximately correct than completely wrong. Bley and Whitby [26] report some of the most important obstacles and opportunities in the calculation of the ISEW.

From what it is known, the calculation of the ISEW has been sparsely implemented only for several European countries: regional Italy [27], Belgium [28], France [29] and Greece [16]. Therefore, the official expression of the proposed ISEW in the reviewed papers here, is described in Equation (1):

$$\text{ISEW} = Cw + Geh + Kn + S\text{-N-Cs} \quad (1)$$

where C_w denotes the weighted consumption, G_{eh} denotes non defensive public expenditure, Kn stands for the net capital growth, S stands for the unpaid work benefit, N stands for the depletion of natural environment and C_s denotes the cost from social problems, which has not been taken into account in the calculations of the reviewed papers due to lack of proper data. Understandably, environmental, or ecological degradation is a wide concept which encompasses many more problems, for which, however, we had no data available to rely on. For instance, the cost of water pollution or the cost of the loss of land and wetlands is not readily published in the publicly available official databases that are usually employed, namely Eurostat, OECD, and World Bank. The same applies for the lack of reliable social data. Since we have not been able to include costs from social problems, Equation (1) is simplified to Equation (2), as demonstrated by Menegaki and Tugcu [30] and Menegaki and Tiwari [31] and the rest of the reviewed papers:

$$ISEW = C_w + G_{eh} + Kn + S - N \quad (2)$$

The method approach in Equations (1) and (2) is also recommended in [18] Gigliarano et al. [27], Menegaki and Tsagarakis [32]. The first two papers concern regional Italy and have included a large variety of available environmental and social data. However, in the reviewed papers contained in this study, this has not been possible. Thus, in each of the reviewed papers first, we have calculated the ISEW for the sampled countries and then we have estimated the conventional energy-GDP growth and new energy-ISEW for those countries, where it was feasible upon data availability for the variables, setting up the energy-growth nexus for the countries the study was focusing on each time. Table 2 explains the details of the calculation and the origin of the data in the sampled papers. Please note that since the current paper is a review of past published papers, new methods of calculation of the involved ISEW components have been evolved. The future researcher must take that into consideration. For example, it would be interesting to recalculate the index with the cost of carbon being \$100 or \$200/ton [7,28]. The same applies with the cost of renewable energies, which is reduced over time as technology improves.

Table 2. The ISEW components, sign, calculation methods and data sources as it has been originally presented in the reviewed papers.

Component	Sign	Calculation Method	Source/Available from
1. Adjusted personal consumption with durables (C_w)	+	We multiplied personal consumption and durables' expenditure (PC) with Gini coefficient (G) and poverty index (P) as: $PC \times (1 - G) \times (1 - P)$	PC: http://data.worldbank.org/indicator/NE.CON.PRVT.CDT.CD . (accessed on 1 January 2015) Gini coefficient: http://data.worldbank.org/indicator/SI.POV.GINI . (accessed on 1 January 2015) Poverty index (headcount ratio): http://data.worldbank.org/indicator/SI.POV.2DAY . (accessed on 1 January 2015)
2. Education expenditure (G_{eh})	+	Public expenditure on education (current operating expenditures in education, including wages and salaries and excluding capital investments in buildings and equipment). Assuming that half of it is defensive, we multiply this amount with 50%.	http://data.worldbank.org/indicator/NY.ADJ.AEDU.CD . (accessed on 1 January 2015)
3. Health expenditure (G_{eh})	+	Public health expenditure is also multiplied with 50% for the same reason as above.	http://data.worldbank.org/indicator/SH.XPD.PUBL . (accessed on 1 January 2015)

Table 2. Cont.

Component	Sign	Calculation Method	Source/Available from
4. Net capital growth (K_n)	±	We have used data on fixed capital accumulation (FCA). We subtracted consumption of fixed capital (CFC) to find the net capital and then calculated its growth rate.	FCA: http://data.worldbank.org/indicator/NE.GDI.TOTL.CD . (accessed on 1 January 2015) CFC: http://data.worldbank.org/indicator/NY.ADJ.DKAP.CD . (accessed on 1 January 2015)
5. Mineral depletion (N)	–	Mineral depletion is the ratio of the value of the stock of mineral resources to the remaining reserve lifetime (capped at 25 years). It covers tin, gold, lead, zinc, iron, copper, nickel, silver, bauxite, and phosphate.	http://data.worldbank.org/indicator/NY.ADJ.DMIN.CD . (accessed on 1 January 2015)
6. Energy depletion (N)	–	It is the ratio of the value of the stock of energy resources to the remaining reserve lifetime (capped at 25 years). It covers coal, crude oil, and natural gas.	http://data.worldbank.org/indicator/NY.ADJ.DNGY.CD . (accessed on 1 January 2015)
7. Forest depletion (N)	–	Net forest depletion is calculated as the product of unit resource rents and the excess of roundwood harvest over natural growth.	http://data.worldbank.org/indicator/NY.ADJ.DFOR.CD . (accessed on 1 January 2015)
8. Damage from CO ₂ emissions (climate change-long-run environmental damage) (N)	–	It is estimated to be \$20 per ton of carbon (the unit damage in 1995 U.S. dollars) times the number of tons of carbon emitted. World bank estimations are based on Samuel Fankhauser's "Valuing Climate Change: The Economics of the Greenhouse" (1995).	http://data.worldbank.org/indicator/NY.ADJ.DCO2.CD . (accessed on 1 January 2015)

Note: This type of the ISEW calculation has been applied by Menegaki and Tsagarakis [27]. The notation following the definition of components in this table, is the one represented in Equation (2).

3. Methodology

The current section will provide a summary of the methodologies used in the series of papers the current review focuses on. Those methodologies are varied depending on the different characteristics of the data and the diagnosed problems. The section is further divided into three sub-sections on unit root testing, cointegration and causality, respectively. The section serves an informative purpose because the current study is a review of previous studies and not a new empirical one. Thus, this section does not describe the employed methodologies from scratch as this can be done in the relevant original papers. These papers are: Menegaki and Tugcu [33], Menegaki et al. [34], Menegaki and Tugcu [35], Menegaki and Tiwari [31], Menegaki and Tugcu [17], Menegaki and Tugcu [30].

3.1. Unit Roots Testing

Testing for unit roots is the first stage in every study in the energy-growth nexus. First, the study by Menegaki and Tugcu [35] in page 29, uses the cross-sectionally augmented IPS test for the investigation of unit roots in cross-sectionally dependent data. Previously, in page 29–31 they have used the Pesaran CD test [36], Pesaran scaled LM test [36] and Baltagi et al. [37] bias-corrected scaled LM test. The presence of cross-sectional dependence was confirmed in three out of four statistics. Second, the study by Menegaki et al. [34] in page 1261 has employed ADF Fisher, PP Fisher (Maddala and Wu, [38] and Choi, [39]) and CIPS (Zt-bar) test (Pesaran, [40]). Third, the study by Menegaki and Tugcu [35] has employed the Pesaran IPS and GIPS (Pesaran et al. [40]) test in page 896 in constant and constant and trend versions. Fourth, the study by Menegaki and Tiwari [31] in pages 499–500 employs a battery of unit root tests such as the Levin et al. [41], the Im et al. [42], the augmented Dickey-Fuller test [43] the Phillips-Perron test [44] and the Breitung *t*-test [45] Hadri Z-test [46] and Heteroskedastic consistent Z test. Fifth, the study by Menegaki and Tugcu [30] in page 81 tests panel unit roots with Im et al. [41] and Choi [47]. None of

the variables was stationary at levels, so they took first differences. Sixth, the study by Menegaki and Tugcu [33] in pg 156 has also used the augmented IPS (Pesaran, [48]), after acknowledging the existence of cross-sectional dependence (Pesaran, [40]).

3.2. Cointegration

Accordingly, this sub-section describes the type of cointegration analysis employed in each of the sampled studies. First, the study by Menegaki and Tugcu [33] in page 31 used a panel cointegration procedure developed by Westerlund [49] which considers the cross-sectional dependence that has been previously acknowledged. Second, the study by Menegaki et al. [34] in page 1261–1262 employed the ARDL cointegration framework which directly hosts both short run and long run relationships. Third, the study by Menegaki and Tugcu [35] in page 897 (Table 4 in the referenced paper) uses the panel ARDL model with a Pooled Mean Group (PMG) estimator. The advantage of this estimator is that it allows the intercepts, the short run coefficients, and error variances to differ across groups of countries, but it constraints the longrun coefficients to be the same. Fourth, the study by Menegaki and Tiwari [31] in pages 501–502 applies the Pedroni cointegration test [50] and based on evidence from the Hausman test they have decided in favour of a dynamic fixed effects model to depict the cointegration relationship estimated with a Generalized Method of Moments (GMM), which revealed that there was no problem of autocorrelation. They have also employed a quantile regression to corroborate the previous results. Fifth, the study by Menegaki and Tugcu [32] in page 83 has also used the Westerlund [49], whereby the underlying idea is to test for the absence of cointegration by determining whether the individual panel members are error correcting. Over the long run, cointegration is employed to investigate whether the variables move along the same path. The confirmation of cointegration also indicates the existence of a causality relationship at least in one direction of the relationship. Menegaki and Tugcu [30] in page 157 have used the Pedroni [51] cointegration with seven test statistics. Four out of the seven statistics are estimated based on pooled data across countries, and three out of the seven are based on averages of the individual autoregressive coefficients for each country.

3.3. Causality

The causality analysis is usually the last step in the energy-growth nexus studies. Causality analysis is necessary to reveal the direction of the causal relationship, which is not revealed in the cointegration analysis. This sub-section provides information as to which causality methods have been employed. First, the study by Menegaki and Tugcu [33] in page 31–32 have employed the Dumitrescu and Hurlin [52] to examine the panel causality context in their data. Second, the study by Menegaki and Tiwari [31] in page 1264 employed panel VECM Granger/Block exogeneity Wald tests. Third, Menegaki and Tugcu [35], within their ARDL approach, have separate long run and short run effects through the elasticities and semi-elasticities in page 897. Fourth, the study by Menegaki and Tiwari [31] in page 503 employs a VECM Granger causality/Block exogeneity Wald tests. Fifth, the study by Menegaki and Tugcu [27] in pages 84–85 has used Konya [53] which is a bootstrap panel Granger causality test and is examined as a set of SUR (seemingly unrelated regression). This test relies on the lag structure and hence this should be carefully decided. Sixth, the study by Menegaki and Tugcu [30] in page 157 has employed a pairwise Granger causality test.

4. Results and Discussion

This section provides summary results of the major and focal points reached in each study about the relationship of energy consumption and sustainable economy vis-a-vis the results from the conventional energy consumption and GDP growth.

Study 1: Sustainable economic growth and energy consumption in Asian countries

[Full study can be found at: Menegaki, A.N., Tugcu, C.T., 2018. Two versions of the Index of Sustainable Economic Welfare (ISEW) in the energy-growth nexus for selected Asian countries. *Sustainable Production and Consumption* 14, 21–35]

This study has separated energy consumption into renewable and non-renewable. It has also used international trade, natural resources rents, financial development, and the consumer price index as covariates. The dependent variable was sustainable economic growth in two versions: “loose” and “strict”. The used data ranged from 1990 to 2015. The results have revealed a bidirectional relationship between each of the two versions of sustainable economic growth and the rest of the covariates as well as between GDP growth and the rest of the covariates. There is only a unilateral relationship between the strict version of sustainable economic growth and international trade, but that was not significant at 5%.

Particularly, there is a bidirectional relationship between economic growth and energy consumption (either renewable or non-renewable) and between sustainable economic growth and energy consumption (either renewable or non-renewable). Thus, the Feedback Hypothesis is overall supported and this shows that energy conservation will negatively affect conventional and sustainable economic growth. The latter will then affect energy consumption and this dependence is mutual and of a spiral type. This constitutes some evidence that economic growth (not least the sustainable one) is coupled with energy consumption and without it, it will be fragile. Asia has achieved very high economic growth rates in recent years but has not managed to correct the inequalities. Environmental degradation could not be escaped and, therefore, Asian countries belong to the 70% of the world’s most vulnerable countries in front of climate change. Based on the parameters constituting the sustainable economic growth, it is apparent that Asian countries are also characterized by poor performance in vital indicators, such as public health expenditure. The progress in major energy goals, such as the improvement in the electrification rates, the increased penetration of renewable energies, and particularly the progress in energy efficiency have not been able to support the required structural change that would enable the confirmation of the conservation or neutrality hypotheses. The latter, if confirmed, signal the existence of energy decoupled economies which are more sustainable. It is interesting to reflect on the result of the Feedback Hypothesis between sustainable economic growth and energy consumption, which shows that energy consumption Granger causes sustainable growth. This has ramifications on the Environmental Kuznets Curve Hypothesis, according to which developing economies cannot help degrading the environment at the first stages of their development until a point is reached, which is the turning point of the EKC, where economies actively start improving their natural environment. Overall, it would be an interesting point of further research to corroborate the findings of the energy-sustainable growth nexus with relevant findings from the EKC curves. One of the most striking implications from the results in the Asian group of countries is that governments need not take different measures for conventional and sustainable economic growth, given that their Granger causal behaviour appears the same.

Study 2: Sustainable economic growth and energy consumption in Europe

[The full study can be found at: Menegaki, A.N., Marques, A.C., Fuinhas, J.A., 2017. Redefining the energy-growth nexus with an index for sustainable economic welfare in Europe. *Energy* 141, 1254–1268]

Detailed results from this study can be found in Menegaki et al. (2017). The study has compared the causal behaviour between conventional economic growth with energy consumption and sustainable economic growth with energy consumption from fossil fuels and renewable resources. Covariates have used the following variables: financial sector, carbon emissions, labour, electricity produced from renewables, electricity produced from non-renewables, capital, exports, natural resource rents and inflation.

Short run causality analysis has revealed bidirectional causality between energy consumption and sustainable economic growth. Sustainable economic growth also positively affects labour, exports, financial development, rents, electricity produced from renewable,

and electricity produced from non-renewables. Energy consumption also positively affects inflation, carbon emissions, labour and capital. The corresponding analysis with conventional economic growth has revealed similar causation findings, except for the variable of labour; the latter was not significant in the conventional economic growth framework.

As far as the negative contribution of the rents to economic growth (conventional or sustainable) is concerned, it has been captured in literature (Fuinhas et al., with a negative sign for specific natural resources, such as oil production. This may be attributed to the high dependence on these resources which allow rent earning, but at the same time hinder the diversification of productive structures of these countries. Nevertheless, this effect is very small in this empirical study, because European countries rely much less on oil production for revenues. Inflation was significant only in the conventional economic growth framework, which may be an indication that sustainable economic growth is robust to price fluctuations. The effect of inflation on conventional economic growth has also been documented in Asia has achieved very high economic growth rates in recent years but has not managed to correct the inequalities Asia has achieved very high economic growth rates in recent years but has not managed to correct the inequalities. In countries with high inflation, businesses suffer, and their operational environment is not favourable. Regarding the significance of labour in the sustainable economy, we need to remember that the reporting for conventional economic growth does not take into account the contributions of unofficial labour and the disservices from unemployment. Therefore, the latter acknowledgements throw some light as to why labour appears significant in the sustainable economy and not the conventional economic growth.

A result that causes scepticism is the positive significance of fossil fuelled electricity only in the conventional economic growth model. This finding is in line with previous literature which supports that renewables hamper economic growth. The current study corroborates this, given the significant negative sign of renewables in the sustainable economic growth framework. The larger coefficient estimated for capital in the welfare nexus than the conventional one shows that shocks, such as the financial crisis which entailed severe investment cuttings, could compromise the implementation of sustainable development in Europe. Sustainable economies need to increase or renew their capital base. Overall, the small differences between the welfare and the economic framework show that these frameworks are not perfect substitutes.

Study 3: Sustainable economic growth and energy consumption in G7 countries

[The full study can be found at: Menegaki, A.N., Tugcu, C.T., 2017. Energy consumption and Sustainable Economic Welfare in G7 countries; A comparison with the conventional nexus. *Renewable and Sustainable Energy Reviews* 69, 892–901]

G7 countries play important roles in the global political and economic scene. Their decisions affect the global financial architecture, and they are usually regarded as exemplar policy actors by developing countries. The study on G7 countries has employed capital, labour, and research and development (R&D) expenditure as a proxy for education and energy consumption. The sustainable economic growth has assumed two versions: “light” and the “strict”.

The Feedback Hypothesis is confirmed only between strict sustainable economic growth and energy consumption, while between the light sustainable economic growth and energy consumption we observe the Conservation Hypothesis. The same hypothesis is also confirmed in the GDP framework. The rest of the covariates all have a positive significant effect, except for labour with a negative sign in the strict welfare and energy consumption, which enters with a negative sign in the light welfare framework.

Based on the results derived from this set of countries, G7 most likely will be resilient to energy conservation measures and their sustainable development progress will not be hindered. Within the framework of the strict welfare, G7 economies show a feedback behaviour which means that resilience is not strong enough.

Study 4: Sustainable economic growth and energy consumption in American countries

[The full study can be found at: Menegaki, A.N., Tiwari, A.K., 2017. The index of sustainable economic welfare in the energy-growth nexus for American countries. *Ecological Indicators* 72, 494–509]

This study is based on data from 1990 to 2013 on 20 American countries. These data are: labour, capital, carbon emissions, energy use, renewable energy, rents, and trade. This study examines the relationship between energy consumption and economic growth (conventional and sustainable). Results do not reveal a relationship between energy consumption and growth whatsoever, but they clearly provide support for the Growth Hypothesis between renewable energy and GDP growth. On the other hand, results also support the Feedback Hypothesis between renewable energy sustainable economic growth. Another important finding is that the speed of adjustment for GDP growth is -0.380 , while for the sustainable growth, it is -0.625 . This entails that if the equilibrium situation in each case is perturbed, the sustainable growth can come to equilibrium at a higher speed (almost double) than the GDP growth.

As far as the energy consumption variable is concerned, this variable is only affected by capital under the sustainable economy framework. Renewable energy resources are affected by trade under both frameworks (GDP growth and sustainable economy). Had we stayed with conventional analysis in the first place, the non-existence of Granger causality between energy and GDP would have been mistaken for the Neutrality Hypothesis. In such a situation conservation measures on energy are not expected to retard economic growth. Contrary to this, the additional information we receive from the renewable energy-sustainable economy, namely the confirmation of the Feedback Hypothesis, provides a useful warning for policy makers: Therefore, applying conservation measures in renewable energy consumption will eventually cause a de-growth result and this, in turn, will impact on the development of renewable energies and it will slow down their penetration in the American countries.

Last, but not least, the results from Menegaki and Tiwari [31] inform us in the sustainable economy framework that the same amount of energy or renewable energy Granger causes a smaller effect on sustainable economy than the GDP economy. This is a sound indication that the sustainable economy is more stable and less prone to the fluctuations that can be caused by the application of energy conservation measures.

Study 5. Sustainable economic growth and energy consumption in emerging economies

[The full study can be found at: Menegaki, A.N., Tugcu, C.T., 2016. The sensitivity of growth, conservation, feedback & neutrality hypotheses to sustainability accounting. *Energy for Sustainable Development* 34, 77–87]

The study is based on 15 emerging economies and uses two versions of sustainable economy. The light and the strict version of sustainable economic growth vis a vis the conventional economic growth as denoted by the GDP growth. Thus, besides the aforementioned variables, the rest of the employed variables are capital, labour, openness of economy (imports and exports) and of course energy consumption. Based on the estimated results, in 8/15 countries, the confirmed hypothesis does not vary between the conventional growth framework and the sustainable economy (strong version). For 13 out of 15 countries, the same hypothesis is observed between the basic and the solid version of sustainable economy. For 8 out of 15 economies the same hypothesis is observed between GDP and the two versions of sustainable economy. Different causalities between the light and strong version of the sustainable economy are noted only for Poland and South Africa. Moreover, Brazil and Malaysia confirm the Feedback Hypothesis in the GDP framework, while for the sustainable economy framework the Growth Hypothesis is supported. Thus, had policy makers ignored the different results applicable between the conventional and the sustainable economy, it would have resulted in the possibility of changing energy consumption by changing welfare. A different situation applies for Colombia and Indonesia. The Growth Hypothesis applies in the GDP economy, while the Feedback Hypothesis applies for the sustainable economy. The latter entails that conservation measures will have repercussions on sustainability and, in turn, on energy.

Study 6. Sustainable economic growth and energy consumption in Sub-Saharan countries

[The full study can be found at: Menegaki, A.N.; Tugcu, C.T. Rethinking the energy-growth nexus: Proposing an index of sustainable economic welfare for sub-saharan africa. *Energy Res. Soc. Sci.* **2016**, *17*, 147–159]

The African region has been in the foreground of the summits of G8 since 2000. Due to its socio-economic and environmental characteristics, this region can play an important role for combating climate change. Thus, the way official assistance, with respect to energy is designed, is important, and such studies can inform policy making towards the right decisions. The study is based on 42 countries within the data span between 1985 and 2013. Besides GDP growth, sustainable economy growth, and energy consumption, the following variables are used: capital, carbon emissions, trade, and inflation. Granger causality results have provided support for the Feedback Hypothesis between energy consumption and the sustainable economy growth. A similar bidirectional relationship has been confirmed between capital and sustainable economy and between trade and sustainable economy. Moreover, we note a unidirectional Granger causality running from sustainable economy to rents and from carbon emissions to sustainable economy. The support for the Feedback Hypothesis between sustainable economy and energy consumption means that each magnitude affects the other and no conservation measures can take place without compromising sustainability. According to Menegaki and Tugcu [11], this finding can be expected to occur in the context of underdeveloped or developing economies which are in need of a minimum threshold of energy consumption that cannot be avoided, and it will put the sustainable economy on track. Thus, it may be the case that it is too early for the studied countries to be controlled in their energy consumption.

5. Concluding Remarks

The new trend of economic thinking and planning, with respect to sustainable economic growth and not the traditional economic growth as revealed by GDP, has led to the investigation of the so called energy-growth nexus from this new perspective. The current paper summarizes the gist causality results from a series of six studies which have been devoted to the investigation of the energy-sustainable economic growth relationship in various groups of countries worldwide. While the idea was first applied to a set of Sub-Saharan countries, mainly because it was a region suffering from poverty and because of the role it could play in the global sustainability, the interesting results the first study reached gave the initiative for the gradual study of an additional set of countries, covering almost the whole world.

Nowadays, besides the abundant studies in the conventional energy-growth nexus field which have been implemented for various single countries and groups of countries, there are a number of studies dealing with the relationship between energy consumption and a sustainable economy. A striking result is that almost all studies, and thus all country sets, provide support for the Feedback Hypothesis between energy consumption and sustainable economy. Despite the different econometric methods and the different timespans and covariates, the studies end up resulting in the same common finding, namely the bidirectional causal relationship between energy consumption and sustainable economy, which entails that sustainability cannot be yet achieved with energy conservation. Despite energy conservation being an action towards sustainability, energy consumption is still much required for the implementation of a sustainable economy. It is most surprising that this result is apparent worldwide with no differentiation between developed and underdeveloped countries. This might reflect the many dimensions of the sustainability agenda, such as the late and insufficient adoption of renewable energies by most countries due to their high cost, and the only recent adoption of circular economy practices, climate change mitigation etc. Generally, the worldwide evidence of the Feedback Hypothesis in the energy-sustainable economy relationship is a signal that sustainability requires a major structural transformation of economies, which is both energy and fossil energy intensive.

Of course, it is understood that the sustainable economy index that the series of studies has employed is far from perfect. However, the criticism received for the Index of Sustainable Economic Welfare is widely known, but still the lack of a better index allows withstanding of this criticism. Next, the main conclusions derived from the sampled studies are presented and compared.

5.1. Study 1 (Asia)

Contrary to other country groups, in the group of Asian countries no different implications appear for economic growth, either conventional or sustainable. Thus, policy makers in the energy sector can apply a uniform energy policy. However, since conservation measures will restrain growth generally, it would be advisable that the policy makers refrain from that altogether. This may be due to the fact that Asian countries in our sample are developing countries, and this entails that they have not yet reached the time point at which they can decouple their growth from energy consumption.

5.2. Study 2 (Europe)

Particularly for the European sample of countries, the positive effect of capital investment is larger in the sustainable nexus than the conventional, which reveals that when economies are faced with financial shocks, such as an economic crisis, reducing investment can also reduce sustainable economic growth. Significant differences exist between the long and short run in the energy-growth relationship of European countries. In the short run, conservation policies put more strain on the GDP rather than the sustainable economy. The opposite applies for the long run horizon. As far as the comparison of results in the conventional energy-growth nexus is concerned, the positive effect of capital investment is lower in the conventional energy-growth nexus as compared to the sustainable one. This highlights the importance of not cutting down on investment, a fact that can seriously delay sustainable growth. Despite this, the study reveals that sustainable growth also affects energy consumption, both in the short and the long run. Thus, energy conservation policies, albeit taking place in the short run, bear long-term implications.

5.3. Study 3 (G7 Countries)

G7 are the seven richest economies, so it is important to observe the energy-growth relationship in them. Basic sustainable growth (as a separate sustainability indicator and defined in the relevant study) is affected negatively by energy consumption, which is some evidence that G7 countries have reached a point in their history of economic growth and development where additional energy consumption can do no better. The same is not suggested with conventional economic growth however, and this underlines the importance of studying these two contexts together (the conventional energy-growth model with the sustainable economy-growth model). In this relationship the energy-growth is mutually caused by each other, thus any energy conservation measures will bring economic growth to a halt. This case study reveals that sustainable economic growth is more fragile in G7 countries than in the Asian or European ones. This may be due to the fact that the seven richest countries have relied much on energy consumption and environment exploitation in order to reach their high growth level.

5.4. Study 4 (American Countries)

In the American group of countries, we find that energy does not affect either type of economic growth. While this lends support for the Neutrality Hypothesis, the picture is different in the separate case of the effect of renewable energy, unveiling a feedback hypothesis which entails that renewable energy conservation will lead to a de-growth of American economies. The situation revealed in this case study is quite different from all the above cases and with no implications for policy making, because it appears that growth is not dependent on energy consumption. The structure of the economy is different and

probably with an advancement in energy efficiency which enables growth decoupled from energy. Thus energy conservation will bear no negative consequences for growth.

5.5. Study 5 (Emerging Economies)

This study suggests caution towards the results received between the different versions of sustainable GDP and the different results reached when comparing the conventional energy-growth nexus with the sustainable energy-growth nexus. It is understandable that the constructed ISEW is far from perfect and has been built based on the available information concerning basic sustainable GDP components. The method used in this study enables reaching results for each country separately. In nine countries, causality results are stable across the conventional growth and the different definitions of sustainable growth that are identified in the study. These countries are Chile, China, Colombia, India, Mexico, Morocco, Philippines, Thailand, and Turkey. In the rest of the countries, there are different results, either between the conventional and sustainable aspect of growth, or between the different versions of sustainability. Hence, one cannot make comparisons between this group of countries and the rest stated in this review.

5.6. Study 6 (Sub-Saharan Countries)

For Sub-Saharan countries it is found that energy conservation policies will restrict sustainable development. Due to its characteristics, this region will play a fundamental role in combating climate change. The huge income inequalities in Sub-Saharan countries require the usage of a more comprehensive measure of economic growth, such as the sustainable GDP. This study has resulted in a bidirectional relationship between energy consumption and sustainable growth, which means that these two magnitudes fuel each other. On the other hand, no relationship is revealed between energy consumption and economic growth, which supports the existence of the Neutrality Hypothesis. Thus, energy conservation will negatively affect sustainable growth but will not affect conventional growth and thus must be taken into consideration by policy makers who pursue sustainability. Conversely to the American sample of studies, where neutrality is evidenced in both cases of economic growth (conventional and sustainable), the Sub-Saharan case study reveals that neutrality is the case only for the conventional economic growth and not its sustainable counterpart.

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