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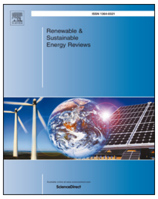

New evidence of energy-growth nexus from inclusive wealth

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ABSTRACT

Gross domestic product (GDP) has been inappropriately used as the main indicator for assessing the sustainability of economic development for a long time. Inclusive wealth (*IW*) offers a new approach to assess sustainability by comprehensively measuring the productive base of the economy that involves three types of capital assets of nations (produced, human and natural capital), and aggregates them into a single measure of wealth. This study proposes an alternative to the literature on the conventional energy – growth nexus that widely uses GDP as a proxy of the growth. This study aims to investigate the impact of energy consumption on wealth in the *IW* framework and forecast the growth of *IW* over the next three decades. For this purpose, this study uses both parametric and non-parametric analyses on 104 countries for 1993–2014. Our results indicate that there is a negative and significant impact of energy consumption on *IW* growth, suggesting an unsustainable pattern of world energy consumption. Using a machine learning technique, it is forecasted that increasing the efficiency of energy consumption leads to a higher growth in average per capita *IW*. This study also suggests that a shift to renewables is a precondition for sustainable development.

1. Introduction

Access to reliable and affordable energy is essential not only for supporting basic human needs but also for creating human well-being. The central role of energy and its sustainability has also been recognized in the United Nation's sustainable development goals (SDGs). However, the pattern of world energy consumption in the past tends to be unsustainable since it is highly associated with the rapid exhaustion of natural resources and environmental pollution. Energy consumption has been a predominant source of climate change, accounting for more than 60% of total global greenhouse gasses (GHG) emission. This trend is expected to increase along with the growing population and increasing economic activity, particularly for developing countries [1]. The negative impact of energy consumption and/or economic development on environmental quality has led to a quandary over whether to boost economic growth as high as possible by encouraging higher energy consumption, or giving precedence to environmental sustainability by curbing energy consumption which might result in lower economic growth [2].

The environmental Kuznets curve (EKC) hypothesis, on the other hand, argues that environmental sustainability can be achieved without restraining economic development. The EKC hypothesis suggests the existence of a turning point in the economy subsequent to which the increasing trend in environmental degradation will be reversed (see Grossman and Krueger [3] for rationale behind the EKC hypothesis). The composition and technical effects of the economy will decouple economic growth from GHG emissions through the introduction of renewable energy sources in the energy mix, investment in new and cleaner energy technologies, and adoption of more stringent environmental regulations. As a result, environmental damages that occurred in the earlier stages of development will be ameliorated, and further economic growth will lead to a better environmental quality. Although the EKC hypothesis proposes a promising concept for sustainability, it has some caveats worth mentioning. For instance, the estimated turning point of the EKC might exist at very high levels of income per capita, which are difficult or even impossible to achieve [4–6]. Additionally, De Bruyn et al. [7] and Sugiawan et al. [8], among others, argue that over the long term, new pollutants and environmental problems might appear, creating a secondary turning point in the economy so that the declining trend in the income-environmental quality relationship will revert back to its former trend.

In addition to the EKC hypothesis, which aims to investigate whether economic development can be detached from environmental degradation, assessment on the sustainability of economic development

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involves massive literature on energy-growth nexus, which seeks to scrutinize the decoupling between energy consumption and economic growth [9]. In the framework of sustainability, energy and environmental conservation policies should be implemented in such a way so as not to hinder economic growth and maintain the utility of future generations from declining. In this respect, numerous studies have investigated the energy-growth nexus by using the per capita income level as a proxy, aiming to find whether energy consumption leads to, is neutral to or is driven by economic development (see for instance Ozturk [10], Wolde-Rufael [11], Karanfil and Li [12], Omri et al. [13], Koçak and Şarkgüneşi [14] and Menegaki and Tugcu [15]). Such empirical literature examines the widely known energy-growth causality relationship hypotheses, i.e., growth, conservation, feedback, and neutrality hypotheses. An energy dependent economy is depicted by either a growth or feedback hypothesis, implying that energy is a stimulus for economic growth. Hence, higher economic growth can be achieved by increasing the level of per capita energy consumption, and vice versa. This type of economy tends to be unsustainable because it is usually characterized by the extensive use of non-renewable energy resources and increasing trend in GHG emissions [16]. On the other hand, a more sustainable economy can be found if either conservation or neutrality hypotheses hold true [15]. These types of energy-growth relationships suggest that energy and environmental conservation policies, aiming to reduce GHG emissions and high dependency on fossil fuels, might be pursued without adversely affecting the economy.

Most of the aforementioned literature attempts to evaluate the sustainability of economic development by using gross domestic product (GDP) as a proxy for well-being. However, Mumford [17] argues that such approaches are not reliable, since flow variables such as GDP are only a measure of current, but not intergenerational, well-being. Furthermore, Gaspar et al. [16] argue that good indicators of well-being need to take into account the quantification of environmental damage and social welfare. Hence, using GDP as a measure of sustainability is inadequate and might be misleading. Several authors, including Arrow et al. [18], UNU-IHDP [19] and Managi and Kumar [20], have proposed a comprehensive measure of well-being, which is referred to as inclusive wealth (*IW*). *IW* offers a novel method for quantifying, measuring and tracking sustainability by comprehensively measuring the productive base of the economy based on three types of capital assets of the nations, i.e., produced, human and natural capital, and aggregates them into a single measure of wealth. These have been the motivation of our work. Our paper aims to investigate the impact of energy consumption on wealth creation in the *IW* framework by using both the generalized method of moments (GMM) estimators, which was developed by Arellano and Bond [21], and system GMM, which was developed by Blundell and Bond [22]. We carry out the analyses on both aggregate and disaggregate values of capital assets. We also predict how the *IW* of nations will progress in the next three decades. For this purpose, we rely on a machine learning approach known as model trees because machine learning is known to provide better predictive accuracy compared to the parametric and semi-parametric models [23,24].

The remainder of this paper is organized as follows: Section 2 describes the empirical strategy of wealth. Section 3 discusses the research methodology and data used. Section 4 presents the main study findings and an analysis of the results. Section 5 presents the study's conclusions and its policy implications.

2. Empirical strategy

Economic development is not only about achieving higher income growth in terms of per capita GDP but also about creating sustainable well-being [25–27]. GDP and well-being are two different terminologies that cannot be used interchangeably, although there are some cases, particularly in less developing countries, where GDP does reflect the true well-being provisionally [28]. Costanza et al. [27] argue that this temporal correlation between GDP and well-being is understandable because there exists a threshold in the economy beyond which increasing income will be counterbalanced by surfacing costs which are associated with environmental damage and natural capital depletion. However, for more than 70 years, GDP has been inappropriately used as the main indicator for measuring the progress toward the well-being of a nation. As a result, the impact of economic development on well-being of a nation is far beyond expectation because most countries' national development policies have mainly focused only on sustaining GDP growth [27]. For instance, Arrow et al. [18] show that although national economies throughout the globe grow rapidly, their growth is followed by the depletion of natural resources and environmental degradation. They add that such a type of development trajectory tends to be unsustainable, since economic growth fails to maintain the well-being over time.

The shortcoming of GDP for gauging well-being is foreseeable because GDP is only a measure of economic quantity, not quality [27]. Additionally, well-being is a complex multidimensional concept, involving not only income and economic activity but also other tangible and intangible assets, such as human capital, social capital, and environmental services [17,20,26,29,30]. Therefore, Managi and Kumar [20] suggest that well-being should be measured based on a set of capital stocks, rather than flow, which form the productive base of economy. Additionally, Gaspar et al. [16] argue that a good indicator of well-being also need to take into account the quantification of environmental damage and social welfare. Therefore, instead of using GDP, some previous studies (see for instance Hamilton and Hepburn [31], Managi and Kumar [20] and Weitzman [28]) suggest the use of wealth as a measure of progress toward the well-being of a nation. Wealth, according to Hamilton and Hepburn [31] is defined as "stock of assets that can generate future income and well-being". Consequently, in the light of sustainability, the focus of economic development needs to shifted, from boosting current GDP by consuming wealth to creating new wealth for sustaining well-being.

Many studies have proposed alternative indicators beyond GDP for measuring wealth and tracking the sustainability of economic development. The literature is divided into two main approaches. The first approach attempts to make the GDP greener, either by offering a more comprehensive system of national accounts (SNA) that includes both marketed and non-marketed resources or by combining GDP with another set of social indicators with arbitrarily chosen weights. For instance, Hamilton [32] and Asheim [33] proposed a concept of green GDP by making a more comprehensive measure of the economic system that includes natural resources depletion and environmental damages into the SNA. Another example is the human development index (HDI), which was initiated in the early 1990s by Mahbub ul Haq and Amartya Sen to overcome the shortcoming of GDP in measuring the progress of human development. The HDI is a composite index that is constructed by aggregating GDP with two other dimensions of wealth, i.e., health and education, into a single measure [25].

In the second approach, indexes of well-being are measured directly. Such an approach assumes that well-being is independent of GDP; hence, rather than measuring economic activity, it measures changes in environmental, social, and human capital. For instance, the ecological footprint (EF), which was introduced in 1990s by Mathis Wackernagel and William Rees, attempts to assess sustainability by tracking the past and current human activities in exploiting ecological assets and compare this to the Earth's regenerative capacity. Sustainability is achieved if the rates of natural resources extraction and waste emission does not exceed the Earth's biophysical limits to naturally regenerate resources and assimilate waste [34].

However, initiatives to find alternatives to GDP for gauging sustainability are not without flaws. For instance, despite the remarkable contribution of HDI in portraying the progress of human development, it overlooks the ecological dimensions of sustainable development and disregards social goods in capital accounts to complement GDP [19]. Furthermore, Mumford [17] argued that instead of measuring the flow of current well-being as green GDP and HDI do, sustainability should be evaluated based on measurement of stock capital assets that form the productive base of economy over time, which reflects intergenerational well-being. Hence, in terms of sustainability, these two alternatives still have noteworthy drawbacks and cannot be used for properly evaluating the sustainability of economic development. In terms of the EF, most of the critiques talk about the relevancy, accuracy and inadequacies of the EF methodology to track all relevant environmental pressures, leading to distorted results and harmful policies (see, for instance Galli et al. [35] for a detailed discussion about persistent debate on the concept of EF).

The *IW* framework [18–20,36] offers a new approach to assess sustainability by measuring stock variables, which are related to the potential intergenerational well-being. Although it is difficult to be measured directly, intergenerational well-being can be determined from the productive base that is used to produce the goods and services that determine current well-being [17,37]. *IW* provides a comprehensive monetary valuation of wealth in terms of the productive base of the economy, involving three types of capital assets of nations, produced, human and natural capital, and aggregates them into a single measure of wealth [20]. The valuation of produced capital covers all types of man-made infrastructure such as roads, buildings, and machines. Additionally, accounting of human capital includes population, knowledge and skill from education, and health. For the case of natural capital, although it does not cover the whole ecosystem services, the its monetary valuation has included both renewable and non-renewable resources, namely forest resources, fisheries, agriculture land, fossil fuels and minerals [20,38].

Growth in the productive base of economy is a necessary but not sufficient condition for increasing intergenerational well-being [39]. Hence, increasing *IW* is not a guarantee that sustainability will be achieved; however, it is only a statement about the potential intergenerational well-being, implying that future generations will have a larger productive base of economy for improving their well-being [17]. Additionally, sustainability in the framework of *IW* does not require that every type of capital has to be sustained. Hence, a decline in one type of capital stock is allowed, as long as it is sufficiently compensated by increasing the social value of other types of capital [19,20]. For instance, consuming non-renewable natural resources such as fossil fuels and minerals for producing economic output today will reduce the stock of natural capital in the future. Therefore, to maintain the total wealth in the future, this loss needs to be compensated by sufficient increase in either produced or human capital such as increasing number of schools and health facilities that will enhance the capabilities of human capital to generate more income in the future. However, Barbier [40] highlights the structural imbalance in most economies, which is attributed to the underpricing of natural capital. As a result, the net proceeds from natural capital conversion are not sufficient enough for making new substantial investments in produced and human capital. This has resulted in massive exploitation of natural resources in an unsustainable manner.

The aforementioned explanations imply that the transition toward a more sustainable economy requires a substantial shift from non-renewable to renewable energy sources [41,42]. The *IW* framework has also recognized the indispensable role of renewable energy toward sustainability in its accounting system and demonstrates that the substitution of renewable for non-renewable energy sources is indeed sustainable [20]. For this purpose, the *IW* framework adopts the concept of renewable energy capital to capture investment in renewable energy facilities, such as solar and wind power plants (see for instance Yamaguchi and Managi [43] for a detailed discussion about renewable energy capital). It is intriguing to note that the *IW* framework considers renewable energy capital as a part of produced capital, instead of being included in natural capital. The main reason behind this uncommon classification is that because renewable energy facilities have a closer resemblance to produced capital. However, unlike non-renewable energy facilities, input for renewable energy facilities comes from renewable resources that will substitute the use of non-renewable resources such as oil and gas [20].

In the past few decades, literature on sustainability has also involved extensive research on the energy-growth nexus, aiming to study the decoupling between energy consumption and economic development. However, the results remain inconclusive due to different samples, empirical methodologies, or both. The literature has identified four testable hypotheses on the possible energy-income relationship (see for instance Ozturk [10], Wolde-Rufael [11], Karanfil and Li [12], Omri et al. [13], Koçak and Şarkgüneşi [14] and Menegaki and Tugcu [15]). First, the *growth hypothesis* postulates that there is a unidirectional causality running from energy consumption to economic growth. This hypothesis indicates an energy dependent economy where energy is a stimulus for GDP growth, implying that a shortage of energy may negatively affect economic growth or may cause poor economic performance. Second, the *conservation hypothesis* postulates that there is a unidirectional causality running from economic growth to energy consumption. This type of relationship indicates a less energy dependent economy, suggesting that energy conservation policies may be implemented with little or no adverse effect on the GDP. The third hypothesis is the *feedback hypothesis* that postulates that there is a bidirectional causal relationship between energy consumption and economic growth. This interdependence suggests that energy consumption and economic growth are interrelated and act as complements to each other. The fourth hypothesis is the *neutrality hypothesis,* suggesting that there is no causal relationship between energy consumption and economic growth. In this view, energy consumption does not influence economic growth and vice versa. Similar to the conservation hypothesis, this type of relationship also implies a more sustainable economy, where energy conservation policies may be pursued without adversely affecting the economy.

Unlike previous studies, this paper focuses on investigating the impact of energy consumption on the sustainability of economic development by using *IW* as the proxy for intergenerational well-being. To the best of our knowledge, this is the first study that investigates the sustainability of energy consumption in the *IW* framework. Additionally, in contrast to previous studies that have mainly focused on granger causality analysis, we employ the GMM estimators, which were developed by Arellano and Bond [21], and system GMM, which was developed by Blundell and Bond [22], to explore the impact of energy consumption on the formation of capital assets. We prefer to use the GMM estimators to address autocorrelation and endogeneity issues that might arise from our model and data. Additionally, in regard to the secondary objectives of our paper to forecast the growth of *IW*, we rely on a relatively new technique of machine learning known as regression trees. Compared to most parametric and semi-parametric models, this technique shows a better predictive performance in terms of root mean squared error, particularly if the sample size or the number of predictor variables is large [23,24]. To improve the predictive performance of a simple regression tree, we employ two methods. The first method, boosted regression trees (BRT), improves the predictive performance of a regression tree by boosting (an adaptive method for combining many simple models) [44,45]. The second method is the model trees, which improved the predictive performance of a regression tree by replacing the leaf nodes with regression models [46].

3. Data and methodology

Our analysis involves a balanced panel of 104 countries over the period 1993–2014. The time span and selection of countries used were constrained by the availability of data. As a proxy of wealth, this paper employs the *IW* data from the 2014 and 2018 Inclusive Wealth Report [19,20], which is measured in constant 2005 US dollars. We also include the disaggregated data of *IW* in terms of produced capital (PC), human capital (HC) and natural capital (NC) in our analysis.

Table 1
Descriptive statistics and correlation matrix.

Descriptive Statistics	*ln IW*	*ln PC*	*ln HC*	*ln NC*	*ln GDP*	*ln EC*	*ln POP*
Minimum	9.634	4.224	6.330	3.743	5.131	4.813	0.4339
1st Quartile	10.830	8.190	10.060	8.381	7.451	6.329	3.1464
Median	11.630	9.342	10.930	9.144	8.533	7.092	4.3534
Mean	11.660	9.430	10.900	9.296	8.658	7.229	4.1136
3rd Quartile	12.450	10.960	11.580	10.080	10.010	8.153	5.0629
Maximum	14.080	12.410	13.800	13.900	11.630	9.742	8.6290
Std. Deviation	0.968	1.698	1.163	1.578	1.488	1.059	1.437
Correlation Matrix							
ln *IW*	1	–	–	–	–	–	–
ln *PC*	0.3227	1	–	–	–	–	–
ln *HC*	0.7928	0.0522	1	–	–	–	–
ln *NC*	0.4047	0.1932	− 0.0161	1	–	–	–
ln *GDP*	0.3513	0.9660	0.0807	0.2017	1	–	–
ln *EC*	0.3989	0.8761	0.1325	0.2705	0.8923	1	–
ln *POP*	− 0.1540	− 0.2797	− 0.0513	− 0.0686	− 0.2504	− 0.2129	1

Additionally, we also utilize some development indicators from the World Bank World Development Indicators of 2017 as predictors, including per capita energy consumption, which is measured in kilograms of oil equivalent; per capita GDP, which is measured in constant 2010 US dollars; and population density, which is measured in people per square kilometer of land area. All variables are expressed in natural logarithms. The descriptive statistics and correlation matrix of the variables are provided in Table 1.

The 2014 *IW* Report [19] shows that during the period 1993–2011, more than 80% of the evaluated countries show positive average growth in GDP per capita; however, only 60% of the countries experienced gains in per capita *IW*. The positive growth of *IW* mainly results from the growth of human capital, which contributed to approximately 55% of overall gains in *IW*. At the same time, the contributions of produced and natural capital are only approximately 32% and 13%, respectively. From Fig. 1, we can see that the growth of per capita *IW* cannot be detached from the level of energy consumption and GDP per capita. In general, countries with high per capita energy consumption but relatively low GDP per capita tend to experience a declining *IW* per capita (marked by red triangles). On the other hand, gains in per capita *IW* (marked by green triangles) can be found in countries that have a higher ratio of per capita GDP to energy consumption. These facts provide us with preliminary information about the energy-wealth relationship, suggesting that the growth of per capita *IW* is correlated with the efficient use of energy. In the next section, we will explore this relationship further by using more reliable statistical methods to obtain robust inferences from our data.

Our paper studies the relationship between energy consumption and wealth based on the following parametric equations:

$$\ln IW_{it} = \alpha_0 + \alpha_1 \ln IW_{it-1} + \alpha_2 \ln EC_{it} + \alpha_3 \ln GDP_{it} + \alpha_4 \ln POP_{it} + \varepsilon_{it} \tag{1}$$

$$\ln PC_{it} = \beta_0 + \beta_1 \ln PC_{it-1} + \beta_2 \ln EC_{it} + \beta_3 \ln GDP_{it} + \beta_4 \ln POP_{it} + \varepsilon_{it} \tag{2}$$

$$\ln HC_{it} = \gamma_0 + \gamma_1 \ln HC_{it-1} + \gamma_2 \ln EC_{it} + \gamma_3 \ln GDP_{it} + \gamma_4 \ln POP_{it} + \varepsilon_{it} \tag{3}$$

$$\ln NC_{it} = \delta_0 + \delta_1 \ln NC_{it-1} + \delta_2 \ln EC_{it} + \delta_3 \ln GDP_{it} + \delta_4 \ln POP_{it} + \varepsilon_{it} \tag{4}$$

where *IW* is the per capita inclusive wealth; *PC* is the per capita produced capital; *HC* is the per capita human capital; *NC* is the per capita natural capital; *EC* is the per capita energy consumption; *GDP* is the per capita GDP; and ε_{it} is the standard error term. Furthermore, UNU-IHDP [18] show a strong correlation between population growth and declining wealth per capita. Hence, to avoid omitted variable bias, our models also include population density (*POP*) as an independent variable. We also include the lags of the dependent variables on the right-hand side of Eqs. (1)–(4) based on our assumption that the current year's wealth is highly influenced by its previous year's value.

The presence of these lagged dependent variables as regressors leads to so-called dynamic panel bias [47]. We also need to anticipate the issue of endogeneity due to the possible feedback effect from wealth to either GDP or energy consumption. Therefore, instead of using ordinary fixed or random effects panel data model, our model will be estimated using the GMM estimators. Arellano and Bond [21] showed that GMM

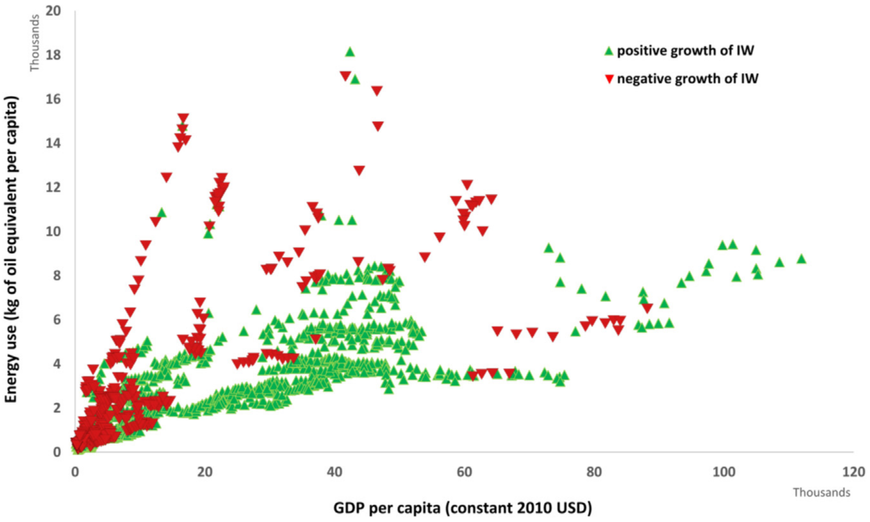

Fig. 1. Changes in global *IW* per capita for 1993–2014.

estimators can handle the issues of autocorrelation and endogeneity that might arise from our model by treating each variable as endogenous and instruments the variables by their own lag. However, Blundell and Bond [22] argued that the Arellano and Bond [21] estimator is likely to suffer from a weak instruments problem, particularly if the regressors display persistence over time. Therefore, they suggested the use of system GMM in which the moment conditions in the differenced model and levels model are combined. We use both the Arellano-Bond and system GMM estimators for our analysis. Furthermore, to ensure the robustness of our models, we need to test the validity of the instruments and the presence of autocorrelation in our models. For this purpose, we conduct the Hansen test of over-identification and the Arellano-Bond test for second order and higher-order serial correlation (AR(2) test). The Hansen test has a null hypothesis of 'the instruments as a group are exogenous', while the Arellano–Bond test for autocorrelation has a null hypothesis of no autocorrelation and is applied to the differenced residuals [48].

For forecasting purposes, instead of using the parametric models, our paper relies on non-parametric machine learning methods known as regression trees. To improve the predictive performance of a single tree, we use the BRT technique and model trees. The BRT technique combines two types of algorithms, i.e., regression trees and boosting, aiming to improve the performance of a single regression tree model by growing many trees, fitting them, and combining them to minimize error. The fitting procedure involves optimizing three parameters simultaneously, i.e., the number of trees, learning rate, and tree complexity [44]. The number of trees indicates the number of trees that are used to form the linear combination of the final BRT model. The learning rate indicates how much the contribution of each tree will be reduced as it is added to the model, while tree complexity indicates the number of nodes in a tree. Additionally, to improve the model's accuracy and reduce overfitting, we can also introduce a stochastic term into our model by setting the value of the bag fraction. Unlike the BRT technique, which attempts to grow many trees, a model tree attempts to improve the accuracy of a regression tree by replacing the single value of leaf nodes with linear regression models. As a result, we can improve the predictive performance of regression trees while maintaining their simplicity [49].

4. Results and discussion

Table 2 provides the estimation results of our model. The first column shows the impacts of energy consumption on *IW*, while the second, third and fourth columns present the impact of energy consumption on produced, human and natural capital, respectively. From the results of the Hansen and Arellano-Bond tests, we confirm the validity of the instruments, and we find no evidence of second or higher-order serial correlation in the first-differenced residuals for all cases.

We first examine the impact of energy consumption on wealth creation, which is the main focus of this paper. As seen in Table 2, both the Arellano-Bond and system GMM estimators show that energy consumption has a negative influence on *IW* growth. In the short-run, a 1% increase in energy consumption leads to a decline in per capita *IW* for approximately 0.0018% for the Arellano-Bond estimator, and 0.0378% for the system GMM estimator. If we carry out our analysis further, then we can see various impacts of energy consumption on disaggregated capital formation. While it provides beneficial impacts on increasing human capital, higher energy consumption leads to the depletion of natural resources. Additionally, we see no significant impacts of energy consumption on produced capital. These results suggest that the declining level of natural capital, which is caused by increasing energy consumption, is not sufficiently compensated by the socio-economic gain in energy consumption in the form of produced and human capital. Accordingly, the net effect of energy consumption on the productive base of the economy is negative, suggesting that the current pattern of energy consumption is not sustainable. Our findings support the earlier

Table 2
The impact of energy consumption on wealth creation.

Variables	*ln IW*		*ln PC*		*ln HC*		*ln NC*	
	Arellano-Bond	***Blundell-Bond***	***Arellano-Bond***	***Blundell-Bond***	***Arellano-Bond***	***Blundell-Bond***	***Arellano-Bond***	***Blundell-Bond***
ln IW_{t-1}	0.9475 (0.0025)***	0.9802 (0.0146)***	–	–	–	–	–	–
ln PC_{t-1}	–	–	0.9986 (0.0020)***	0.9419 (0.0276)***	–	–	–	–
ln HC_{t-1}	–	–	–	–	0.9469 (0.0014)***	0.9912 (0.0018)	–	–
ln NC_{t-1}	–	–	–	–	–	–	0.7842 (0.0036)***	0.9826 (0.0147)***
ln *EC*	− 0.0018 (0.0011)*	− 0.0378 (0.0123)***	− 0.0034 (0.0021)	− 0.0034 (0.0379)	0.0047 (0.0002)***	0.0005 (0.0059)	− 0.0094 (0.0006)***	− 0.0971 (0.0460)**
ln *GDP*	0.0288 (0.0016)***	0.0390 (0.0077)***	0.1377 (0.0030)***	0.0875 (0.0426)***	0.0011 (0.0004)***	0.0001 (0.0047)	0.0312 (0.0030)***	0.0802 (0.0314)**
ln *POP*	− 0.0052 (0.0044)	− 0.0015 (0.0143)	0.0949 (0.0112)***	0.0548 (0.0218)**	− 0.0003 (0.0009)	0.0020 (0.0043)	− 0.3407 (0.0091)***	0.0011 (0.0217)
Diagnostic tests								
AR (2) test	− 0.7427 [0.4577]	− 0.9000 [0.3670]	− 0.3000 [0.7641]	− 0.8100 [0.4150]	0.9062 [0.3648]	0.8300 [0.4070]	0.0072 [0.9942]	− 0.6400 [0.5240]
Hansen test	89.6506 [0.2896]	86.8100 [1.0000]	89.6350 [0.2900]	90.9500 [1.0000]	91.1620 [0.2530]	97.7100 [1.0000]	97.1346 [0.1735]	79.2300 [1.000]

Notes:.
***, ** and * denote statistical significance at 1, 5% and 10% levels, respectively.
Standard errors in parentheses; p-values in brackets.

Table 3
Predictive performance of BRT model.

Summary Statistics	*ln IW*			*ln PC*			*ln HC*			*ln NC*		
	Actual	*BRT*	*M5P*	*Actual*	*BRT*	*M5P*	*Actual*	*BRT*	*M5P*	*Actual*	*BRT*	*M5P*
Minimum	9.641	9.663	9.639	4.224	4.615	4.248	6.357	6.419	6.357	4.095	4.029	4.122
1st Quartile	10.846	10.846	10.846	8.095	8.076	8.098	10.092	10.088	10.090	8.359	8.366	8.364
Median	11.688	11.683	11.683	9.381	9.360	9.363	10.935	10.931	10.932	9.118	9.113	9.114
Mean	11.692	11.692	11.692	9.446	9.448	9.446	10.938	10.939	10.938	9.317	9.315	9.317
3rd Quartile	12.457	12.452	12.453	11.028	11.063	11.039	11.588	11.588	11.589	10.085	10.101	10.102
Maximum	14.010	13.961	13.997	12.388	12.336	12.401	13.676	13.696	13.689	13.897	13.660	13.898
MAE	–	0.009	0.009	–	0.023	0.018	–	0.008	0.003	–	0.016	0.014
Correlation	–	0.999	0.999	–	0.999	0.999	–	0.999	0.999	–	0.999	0.999

results from Gaspar et al. [16] and Menegaki and Tugcu [15] that found a negative impact of energy consumption on sustainability by using the Index of Sustainable Economic Welfare as a proxy of wealth.

We continue our analysis on population growth. Although we find no significant impact of population growth on per capita *IW* for both estimators, population growth shows a positive and significant impact on produced capital. Additionally, we find that population growth exerts a negative pressure on the environment, causing a decline in natural capital. Our findings imply that uncontrolled population growth is unfavorable for sustainability. This result is not unexpected. A growing population requires additional resources for satisfying basic human needs. Hence, a growing population is likely to place escalating pressures on natural capital. Furthermore, as populations increase, the demand for additional infrastructure for supporting human well-being also increases. Accordingly, a higher population level will lead to increasing produced capital. However, due to economic constraints, produced capital grows at a slower rate than the growth rate of a population, which can be seen from the relatively small coefficient of *lnPOP*, which is only 0.0949 for the Arellano-Bond estimator, and 0.0548 for the system GMM estimator. This scenario will result in social and economic inequalities, which eventually prevent the growing population from providing significant contributions to the increasing human capital. Cumulatively, the impact of population growth on per capita *IW* is neutral. Our finding contradicts the earlier study from Lutz et al. [50], arguing that a sustainable development path is characterized by a rapid social development and a relatively low population growth. However, our finding supports Casey and Galor [51], who found that lower population growth leads to a higher environmental quality.

The impact of per capita GDP on sustainability is rather intriguing. We confirm positive and significant impacts of GDP on all types of capital assets. GDP acts as a significant driver of produced, human and natural capital growth, where the highest impact can be found in produced capital. As seen in Table 2, a one percent increase in per capita GDP leads to around a 0.14% increase in produced capital. This result seems to be obvious since higher economic growth is usually followed by an increasing demand of infrastructure for education, health and for creating a better standard of living. As a result, economic growth will lead to increasing produced and human capital. This finding is consistent with that of Arto et al. [52], showing a strong correlation between GDP and living standard, although it will decouple at high income levels. The positive impact of GDP on natural capital, on the other hand, might be beyond our expectation, but it is not without explanation. One might expect that economic growth will place continuous pressures on natural capital since increases in output require more inputs. However, economic growth also creates advancement in technology, which leads to the improvement of either extraction or exploration efficiency. Such an effect is captured by the positive and significant impact of economic growth on natural capital. This confirms the earlier study of Sawada and Managi [53], showing that technological changes affect the efficient extraction of non-renewable resources. Taken as a whole, higher per capita GDP growth convincingly leads to a higher per capita *IW*, suggesting a promising sustainable future.

Next, we aim to forecast the growth of *IW* over the next three decades. For this purpose, we use both the BRT technique and model trees. To assess the accuracy of our models, we spilt our data into training and test sets. The training set consists of 70% randomly selected data, while the rest of the data will be used for quasi out of sample testing. For estimating the BRT model, we use the R programming environment with the add-on package *gbm*, which was developed by Ridgeway [54], and *dismo*, which was developed by Hijmans et al. [55]. For our estimation, we set the tree complexity equal to five, the learning rate equal to 0.01, and the bag fraction equal to 0.5. At the same time, the optimum number of trees is determined by the *dismo* package using cross-validation. For estimating the model trees, we use the M5-prime (M5P) algorithm, which was developed by Wang and Witten [46]. The M5P algorithm is available in the R programming environment via the *RWeka* package, which was developed by Hornik et al. [56]. We begin our forecasting by calibrating our models using the training set. Afterwards, we assess the predictive performance of our model using the test set.

The summary statistics of our forecast are provided in Table 3. We evaluate the goodness of fit of our models based on the correlation coefficients, mean absolute error (MAE) values and comparison of summary statistics between the predicted and true values. First, the correlation coefficient indicates how well the predicted values correspond to the true values, ranging between − 1 and + 1. A correlation close to these extreme values indicates a perfectly linear relationship, while near zero values indicate the absence of a linear relationship [49]. Our models show a very high correlation coefficient of 0.999 for all cases, suggesting a strong association between the predicted and the true values. Furthermore, to measure how far off our predictions are from the actual data, we need to examine the MAE values. The relatively small MAE values for all cases suggest that both methods demonstrate a fairly good predictive performance. However, the M5P model trees outperform the BRT technique by providing smaller MAE values. Finally, we also need to check the summary statistics to evaluate the agreement between the predicted and true values. In general, our models show a good predictive performance between the first and third quartiles, but they fail to accurately predict the extreme values of the data. Hence, their predictions fall on a slightly narrower range than the true values. Once again, the M5P model trees outperform the BRT technique by providing more accurate predictions.

The summary statistics in Table 3 provide clear evidence that the M5P model trees is more superior than the BRT technique; hence, we will use the M5P model trees for out of sample forecasting. For this purpose, we use the world population prospect of the United Nations to obtain the projected global population growth until 2050. Additionally, we assume that the global economy grows at a constant rate of 2.6% per annum. We use three different scenarios for the annual growth of the world's per capita energy consumption, i.e., 0.5, 1.0% and 1.5% per annum. The summary of our forecasts is presented in Figs. 2 and 3.

Fig. 2 shows the projections of global average per capita *IW* with three different scenarios. From Fig. 2, we can see that the world's average per capita *IW* is expected to increase in the next three decades,

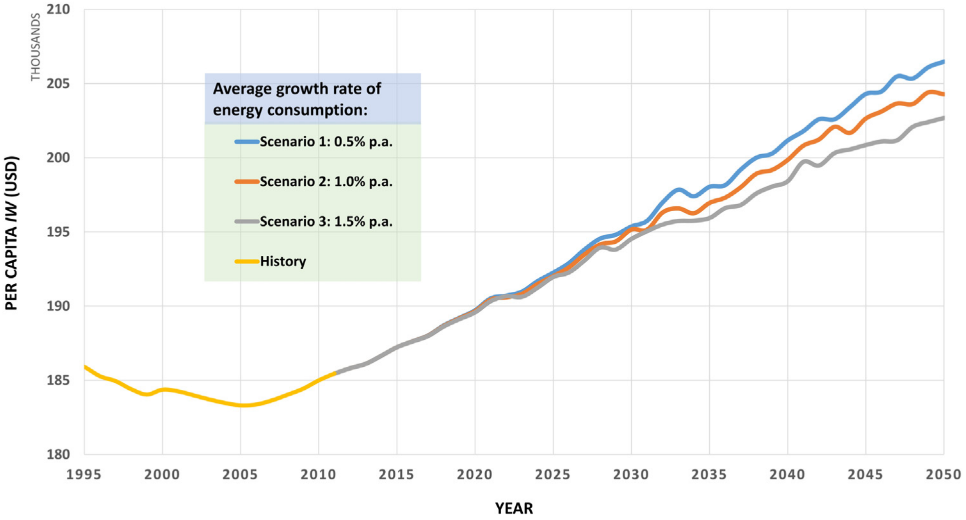

Fig. 2. Projections of global average per capita *IW*.

suggesting a potential increase in intergenerational well-being. However, we can also notice that the growth of average per capita *IW* is determined by the level of energy consumption. In line with our parametric models, our forecast models show that a lower growth of per capita energy consumption leads to a higher growth of average per capita *IW*. Assuming that the economy grows steadily without being driven by energy consumption, we find that reducing the average growth of energy consumption by 1% per year will lead to a 1.8% increase in average per capita *IW* in the end of our study period.

A more detailed country analysis of the average change of per capita *IW* and capital assets is provided in Fig. 3. In Fig. 3, we divided our analysis into two study periods, i.e., the current study period (1993–2014), which is denoted by orange bars, and the future study period (2015–2050), which is denoted by blue bars. As seen in Fig. 3, in the next three decades, the productive base of the economy grows at a positive rate in more than 76% of the countries in our study. This number is higher than the previous study period, where only 70% of the countries showed a positive average growth rate of *IW* per capita. Additionally, we also forecast that some countries with a negative average growth of per capita *IW* in the current study period will be able to reduce the declining rate of *IW* per capita in the next study period. Hence, our finding suggests that the future economy is likely to grow in a more sustainable way.

Although our models forecast a promising sustainable future, this result is not without caution, since growth in the productive base of an economy is dominated by the rapid expansion of produced capital, moderate increase of human capital and steady depletion of natural capital. Additionally, both our parametric and non-parametric models confirm that the current pattern of energy consumption tends to be unsustainable, since attempts to achieve higher per capita *IW* will be hindered by an increasing level of energy consumption. This is likely due to the domination of fossil fuels in the global energy mix, which in 2015 accounted for more than 80% of total energy consumption. Rapid investment in non-renewable energy facilities to meet the growing demand of energy consumption has led to a significant increase in produced capital. However, such energy facilities would require a large amount of input from non-renewable resources, such as oil and gas. As a result, there will be a significant decline in natural capital alongside produced capital growth, as projected by our model. Furthermore, our models also forecast that the same growth pattern is likely to be observed in the future.

In the light of the SDGs, which aim to ensure universal access to affordable, reliable and modern energy services, these findings corroborate the existence of the so-called ethical dilemma of energy consumption, since many people are currently suffering from lack of access to electricity and clean cooking facilities. In 2016, despite the improving access to electricity in most regions, the number of people who has no access to electricity was estimated around 1.1 billion, accounting for approximately 14% of the world's population. Additionally, 2.8 billion people was estimated to have no access to clean cooking facilities [57]. Therefore, efforts for improving access to modern energy services are likely to be followed by hypothetical loss of well-being, which is indicated by a lower growth of projected per capita *IW*, unless there are sustained and concerted efforts to make a transition to renewable energy sources. In the *IW* framework, the benefits of making new investment in renewable energy capital are at least threefold. First, investment in renewable energy capital, such as solar panels and wind farms, may positively affect the total *IW* by increasing produced capital because those renewable energy facilities are literally manufactured structures [20]. Second, unlike conventional fossil fuel power plants which need to be fueled by consuming significant amount of non-renewable natural resources, renewable energy facilities rely on input from renewable natural resources, such as wind and solar. Therefore, the high dependency on fossil fuel might be reduced and the depletion of natural capital can be averted [20]. Finally, investment in renewable energy capital may also affect the total *IW* positively through increasing health capital, because renewable energy capital is associated with healthier environment compared to that of fossil fuels (see for instance Dincer [42], Diesendorf and Elliston [58] and West et al. [59]).

5. Conclusions and policy implications

The objective of this study was to investigate the impact of energy consumption on wealth creation in the inclusive wealth (*IW*) framework and forecast the growth of *IW* over the next three decades. From the estimation results, we found a negative and significant impact of energy consumption on per capita *IW* growth, suggesting an unsustainable pattern of world energy consumption, since higher energy consumption leads to lower growth of per capita *IW* and vice versa. In contrast, economic growth was found to have a significant and favorable impact on the sustainability of economic development by promoting per capita *IW* growth. We also found that uncontrolled population growth was associated with a declining trend in the productive base of economy. Our non-parametric models forecasted that over the next three decades, the average growth of per capita *IW* should increase alongside economic growth. We also found that the number of countries that should follow a sustainable development path would likely


AVERAGE CHANGE OF PER CAPITA *IW*

AVERAGE CHANGE OF PER CAPITA PC

AVERAGE CHANGE OF PER CAPITA HC

AVERAGE CHANGE OF PER CAPITA NC

Fig. 3. Changes in productive base of economy for 1993–2050.

increase in the future. However, the growth of per capita *IW* will be hindered by increasing levels of energy consumption and population growth.

Although suggesting new policies is beyond the scope of this paper, our findings highlight some important policy implications. First, our models suggest that energy conservation policies can be promoted without threatening the sustainability of economic development. However, these policies should be enacted carefully due to the possible link between energy consumption and economic growth. If there exists a unidirectional causality from energy consumption to economic growth, then policies aiming to reduce energy consumption will affect *IW* growth both directly and indirectly through GDP growth. Hence, the outcomes of these policies will highly depend on the elasticity between energy consumption-economic growth and energy consumption-*IW* growth. Second, our findings highlight the necessity for increasing the efficiency of energy consumption, which will result in at least two impacts on sustainability. First, the deployment of more energy efficient technologies will directly influence the growth of *IW* by limiting the growth of energy consumption while maintaining the positive growth of economic development. Second, more efficient energy use will increase the productive base of economies by reducing the declining rate of natural capital while increasing the socio-economic gains in produced and human capital. Finally, our findings emphasize that a shift to renewables is a prerequisite for sustainable development since renewable energy capital will positively affect the total wealth by threefold through increasing produced capital, reducing the depletion rate of natural capital and reducing the negative impact of energy use on human capital.

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