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**Article**

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Energy Reports

**Provided in Cooperation with:**

Elsevier

*Suggested Citation:* Liu, Bowen; Matsushima, Jun (2019) : Annual changes in energy quality and quality of life: A cross-national study of 29 OECD and 37 non-OECD countries, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 5, pp. 1354-1364, <https://doi.org/10.1016/j.egy.2019.09.040>

This Version is available at:

<https://hdl.handle.net/10419/243675>

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## Research paper

## Annual changes in energy quality and quality of life: A cross-national study of 29 OECD and 37 non-OECD countries

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## ARTICLE INFO

## Article history:

Received 24 March 2019

Received in revised form 27 August 2019

Accepted 14 September 2019

Available online xxxx

## Keywords:

Energy return on investment (EROI)

Quality of life (QoL) sep Energy consumption

Gross domestic product (GDP)

Regression analysis

Energy price

## ABSTRACT

Since the efficiency of obtaining energy is decreasing, it is important to determine how the degradation in energy quality will influence society. Despite the rising importance of net energy, few quantitative studies have been conducted on the relationship between energy quality and quality of life (QoL). Energy return on investment on a society scale at a national level (EROI<sub>soc</sub>) is used as an indicator of energy quality, energy consumption (EC) per capita is used to represent energy quantity, and gross domestic product (GDP) per capita is used as an economic factor. Eight indices are used for QoL. Simple linear regression analysis is used to discuss the correlation coefficients between the three indicators (EROI<sub>soc</sub>, GDP per capita, and EC per capita) and eight QoL indices for 29 OECD and 37 non-OECD countries, and their annual changes over the 25 years from 1990 to 2015. We demonstrate that the relationship between the three indicators and eight QoL indices changes annually and differs between OECD and non-OECD countries. We also demonstrate that although GDP per capita is the most influential factor among the three indicators for the Human Development Index (HDI), which is one of the best-known composite indices of well-being, the importance of GDP per capita for non-OECD countries has declined, especially in times of increasing energy prices, while the importance of EROI<sub>soc</sub> for OECD countries has increased.

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## 1. Introduction

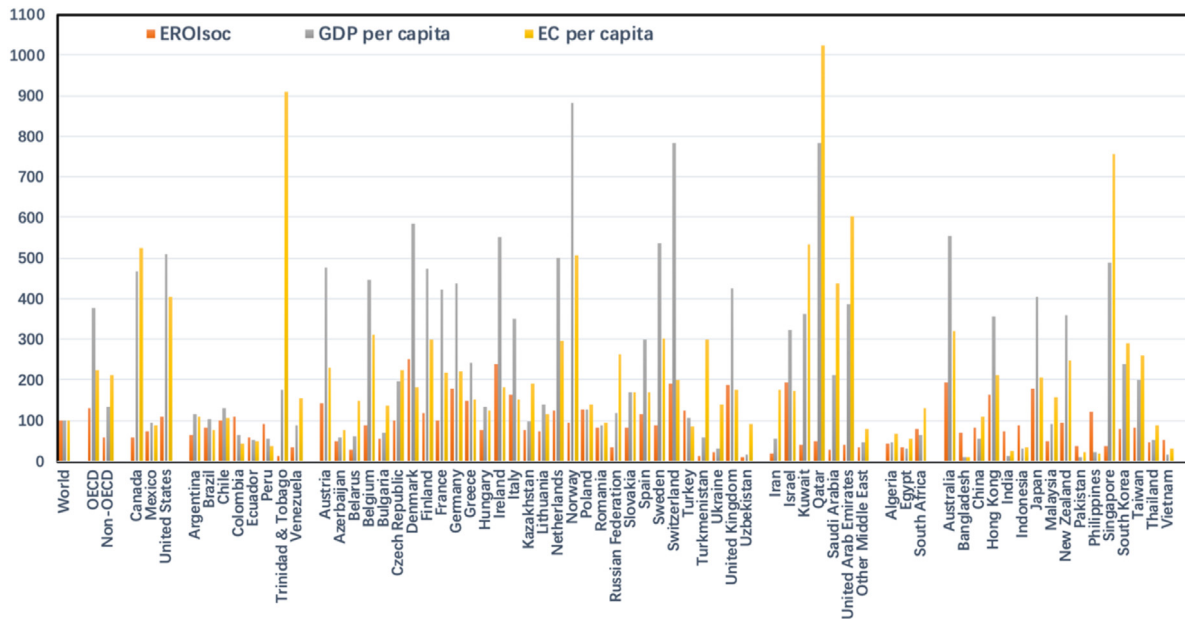
Although fossil fuel resources are among the most important global commodities and are essential for the production and distribution of the rest (Hall et al., 2014), the depletion of accessible fossil fuel reserves has outpaced improvements in technologies used to extract fuel (e.g., Gagnon et al., 2009). Energy quality, which has several definitions, such as those based on the contrast between different forms of energy, reflects the energy's utility (Hall and Klitgaard, 2012). It can be measured by many indicators, such as exergy, which is the capacity of energy to do physical work, or energy return on investment (EROI), which is the ratio of usable energy obtained to the energy used to obtain it. EROI is used in net energy analysis for measuring and comparing the net energy availability to the economy from different energy sources and processes (Brand-Correa et al., 2017). Cleveland (2005) calculated the EROI for oil and gas extraction in the US from 1954 to 1997, and found that the EROI shows a rise to a maximum in the early 1970s, a sharp decline throughout the 1970s, a recovery in the 1980s, and then another modest decline in the

1990s. Guilford et al. (2011) extended the work by Cleveland (2005) by including additional data, and estimated that the EROI for production for the United States' oil industry dropped from roughly 24:1 in 1954 to 11:1 in 2007. They also found that there is a clear inverse correlation between EROI and drilling rates, suggesting that depletion has more importance than technology in the U.S. oil and gas industry. Gupta and Hall (2011) provided a review of the literature available on data for the EROI of the 12 sources of fuel/energy: oil and natural gas, coal, tar sands, shale oil, nuclear, wind, solar, hydropower, geothermal, wave/tidal, and corn ethanol. Finally, they pointed out that the EROI of the fossil fuels we depend on most are in decline, whereas the EROI for those fuels we hope to replace them with are lower than we have enjoyed in the past.

Since the efficiency of obtaining energy has decreased, it is important to determine how this change will influence society. Several studies (Cottrell, 1955; White, 1959; Odum, 1971, 1973; Cleveland et al., 1984; Smil, 2003; Hall and Klitgaard, 2012; Carbajales-Dale et al., 2014) have indicated the importance of net energy to society. Cottrell (1955) mentioned that the energy available to man limits what he can do, and influences what he will do. White (1959) provided a profound understanding of the relationship between technology, ecology, and culture in

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**Fig. 1.** Overview of normalized EROI<sub>soc</sub>, GDP per capita, and EC per capita (averaged over 2007–2016) for 66 countries. The World average is normalized to 100 for the three indicators.

**Table 1**  
List of the 29 OECD and 37 non-OECD countries used in the present study.

Region	Countries
OECD	Canada, Mexico United States Chile, Australia, Czech Republic, Denmark, Finland France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, Netherlands, Norway, Poland, Slovakia, Spain, Sweden, Switzerland, Turkey, United Kingdom, Israel, Australia, Japan, New Zealand, South Korea
Non-OECD	Argentina, Brazil, Colombia, Ecuador, Peru, Trinidad & Tobago, Venezuela, Azerbaijan, Belgium, Bulgaria, Kazakhstan, Romania, Russian Federation, Turkmenistan, Ukraine, Uzbekistan, Iran, Kuwait, Qatar, Saudi Arabia, United Arab Emirates, Algeria, Egypt, South Africa, Bangladesh, China, Hong Kong, India, Indonesia, Malaysia, Pakistan, Philippines, Singapore, Taiwan, Thailand, Vietnam

the development of civilizations, and finally he pointed out the importance of the society’s ability to exploit energy as an indicator of progress. Odum (1971) warned that there may be a long period of leveling energy budgets, and the expanding economy may be gone and finally the citizens will sense this process as inflation. Odum (1973) proposed that the true value of an energy source is the net energy to sustain a society. Cleveland et al. (1984) found a close relation between various aspects of energy use and gross national product (GNP), labor productivity, and price levels in the United States. They emphasized the economic importance of changes in the quality and availability of fuel and other natural resources faced by the United States. Declining EROI for fuels and increasing energy costs for nonfuel resources have a negative impact on economic growth, productivity, inflation, and technological change. Smil (2003) described the effect of energy issues on the economy, on quality of life (QoL), on the environment, and in wartime.

However, few quantitative studies have been conducted on the effects of net energy on QoL. The first attempt to study the correlation between QoL and EROI was made by Lambert et al. (2014). They used regression analysis to determine how EROI in a society is related to six QoL indices: the Human Development Index (HDI), percentage of children underweight, average health expenditures per capita, female literacy rate, Gender Inequality

Index (GII), and improved access to clean water for rural communities. Moreover, they created the Lambert Energy Index (LEI), which includes EROI, average energy use per capita, and the Gini index, to account for various QoL indices. They found that LEI has a more positive correlation with HDI, female literacy rate, and health expenditures, and a more negative correlation with percentage of children underweight and GII compared to those for EROI. However, they did not demonstrate the annual changes in the relation between QoL and EROI, GDP, and EC. Furthermore, although Lambert et al. (2014) investigate the correlation between QoL and EROI for twelve developing countries, they did not perform a detailed comparison between developing and developed countries.

Therefore, in this study, we expand on the study of Lambert et al. (2014) to investigate the annual changes in the relationship between three indicators (EROI, GDP per capita, and EC per capita) and eight QoL indices, comparing between 29 OECD and 37 non-OECD countries.

## 2. Methods

This section describes the methods used to calculate EROI and the selection of QoL indices, and explains the regression analyses used to investigate the relation between energy quality and QoL. Considering the availability and accessibility of data, 1990–2015 was chosen as the period and 29 OECD and 37 non-OECD countries were chosen for analysis (Table 1).

### 2.1. Calculation of EROI<sub>soc</sub>

Different types of EROIs are defined on different system boundaries. EROI<sub>std</sub> is defined as standard EROI, whose system boundary is the mine mouth. EROI<sub>poi</sub> is defined as EROI at the point of use and expands the calculation of EROI<sub>std</sub> to include the cost of refining and transporting the fuel during the refining process (Murphy and Hall, 2010). Furthermore, on a society scale, it is necessary to consider all sorts of fuels. Since measuring precisely such energy is complicated, some approximate approaches have been proposed to express EROI on a society scale. Hall et al. (1986) calculated the EROI of imported oil (EROI<sub>io</sub>), which is the

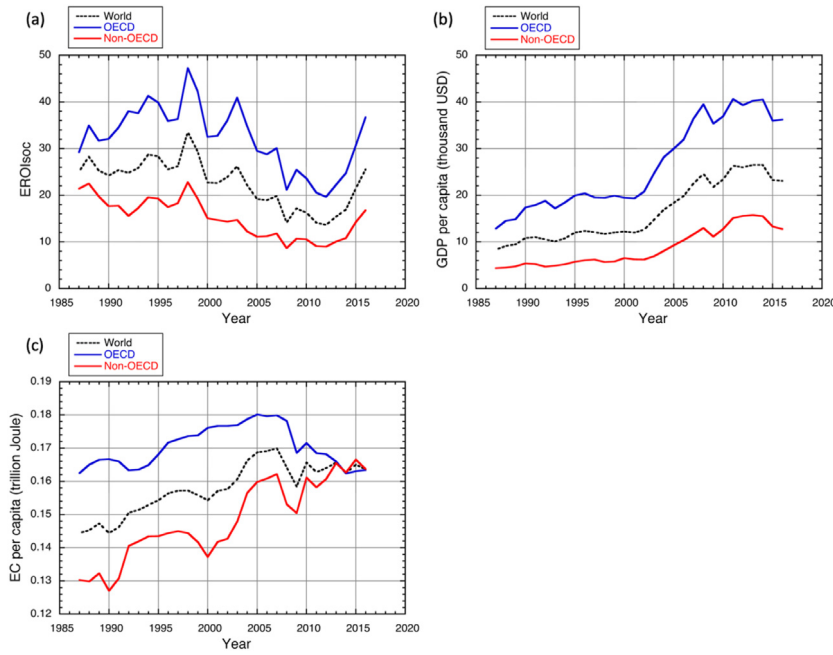


Fig. 2. Annual values of (a)  $EROI_{soc}$ , (b) GDP per capita, and (c) EC per capita over 30 years, 1987 to 2016.

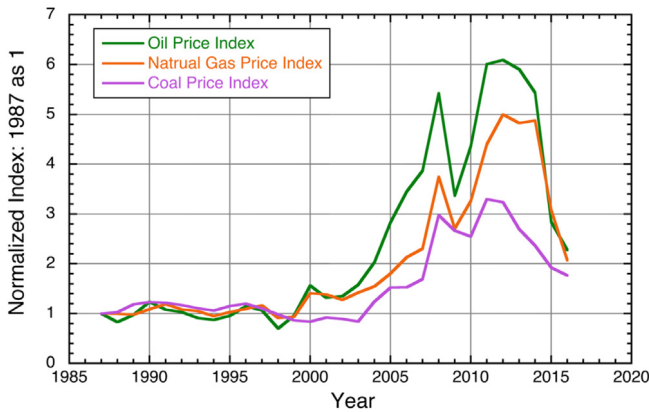


Fig. 3. Normalized indicators of the prices of oil (green), coal (magenta), and gas (orange) (values in 1987 taken as 1) for 1987–2016. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ratio between the energy value of the amount of fuel purchased by a U.S. dollar relative to the amount of oil required to generate a U.S. dollar's worth of goods and services. Lambert et al. (2014) proposed an EROI on a society scale at a national level ( $EROI_{soc}$ ) by extending the definition of  $EROI_{io}$  to include all fuel sources, domestic and imported, that a nation uses.

Lambert et al. (2014) used the following equation to calculate  $EROI_{soc}$ :

$$EROI_{soc} = \frac{GDP}{E_T} \times \frac{\eta_1 E_{U1} + \eta_2 E_{U2} + \dots + \eta_n E_{Un}}{\eta_1 E_{P1} + \eta_2 E_{P2} + \dots + \eta_n E_{Pn}} \quad (1)$$

where GDP divided by  $E_T$  (total energy consumption (EC) per year) is the economic efficiency, which indicates how many dollars are produced from the consumption of 1 unit of energy.  $E_{Un}$  and  $E_{Pn}$  are the energy per unit of fuel (MJ) and price per unit of fuel (USD) for energy  $n$ , respectively.  $\eta_n$  is the net contribution of energy  $n$  to the total annual EC for a society.  $EROI_{soc}$  represents the thermodynamic difference for each fuel and its contribution to the production of goods and services in a given year for a

nation's economy (Lambert et al., 2014). In order to include many countries and investigate the annual changes in the relationship between energy quality and QoL, Eq. (1) for calculating  $EROI_{soc}$  proposed by Lambert et al. (2014) was modified as follows:

$$EROI_{soc} = \frac{GDP \times (\eta_1 P_1 + \eta_2 P_2 + \dots + \eta_n P_n)}{E_T} \quad (2)$$

where  $E_T$  is total EC in a year and  $\eta_n$  is the net contribution of energy  $n$  to the total annual EC for a society.  $P_n = \frac{E_{Un}}{E_{Pn}}$  is the inverse of price of energy (MJ/USD), and thus  $P_n$  represents how much energy (MJ) a U.S. dollar can buy for a particular energy  $n$ . GDP data were taken from World Economic Outlook Database October 2017 Edition (IMF (International Monetary Fund), 2017). Total EC was taken from BP Statistical Review of World Energy June 2017 (BP (British Petroleum), 2017). The direct price of energy was taken from Electric Power Annual 2016 (EIA (Energy Information Administration), 2017) and Renewable Power Generation Cost (levelized cost of electricity) (IRENA (International Renewable Energy Agency), 2017).

Eq. (2) can be explained as follows. First, for a society in a specific year, the annual total EC ( $E_T$ ) is the energy investment, and GDP is the return on EC. Second, to measure the energy return, GDP was converted into various types of energy by using the price  $P_n$  and considering the weight  $\eta_n$ . A country that imports all its energy and a country that produces all its energy will be evaluated in the same way. Third, the energy return was divided by the energy investment ( $E_T$ ). Finally, the  $EROI_{soc}$  for a country in a year was calculated.

There are two assumptions in the proposed method. First, it is assumed that all countries use the same prices of energy when their GDP is evaluated (GDP is converted to nominal energy return). Since all the types of energy have prices in U.S. dollars for a year, there is no need to consider changes in the value of money, such as those due to inflation and exchange rates. Second, considering the accessibility of data, it is assumed that nuclear, hydroelectricity, and other renewable energy sources are not purchased in the market and that each energy type has a cost, which is the same worldwide in a specific year, to produce electricity. It is assumed that these costs are the prices of nuclear, hydroelectricity, and other renewable energy sources. Because of

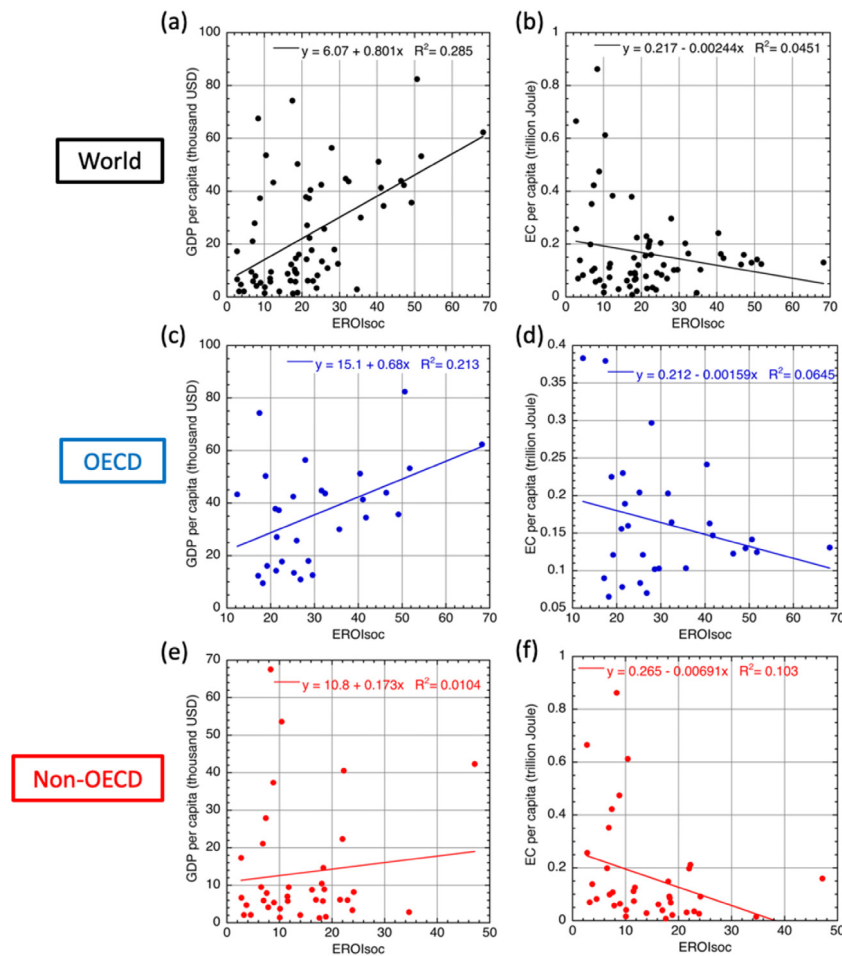


Fig. 4. Correlations among the three indicators ( $EROI_{soc}$ , GDP per capita, and EC per capita) for (a) World, (b) OECD, and (c) non-OECD.

these assumptions,  $EROI_{soc}$  might be underestimated (overestimated) for countries in which energy can be purchased for a lower (higher) price. However,  $EROI_{soc}$  is still the most precise indicator for studies on a global scale. Instead of finding the most suitable  $EROI_{soc}$  for a country, the focus here is on the relationship between  $EROI_{soc}$  and other indices on a global scale.

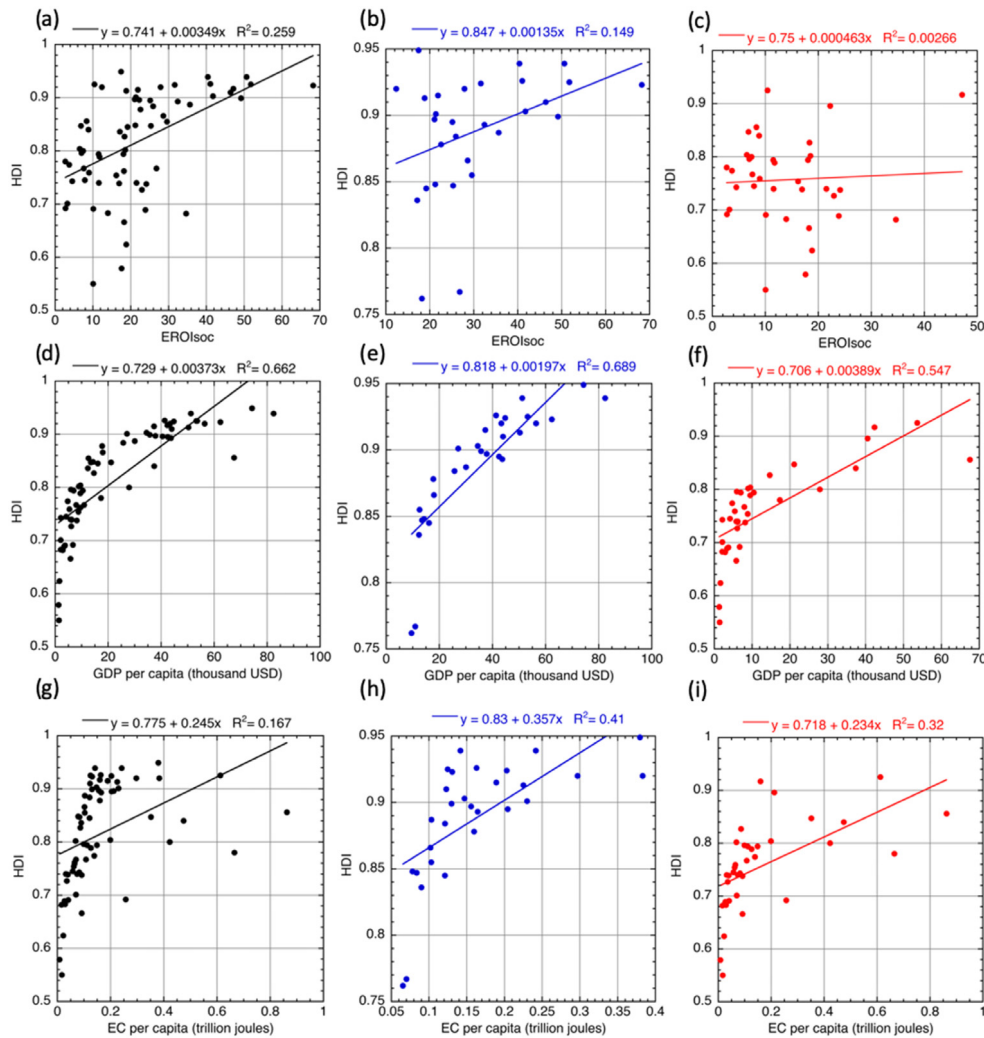
## 2.2. Indices of quality of life

This study used two standards to select the QoL indices. First, an index must be available, meaningful, and objective. Second, when the selected indices are combined, they must adequately reflect real life. That is, they should include education, health, safety, the environment, and so on. Based on these standards, nine indices were selected: HDI, GII, Corruption Perceptions Index (CPI), Environmental Performance Index (EPI), Education Index (EI), life expectancy at birth (LEB), total unemployment rate (TUR), and under-five mortality rate (UMR). HDI, GII, EI, LEB, TUR, and UMR data were taken from the United Nations Development Programme (UNDP) (<http://hdr.undp.org/en>). CPI data were taken from Transparency International (<https://www.transparency.org>). EPI data were taken from Yale University (<http://epi.yale.edu>). In order to get a positive coefficient in simple linear regression, GII was calculated as  $(1 - GII)$ , and the signs of TUR and UMR were inverted.

The HDI quantifies the average achievement of a country in three dimensions, namely a long and healthy life, measured by the life expectancy index; knowledge, measured by EI; and a decent standard of living, measured by the GDP Index (GDPI),

and is meant to capture those dimensions of well-being that are closely correlated with income such as housing, nutrition, and clothing (Nguefack-Tsague et al., 2011). The HDI implies the essential choices for people to lead a long and healthy life, to acquire knowledge, and to have access to resources needed for a decent standard of living (UNDP (United Nations Development Programme), 1990). The HDI was created to emphasize that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone. The HDI can also be used to question national policy choices, asking how two countries with the same level of gross national income (GNI) per capita can end up with different human development outcomes. These contrasts can stimulate debate about government policy priorities (UNDP (United Nations Development Programme), 2018).

The GII was developed by the UNDP in 2010 to cover the shortcomings of the previous indicators, the Gender Development Index (GDI) and the Gender Empowerment Measure (GEM), both of which were introduced in the 1995 Human Development Report. The GII measures the inequality in between women and men under three dimensions: health, empowerment, and labor market. These dimensions are derived from five major indicators, including percentage of higher (secondary level and above) education attainment by women, parliamentary representation by women, labor force participation by women, maternal mortality rate, and adolescent fertility rate (Brinda et al., 2015). The GII indicates the loss in potential human development arising from inequality in between the gains of women and men in these dimensions (Giray and Ergut, 2014).



**Fig. 5.** Comparisons of (a–c)  $EROI_{soc}$ , (d–f) GDP per capita, and (g–i) EC per capita with HDI for the World (black), OECD (blue), and non-OECD (red) in 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The CPI was developed in 1995 by the NGO Transparency International as a composite indicator that measures perceptions of corruption in the public sector in different countries around the world (Saisana and Saltelli, 2012). The thirteen sources of information (African Development Bank Governance Ratings, Bertelsmann Foundation Sustainable Governance Indicators, Bertelsmann Foundation Transformation Index, Economist Intelligence Unit Country Risk Ratings, Freedom House Nations in Transit, Global Insight Country Risk Ratings, IMD World Competitiveness Yearbook, Political and Economic Risk Consultancy Asian Intelligence, Political Risk Services International Country Risk Guide, Transparency International Bribe Payers Survey, World Bank Country Performance and Institutional Assessment, World Economic Forum Executive Opinion Survey, World Justice Project Rule of Law Index) are used to build the CPI, and the sources differ in the number of countries.

The EPI ranks how well countries perform on high-priority environmental issues in two broad policy areas: protection of human health from environmental harm and protection of ecosystems. Within these two policy objectives, the EPI scores country performance in nine issue areas that span high-priority environmental policy issues, including air quality, forests, fisheries, and climate and energy (Hsu et al., 2014).

The EI is calculated from the mean years of schooling and the expected years of schooling (UNDP (United Nations Development

Programme), 2018). The LEB is defined as the number of years a newborn infant could expect to live if prevailing patterns of age-specific mortality rates at the time of birth stay the same throughout the infant's life (UNDP (United Nations Development Programme), 2018). The TUR is defined as unemployed persons as a percentage of the total number of people employed and unemployed. The UMR is defined as the probability of dying between birth and exactly age 5, expressed per 1,000 live births (UNDP (United Nations Development Programme), 2018).

### 2.3. Regression analysis

Simple linear regression analysis was used to examine the changes in influence and correlation over a long period of time. For simple linear regression analysis,  $EROI_{soc}$ , GDP per capita, or EC per capita was used as the independent variable and QoL indices were used as the dependent variables. Simple linear regression analysis was used to analyze the correlation between  $EROI_{soc}$ , EC per capita, or GDP per capita ( $X$ ) and a QoL index ( $Y$ ). The correlation coefficients were obtained to estimate how much  $EROI_{soc}$ , GDP per capita, and EC per capita influence a QoL index. The relationship between the dependent variable ( $Y$ ) with the independent variable ( $X$ ) is expressed in a general linear model:

$$Y = \alpha X + \beta \quad (3)$$

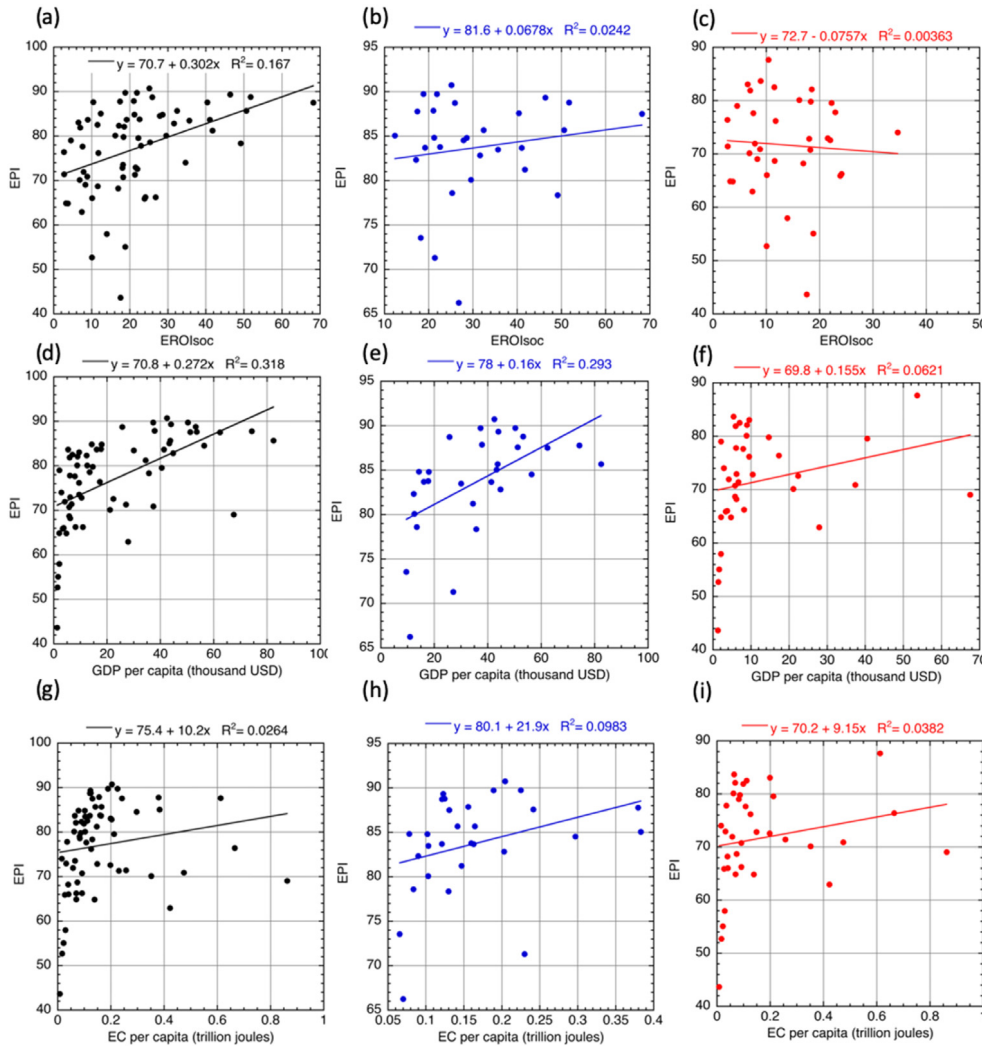


Fig. 6. Same as Fig. 5, except with EPI.

where  $\alpha$  is the regression coefficient, and  $\beta$  is the intercept value. The correlation coefficient ( $r$ ) is calculated by the following equation:

$$r = \frac{\frac{1}{N} \sum_{i=1}^N (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - \bar{X})^2} \sqrt{\frac{1}{N} \sum_{i=1}^N (Y_i - \bar{Y})^2}}$$

where  $X_i$  is the independent variable (i.e.,  $EROI_{soc}$ , GDP per capita, or EC per capita) for the  $i$ th country,  $Y_i$  is the dependent variable (i.e., a QoL index) for the  $i$ th country,  $\bar{X}$  and  $\bar{Y}$  are the average of  $X_i$  and  $Y_i$ , respectively. To measure the strength of a linear relationship between the two variables, we performed a t-test. P-values less than 0.05 were considered statistically significant.

### 3. Results and discussion

#### 3.1. Annual changes of $EROI_{soc}$ , GDP per capita, and EC per capita during 1987–2016

Fig. 1 shows an overview of normalized  $EROI_{soc}$ , GDP per capita, and EC per capita averaged over a recent 10-year period (2007–2016) with the World average normalized to 100, where the World comprising 29 OECD and 37 non-OECD countries (66 countries total). The separate average values of these three indicators for the OECD and non-OECD countries (hereinafter, OECD

and non-OECD) are included in Fig. 1. We can see that all three average values of OECD are larger than those of non-OECD.

The annual changes of  $EROI_{soc}$ , GDP per capita, and EC per capita for the World, OECD, and non-OECD over 30 years, 1987 to 2016, are shown in Fig. 2. As shown in Fig. 2(a),  $EROI_{soc}$  of OECD is larger than that of non-OECD over this period. The three curves of  $EROI_{soc}$  for the World, OECD, and non-OECD have similar trends and reach their peaks in 1998, and then decrease with year from 1998 to 2011 but increase again from 2011 to 2016. On the other hand, Fig. 3 shows normalized indicators of the prices of oil, coal, and gas (values in 1987 taken as 1) for 1987–2016. By comparing Figs. 2(a) and 3, we can see that  $EROI_{soc}$  is inversely proportional to energy price over this period. In Fig. 3, prices began to increase dramatically in 2002, which is mainly due to the rapidly increasing demand in emerging economies such as China and India, and then enter a valley after the financial crisis in 2008. Then, they rapidly increased, reaching highs from 2011 to 2012; at this time,  $EROI_{soc}$  was at its lowest level. Oil, gas, and coal have recently become cheaper; the prices in 2015 were approximately the same as those in 2005, and so the  $EROI_{soc}$  values are approximately the same as well. It can thus be inferred that energy prices greatly influenced  $EROI_{soc}$ . If there are no sudden changes in GDP or EC, predicting energy prices might be the key to predicting  $EROI_{soc}$ . Energy prices fell in 2014 because the United States became the largest oil producer and the demand in emerging economies decreased. Since energy prices returned

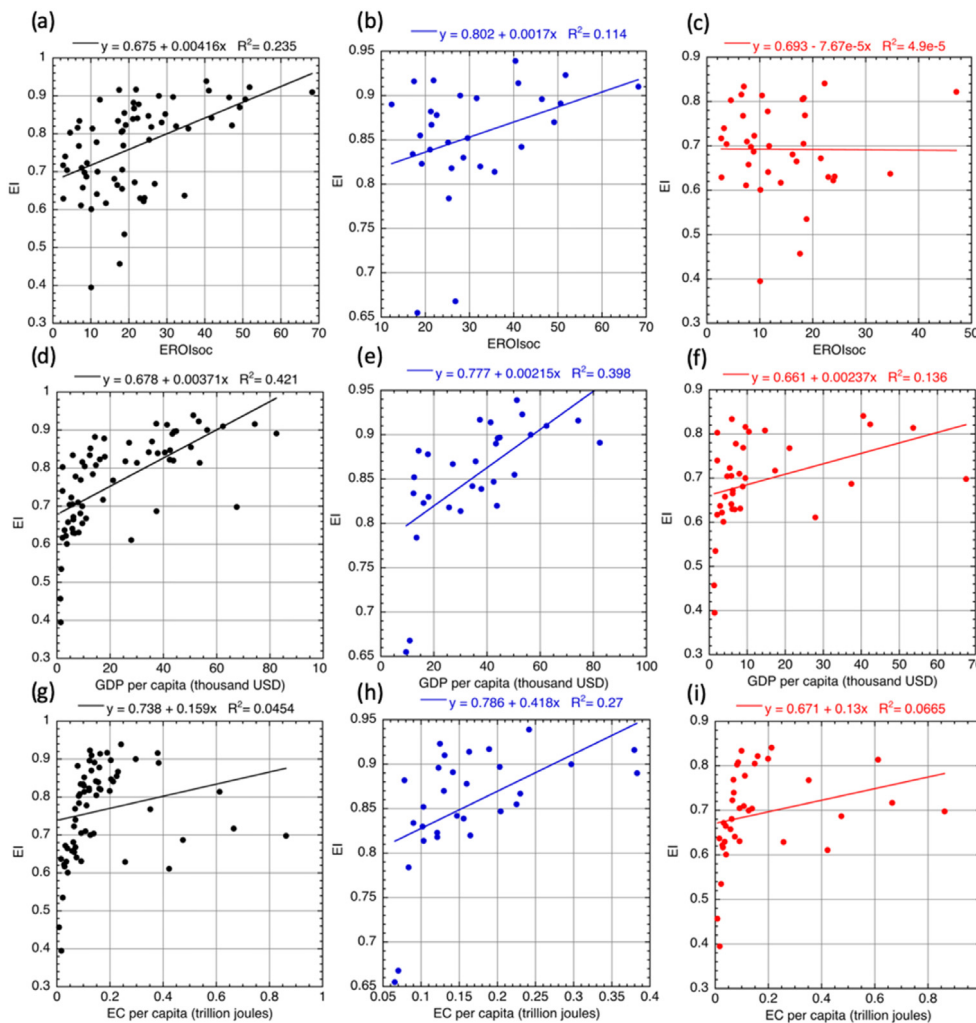


Fig. 7. Same as Fig. 5, except with EI.

to their 2005 levels, the steep drop in prices will likely stop and the prices will remain steady in the future, resulting in a steady  $EROI_{soc}$ .

In Fig. 2(b), GDP per capita of OECD is larger than that of non-OECD over the period 1987–2016. The three curves of GDP per capita for the World, OECD, and non-OECD have similar trends and increase steadily until 2001. Then, they increase more rapidly from 2002 to 2008, which almost corresponds to the era of high energy prices, after which GDP per capita became stagnant following the financial crisis in 2008. In Fig. 2(c), the trend of EC per capita differs between OECD and non-OECD: the curve of EC per capita for OECD suddenly decreases after the financial crisis in 2008, while the curve for non-OECD drops temporarily in 2008 but then increases steadily. The correlations among these three indicators ( $EROI_{soc}$ , GDP per capita, and EC per capita) for World, OECD, and non-OECD are shown in Fig. 4. According to the R-squared values in Fig. 4,  $EROI_{soc}$  is independent of EC per capita, but is weakly correlated with GDP per capita. Furthermore, we can find the difference between OECD and non-OECD: for example, R-squared values of OECD (Fig. 4c) are higher than those of non-OECD (Fig. 4e).

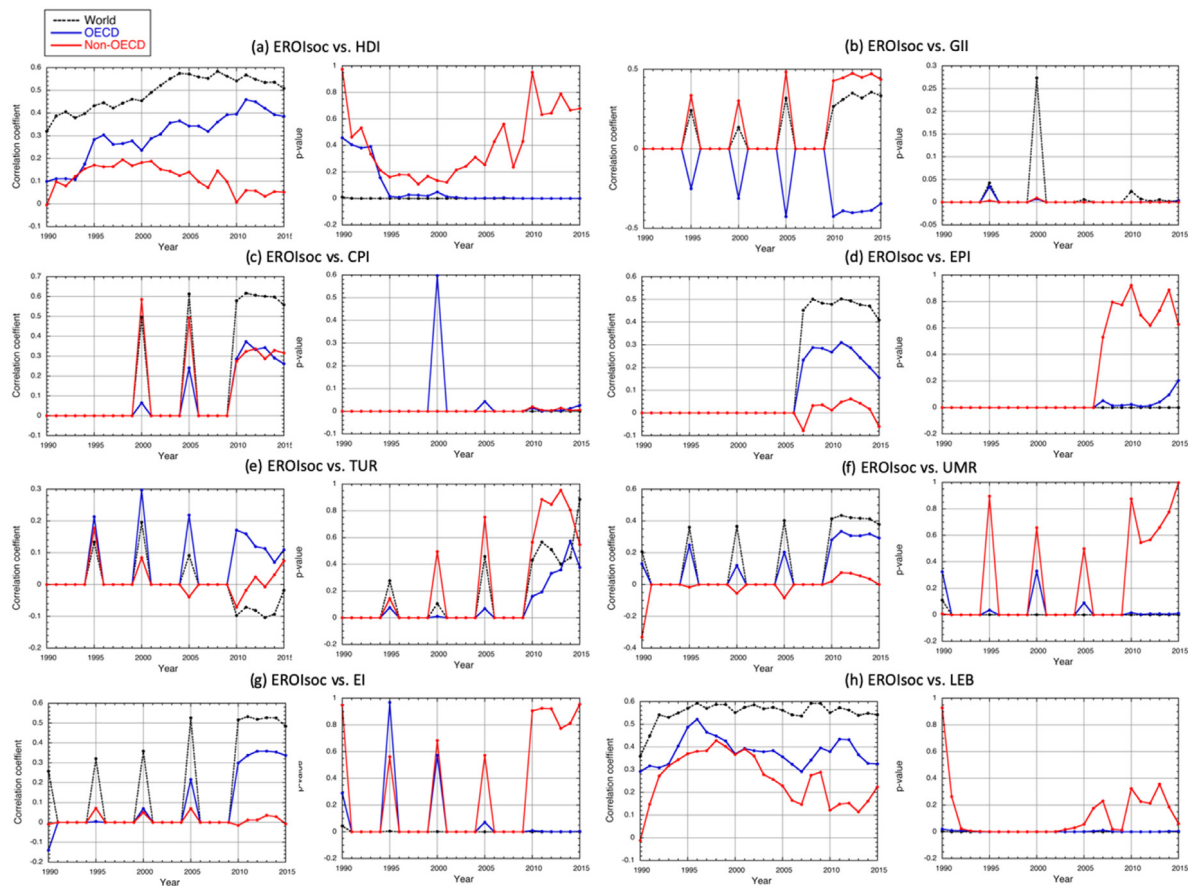
### 3.2. Results of simple regression analysis: change of influences during 1995–2015

For simple linear regression analysis,  $EROI_{soc}$ , EC per capita, or GDP per capita was used as the independent variable and eight

QoL indices were used as the dependent variables. As examples of simple linear regression analysis, Figs. 5–7 show comparisons of  $EROI_{soc}$ , GDP per capita, and EC per capita with HDI, EPI, and EI, respectively, for the World, OECD, and non-OECD in 2015. Figs. 8–10 show the annual changes in correlation coefficients over 1990–2015 between  $EROI_{soc}$ , GDP per capita, and EC per capita, respectively, and eight QoL indices. The corresponding p-values are shown at the right-hand side of each figure pair.

Comparing OECD and non-OECD in Figs. 8(a), 9(a), and 10(a), the correlation coefficients between GDP per capita and HDI are highest, while the correlation coefficients between  $EROI_{soc}$  and HDI are lowest. In these three figures, the correlation coefficients of OECD are higher than those of non-OECD over the period 1990–2015, but the trend of the correlation coefficients differs between OECD and non-OECD. In the case of  $EROI_{soc}$  and HDI (Fig. 8(a)), the correlation coefficients of OECD increase steadily, while those of non-OECD decrease steadily. This implies that the importance of  $EROI_{soc}$  for HDI increases in OECD but decreases in non-OECD. In the case of GDP per capita and HDI (Fig. 8(b)), the correlation coefficients of OECD suddenly increase in 1996 and then remain almost constant with only slight fluctuations, while those of non-OECD decrease steadily after 1998 and reach a trough in 2011–2012, which corresponds to the era of highest energy prices. This implies that the importance of GDP per capita for HDI does not largely change in OECD but decreases in non-OECD and its rate of decrease is highest in the era of highest





**Fig. 8.** Annual correlation coefficients over 1990–2015 between  $EROI_{soc}$  and eight QoL indices: (a) HDI, (b) GII, (c) CPI, (d) EPI, (e) TUR, (f) UMR, (g) EI, and (h) LEB.

energy prices. In the case of EC per capita and HDI (Fig. 8(c)), the correlation coefficients of OECD decrease steadily, while those of non-OECD increase steadily until 2000 and then decrease steadily. This implies that the importance of EC per capita for HDI decreases in OECD, and increases in non-OECD until 2000 and then decreases.

Comparing the correlation coefficients for GII in Figs. 8(b), 9(b), and 10(b), the correlation coefficients for non-OECD are higher than those of OECD. This implies that the importance of the three indicators ( $EROI_{soc}$ , GDP per capita, and EC per capita) for GII in non-OECD is larger than that of OECD. No trend for changes in the coefficient for GII was found.

Comparing the correlation coefficients for CPI in Figs. 8(c), 9(c), and 10(c), the correlation coefficients between GDP per capita and CPI are highest, while the correlation coefficients between  $EROI_{soc}$  and CPI are lowest. There are no significant differences between OECD and non-OECD except for the case of  $EROI_{soc}$ .

Comparing the correlation coefficients for EPI in Figs. 8(d), 9(d), and 10(d), the correlation coefficients for OECD are higher than those of non-OECD. This implies that the importance of the three indicators ( $EROI_{soc}$ , GDP per capita, and EC per capita) for EPI in OECD is larger than that of non-OECD. We also find a trend of decreasing correlation coefficients between EC per capita and EPI (Fig. 10(d)).

Comparing the correlation coefficients for TUR in Figs. 8(e), 9(e), and 10(e), the correlation coefficients between GDP per capita and TUR are moderate and somewhat higher than those of EC per capita and TUR. Note that the curve for the correlation coefficients between  $EROI_{soc}$  and TUR cannot be adequately interpreted due to consistently higher p-values.

Comparing the correlation coefficients for UMR in Figs. 8(f), 9(f), and 10(f), there are no significant differences between the

three indicators ( $EROI_{soc}$ , GDP per capita, and EC per capita) except for the case of  $EROI_{soc}$  for non-OECD. Note that the curve for the case of  $EROI_{soc}$  for non-OECD cannot be adequately interpreted due to consistently higher p-values.

Comparing the correlation coefficients for EI in Figs. 8(g), 9(g), and 10(g), the correlation coefficients for OECD are higher than those of non-OECD in the case of GDP per capita and EC per capita. Furthermore, focusing on the three indicators ( $EROI_{soc}$ , GDP per capita, and EC per capita) for OECD in the period after 2010, the correlation coefficients between GDP per capita and EI are highest, while the correlation coefficients between  $EROI_{soc}$  and EI are lowest. Note that the curve for the case of  $EROI_{soc}$  for non-OECD cannot be adequately interpreted due to consistently higher p-values.

Comparing the correlation coefficients for LEB in Figs. 8(h), 9(h), and 10(h), the correlation coefficients of OECD are higher than those of non-OECD but the trend of the correlation coefficients differs between OECD and non-OECD. In the case of  $EROI_{soc}$  and LEB (Fig. 8(h)), the correlation coefficients of OECD remain almost constant with only slight fluctuations, while those of non-OECD increase steadily until 1998 and then decrease steadily with slight fluctuations. In the case of GDP per capita and LEB (Fig. 9(h)), the correlation coefficients of OECD decrease steadily with slight fluctuations, while those of non-OECD increase steadily until 1995 and then decrease steadily and reach a trough in 2006–2012, which corresponds to the era of higher energy prices. In the case of EC per capita and LEB (Fig. 10(h)), the correlation coefficients of OECD decrease steadily with slight fluctuations, while those of non-OECD decrease steadily until 2008 and then remain almost constant.

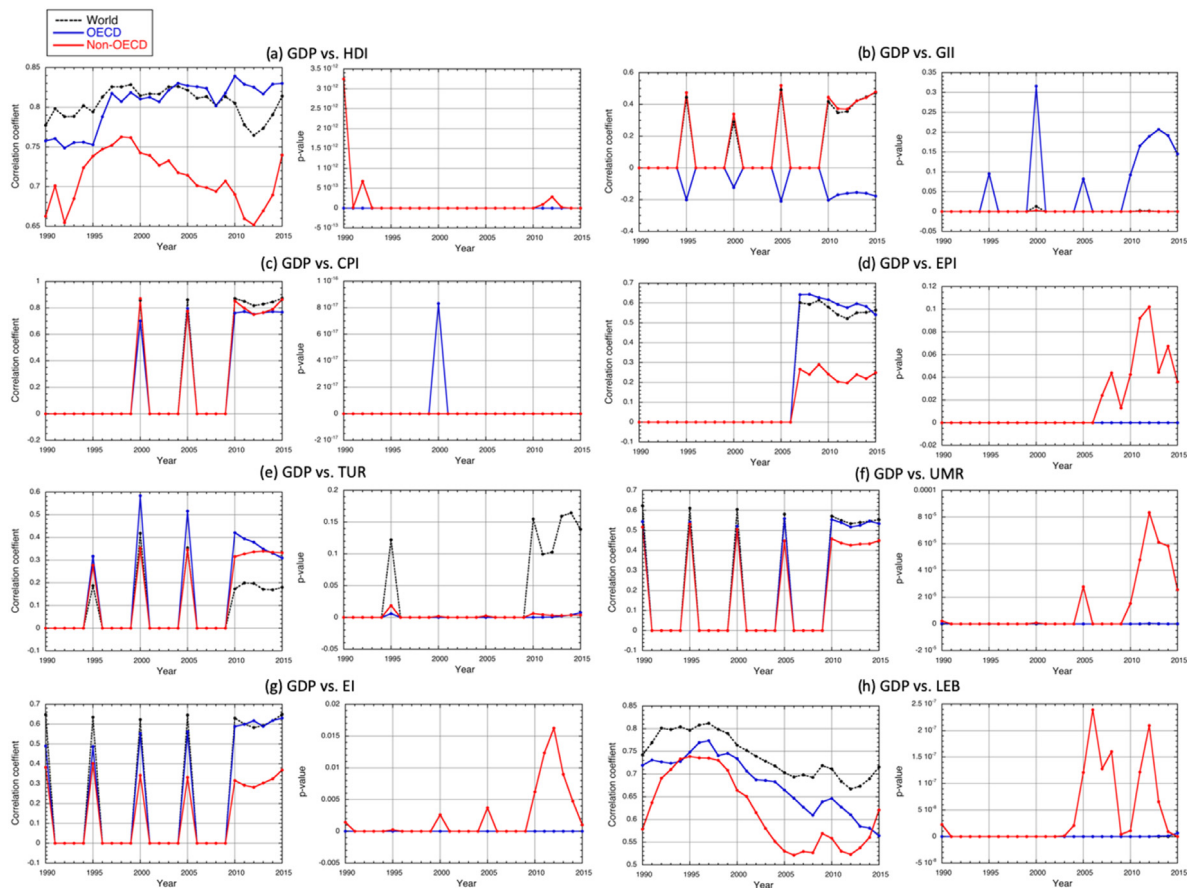


Fig. 9. Same as Fig. 8, except with GDP per capita.

### 3.3. Comparison with existing results

By modifying the calculation method for  $EROI_{soc}$  proposed by Lambert et al. (2014), we were able to use 25-year data from 1990 to 2015, enabling us to investigate the annual changes in the relationship between the three indicators ( $EROI_{soc}$ , GDP per capita, and EC per capita) and eight QoL indices, comparing between 29 OECD and 37 non-OECD countries. The contribution of this study is that we have found that the relationship between the three indicators and eight QoL indices changes annually and differs between OECD and non-OECD. Although historically, life expectancy, literacy rates, per capita income, mortality, and morbidity statistics have been widely employed to construct various indices of wellbeing, one of the best-known composite indices of well-being is the HDI (Rahman et al., 2003). Although many studies have demonstrated a strong correlation between energy use and GDP (e.g., Cleveland et al., 1984), it is now widely recognized that GDP per capita is not an adequate indicator of the development level of a country, as many important dimensions of well-being are imperfectly captured by it (Nguefack-Tsague et al., 2011). Our study demonstrated that although GDP per capita is the most influential factor among the three indicators for HDI, the importance of GDP per capita for non-OECD has declined, especially in times of increasing energy prices, while the importance of  $EROI_{soc}$  for OECD has increased. This may imply that GDP per capita is still an important indicator for OECD countries even in the era of high energy prices.

### 3.4. Limitations of this study

Herendeen (2015), who attempted to connect EROI, based on the input–output method, with the price of energy, stated that

price is important in energy policy for obtaining a significant and lasting response at societal and personal levels, and thus net energy is relevant to the extent that it can be used to predict the prices of energy, goods, and services. In the formula used to calculate  $EROI_{soc}$  in the present study, it is assumed that the indicator depends on the quotient of GDP divided by EC and the weighted energy prices. Consequently, the obtained value of  $EROI_{soc}$  is significantly related to energy prices. More importantly, it is noticed that  $EROI_{soc}$  can influence QoL indices and that the coefficients for  $EROI_{soc}$  are likely to be positively correlated with energy prices during 1990–2015.  $EROI_{soc}$  is thus regarded as explaining the connection between energy price and QoL. Furthermore, this study examined the differences between OECD and non-OECD but the differences among individual countries were not investigated. Future studies could concentrate on a specific region. Moreover, on a country scale, focusing on a country that imports all of its energy, such as Japan, might yield interesting results from a time-series analysis. Finally, a similar method can be used to study other types of EROI.

Shin (2015) summarized existing studies on QoL and pointed out that it can be measured objectively or subjectively. The objective approach focuses on the socioeconomic conditions and physical environments in which people live, and the goods and services they can access either individually or collectively. The objective approach includes the assumption that people will have a higher QoL and will be happier from such life conditions. More specifically, it is assumed that QoL is higher when a person is more educated and informed, lives longer, and consumes more goods and services (Shin, 2015). On the other hand, the subjective approach asks people directly about how they feel and whether they are happy. Since the assumption on which the

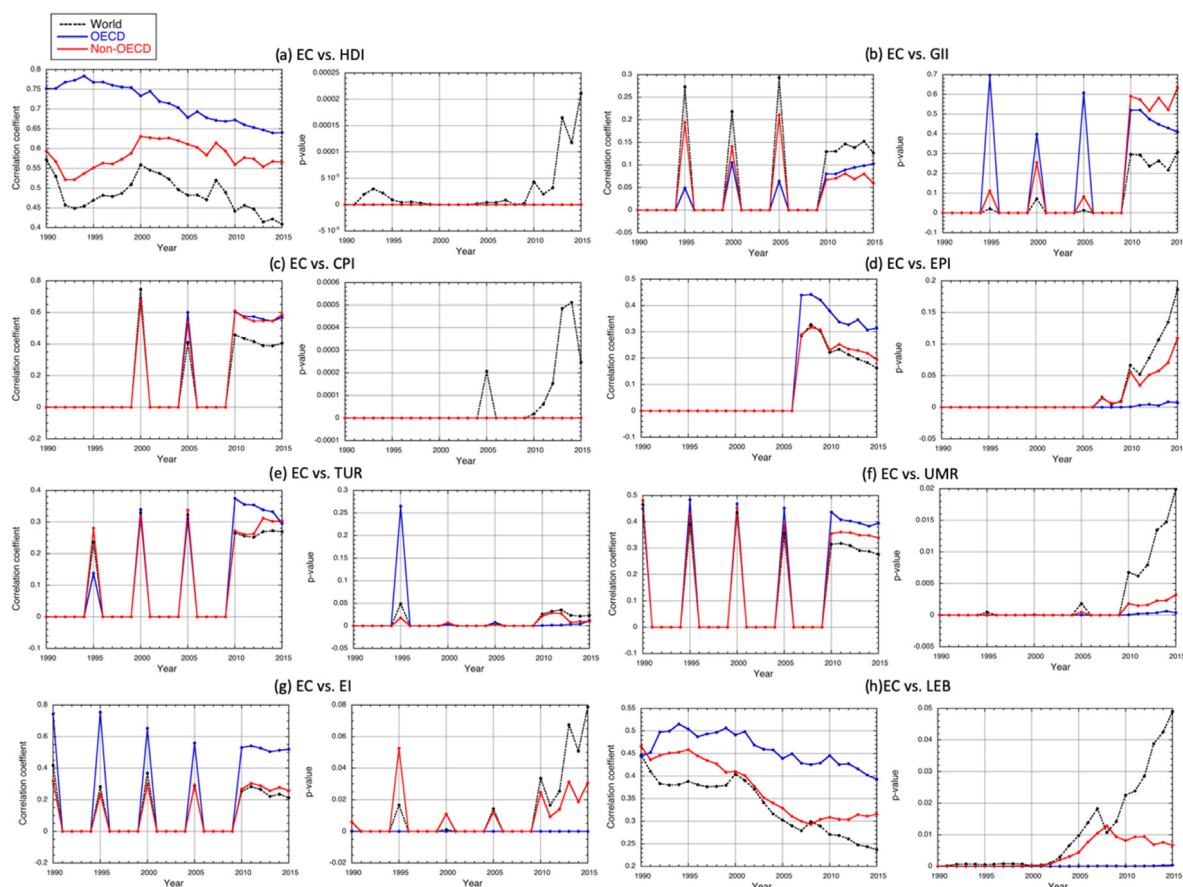


Fig. 10. Same as Fig. 8, except with EC per capita.

objective approach is based can be invalid in some situations, objective and subjective approaches should be combined. For instance, Ryan and Deci (2001) have used various indicators to determine what most influences scores of happiness. They found that when people lack resources or a country is developing at high speed, money, infrastructure, and an abundance of material goods greatly influence happiness, whereas when a society is developed and people do not experience poverty, factors such as communication, education, and spiritual life become more important than material goods. Future studies could take subjective approaches into account.

#### 4. Conclusion

This study investigated the relationship between three indicators ( $EROI_{soc}$ , EC per capita, and GDP per capita) and eight QoL indices, comparing between 29 OECD and 37 non-OECD countries over the 25 years from 1990 to 2015.  $EROI_{soc}$  was selected as an indicator of energy quality, EC per capita was used to represent energy quantity, and GDP per capita was used as an economic factor. In order to include many countries and investigate the annual changes in the relationship between energy quality and QoL, the method for calculating  $EROI_{soc}$  proposed by Lambert et al. (2014) was modified. Simple linear regression analysis was applied to determine the correlation coefficients between the three indicators and eight QoL indices, and their annual changes from 1990 to 2015. We have found that the relationship between the three indicators ( $EROI_{soc}$ , GDP per capita, and EC per capita) and eight QoL indices changes annually and differs between OECD and non-OECD. More specifically, our study demonstrated that although GDP per capita is the most influential factor among the

three indicators in HDI, which is one of the best-known composite indices of well-being, the importance of GDP per capita for non-OECD has declined, especially in times of increasing energy prices, while the importance of  $EROI_{soc}$  for OECD has increased.

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