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On the correlation between the Human Development Index and electrical energy use

Sobre a correlação entre o Índice de Desenvolvimento Humano e o uso de energia elétrica

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Abstract: This paper examines why scholars fail to agree about the causality direction that characterizes the correlation between the United Nations Human Development Index (HDI) and electrical energy use, and tries to mathematically describe this correlation, from empirical evidence, through a logarithmic formula. It was found out that this use grows faster than that of primary energy in developed and developing countries, a sign that indicates the indispensability and versatility of this secondary (electrical) form of energy, for which there seems to be a minimum per capita use value, weighted in terms of energy intensity, if a country or region is to climb up to the higher level of the HDI ranking. The correlation curve, however, assumes an asymptotic shape as HDI gets higher, thus indicating that this use has points of saturation. The aforementioned formula, aimed at simplifying energy policies, was tested globally, regarding its accuracy, in relation to actual HDI values.

Keywords: Electrical energy, Human Development Index, correlation, energy intensity.

Resumo: Este artigo examina por que os estudiosos não concordam sobre a direção da causalidade relativa à correlação entre o Índice de Desenvolvimento (IDH) e o uso de energia elétrica e procura descrever matematicamente essa correlação, a partir de evidências empíricas, mediante uma fórmula logarítmica. Verificou-se que esse uso cresce mais rápido do que o de energia primária nos países desenvolvidos e em desenvolvimento, o que indica a indispensabilidade e versatilidade dessa forma secundária (elétrica) de energia, para a qual parece haver um valor mínimo de uso *per capita*, ponderado em função da intensidade energética, se um país ou região almeja alcançar o nível mais alto do IDH. A curva de correlação, no entanto, assume uma forma assimptótica à medida que o IDH aumenta, indicando que esse uso possui pontos de saturação. A fórmula mencionada, visando a simplificar as políticas energéticas, foi testada globalmente, quanto à sua precisão, em relação aos valores reais do IDH.

Palavras-Chave: Energia elétrica, Índice de Desenvolvimento Humano, correlação, intensidade energética.

1 Introduction

From a strict point of view, the evolution of human culture is strongly linked to the discovery of new energy sources and the development of corresponding conversion technologies [1]. Most notably, since the beginnings of the Industrial Revolution, humans have been dependent on vast amounts of controllable energy that are, for the most part, extracted from fossil fuels [2] [3].

Yet, energy is not a variable in most traditional models of economic growth [4] and, in cases in which it is, investigating its unified role in economics requires studying the aggregation of different energy flows. For this purpose, many methods have been proposed, although none of them is universally accepted [5] [6]. Besides that, since the late 1970s, when Kraft and Kraft [7] presented their seminal note about the correspondence between energy use and economic growth, there have been several studies dedicated to corroborating (or challenging) the results obtained by these pioneer authors, but no common sense has been achieved [8].

This paper has two main purposes. First, it attempts to explain why scholars fail to agree about this correlation; and second, it aims at presenting an objective way to correlate electrical energy use and human development, the latter being a desirable effect of economic growth.

2 Material and methods

Scientific studies usually attempt to statistically establish the causality direction that rules the correlation between energy use and economic growth / human development, but have failed to agree in their results, and the question seems to be far beyond a common answer, although it is possible to distinguish four basic inferences [9]. The first of them sees a direct correspondence between the two variables, running from energy use to economic growth. The second one also sees a correspondence, but in the opposite direction, i.e., from economic growth to energy use. The third one treads a middle path, finding a bidirectional correlation, while the fourth inference rules out any correlation – in this case, the two variables would not be correlated [9].

Such controversy has some evident implications. A policy of energy saving, for example, would adversely impact the economic growth according to the first theory, but would be neutral according to the fourth and even desirable according to the second (in this latter case, meaning that additional infra-structural investment on energy supply would be rendered unnecessary).

2.1 Why statistics cannot properly determine causation

The conflict about the causality direction probably results from an inherent incapability of manipulating all the intervenient variables that, to some extent, affect the phenomenon [10]. Also, the researcher is an unremovable part of the researched framework, thus subjectively ending up interfering with the results [11], being unable to see the reality from the outside, a point of view that would be essential to unequivocally affirm that something happened prior to another thing.

Anyway, to precisely labelling events as cause or effect, they would have to be plotted along some sort of “arrow of time” [12] – an abstract entity that is dependent on the thermodynamic asymmetry. That is the reason why the only way to undisputedly distinguish cause from effect is by measuring entropy – i.e., by asking help from the second law of thermodynamics: as the arrow of time always points to higher entropy, the lower the entropy, the less advanced the events will be along the arrow of time. But then again, this measure is not practically possible to be performed [12].

2.2 When the method seems to be more important than the test

Despite these impossibilities, in order to make any study of this kind scientifically accepted, some probabilistic tests seem to be appropriate – standard econometric analyses are indeed useful to detect correlations, for example. The complexity of the problem appears to grow, however, as scholars make use of probabilistic tests that seem to suffer from what has been called “statistical machismo” [13], whose main symptom is the adoption of the most complicated and exotic statistical method / tool that is currently available in order to define not only correlations, but the causality direction of events that are correlated to each other.

The vast majority of studies about energy and economic growth / human development use varieties of Granger tests (to mention a few of them: [14] [15] [16] [17] [18]), even though the late Granger [19] himself had warned about possible adverse implications of an indiscriminate use of his method. While this behaviour may be a result of the popularization of computer-based statistical tools, now available to a larger public, the considerable disagreement between the results obtained should be a clear indication that there is something wrong with such approach.

With all due respect for the researchers involved with the issue, the whole controversy may be attributed to the impossibility of unequivocally determining cause and effect (i.e., the causality direction) without recurring to entropy, regardless of the complexity of the method they can possibly adopt. In such case, the complexity, besides being costly (a waste of time and – no pun intended – energy), does not necessarily aggregate certainty to the results. On the contrary, it is a source of controversy.

As Eddington [12] pointed out, even if “the direction of the [time’s] arrow could be determined by statistical rules, […] its significance as a governing fact ‘making sense of the world’ could only be deduced on teleological assumptions.” This is corroborated by Kant’s [20] claim that even the very ability to make hypothetical judgements requires the concept of cause and effect; i.e., some aprioristic knowledge is required to support any claim stating that a certain property is connected to another.

As a result, a compromising amount of deviation is inherently part of statistical tests, as a side effect of subjectivity – the scholar / researcher is, ultima ratio, the one who decides the method, the period under analysis and the lag (stationarity) between variables. In such scenario, discrepancies are exacerbated by the fact that even a small variance in determining the lag can be enough to completely change results and, consequently, conclusions, as has been demonstrated by Akarca and Long [21], whose study was the first to defy the 1978 Kraft and Kraft paper. In other words, it seems that it is the researcher, rather than the statistical method all by itself, who ultimately defines the direction of causality, thanks to the interference induced to the experiment, something that is independent of the test methodology applied.

To partially circumvent these limitations, the use of “as few variables as you dare, as many as you must” [22] would be an ideal first step, allowing the researcher to focus on a smaller amount of information, which could thus be more easily controlled [10]. This is only useful, however, if the chosen variables are intrinsically correlated to the facts of life that, although in a mediate way, are the ones that politics care about. In general, scholars’ studies deal with energy at large (primary energy), and not with electrical energy in particular; in the same way, such studies are usually directed to economic growth, and not to human development, despite the marked differentiation that has to be made about these latter two, as pointed out by the United Nations (UN) [23] [24]. About that, energy is arguably a propeller for economic growth (in a more direct way) and for human development (mediately) [25] [6] [26] [5].

3 Theory / calculation

Despite the scholars’ thematic preference for energy in general (i.e., primary energy), it should be first noted that the energy that is prominent, because no other can replace it (at least in the foreseeable future), is the electrical one. Without it, even the exploration and use of fossil fuels, which are considered the basis of contemporary society, representing 67.4% of the total primary energy nowadays [3] would be rendered impossible, as well as any sort of computers and the internet, which is accounted for as the driver of a new social revolution [27] [28].

3.1 The correlation between electrical energy use and human development

The UN is aware of how important electrical energy is to human development and has highlighted, although in a highly variable degree of assertion, the insurmountable barrier imposed, by the lack of this energy, to the nations success – this energy makes possible the use of newer technologies and is also a pervasive input to several human activities [29] [23] [30] [31].

So, it is not by chance that the percentage of the total primary energy that is accounted for by electrical energy has been ever increasing, and the limits to its use seem to be only coupled with the state of the art. For example, some years ago electric vehicles were confined to a niche market or to some indefinite time in the future – batteries were too heavy, range was too low (both because of a low energy density when compared to the likes of fossil fuels) and the costs were too high [32].

Today, however, one can argue that “the future has already arrived”, although “it’s just not evenly distributed yet” [33]. In Germany, for example, combustion engines vehicles are to be legally banned from 2030 [34], in a trend that will be possibly followed by other developed nations, while in some developing countries, such as Brazil, such transition is far behind that schedule, even in the most optimistic forecasts: the local government’s Energy Research Enterprise predicts hybrid systems (combustion engine and electric motor running together) holding a share, by 2050, of around 31% in the total number of sold vehicles [35].

In any case, when one sees the historical pattern of energy use and thinks of these possibilities, a strong correlation between electrical energy use and HDI perfectly makes sense, and this also puts the value of the discussion about the direction of causality in a different perspective, since it is quite reasonable to affirm that, from the very beginning, development demands energy, and not the opposite.

If one considers, based on the facts “making sense of the world” [12], that energy is preponderantly a cause for (and not an effect of) economic growth and human development, and that the post development use of energy, usually also relevant, although arguably a second-level effect of the initial use, is also a cause for additional use, it is anyway fair to say that these two variables – electrical energy use and human development – could be possibly defined as a function of each other, by a relatively simple formula.

3.2 The importance of weighting energy use

One obvious way to pre-start the building up of such formula is observing the graphical pattern of these two variables, i.e., how they develop when covering a certain range of countries or regions in a certain time. However, in order to minimally avoid discrepancies in the energy use measurement – such use would be, for example, a result of a more / less rational, productive use of energy, or a consequence of the preponderance of a certain industrial matrix in some country / region (aluminum industry, for example, is very energy demanding) [36] –, it should be weighted in terms of energy intensity, here defined as the correspondence between an amount of energy used and the Gross National Product (GNP) that this amount aggregates [37]. In a global measure, purchasing power parity dollars ($ PPP) must be used to avoid local, particular influences, such as artificial currency depreciation (exchange rate) determined by fiat, thus making possible an international comparison (just as it happens to HDI) [38].

Although energy intensity is usually related to primary energy, it can be satisfactorily used for weighting electrical energy use, since both energies show nearly identical graphical trends through the years (graph’s horizontal axis in Figure 1), even though their development is uneven – with both starting from level 1 (to allow a more properly comparison), electrical energy use tends to go higher on the graph (vertical axis in Figure 1), meaning its percentage of total primary energy is ever higher, as can be seen in Figure 1 and Figure 2 (primary data source: [39]), the first corresponding to a developed country (the United Kingdom) and the second to a developing one (Brazil).

Since electrical energy seems to have a growing preponderance in relation to the total primary energy used, and since its intensity seems to be properly weighed from the primary energy one, it is reasonable to verify whether there is a graphic pattern highlighting any non-random correlation between these two variables: the weighted per capita electrical energy use, hereinafter referred to as PCEEU and calculated on a monthly basis, and HDI (Figure 3; primary data sources: [40] [24] [39].

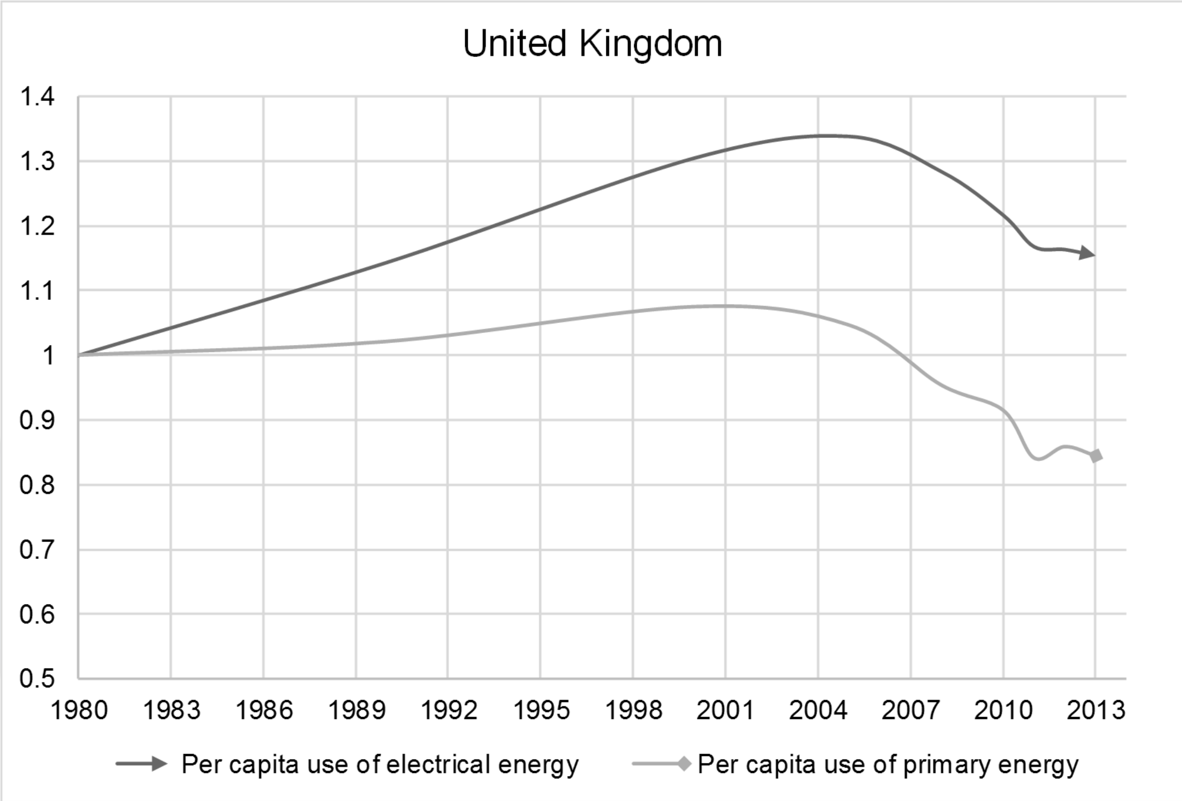

Figure 1: Tendencies regarding per capita energy use (primary and electrical) – United Kingdom.

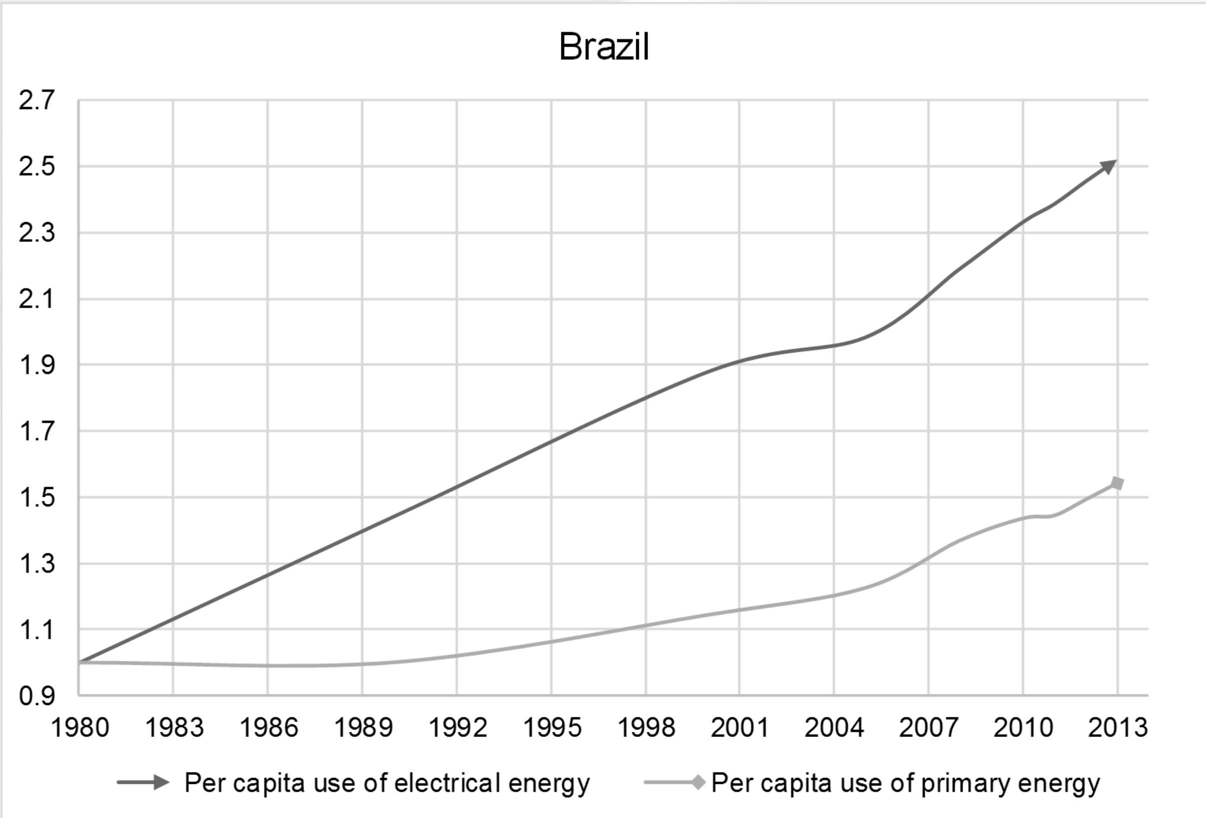

Figure 2: Tendencies regarding per capita energy use (primary and electrical) – Brazil.

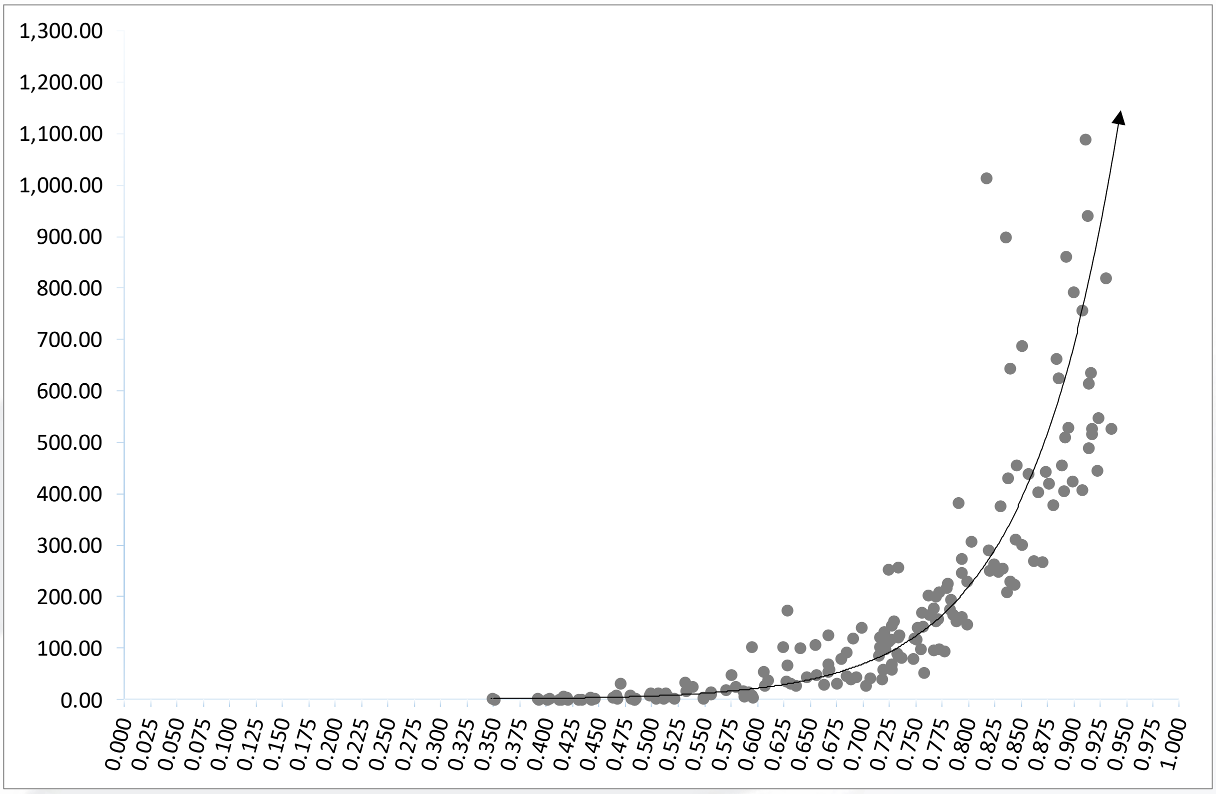

Figure 3: Dispersion of countries according to their HDI values and in relation to their respective PCEEU.

From the HDI distribution pattern (along the horizontal axis in Figure 3) and the PCEEU (vertical axis in the same figure), both covering almost every single country (round-shaped dots) in 2014 (Figure 3), it is possible to notice that the line grouping the countries together assumes a smooth, asymptotically curved shape, a sign that (1) HDI and PCEEU are correlated to each other, and that (2) this correlation is weakened as HDI gets higher.

3.3 Limits for a productive use of electrical energy – saturation points

The behaviour made obvious by the asymptotic curve indicates that saturation points tend to appear after a certain level of energy use is reached, a symptom that productive electrical energy use is dependent on the state of the art and on the local development level. In a simple, practical example, the adequate use levels in 2019 are in general much higher than those of, say, 1919, since there were very few uses to electrical energy a hundred years ago. For the same reason these levels are higher, although close to saturation, in developed countries, which, contrary to developing ones, usually make use of electrical energy in every way that is humanly possible (again, the user is referred to the patterns shown in Figures 1, 2 and 3). These observed patterns then tell that developed countries tend to present weaker correlations between HDI and energy use, thus shaping the asymptotic curve shown in Figure 3.

4 Results and discussion

The aforementioned hypotheses are corroborated by some statistics tests herein reported, covering the ten biggest economies in the world – a group that accounts for over 60% of the global gross domestic product (GDP) and includes developed and developing countries. It is worth note once again that these tests, whose results are summarized in Table 1 (primary data sources: [24] [39]), can be considered satisfactory in determining correlation, which is mainly indicated by R-square, while the causation is doubtfully, weakly assumed from P-value and from Residuals after the a priori (i.e., before data processing) determination of both directionalities, according to the statements previously presented in this paper. These tests were run using Excel® Statistical Package.

Table 1: Regression statistics – summary and synthesis. Variables: PCEEU and HDI. Causality running from one variable to the other, in both directions.

Regression statistics – summary of results. Confidence Interval: 95%. Period: 1990-2013.

Direction of causality: PCEEU → HDI

	Germany	United States	France	Japan	United Kingdom
R-square:	0.7337038422	0.5007491542	0.8483941444	0.7285030500	0.2132455252
P-value (intersection):	0.0024497600	0.0000000016	0.0000000023	0.0000000000	0.0025373423
Significance F:	0.0000000924	0.0001098782	0.0000000002	0.0000001147	0.0231085827
Residuals – % (dep. var.):	1.61%	1.02%	1.12%	1.09%	3.49%

	Brazil	China	India	Indonesia	Russia
R-square:	0.9254088246	0.9191781883	0.9321982450	0.9714565118	0.5490936042
P-value (intersection):	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
Significance F:	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000344412
Residuals – % (dep. var.):	1.42%	2.84%	2.51%	1.02%	1.65%

	World
R-square:	0.9712528561
P-value (intersection):	0.0000000000
Significance F:	0.0000000000
Residuals – % (dep. var.):	0.72%

Residuals – simple average: 1.68%

Direction of causality: PCEEU ← HDI

	Germany	United States	France	Japan	United Kingdom
R-square:	0.7337038422	0.5007491542	0.8483941444	0.7285030500	0.2132455252
P-value (intersection):	0.6816997982	0.1089793799	0.0004679076	0.0004108747	0.0291720270
Significance F:	0.0000000924	0.0001098782	0.0000000002	0.0000001147	0.0231085827
Residuals – % (dep. var.):	2.36%	2.57%	2.13%	3.14%	4.20%

	Brazil	China	India	Indonesia	Russia
R-square:	0.9254088246	0.9191781883	0.9321982450	0.9714565118	0.5490936042
P-value (intersection):	0.0000000012	0.0000000000	0.0000000002	0.0000000000	0.0099711493
Significance F:	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000344412
Residuals – % (dep. var.):	3.47%	15.31%	6.61%	5.31%	5.18%

	World
R-square:	0.9712528561
P-value (intersection):	0.0000000000
Significance F:	0.0000000000
Residuals – % (dep. var.):	1.85%

Residuals – simple average: 4.74%

Regression statistics – indicators

Country	Spurious relationship	Determination	Direction – Residuals	Direction – P-value
Germany	Yes	high	→	→
United States	Yes	moderate	→	→
France	No	very high	→	→
Japan	No	high	→	→
United Kingdom	No	low	→	→
Brazil	No	very high	→	→
China	No	very high	→	→
India	No	very high	→	→
Indonesia	No	very high	→	→
Russia	No	moderate	→	→
World	No	very high	→	→

4.1 Building up and developing the formula

Going back to Figure 3, it is possible to ask the computer program Excel® to reveal the formula of the curve. By doing so, the return is *PCEEU* = 0.0209 * $e^{11.59\ HDI}$, for which the R-square is 89%. This formula can be mathematically developed, in order to isolate HDI as a function of PCEEU, as shown in Equation 1.

$$e^{11.59\,HDI} = \frac{PCEEU}{0.0209} \leftrightarrow log_e\left(\frac{PCEEU}{0.0209}\right) = 11.59\,HDI \leftrightarrow \boldsymbol{HDI} = \frac{\boldsymbol{log_e}\left(\frac{PCEEU}{0.0209}\right)}{\mathbf{11.59}} \quad (1)$$

Once the “very high” HDI starts at 0.800, this value is used in the formula to calculate the corresponding PCEEU. The result is 222.29 kWh, rounded down to 222 kWh and provisionally taken as the minimum necessary to achieve that HDI level. To give credit to this hypothesis, the number obtained should be challenged by specific empirical data, which is provided, for example, by the World Bank indicators [39].

4.2 Validating the minimum PCEEU that is compatible with a “very high” HDI

By segmenting Figure 3 into Figure 4 and Figure 5 (primary data sources: [40] [24] [39]), it is possible to see that there is a barrier separating countries with a “very high” HDI (i.e., equal to or higher than 0.800 according to the current UN methodology) from those with a “high” index (higher than 0.700 and lower then 0.800) [19]. The three lowest PCEEU of the “very high” HDI group are 210.08 kWh (Argentina), 225.41 kWh (Poland) and 230.19 kWh (Lithuania). The geometric mean of these three values is 221.73 kWh and the arithmetic mean is 221.89 kWh.

Thus, the aforementioned barrier really seems to be currently around 222 kWh. There are only two real exceptions – Albania and Libya –, both with a PCEEU higher than that but with HDI values that are considerably far from the “very high” level – respectively, 0.733 and 0.724. There are four other countries (the Bahamas, Oman, Uruguay and Russia) ranking at the “high” HDI level and using more than 222 kWh per capita, but all of them are on the verge of the “very high” status, with HDI ranging from 0.790 to 0.798, too close to 0.800 to be considered real exceptions. Additionally, none of the countries belonging to the “medium” or to the “low” HDI groups (not shown here) is even close to the 222 mark.

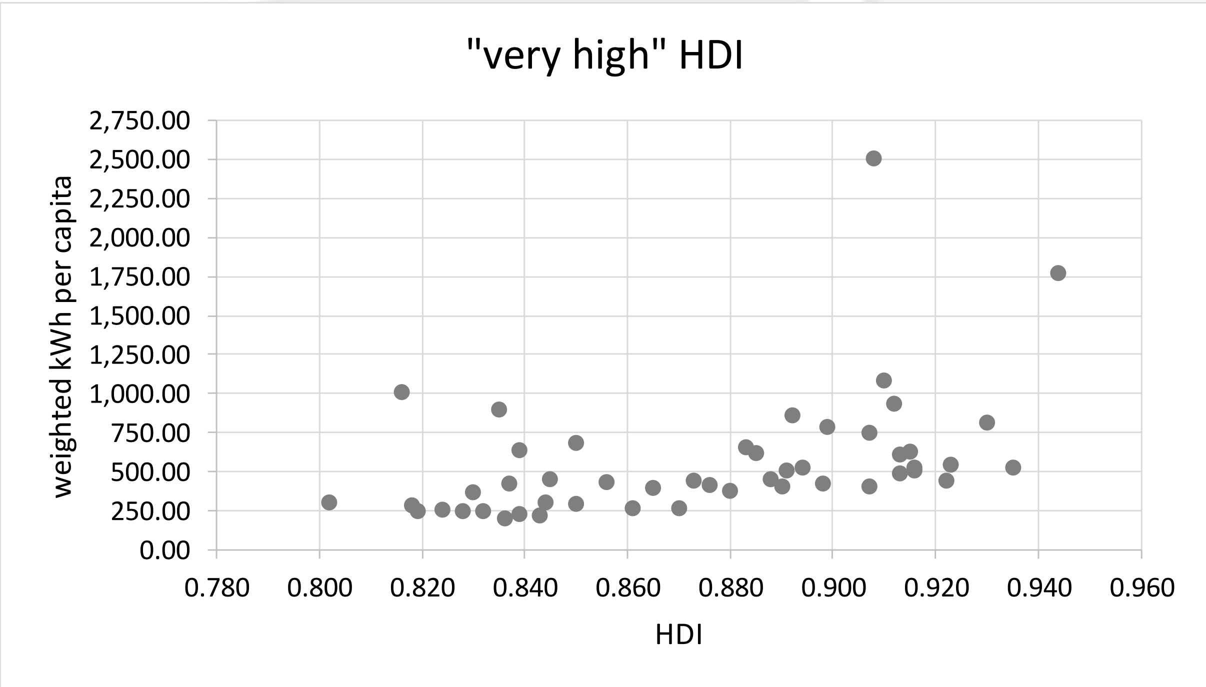

Figure 4: Dispersion of “very high” HDI countries according to their respective PCEEU.

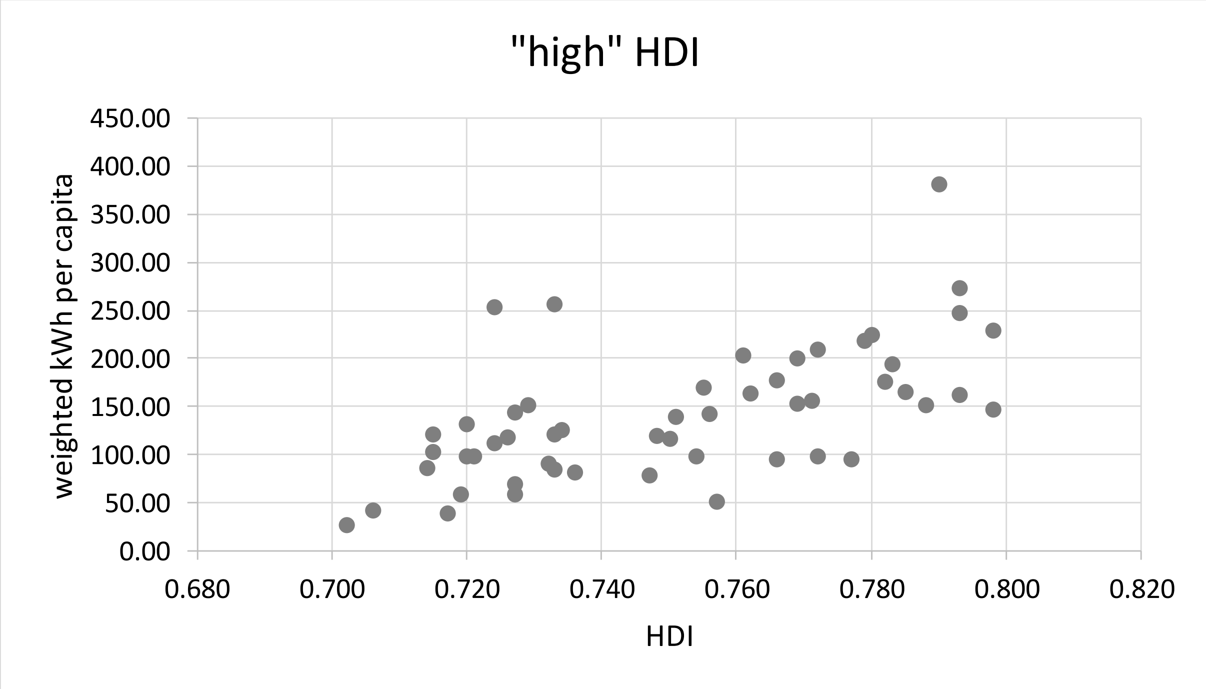

Figure 5: Dispersion of "high" HDI countries according to their respective PCEEU.

Libya and Albania cases can be explained, anyway, by very particular circumstances – an unrestricted, non-productive and even illegal residential use of energy, made possible by a high supply capacity that is a remnant of the Iron Curtain times (Albania was then a satellite of the former Soviet Union) [41] [42], and an economy that is almost entirely dependent – 70% of GDP and 95% of government revenues – on oil industry (a high energy-demanding sector) in a country that has been highly unstable since the end of the Gaddafi era, in 2011 [43] [44].

4.3 Testing the accuracy of the formula for a comprehensive set of countries through the years

In order to validate the formula for a wide-ranging use, it should be tested not only for as many countries as possible, but also through a certain period. Although some discrepancies are expected through this process, given that the state of the art is not static, the general graphical patterns thus generated are expected to be kept undistorted, since the thesis' fundamentals are supposed to remain basically the same.

These patterns can be checked by comparing Figure 6 and Figure 7 (primary data sources: [24] [39]), which cover the 1990-2014 period (since the creation of the HDI) and 16 countries. These countries have been chosen because they are the world's biggest economies in absolute values, accounting for more than 70% of the global GDP [35] and, as well as the first group (which is encompassed by this bigger one), including rich and poor, developed and developing countries. The reason to not graphically select all world countries is only because it is not feasible to properly display the results in this paper. It must be said, however, that the results are equally undistorted when all countries (133, for which there are HDI and energy use values for the mentioned period) are considered – results obtained are on average 96.58% of the actual HDI.

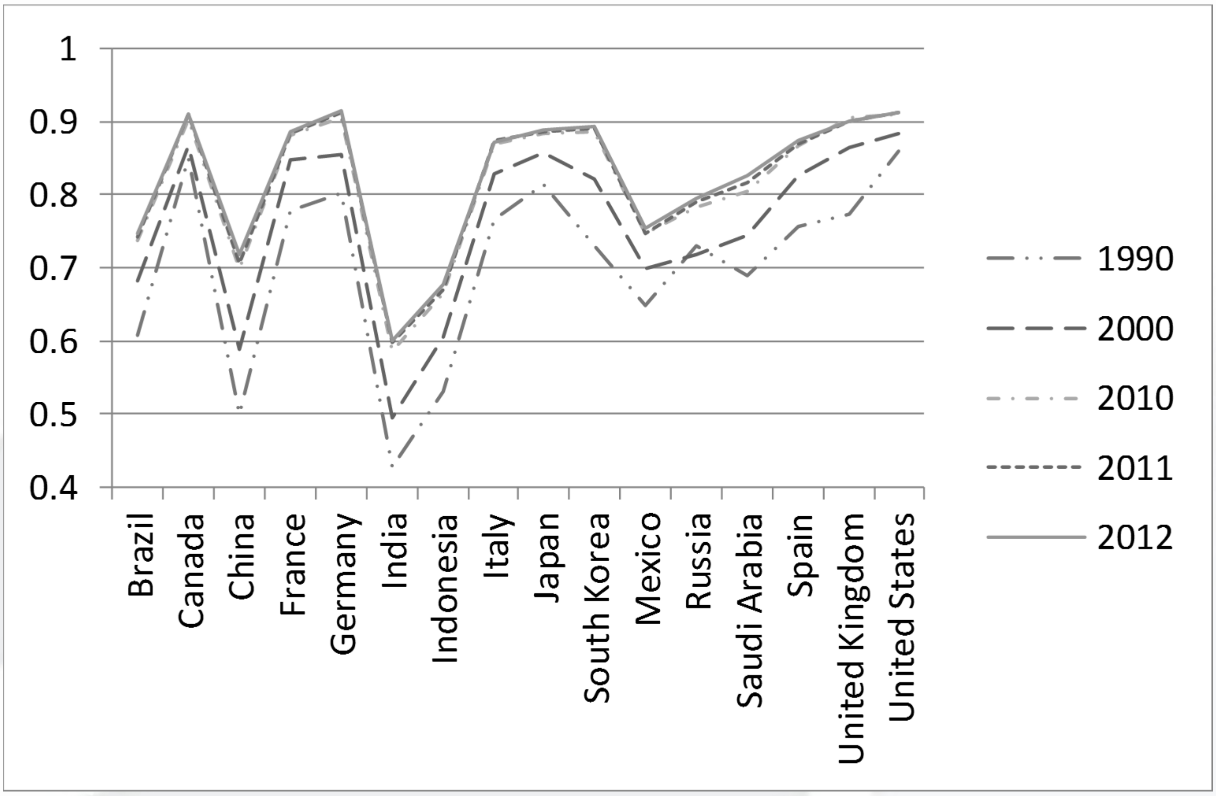

Figure 6: HDI distribution for the world's 16 largest economies (PPP GDP) (representing over 70% of the world's PPP GDP) – actual values.

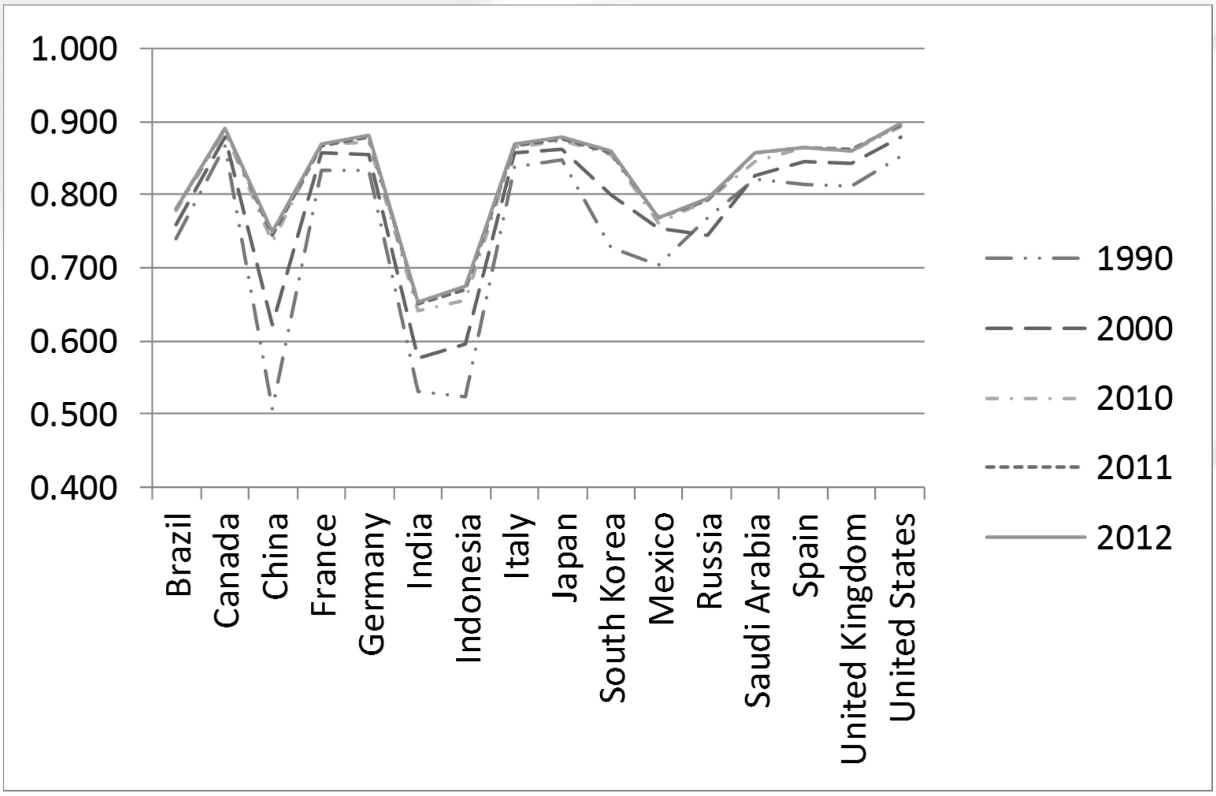

Figure 7: HDI distribution for the world's 16 largest economies (PPP GDP) – HDI values obtained via the logarithmic formula.

As can be seen through Figures 6 and 7, the logarithmic formula seems to be able to, all by itself and satisfactorily, predict HDI from weighted electrical energy per capita use, thus elegantly prescinding, at least in a first cognition, from a complex set of a myriad of variables, which, thanks to its inherent complexity, tends to lead to controversy and spurious results, thus jeopardizing energy public policies and, consequently, the achievement of the desired level of economic growth and human development.

5 Conclusions

Given the affordability and indispensability of electrical energy, its use tends to grow faster than that of primary energy (i.e., electrical energy accounts for an ever-higher share of the total primary energy), although both growths show, regarding other aspects, a similar development pattern.

Statistical tests, regardless of their complexity, are inherently incapable of unequivocally determining the direction of causal correlation between energy and economic / human development, mainly because this direction can only be determined a priori, from the facts making sense of the world.

The correlation between electrical energy use (weighted in terms of energy intensity) and HDI graphically shows a smooth, asymptotic curve that can be objectively defined by a very simple mathematical formula, which has been validated universally and through the years. This formula indicates that there is a minimum per capita use of electrical energy if a country is to achieve a “very high” HDI. This indication seems to be consistent with empirical observations.

The asymptotic pattern indicates there are maximum values for development-inducing energy use (saturation points), which are limited by the state of the art.

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