International Journal of Energy and Environmental Research
Vol.5, No.3, pp.1-18, November 2017
Published by European Centre for Research Training and Development UK (www.eajournals.org)

SETTLEMENT BY ENERGY – CAN RENEWABLE ENERGIES SUSTAIN OUR CIVILISATION?

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ABSTRACT: *This article contributes to explaining the recently observable acceleration in the growth of output in renewable energies, through studying the fundamental role of renewable energies in sustaining human settlement. A model of general equilibrium is introduced, based on the logic of the original production function by Cobb and Douglas, where the size of the human population in a given place at a given time is in equilibrium with the available food and energy. Empirical check provided for the model strongly suggests that renewable energies can sustain the majority of local human populations on Earth, and most countries, with the intriguing exception of China and India, can sustain significantly bigger populations than their present ones, by reorienting their economies totally to renewable energies.*

KEYWORDS: Renewable Energies, Production Function, General Equilibrium, Sustainability, Technological Change

JEL Code(s): C52, O3, Q01

INTRODUCTION

The purpose of this article is to explore the social and economic role of renewable energy, and more specifically, to assess the relative importance of renewable energies in the development of human communities. In 2007 – 2008, the rate of growth in the market of renewable energies changed, and became higher than the rate of growth in the overall, final consumption of energy. This change in trends is observable on the grounds of data published by the World Bank, regarding the consumption of energy per capita (https://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE), and the share of renewable energies in that overall consumption (https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS). This change of slope was something of a historical precedent since 1990. In 2007 – 2008, something important happened, and still, to the author's knowledge, there is no research explaining what that something could possibly have been. Some kind of threshold has been overcome in the absorption of technologies connected to renewable energies. This article is a contribution to explaining that phenomenon, by bringing a fundamental study of substitution between renewable energies and the non-renewable ones, in the process of sustaining human settlement.

Technologies have the peculiar capacity of bending social structures around them, and, in return, social structures tend to give birth to technologies either adapted to social environment, or apt to bring a specific kind of change in said environment. Still, that mutual shaping of technology and society seems to be far from recurrently progressive. Since the seminal metaphor of struggling civilisations, to find in Arnold Toynbee's 'Study of History'(Toynbee 1946[1]), the idea of developmental leaps seems to have caught on. In an interesting book,

[1] Toynbee, J. A., 1946, Study of history. University press, 1946, pp. 69

entitled 'Shock of the old: Technology and global history since 1900' (Edgerton 2011[2]), David Edgerton points out that we commonly live in an illusion of constant technological progress, i.e. of a process, which consistently brings improvement in the conditions of living, as technology changes. Edgerton shows, quite convincingly, that technological change is not necessarily to put at equality with technological progress. According to his findings, there were just a few periods of real technological progress since 1900: between 1900 and 1913, followed by another between 1950 and 1973. Save for those short windows in time, the link between technological change and the conditions of living is really ambiguous. The findings and intuitions by David Edgerton inspire to study very carefully those historical moments of obvious technological leap, as the 2007 – 2008 change in the growth rate of output in renewable energies.

Probably since the works of Karl Marx, the concept of mutual interaction between technology and society has been quite vivacious (see for example: Mumford 1964[3], McKenzie 1984[4], Kline and Pinch 1996[5]). Some research suggests that we are talking about an interaction full of bends and turns, far from being fully logical and straightforward (see: David 1990[6], Vincenti 1994[7]). Still, some clear patterns are identifiable in this interaction. Technologies can truly and deeply transform social structures when they have the capacity to simplify themselves for their end-users (see Mahoney 1988[8]), whilst creating an increasing complexity inside themselves (Ceruzzi 2005[9]). As far as renewable energies are concerned, some research suggests that broad technological mixes, combining many different sources of energy, are more easily absorbable in the social environment than the mono-energy solutions (see: Sen, Bhattacharyya[10]). In other words, renewables truly catch on, when they can offer many, simple Ford-Model-T-equivalents of power: accessible and cheap. On the other hand, the development of renewable energies as an industry seems to be closely and mutually correlated with the most simply approached growth of production and exports in all the industries surrounding renewables (see: Lund 2009[11])

The central intuition of the here-presented research is that that human societies are sustained by energy, and we absorb energy through two fundamental channels: by feeding ourselves and by developing technologies, which, in turn, tap into non-edible energies. The social (i.e. society-building) role of renewable energies can be approached as the capacity of essential energy-tapping technologies to sustain human population, or, in mathematical terms, as a function where 'Population = f(Absorption of energy)'. Empirical research supplies strong evidence that renewable energies have a substantial capacity to create sustainable societies in

[2] Edgerton, D. (2011). Shock of the old: Technology and global history since 1900. Profile books
[3] Mumford, L., 1964, Authoritarian and Democratic Technics, Technology and Culture, Vol. 5, No. 1 (Winter, 1964), pp. 1-8 Published by: The Johns Hopkins University Press on behalf of the Society for the History of Technology
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[6] David, P. A. (1990). The dynamo and the computer: an historical perspective on the modern productivity paradox. The American Economic Review, 80(2), 355-361.
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places, where such structures previously couldn't sustain themselves (UNFCC 2015[12], World Bank ESMAP 2016[13]). Thus, the role of renewable energies can be studied as their capacity to supplant the non-renewable ones in sustaining a human population in a given place at a given moment. The economic wisdom in approaching deep social changes is that such leaps can take place when a new combination of factors creates as sustainable an equilibrium as an old combination. The so-called 'new economic geography', with, among others, the seminal contributions by Paul Krugman (Krugman 1991[14]; Krugman 1998[15]) comes as a significant support. The same mechanisms, which sustain economic equilibrium, act as factors of spatial differentiation in human settlement, through the distinction into economic core and its periphery. Going even deeper in theory, it can be noticed that the fundamental framework of this paradigm taps into the logic of the original production function, as it had been formulated by Prof Charles W. Cobb and Prof Paul H. Douglas (Cobb, Douglas 1928[16]).

All the above premises have inspired the author to conduct further research as a verification, and exploration, of the following **hypothesis: the geographical structure of human settlement, as measured with the size of population in a given country at a given moment, is significantly determined by the capacity of the population in question to sustain general equilibrium on the grounds of available energy**.

The model

The theoretical model used in the here-presented research is based on the original production function, as it had been formulated by Prof Charles W. Cobb and Prof Paul H. Douglas (Cobb, Douglas 1928) as well as on a later adaptation of the same logic in the so-called 'new economic geography' (see for example: Krugman 1991; Krugman 1998). Mathematically, this is a combination of two factors, which together produce an aggregate utility, with each factor contributing to said aggregate utility through a logarithm, and the magnitudes of their respective logarithms summing up to one, whilst reflecting the relative importance of the given factor in generating aggregate utility. In the original theory of production by Cobb and Douglas, as well as in the application to economic geography by Paul Krugman, one of the two factors is supposed to be the dominant one, i.e. endowed with significantly higher a logarithm. In the geographical application, this precise factor is supposed to be, in the same time, pivotal in creating spatial differentiation of human settlement: it is the logic of core as opposed to periphery. The general, mathematical construct is as shown in equation (1), where F1 and F2 are the two factors producing aggregate utility 'U', and 'A' is a scale factor (is shows the proportion between the output of the two factors combined on the right side of the equation, and aggregate utility on the left side). The factor endowed with power μ is assumingly the dominant and differentiating one.

$$(1)\ U = F1^{\mu} \times F2^{1-\mu} \times A \qquad \mu < 1$$

[12] United Nations Climate Change Secretariat (UNFCC), 2015, Climate Action Now: Summary for Policymakers 2015, ISBN 978-92-9219-163-4
[13] World Bank, 2016, Assessing and Mapping Renewable Energy Resources, Energy Sector Management Assistance Program (ESMAP), Knowledge Series 025/16
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[16] Charles W. Cobb, Paul H. Douglas, 1928, A Theory of Production, The American Economic Review, Volume 18, Issue 1, Supplement, Papers and Proceedings of the Fortieth Annual Meeting of the American Economic Association (March 1928), pp. 139 - 165

As suggested in the original work by Cobb and Douglas, the general type of equation (1) has real explanatory power when the scale factor ‘A’ displays recurrent a value, with low variability (Cobb, Douglas 1928). Obviously, the respective logarithms ascribed to both factors on the right side play a significant role in obtaining such a recurrent scale factor, which, in turn, means that the choice of the dominant factor (raised to power μ) is significant for obtaining a robust equation. Such choice can be made through the original methodology by Cobb and Douglas, i.e. through partial differentiation of aggregate utility on each of the factors. A slight mutation of this original approach consists in linear regression of natural logarithms in, respectively, aggregate utility, on those of the input factors. The coefficients of such regression can be a good starting point for testing the actual powers, which will yield a robust equation in the type (1). The choice of the dominant factor can also be based on the logic presented by Paul Krugman (Krugman 1991): the dominant factor, raised to the dominant power μ should be that of the two, which allows more precise a definition of distinct component goods, with clearly cut rates of substitution between them.

In the present model it is being hypothesised that any human community strives to maximize the absorption of energy from environment. Aggregate utility derived from this absorption is the size of population in the given time and place, to be subsequently represented as ‘**N**’. Absorption of energy takes place through its use ‘**E**’ (e.g. fuel burnt in vehicles or electricity used in house appliances) and through its absorption as food, further symbolized as ‘**F**’. Thus, we have two consumables - energy and food – and one of the theoretical choices to make is to point at one of them as dominant a factor. In this model, the last path of choice, i.e. that suggested by Paul Krugman (Krugman 1991) has been chosen. Patterns of mutual substitution between different foodstuffs seem highly idiosyncratic, with respect to geographical regions. On the other hand, different forms in the final use of energy are much more unequivocally defined due to the global reach of the core technologies in human civilisation. Hence, patterns and rates of substitution seem to be much clearer in the final use of energy, than in the absorption of food. This intuition leads to positing equation (2):

$$(2)\ N = E^{\mu} \times F^{1-\mu} \times A \qquad \mu < 1$$

It can be plausibly assumed that quantities of input on the right side in equation (2) are actually intensities per capita in, respectively, energy use and absorption of food, rather than their absolute volumes. Thus, a mutation of equation (2) is being posited, as equation (3), where:

$$(3)\quad N = \left({}^{E}/_{N}\right)^{\mu} \times \left({}^{F}/_{N}\right)^{1-\mu} \times A \qquad \mu < 1$$

Although the scale factor ‘A’ in both equations, i.e. (2) and (3), can technically take any value, the author assumes that it is worth adopting the original logic by Cobb and Douglas, and expect A to be slightly above 1, let’s say 1 < A < 1,1. It follows from the view that the right side of equations (2) and (3) produces something like a potential to create output visible on the left side, and yet those two factors do not exhaust all the phenomena, which make that output.

In the next section, and empirical check for the model is being provided.

The empirical check

The fundamental purpose of the here-presented empirical study is to assess the relative importance of renewable energies in the development of human communities, and the assessment has been conducted using the model presented in the previous section. Naturally, that empirical goal has been achieved in stages, starting from the fundamental evaluation of robustness in the model, passing through assessing the importance of the overall energy use in the formation of human population, to arrive, finally, at assessing the specific role of renewable energies. This section gives a synthetic account of quantitative experiments conducted by the author in a compound dataset, made of Penn Tables 9.0 (Feenstra et al. 2015[17]), enriched with data published by the World Bank (regarding the consumption of energy and its structure regarding 'renewable <> non–renewable'), as well as with data published by FAO with respect to the overall nutritive intake in particular countries. Data regarding energy, and that pertaining to the intake of food, is limited, in both cases, to the period 1990 – 2014, and the initial, temporal extension of Penn Tables 9.0 (from 1950 to 2014) has been truncated accordingly. For the same reasons, i.e. the availability of empirical data, the original, geographical scope of the sample has been reduced from 188 countries to just 116.

The first step in quantitative experimenting consisted in testing many different combinations of the available empirical variables, and different values on the parameter μ, so as to satisfy the general condition of stable and recurrent value in the scale factor 'A' in equations (2) and (3). The actually possible to achieve, minimal variances in the scale factor 'A' of both equations seem a fundamental test of robustness. Thus, formal conditions (5) and (6), have been posited, where 'var' stands for variance over time:

$$(5) \quad \min_{1990\rightarrow2014} var(A) = \min_{1990\rightarrow2014} var\left(\frac{N}{E^{\mu}\times F^{1-\mu}}\right)$$

$$(6) \quad \min_{1990\rightarrow2014} var(A) = \min_{1990\rightarrow2014} var\left(\frac{N}{\left(E/_N\right)^{\mu}\times\left(F/_N\right)^{1-\mu}}\right)$$

The author strived for narrowing down the possible values of the scale factor 'A' as close as possible to the original '1,01' found by Cobb and Douglas (Cobb, Douglas 1928). In formal mathematical terms, it means another pair of minimizing conditions, where the value being minimized is the average difference 'A – 1' over the period 1990 – 2014, whilst keeping this difference positive. The author believes that conditions (5) and (6) give enough information about the methodology adopted, and thus, for the sake of saving editorial space, these two following conditions are not specified separately, as equations. Once again in order to stay in the original spirit of Cobb and Douglas, the value of the parameter μ was being optimized up to the second decimal point. With an expected average A slightly above 1, the reasonably low variance means something not greater than 1/10th .

The first few quantitative experiments had shown that equation (2) is not really workable. The values of the scale factor 'A', when computed with aggregates in the consumption of energy, and in the alimentary intake, were two-digit values, thus very far from the condition of minimizing 'A – 1,01'. On the other hand, equation (3), with intensities per capita, seems to work smoothly. The empirical variables able to satisfy both equation (3), and condition (6), are: final use of energy per capita, in tons of oil equivalent (factor E/N), and alimentary intake of energy per capita, measured annually in mega-calories (thousands of kcal), and averaged over the period studied. Thus, the empirical mutation of equation (3) that produced reasonably robust results is the one, where a relatively volatile (i.e. changing every year) consumption of

[17] Feenstra, Robert C., Robert Inklaar and Marcel P. Timmer (2015), "The Next Generation of the Penn World Table" American Economic Review, 105(10), 3150-3182, available for download at www.ggdc.net/pwt

energy is accompanied by a long-term, de facto constant over time, alimentary status of the given national population. Thus, robust results can be obtained with an implicit assumption that alimentary conditions in each population studied change much more slowly than the technological context, which, in turn, determines the consumption of energy per capita. On the left side of the equation, those two explanatory variables matched with population measured in millions. In the logic of production function, empirical values are absolute ones, i.e. not logarithms or standardized values. Thus, the choice of correct units on both sides of the equation is crucial for further testing of the model.

Table 1, in the Appendix, gives the results of testing equation (3), with the above mentioned empirical variables, in 116 countries. The first numerical column of the table gives the arithmetical average of the scale factor 'A', calculated over the period studied, i.e. 1990 – 2014. The second column provides the variance of 'A' over the same period of time (thus the variance between the annual values of A), and the third specifies the value in the parameter 'μ' – or the logarithm ascribed to energy use per capita – at which the given values in A have been obtained. In other words, the mean A, and the variance of A specify how close to equilibrium assumed in equation (3) has it been possible to come in the case of a given country, and the value of μ is the one that produces that neighbourhood of equilibrium. The results from Table 1 seem to confirm that equation (3), with these precise empirical variables, is robust in the great majority of cases.

Most countries studied satisfying the conditions stated earlier: variances in the scale factor 'A' are really low, and the average value of 'A' is possible to bring just above 1. Still, exceptions abound regarding the theoretical assumption of energy use being the dominant factor that shapes the size of the population. In many cases, the value of the exponent μ that allows a neighbourhood of equilibrium is far below μ = 0,5. According to the underlying logic of the model, the magnitude of μ is informative about how strong an impact does the differentiation and substitution (between renewable energies, and the non-renewable ones), have on the size of the population in a given time and place. In countries with μ > 0.5, population is being built mostly through access to energy, and through substitution between various forms of energy. Conversely, in countries displaying μ < 0,5, access to food, and internal substitution between various forms of food becomes more important regarding demographic change. United States of America come as one of those big surprises. In this respect, empirical check brings a lot of idiosyncrasies to the initial lines of the theoretical model.

Countries accompanied with a (!) are exceptions with respect to the magnitude of the scale factor 'A'. They are: China, India, Cyprus, Estonia, Gabon, Iceland, Luxembourg, New Zealand, Norway, Slovenia, as well as Trinidad and Tobago. They present a common trait of satisfactorily low a variance in scale factor 'A', in conformity with condition (6), but a mean 'A' either unusually high (China A = 1.32, India A = 1.40), or unusually low (e.g. Iceland A = 0.02), whatever the value of exponent 'μ'. It could be just a technical limitation of the model: when operating on absolute, non-transformed values, the actual magnitudes of variance on both sides of the equation matter. Motor traffic is an example: if the number of engine-powered vehicles in a country grows spectacularly, in the presence of a demographic standstill, variance on the right side is much greater than on the left side, and this can affect the scale factor. Yet, variances observable in the scale factor 'A', with respect to those exceptional cases, are quite low, and a fundamental explanation is possible. Those countries could be the cases, where the available amounts of food and energy either cannot really produce as big a population as there really is (China, India), or, conversely, they could produce much bigger a population than the current one (Iceland is the most striking example). From this point of view, the model could be able to identify territories with no room left for further demographic growth, and those with comfortable pockets of food and energy to sustain much bigger populations. An interpretation in terms of economic geography is also plausible: these could be situations, where official, national borders cut through human habitats, such as determined by energy and food, rather than circling them.

Partially wrapping it up, results in Table 1 demonstrate that equation (3) of the model is both robust and apt to identify local idiosyncrasies. The blade having been sharpened, the next step of empirical check consisted in replacing the overall consumption of energy per capita with just the consumption of renewable energies, as calculated on the grounds of data published by the World Bank, and in retesting equation (3) on the same countries. Table 2, in the Appendix, shows the results of those 116 tests. The presentational convention is the same (just to keep in mind that values in A and in μ correspond to renewable energy in the equation), and the last column of the table supplies a quotient, which, fault of a better expression, is named 'rate of substitution between renewable and non-renewable energies'. The meaning of that substitution quotient appears as one studies values observed in the scale factor 'A'. In the great majority of countries, save for exceptions marked with (!), it was possible to define a neighbourhood of equilibrium regarding equation (3) and condition (6). Exceptions are treated as such, this time, mostly due to unusually (and unacceptably) high a variance in scale factor 'A'. They are countries where deriving population from access to food and renewable energies is a bit dubious, regarding the robustness of prediction with equation (3).

The provisional bottom line is that for most countries, it is possible to derive, plausibly, the size of population in the given place and time from both the overall consumption of energy, and from the use of just the renewable energies, in the presence of relatively constant an alimentary intake. Similar, national idiosyncrasies appear as in Table 1, but this time, another idiosyncrasy pops up: the gap between μ exponents in the two empirical mutations of equation (3). The μ ascribed to renewable energy per capita is always lower than the μ corresponding to the total use of energy – for the sake of presentational convenience they are further being addressed as, respectively, μ(R/N), and μ(E/N) - but the proportions between those two exponents vary greatly between countries. It is useful to go once again through the logic of μ. It is the exponent, which has to be ascribed to the consumption of energy per capita in order to produce a neighbourhood of equilibrium in population, in the presence of relatively constant an alimentary regime. For each individual country, both μ(R/N) and μ(E/N) correspond to virtually the same mean and variance in the scale factor 'A'. If both the total use of energy, and just the consumption of renewable energies can produce such a neighbourhood of equilibrium, the quotient 'μ(E/N)/μ(R/N)' reflects the amount of total energy use, in tons of oil equivalent per capita, which can be replaced by one ton of oil equivalent per capita in renewable energies, whilst keeping that neighbourhood of equilibrium. Thus, the quotient μ(E/N)/μ(R/N) can be considered as a levelled, long-term rate of substitution between renewable energies and the non-renewable ones.

One possible objection is to be dealt with at this point. In practically all countries studied, populations use a mix of energies: renewable plus non-renewable. The amount of renewable energies used per capita is always lower than the total use of energy. Mathematically, the magnitude of μ(R/N) is always smaller than the one observable in μ(E/N). Hence, the quotient μ(E/N)/μ(R/N) is bound to be greater than one, and the resulting substitution ratio could be considered as just a mathematical trick. Still, the key issue here is that both 'E/N^{μ}' and 'R/N^{μ}'

can produce a neighbourhood of equilibrium with a robust scale factor. Translating maths into the facts of life, the combined results of tables 1 and 2 (see Appendix) strongly suggest that **renewable energies can reliably produce a general equilibrium in, and sustain, any population on the planet, with a given supply of food**. If a given factor A is supplied in relatively smaller an amount than the factor B, and, other things held constant, the supply of A can produce the same general equilibrium than the supply of B, A is a natural substitute of B at a rate greater than one. Thus, $\mu(E/N)/\mu(R/N) > 1$ is far more than just a mathematical accident: it seems to be the structural property of our human civilisation.

Still, it is interesting how far does $\mu(E/N)/\mu(R/N)$ reach beyond the 1:1 substitution. In this respect, probably the most interesting insight is offered by the exceptions, i.e. countries marked with (!), where the model fails to supply a 100%-robust scale factor in any of the two empirical mutations performed on equation (3). Interestingly, in those cases the rate of substitution is exactly $\mu(E/N)/\mu(R/N) = 1$. Populations either too big, or too small, regarding their endowment in energy, do not really have obvious gains in sustainability when switching to renewables. Such a $\mu(E/N)/\mu(R/N) > 1$ substitution occurs only when the actual population is very close to what can be modelled with equation (3). Two countries – Saudi Arabia and Turkmenistan – offer an interesting insight into the underlying logic of the $\mu(E/N)/\mu(R/N)$ quotient. They both present $\mu(E/N)/\mu(R/N) > 2$. Coherently with the explanation supplied above, it means that substituting renewable energies for the non-renewable ones, in those two countries, can fundamentally change their social structures and sustain much bigger populations. Intriguingly, they are both ‘resource-cursed’ economies, with oil and gas taking so big a chunk in economic activity that there is hardly room left for anything else.

CONCLUSION

The purpose of research presented in this article was to bring at least tentative an explanation for the acceleration of growth, observable in the global market of renewable energies since 2007. This incidental research goal has been approached from a fundamental, theoretical perspective of production function, where a combination of food and energy supposedly produces a general equilibrium in the size of population, i.e. a state, where the given population uses the available sources of food and energy so as to sustain its own number, and the incremental change in this number. Empirical research presented proved, firstly, that a theoretical model deriving the size of population from the consumption of food and energy is robust in empirical application. In a sample of 116 national populations, representing some 80% of mankind in general, an equation coherent with the original production function (Cobb, Douglas 1928), based on the consumption of energy and food per capita, produced aggregates recurrently close to the actual demographic size of those countries. Moreover, the same general equilibrium between population, food, and energy can be produced with just the renewable energies in the equation. In author’s view, **it proves the capacity of renewable energies to sustain the majority of local human populations on Earth, with a substitution rate greater than one, as compared to non-renewable energy. Most countries on the planet, with just an exception in the cases of China and India, seem being able to sustain significantly bigger populations than their present ones, through shifting to 100% renewable energies.** In two ‘resource-cursed’ cases, namely Saudi Arabia and Turkmenistan, this demographic shift, possible with renewable energies, seems not less than dramatic.

Those empirical results open interesting theoretical paths. Firstly, the old-school production function is surprisingly robust a research tool regarding fundamental equilibria in the socio-economic order. With all the criticism possible to formulate with respect to this theoretical approach, it still works. Secondly, as the shift to renewable energies is a technological change, we have here a case of a technology (or rather a family of technologies) literally able to bend social structures around it. This is a strong case for the advocates of at least limited technological determinism. Thirdly, it could be insightful to check, whether at all and how possibly can the substitution between renewable energies and the non-renewable ones produce a geographical structure with an economic core surrounded by a periphery, in the lines of economic geography by Paul Krugman (Krugman 1991).

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APPENDIX

Table 1 Parameters of the function: Population = (Energy use per capita[18])$^{\mu}$*(Food intake per capita[19])$^{(1-\mu)}$

Country name	Average daily intake of food, in kcal per capita	Mean scale factor 'A' over 1990 - 2014	Variance in the scale factor 'A' over 1990 - 2014	The exponent 'µ' of the 'energy per capita' factor
Albania	2787,5	1,028719088	0,048263309	0,78
Algeria	2962,5	1,00792777	0,003115684	0,5
Angola	1747,5	1,042983003	0,034821077	0,52
Argentina	3085	1,05449632	0,001338937	0,53
Armenia	2087,5	1,027874602	0,083587662	0,8
Australia	3120	1,053845754	0,005038742	0,77
Austria	3685	1,021793945	0,002591508	0,87
Azerbaijan	2465	1,006243759	0,044217939	0,74
Bangladesh	2082,5	1,045244854	0,007102476	0,21
Belarus	3142,5	1,041609177	0,016347323	0,8
Belgium	3655	1,004454515	0,003480147	0,88
Benin	2372,5	1,030339133	0,034533869	0,61
Bolivia (Plurinational State of)	2097,5	1,019990919	0,003429637	0,62
Bosnia and Herzegovina (!)	2862,5	1,037385012	0,214843872	0,81
Botswana	2222,5	1,068786155	0,009163141	0,92
Brazil	2907,5	1,013624942	0,003643215	0,26
Bulgaria	2847,5	1,058220643	0,005405994	0,82
Cameroon	2110	1,021629875	0,051074111	0,5
Canada	3345	1,036202396	0,007687519	0,73
Chile	2785	1,027291576	0,003554446	0,65
China (!)	2832,5	1,328918607	0,002814054	0,01
Colombia	2582,5	1,074031013	0,013875766	0,44
Congo	2222,5	1,078933108	0,024472619	0,71
Costa Rica	2802,5	1,050377494	0,005668136	0,78
Côte d'Ivoire	2460	1,004959783	0,007587564	0,52
Croatia	2655	1,072976483	0,009344081	0,72
Cyprus (!)	3185	0,325015959	0,00212915	0,99
Czech Republic	3192,5	1,004089056	0,002061036	0,84

[18] Current annual use per capita, in tons of oil equivalent
[19] Annual caloric intake in mega-calories (1000 kcal) per capita, averaged over 1990 – 2014.

Denmark	3335	1,007673381	0,006893499	0,93
Dominican Republic	2217,5	1,062919767	0,006550924	0,65
Ecuador	2225	1,072013967	0,00294547	0,6
Egypt	3172,5	1,036345512	0,004306619	0,38
El Salvador	2510	1,013036366	0,004187964	0,7
Estonia (!)	2980	0,329425185	0,001662589	0,99
Ethiopia	1747,5	1,073625398	0,039032523	0,31
Finland (!)	3147,5	0,788769669	0,002606412	0,99
France	3557,5	1,019371541	0,001953865	0,53
Gabon (!)	2622,5	0,961643759	0,016248519	0,99
Georgia	2350	1,044229266	0,059636113	0,76
Germany	3440	1,009335161	0,000335601	0,48
Ghana	2532,5	1,000098029	0,047085907	0,48
Greece	3610	1,063074	0,003756555	0,77
Haiti	1815	1,038427773	0,004246483	0,56
Honduras	2457,5	1,030624938	0,005692923	0,67
Hungary	3440	1,024235523	0,001350114	0,78
Iceland (!)	3150	0,025191922	2,57214E-05	0,99
India (!)	2307,5	1,403800869	0,024395268	0,01
Indonesia	2497,5	1,001768442	0,004578895	0,2
Iran (Islamic Republic of)	3030	1,034945678	0,001105326	0,45
Ireland	3622,5	1,007003095	0,017135706	0,96
Israel	3490	1,008446182	0,013265865	0,87
Italy	3615	1,007727182	0,001245927	0,51
Jamaica	2712,5	1,056188543	0,01979275	0,9
Japan	2875	1,0094237	0,000359135	0,38
Jordan	2820	1,015861129	0,031905756	0,77
Kazakhstan	3135	1,01095925	0,021868381	0,74
Kenya	2010	1,018667155	0,02914075	0,42
Kyrgyzstan	2502,5	1,009443502	0,053751489	0,71
Latvia	3015	1,010440502	0,023191031	0,98
Lebanon	3045	1,036073511	0,054610186	0,85
Lithuania	3152,5	1,008092894	0,025234007	0,96
Luxembourg (!)	3632,5	0,052543325	6,62285E-05	0,99
Malaysia	2855	1,017853322	0,001002682	0,61
Mauritius	2847,5	1,070576731	0,019964794	0,96
Mexico	3165	1,01483014	0,009376118	0,36
Mongolia	2147,5	1,061731985	0,030246541	0,9

Morocco	3095	1,07892333	0,000418636	0,47
Mozambique	1922,5	1,023422366	0,041833717	0,48
Nepal	2250	1,059720031	0,006741455	0,46
Netherlands	2925	1,040887411	0,000689576	0,78
New Zealand (!)	2785	0,913678062	0,003946867	0,99
Nicaragua	2102,5	1,045412214	0,007065561	0,69
Nigeria	2527,5	1,069148598	0,032086946	0,28
Norway (!)	3340	0,760631741	0,001570101	0,99
Pakistan	2275	1,062522698	0,020995863	0,24
Panama	2347,5	1,007449033	0,00243433	0,81
Paraguay	2570	1,07179452	0,021405906	0,73
Peru	2280	1,050166142	0,00327043	0,47
Philippines	2387,5	1,0478458	0,022165841	0,32
Poland	3365	1,004848541	0,000688294	0,56
Portugal	3512,5	1,036215564	0,006604633	0,76
Republic of Korea	3027,5	1,01734341	0,011440406	0,56
Republic of Moldova	2762,5	1,002387234	0,038541243	0,8
Romania	3207,5	1,003204035	0,003181708	0,62
Russian Federation	3032,5	1,050934925	0,001953049	0,38
Saudi Arabia	2980	1,026310231	0,007502008	0,72
Senegal	2187,5	1,05981161	0,021382472	0,54
Serbia and Montenegro	2787,5	1,0392151	0,012416926	0,8
Slovakia	2875	1,011063497	0,002657276	0,92
Slovenia (!)	3042,5	0,583332004	0,003458657	0,99
South Africa	2882,5	1,053438343	0,009139913	0,53
Spain	3322,5	1,061083277	0,004844361	0,56
Sri Lanka	2287,5	1,029495671	0,001531167	0,5
Sudan	2122,5	1,028532781	0,044393335	0,4
Sweden	3072,5	1,018026405	0,004626486	0,91
Switzerland	3385	1,047790357	0,007713383	0,88
Syrian Arab Republic	2970	1,010909679	0,017849377	0,59
Tajikistan	2012,5	1,004745997	0,078394669	0,62
Thailand	2420	1,05305435	0,004200173	0,41
The former Yugoslav Republic of Macedonia	2755	1,064764097	0,003242024	0,95

Togo	2020	1,007094875	0,014424982	0,66
Trinidad and Tobago (!)	2645	0,152994618	0,003781236	0,99
Tunisia	3230	1,053626454	0,001201886	0,66
Turkey	3510	1,02188909	0,001740729	0,43
Turkmenistan	2620	1,003674668	0,024196536	0,96
Ukraine	3040	1,044110717	0,005180992	0,54
United Kingdom	3340	1,028560563	0,006711585	0,52
United Republic of Tanzania	1987,5	1,074441381	0,031503549	0,41
United States of America	3637,5	1,023273537	0,006401009	0,3
Uruguay	2760	1,014226024	0,019409309	0,82
Uzbekistan	2550	1,056807711	0,031469698	0,59
Venezuela (Bolivarian Republic of)	2480	1,048332115	0,012077362	0,6
Viet Nam	2425	1,050131152	0,000866138	0,31
Yemen	2005	1,076332698	0,029772287	0,47
Zambia	1937,5	1,0479534	0,044241343	0,59
Zimbabwe	2035	1,063047787	0,022242317	0,6

Source: author's

Table 2 Parameters of the function: Population = (Renewable energy use per capita[20])$^{\mu}$(Food intake per capita[21])$^{(1-\mu)}$*

Country name	Mean scale factor 'A' over 1990 - 2014	Variance in the scale factor 'A' over 1990 - 2014	The exponent 'μ' of the 'renewable energy per capita' factor	The rate of substitution between renewable and non-renewable energies[22]
Albania	1,063726823	0,015575246	0,7	1,114285714
Algeria	1,058584384	0,044309122	0,44	1,136363636
Angola	1,044147837	0,063942546	0,49	1,06122449
Argentina	1,039249286	0,005115111	0,39	1,358974359
Armenia	1,082452967	0,023421839	0,59	1,355932203
Australia	1,036777388	0,009700331	0,52	1,480769231
Austria	1,017958672	0,007854467	0,71	1,225352113
Azerbaijan	1,07623299	0,009740098	0,47	1,574468085

[20] Current annual use per capita, in tons of oil equivalent
[21] Annual caloric intake in mega-calories (1000 kcal) per capita, averaged over 1990 – 2014.
[22] This is the ratio of two logarithms, namely: μ(renewable energy per capita) / μ(total energy use per capita)

Bangladesh	1,088818696	0,017086232	0,2	1,05
Belarus (!)	1,017676486	0,142728478	0,51	1,568627451
Belgium	1,06314732	0,095474709	0,52	1,692307692
Benin (!)	1,045986178	0,101094528	0,58	1,051724138
Bolivia (Plurinational State of)	1,078219551	0,034143037	0,53	1,169811321
Bosnia and Herzegovina	1,077445974	0,084400986	0,66	1,227272727
Botswana	1,022264687	0,056890261	0,79	1,164556962
Brazil	1,066438509	0,005012883	0,24	1,083333333
Bulgaria (!)	1,022253185	0,190476288	0,55	1,490909091
Cameroon	1,040548202	0,059668736	0,5	1
Canada	1,02539319	0,005170473	0,56	1,303571429
Chile	1,006307911	0,001159941	0,55	1,181818182
China	1,347729029	0,003248871	0,01	1
Colombia	1,016164864	0,019413193	0,37	1,189189189
Congo	1,041474959	0,030195913	0,67	1,059701493
Costa Rica	1,008081248	0,01876342	0,68	1,147058824
Côte d'Ivoire	1,013057174	0,009833628	0,5	1,04
Croatia	1,072976483	0,009344081	0,72	1
Cyprus (!)	1,042370253	0,838872562	0,72	1,375
Czech Republic	1,036681212	0,044847525	0,56	1,5
Denmark	1,008202138	0,059873591	0,68	1,367647059
Dominican Republic	1,069124974	0,020305242	0,53	1,226415094
Ecuador	1,008104202	0,025383593	0,47	1,276595745
Egypt	1,03122058	0,016484947	0,28	1,357142857
El Salvador	1,078008598	0,028182822	0,64	1,09375
Estonia (!)	1,062618744	0,418196957	0,88	1,125
Ethiopia	1,01313572	0,036192629	0,3	1,033333333
Finland	1,065855419	0,021967408	0,85	1,164705882
France	1,021262046	0,002151713	0,38	1,394736842
Gabon	1,065944525	0,011751745	0,97	1,020618557
Georgia	1,011709194	0,012808503	0,66	1,151515152
Germany	1,008843147	0,03636378	0,31	1,548387097
Ghana (!)	1,065885579	0,106721005	0,46	1,043478261
Greece	1,033613511	0,009328533	0,55	1,4
Haiti	1,009030442	0,005061414	0,54	1,037037037
Honduras	1,028253048	0,022719417	0,62	1,080645161
Hungary	1,086698434	0,022955955	0,54	1,444444444

Iceland	0,041518305	0,000158837	0,99	1
India	1,414055357	0,025335408	0,01	1
Indonesia	1,003393135	0,008680379	0,18	1,111111111
Iran (Islamic Republic of)	1,06172763	0,011215001	0,26	1,730769231
Ireland	1,075982896	0,02796979	0,61	1,573770492
Israel	1,06421352	0,004086618	0,61	1,426229508
Italy	1,072302127	0,020049639	0,36	1,416666667
Jamaica	1,002749054	0,010620317	0,67	1,343283582
Japan	1,082461225	0,000372112	0,25	1,52
Jordan	1,025652757	0,024889809	0,5	1,54
Kazakhstan	1,078500526	0,007887364	0,44	1,681818182
Kenya	1,039952786	0,031445338	0,41	1,024390244
Kyrgyzstan	1,036451717	0,011487047	0,6	1,183333333
Latvia	1,02535782	0,044807273	0,83	1,180722892
Lebanon	1,050444418	0,053181784	0,6	1,416666667
Lithuania (!)	1,076146779	0,241465686	0,72	1,333333333
Luxembourg (!)	1,080780192	0,197582319	0,93	1,064516129
Malaysia	1,018207799	0,034303031	0,42	1,452380952
Mauritius	1,081652351	0,082673843	0,79	1,215189873
Mexico	1,01253558	0,019098478	0,27	1,333333333
Mongolia	1,073924505	0,017542414	0,6	1,5
Morocco	1,054779512	0,005553697	0,38	1,236842105
Mozambique	1,062086076	0,047101957	0,48	1
Nepal	1,02819587	0,008319264	0,45	1,022222222
Netherlands	1,079123029	0,043322084	0,46	1,695652174
New Zealand	1,046855187	0,004522505	0,83	1,192771084
Nicaragua	1,034941617	0,021798159	0,64	1,078125
Nigeria	1,03609124	0,030236501	0,27	1,037037037
Norway	1,019025526	0,002937442	0,95	1,042105263
Pakistan	1,068995505	0,026598749	0,22	1,090909091
Panama	1,001556162	0,038760767	0,69	1,173913043
Paraguay	1,049861415	0,030603983	0,69	1,057971014
Peru	1,06820116	0,008122931	0,41	1,146341463
Philippines	1,045289953	0,035957042	0,28	1,142857143
Poland	1,035431925	0,035915212	0,39	1,435897436
Portugal	1,044901969	0,003371242	0,62	1,225806452
Republic of Korea	1,06776762	0,017697832	0,31	1,806451613
Republic of Moldova	1,009542233	0,033772795	0,55	1,454545455

Romania	1,011030974	0,079875735	0,47	1,319148936
Russian Federation	1,083901796	0,000876184	0,24	1,583333333
Saudi Arabia	1,099133179	0,080054524	0,27	2,666666667
Senegal	1,019171218	0,032304226	0,49	1,102040816
Serbia and Montenegro	1,042141223	0,00377058	0,63	1,26984127
Slovakia	1,062546838	0,08862799	0,61	1,508196721
Slovenia	1,00512965	0,039266211	0,81	1,222222222
South Africa	1,056957556	0,012656394	0,41	1,292682927
Spain	1,017435095	0,002522983	0,4	1,4
Sri Lanka	1,003117252	0,000607856	0,47	1,063829787
Sudan	1,00209188	0,060026529	0,38	1,052631579
Sweden	1,012941105	0,003898173	0,77	1,181818182
Switzerland	1,07331184	0,000878485	0,69	1,275362319
Syrian Arab Republic	1,048889583	0,03494333	0,38	1,552631579
Tajikistan	1,03533923	0,055646586	0,58	1,068965517
Thailand	1,012034765	0,002131649	0,33	1,242424242
The former Yugoslav Republic of Macedonia (!)	1,021262823	0,379532891	0,72	1,319444444
Togo	1,030339186	0,024874996	0,64	1,03125
Trinidad and Tobago	1,086840331	0,014786844	0,69	1,434782609
Tunisia	1,042654904	0,000806403	0,52	1,269230769
Turkey	1,0821418	0,019688124	0,35	1,228571429
Turkmenistan (!)	1,037854925	0,614587094	0,38	2,526315789
Ukraine	1,022041527	0,026351574	0,31	1,741935484
United Kingdom	1,028817158	0,017810219	0,3	1,733333333
United Republic of Tanzania	1,0319973	0,033120507	0,4	1,025
United States of America	1,001298132	0,001300399	0,19	1,578947368
Uruguay	1,025162405	0,027221297	0,73	1,123287671
Uzbekistan	1,105591195	0,008303345	0,36	1,638888889
Venezuela (Bolivarian Republic of)	1,044353155	0,012830255	0,45	1,333333333
Viet Nam	1,005825608	0,003779368	0,28	1,107142857

Yemen	1,072879389	0,058580323	0,3	1,566666667
Zambia	1,045147143	0,038548336	0,58	1,017241379
Zimbabwe	1,030974989	0,008692551	0,57	1,052631579

Source: author's