Report

Energy constrains to increasing complexity in the biosphere

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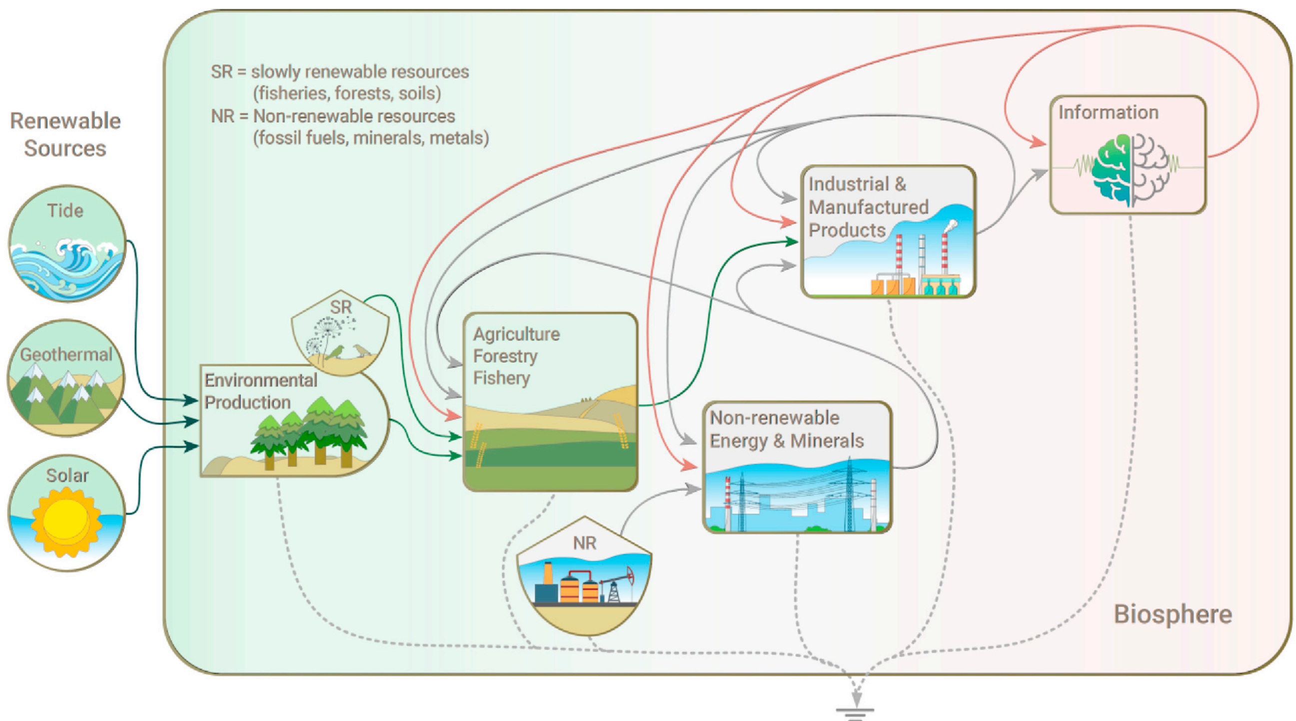
Graphical abstract



Public summary

- A well-defined representation of the self-organizing hierarchical structure of biosphere is provided
- Additional evidence shows transformation processes result in work potentials (exergy) of differing quality depending on placement within the hierarchy
- Expansion of higher levels of organization (i.e., information) are constrained by availability of resources requiring investments of nearly 20,000 times the energy invested at the top of the biosphere hierarchy
- The understanding of energy constrains may lead to better resource management and economic policy perspectives

Report

The Innovation

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Thirty years ago, the systems ecologist Howard T. Odum introduced the concept of transformity, which is a thermodynamic measure of quality within the trial and error evolutionary dynamics of ecosystems, namely an indicator of rank in the hierarchical system structure of the biosphere. Based on a global database of individual processes and whole economies, this paper extends, refines, and updates Odum's idea, demonstrating the strength of the postulated relation. In particular, an inverse linear logarithmic relationship is shown to hold between resource quantity (exergy) and quality (emergy), which is the result of an overall energetic efficiency characteristic of energy transformation processes of the biosphere. This relation extends from natural renewable energy sources to human information (including global internet data flows) and know-how embedded in national economies, thus identifying a consistent theory of hierarchical organization of the biosphere grounded in energetics and ultimately setting constraints to illusions of unlimited growth.

Keywords: **complexity; self-organizing system; hierarchical structure; energetic efficiency**

INTRODUCTION

The concept of self-organization, i.e., the spontaneous emergence of ordered structures from interactions among initially disordered parts, permeates all branches of science, including natural and, among others, physical sciences,[1,2] social theories, informatics, and economics.[3–7] As an organizing principle of complex systems, it has allowed science to overcome the limitations of the deterministic approach to natural laws and a thermodynamic paradigm that forbids increases in order in a world of increasing entropy.

Thirty years ago, the article "Self-organization, transformity and information" by H.T. Odum, based on his acceptance lecture for the Crafoord Prize of the Royal Swedish Academy of Sciences, was published in *Science*.[8] It extended the purely ecological meaning of self-organization, suggesting the existence of an energy hierarchy within biosphere transformation processes, including human systems and information. A main facet of the energy hierarchy concept was the concept of *energy quality*, expressed by the amount of one form of available energy (i.e., exergy) required to generate an output form. This ratio was called *transformity*, applicable to materials, energy sources, and information processes. The total available energy, directly or indirectly required over the whole supply chain to generate an output product or service, is named emergy. *Solar emergy*, whose units are *solar emjoules* (sej), is the form of emergy commonly used to express the different flows of energy and resources within a system on the same solar-referred basis. In his 1988 *Science* article, H.T. Odum, postulated that transformity "… may be used as an energy-scaling factor for the hierarchies of the universe including information."

Because of the thermodynamics of all transformation processes, more available energy is consumed than provided (as is well known, the coal to electricity conversion requires roughly 4 joules of coal to make 1 joule of electricity), but the output that is delivered is of a higher quality, leading to another assertion by Odum "… a transformation is useful only if it is to a higher quality, that can amplify more with less energy."[9] It is a hypothesis that self-organizing systems use stores and flows of energy, materials, and information for purposes commensurate with what is required for their formation. Therefore, a joule of electricity should be capable of doing at least the work of 4 joules of coal.[10] The immediate consequence is that higher-quality processes (electricity, information flows, and networks, such as the internet) have huge costs, supported by a much larger base of diverse and lower-quality resources, placing an upper limit to the growth of natural and human-dominated assets.[11]

The concepts of emergy and transformity contributed to an integrated description of the biosphere as a system of transformation processes yielding ever more complex and higher-quality components. While not exempt from initial criticisms,[12] this theory, now widely cited, led to its application at multiple scales, from DNA to biological systems,[13,14] to galaxies[15] (e.g., some researches extended the embodied solar energy to embodied cosmic exergy based on the revealed scarcity of cosmic exergy availability in the material earth[16]), and including both natural and anthropic processes. Since the publication of Odum's seminal paper,[8] many applications of emergy, evaluating products and processes, have led to resource management suggestions and policy alternatives. The number of research articles that have employed emergy, as cited in two recent papers,[17,18] has totaled over 700 by 2014, with several papers recently stressing the relationship between emergy and exergy.[19–22] While there have been a wealth of papers that use emergy for case studies and methodological improvements, especially at technological,[23] industrial,[24] regional,[25] national,[26] and global levels,[27] only a recent one[28] has started exploring the implications of Odum's original propositions[8] using empirical data from the literature. However, while Odum's paper explored the hierarchical organization using the transformity concept (by collecting over 700 transformities from the literature), there are still issues with the method employed, that need to be addressed and refined. In fact, the study plotted energy against transformity, implicitly assuming that all previous quantifications were based on available energy (exergy). Moreover, it included both material and energy flows, mixing mass and energy values. By contributing to a rough first exploration of the relation between energy quality and quantity, a study[28] provided the opportunity for further refining and deeper understanding. Using exergy, as we do in this study, it removes

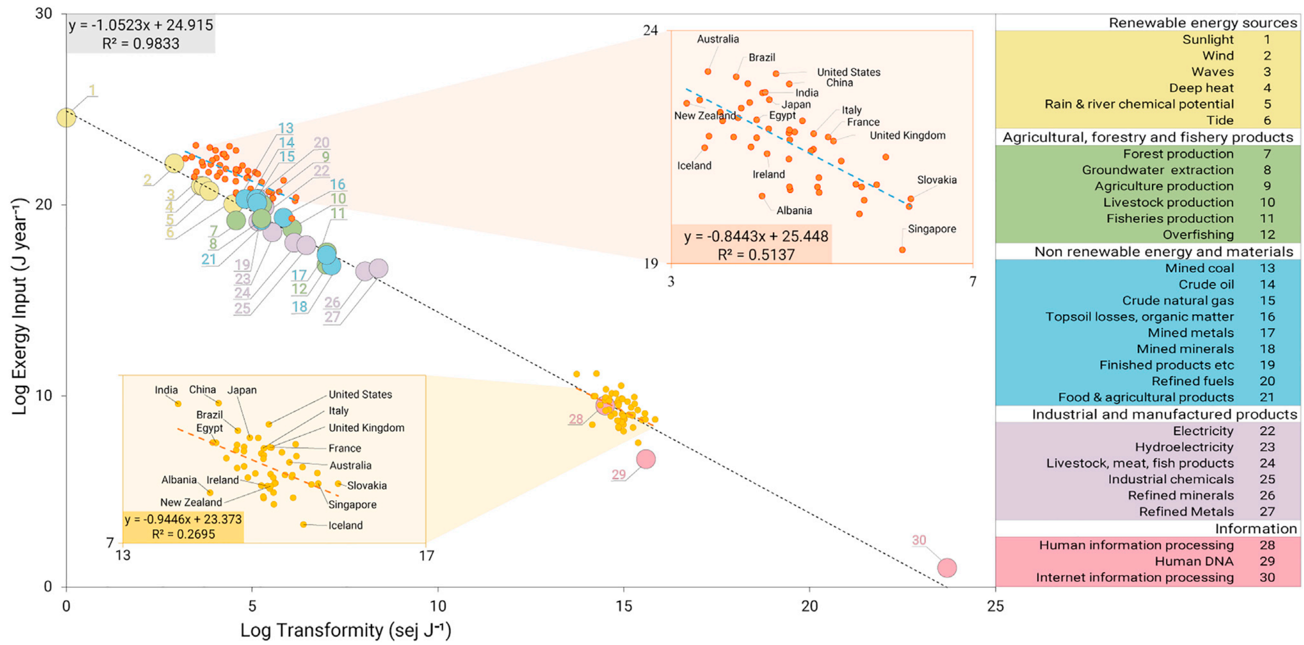

Figure 1. Log-log plot of transformity versus available energy for hierarchical transformation processes of the biosphere The large dots, represent five different groups (and colors) of aggregate transformation processes and their respective products: renewable energy sources (1–6), agricultural, forestry, and fishery products (7–12), non-renewable energy and materials (13–21), industrial and manufactured products (22–27), and information (28–30). Small orange dots depict the average performance (sej J^{-1}) of 37 "developed" and 13 "developing" economies. The small yellow dots show transformity of information of each country's population plotted against the exergy of the information representing human know-how.

some ambiguities and apparent contradictions of using different types of energy and allow an appropriate comparison of systems belonging to different categories. In addition to using exergy, our study adopts a different grouping scheme of processes to escape the risk that *a priori* choices affect the final results.

In this study, we provide a well-defined representation of the self-organizing hierarchical structure of the biosphere and additional evidence that transformation processes result in work potentials (exergy) of differing quality, depending on their placement within the hierarchy, providing new insights for understanding the complex systems of which humans are a part. Such an understanding may lead to better resource management and economic policy perspectives. For instance, while there has been much talk of human society entering an information age, where information becomes the driving force of all economic productivity, such an age is highly unlikely if there is not sufficient available energy to power the underpinning hierarchy of processes that make information generation possible. Through this study, we document an overall macro transfer efficiency of the biosphere and suggest that expansion of higher levels of organization (i.e., information) are constrained by availability of resources requiring investments of nearly 20,000 times the energy invested at the top of the biosphere hierarchy.

RESULTS

Figure 1 shows a set of processes and national economies, whose performances are graphed as exergy of input (theoretical work potential of resources) on the vertical axis versus quality of output (transformity = total driving emergy/exergy of process output) on the horizontal axis (calculations are shown in the supplemental information). When the biosphere is viewed as a self-organizing hierarchical system of energy transformations, items at higher hierarchical level are characterized by smaller output exergy, while the quality of the output increases in a logarithmically linear fashion.

The large dots represent four different groups (and colors) of aggregate transformation processes and their respective products: renewable energy sources (1–6), agricultural, forestry, and fishery products (7–12), non-renewable energy and materials (13–21), and industrial and manufactured products (22–27). When graphed as in Figure 1 on a log-log plot, a linear regression (black dotted line; R^2 = 0.98; r = −1.05) is obtained, showing an average stable relation between energy quantity and quality. The relation suggests that an increase of energy quality (i.e., transformity) by one order of magnitude may correspond to only 14% of the input exergy transferred to the higher quality level, while the remaining 86% is dispersed; in other words, it results a relative efficiency of 14%.

Figure 1 also shows a cluster of smaller orange dots, denoting input exergy and emergy intensities for 37 developed and 13 developing economies (emergy intensity = total driving emergy/exergy of country output) (see supplemental information; Table S3). The dots depict the average performance (sej J^{-1}) of these countries plotted against the exergy of their inflowing resources. The available data show a log-linear scaling for countries' emergy intensities, which are located in the region between 3 and 7 of log transformity (Figure 1, orange small dots; R^2 = 0.79; r = −0.94). The regression line of countries lays slightly above the regression line of the aggregate transformation processes (large dots) displaying higher exergy use for the same average emergy intensity, indicative of a lower overall efficiency of transformation of resources into national economic output.

The cybernetic nature of ecosystems, as well as socio-economic systems,[29] is another perspective that was discussed in Odum's paper in *Science* 30 years ago. Like natural ecosystems, socio-economic systems develop, use, and feedback information in actions that coordinate, regulate, and control the transformation of matter and energy.[30] Both Odum[8] and Abel[31] have pointed out that the creation of information occurs in transformation processes, driven by essential emergy inputs. Information, complexity (i.e., the presence of structured systems), and emergy inputs are inextricably related.[32] In Figure 1, three transformities of information (red dots) are included, showing a continuation of the trend line found for the aggregate process data. The three transformities are, human information processing (log transformity = 14.5), human DNA (log transformity = 15.6), and world wide web information processing (log transformity = 23.7).

In addition to the large red dots representing three different scales of information processing, the cluster of small yellow dots represents the transformity of human information for 37 developed and 13 developing economies (see supplemental information; Table S8). The data represent the transformity of information of each country population plotted against the exergy of the information and are suggestive of human know-how of each economy.[33] It is neither the information content of the biodiversity nor the information content of human DNA but, instead, the information content, in the form of know-how of socio-economic systems.

DISCUSSION

Tradeoff between complexity and scale

Transfer efficiencies have been used to infer the amount of production at higher hierarchical levels that production at lower levels can globally support.[34] The quantification of transfer efficiencies help to understand the link of individual processes to larger-scale processes within systems.[35] This fraction of transferred exergy is well within the range of transfer efficiencies postulated by Lindeman[36] and Pauly and Christensen.[37] An average 14% transfer efficiency is much lower than the 50% efficiency postulated by Odum and Pinkerton[38] as the optimum for maximum power output by physical and biological systems. Their optimum efficiency, of course, is hardly if ever achieved, but the fact that the myriad transformation processes of the biosphere find an overall efficiency of 14% supports the conjectures of Lotka[39] and Odum[8,9] that "... one of the many realities of the natural world is that living and also man-made processes do not operate at the highest efficiencies that might be expected of them," but instead, sacrifice efficiency for more power output.

In 1906, Pareto defined human society as a hierarchical collectivity, and postulated what was termed Pareto's law on the distribution of income.[40] He derived the well-known log-log relationship between the number of individuals receiving an income at or above a certain amount plotted against the total income of the selected population (i.e., a cumulative distribution). The straight line observed by Pareto allowed him to postulate that, due to the rigidity of the distribution, there was only one way to increase economic welfare (i.e., the share of the poorer classes in the national income), and that was to increase total production of the economy. Zipf, based on his original rank size distribution of cities[41] found much the same relationship as Pareto when he graphed empirical data of such things as: number of businesses versus number of businesses of like kind, number of employees versus number of specific occupations, and the size of cities versus their rank. Zipf's number-frequency relationships have the same form as do those of Pareto, expressed by a linear equation relating the log of the number of individuals in any class X, and the log of X. Both Pareto and Zipf suggested that these relationships indicate a measure of organization and that departures from straight line slopes indicate disunity[40] or inequality.[41]

Here, we postulate the existence of a simple rule to explain the apparent Pareto and Zipf distribution of phenomena. The available energy output of any transformation process (product, service, earthquake, war, economic system, etc.) requires, on average, at least 7 times the available energy as input. This is not to say that all transformation processes strictly adhere to this 7× rule, only that, across the 24 orders of magnitude of energy intensity found in the biosphere, the average transfer efficiency is 14%, thus yielding the 7:1 ratio of input to output.

While rank size distributions describe the existence of a constant relation between the size of cities, for instance, these ranks, based on observations, do not provide an explanation on the cause of this phenomenon. Here, we suggest a mechanism. The concentration of enough available energy to support a higher-level component within a landscape requires many processes, each yielding a small but significant quantity of available energy, that, when added together with others of the same size, results in a sufficient quantity of available energy to support the higher-level component. This is quite evident in ecological food chains, where many smaller organisms are thermodynamically necessary to support larger organisms at higher trophic levels, the end result of which is a hierarchy of energy transformations. As a consequence of the second law of thermodynamics, biosphere transformation hierarchies cannot be flat, just as it is impossible to have flat food pyramids in ecology.

Bear in mind that while the "currency" of ecosystem food chains is carbon, and they represent relatively simple hierarchical organization, the self-organizing hierarchy of the biosphere we describe here is composed of many different hierarchies of different kinds (i.e., ecological, technological, social, and economic). While each has its characteristic structural organization, they fit within the larger biosphere by virtue of their overall available energy flow and transformity. We suggest that there is a natural hierarchy of energy transformation processes of the biosphere and that the transformity of any single process provides information on its place within the hierarchy.

In general, our data suggest that there is continuity to the hierarchical system of the biosphere organized as a power law (power law exponent = -1.054), which indicates a high degree of self-organization. Odum had postulated that self-organization results from the maximization of power,[9] a characteristic of natural and human-dominated systems. Bejan and Lorente[42] have suggested that self-organization results in configurations (arrangements, patterns) that provide greater and greater access to the available energy that flow through them. These scaling relationships ultimately help explain and predict transformation processes emerging at all levels of hierarchical organization at different scales in time and space.

The regression lines in Figure 1 provide an interesting relation and a general theorem that relates the work potential of resources (exergy) to a system performance through its emergy intensity. The sum of the independent exergy inputs that drive the biosphere (solar, tidal, and geothermal exergy) yields a log of about 24, while the corresponding log transformity is zero. On the other hand, when the log of exergy tends toward zero the log transformity tends to a maximum value of 24; a boundary that may represent the highest achievable process of ordering and energy concentration in the biosphere.

Odum's self-organization theory[8] provides a fascinating array of quantitative predictions about natural and human-dominated systems. The results of our analysis of these global data is consistent with Odum's postulated scaling relationship and suggests three interesting suppositions: (1) the amount of exergy lost (dissipated) in the cascade of transformation steps in the energetic systems of the biosphere is consistently about 86%; (2) the existence of a higher boundary of energy quality in the biosphere expressed as log transformity about 24 (Figure 1); and (3) a general theory of scaling in energy transformations of self-organizing systems that leads to hierarchical organization.

Multi-scale evolutionary processes

Although the discussions above help us recognize the fundamental properties and limitations of systems, our understanding of most complex systems will inevitably be imperfect and incomplete; and, regardless of how well considered a plan is, a truly complex system will always present elements that were not considered ahead of time. Natural and human-dominated systems of the biosphere are constrained by the availability of renewable and non-renewable exergy and at the same time affected by relatively low-efficiency conversion rates, yet they self-organize into complex hierarchical structures to optimize benefits. This complexity is made possible by transformation processes that degrade considerable quantities of available energy, and then generate smaller amounts of higher-quality energy and material flows, which are capable of greater useful work and feedback control on lower hierarchical levels, thus finally improving sustainability, furthering complexity and increasing dynamic stability. Given the absence of perfect knowledge, how can the success of systems we design or are part of be assured? While the success of many systems rests on the assumption that good decisions will be made, some systems may perform very well despite the fallibility of the decision makers. The study approaches this observation scientifically by (implicitly or explicitly) considering the decision makers themselves as part of the system and of limited complexity/decision-making ability. The question, thus, becomes: how do we design systems that exceed the complexity of the decision makers within them?

The common characteristic of these systems is their embodiment of some sort of evolutionary process, i.e., a process in which successful changes are followed and further modified by other systems while unsuccessful changes are not. The classical evolutionary processes are the biological ones. Due to variability introduced by random mutations, organisms with the complexity and scale of humans evolved from single-cell organisms. Exposure to random shocks affect socio-economic systems dynamics (see Figure 2 and Table S9 in supplemental information). Most countries have a higher transformity, moving from left to right from 2001 to 2014,

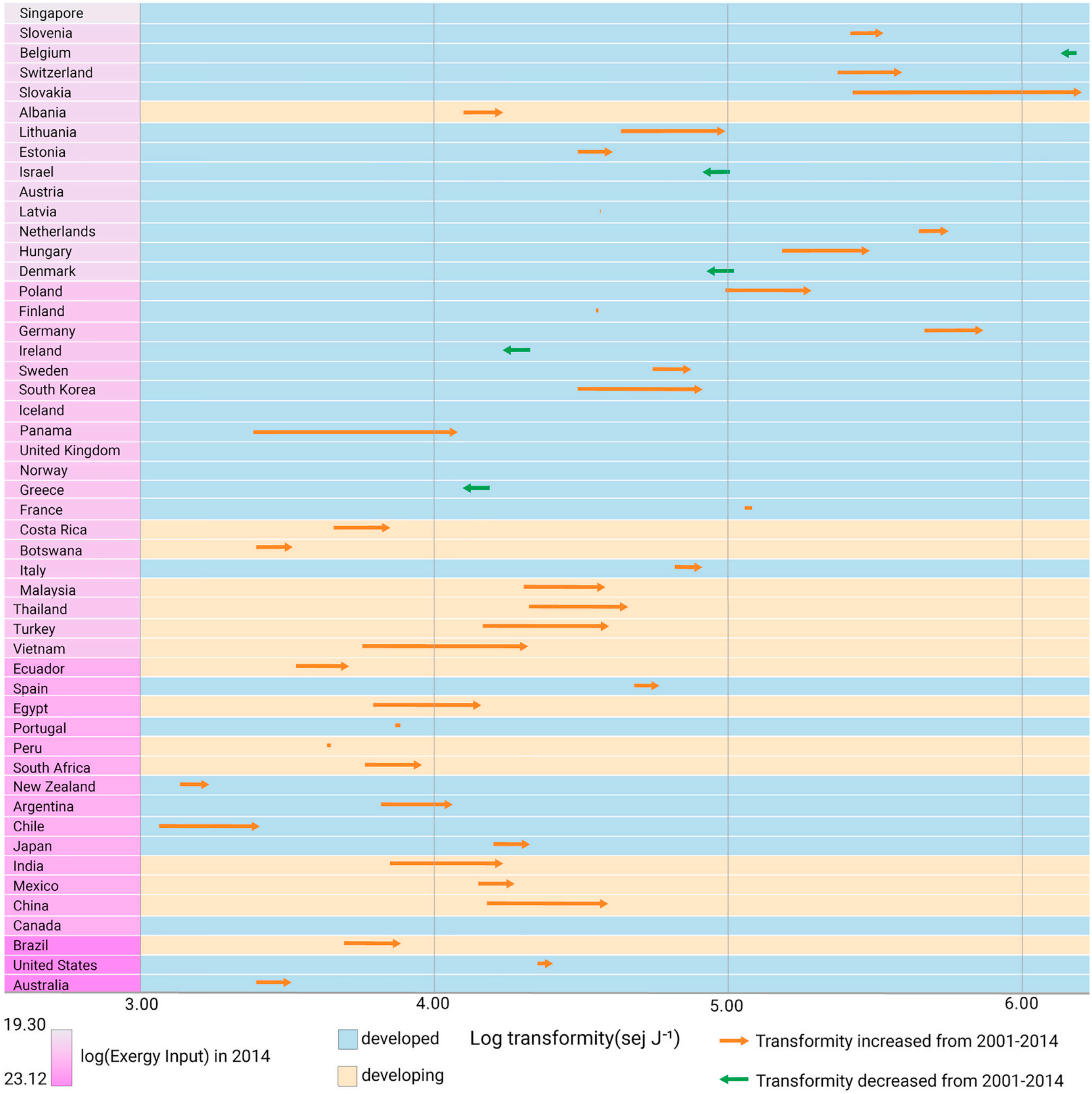

Figure 2. The development changes from 2001 to 2014 in 50 countries The developed countries are highlighted in blue and the developing countries are in yellow.

and a few countries have lower transformities, moving from right to left, with no change for Canada and the United Kingdom. Developed countries are generally on the top of the figure, indicating that the quality (resource use, production processes, etc.) of developed countries is higher, while developing countries are generally placed on the bottom.

The practical applications of these relations highlight the importance of a consistent theory of hierarchical organization grounded in energetics. While some relate the number of processes in a system only with size, surely being a relevant factor, the underlying flows of available energy (true drivers of complexity) remain hidden when plotting size versus complexity, as they are two sides of the same coin. As shown in this study, complexity results from hierarchical self-organization, being, in turn, the natural outcome of systems of energy transformations.

It is important to distinguish between the complexity of a hierarchy and the complexity of decision making of a certain community, national government, or larger-size organization. No type of hierarchy is inherently better than any other. For a particular resource endowment and emergy-driven pattern, the best hierarchy is the one whose complexity profile matches the tasks that it is trying to perform. Consequently, policy makers should consider not just the overall complexity profile of countries but also how well subdivisions in countries match those within their resource endowment and emergy-driven pattern.

The relations highlighted in this paper provide an unambiguous assertion that transformation hierarchies affect the allocation of resources. Thus, the growth of higher-quality components (technology, information, government, etc.) requires not only the necessary resource investment to drive the component, but all the exergy necessary for the lower levels of the hierarchy that support it. If we assume a five-component hierarchy, the addition of one unit of exergy at the top hierarchy level, on average requires investment of about 19,000 units at the bottom (1/(14% × 14% × 14% × 14% × 14%)).

To put it another way, transformities are a way of indicating that, for each unit of exergy of a given resource quality, it takes investment of much larger quantities in lower levels of the hierarchy. As a consequence, continued expansion of high-quality components, such as information, is not merely an investment of direct exergy in education, but investment in the entire exergy "food web" that is necessary to support it. Transformity is a way of acknowledging the quantity of the required indirect investments.

Practically speaking, as the world strives for organization of higher levels of complexity (larger corporations or global governmental entities, etc.), these higher hierarchical levels require enormous quantities of resources for their direct and indirect support. However, as the total quantity of energy is limited, the size and complexity of global hierarchies is limited. This might lead to instabilities and eventual collapse of complex organizations or societies. This depends on the fact that increasing complexity (i.e., the addition of structures, specializations, and connections among them) necessitates a greater energy availability, generating a pressure on resources, under which past societies have collapsed.[43] Results, then, suggest that future research should be directed toward the analysis of available energy hierarchies in larger-scale organizations, such as the United Nations, the European Union, NATO, international trade agreements, and major global banks.

MATERIALS AND METHODS

Data compilation

Recent analysis and data mining of large global datasets of energy, material, and information flows have allowed us to revisit the energetic basis for hierarchical self-organization first posited by H.T. Odum in *Science* in 1988.[8] Using statistical data from 213 countries (derived from the National Emergy Accounting Database [NEAD]) (NEAD: http://www.emergy-nead.com/home, see supplemental information), we have computed exergy content of aggregated classes of energy, materials, and information flows supporting the production processes of the global economy.

NEAD compiles detailed information for over 213 countries/regions for the full array of resources that underlie economies. These include environmental flows (e.g., solar radiation, tidal momentum, and geothermal exergy, as well the available energy in precipitation, wind, and waves), the flows of natural capital stocks (e.g., soil, water, forests, fish), mined materials (e.g., metals, fuels), and economically transformed goods and services (e.g., agricultural commodities, manufactured goods, services).

Using standard conversions (mass = J/kg, energy = high heat values) we computed exergy of individual material and energy flows supporting countries, then they were combined (summed) into the aggregate flows listed in Figure 1. NEAD contains a full list of emergy intensities or unit emergy values (UEVs = sej J^{-1} or sej kg^{-1}) for commodity, mineral, and energy flows. A weighted average transformity was computed for each of the aggregate flows. The large dots represent the exergy of global flows of each aggregate flow versus the transformity of that flow.

The data for the two sets of smaller dots were handled in a similar way as the data for the global dataset. Emergy intensities (sej J^{-1}) of economies (small yellow dots) were computed by dividing the sum of emergy inputs by the sum of the exergy of the output of each country. The exergy and transformity of country know-how (small red dots) were computed by dividing the emergy input by the exergy of human information processing. Full details of these calculations can be found in the supplemental information.

Significance statement

In this study, we provide a well-defined representation of the self-organizing hierarchical structure of the biosphere and additional evidence that transformation processes result in work potentials (exergy) of differing quality depending on placement within the hierarchy, providing new insights for understanding the complex systems of which humans are a part. Such understanding may lead to better resource management and economic policy perspectives. For instance, while there has been much talk of human society entering an information age, where information becomes the driving force of all economic productivity, such an age is highly unlikely if there is not sufficient available energy to power the underpinning hierarchy of processes that make information generation possible. In this study we document an overall macro transfer efficiency of the biosphere and suggest that expansion of higher levels of organization (i.e., information) are constrained by availability of resources requiring investments of nearly 20,000 times the energy invested at the top of the biosphere hierarchy.

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AUTHOR CONTRIBUTIONS

G.L. and Z.Y. were responsible for overall project supervision, conceptualization, data curation, and project management. B.F.G., M.C., F.A., F.G., and C.M.V.B.A. provided early conceptualization of the project direction. G.L., J.P., N.Y., Y.H., and L.Z. were instrumental in formal analysis of data. G.L., M.C., M.T.B., and S.U. contributed to methodology development, conducted validation, and contributed to the writing of early drafts and final draft review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

LEAD CONTACT WEBSITE

Data are available at NEAD website: http://www.emergy-nead.com/home.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.xinn.2021.100169.

The Innovation, Volume *2*

Supplemental Information

Energy constrains to increasing complexity in the biosphere

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Supplementary Materials for

Energy constrains to increasing Complexity in the Biosphere

Materials and Methods

1. General NEAD database structure and methods

The National Environmental Accounting Database (NEAD, available at the web address http://www.emergy-nead.com/home) compiles detailed information for over 213 countries/regions for the full array of resources that underlie economies. These include environmental flows (e.g.: sunlight, rainfall), natural capital stocks (e.g.: soil, water, forests, fish), mined materials (e.g.: metals, fuels) and economically transformed goods and services (e.g.: agricultural commodities, manufactured goods, services). Data for commodities and trade flows cover the years 2000-2014. Long-term average data are used for climate and hydrology flows.

1.1 General Database Structure

The organization of the NEAD is illustrated in Fig. S1. Within Excel spreadsheets, primary raw unit data are compiled by country codes and linked to tables of energy content values and unit emergy values (UEVs) from the literature. All UEVs are set relative to the latest baseline, fixed at 12.0E+24 seJ year^{-1} [1]. Emergy calculations are executed and organized according to a standardized template format, with results loaded into forms, which display a main emergy table, its related notes, as well as several tables summarizing flows and indices.

1.2 Primary data acquisition and data processing

National emergy accounting requires a wide variety of data from multiple sources. Compiling data for a single country can be time consuming and conflicting data are frequently observed for the same flows. Details on data sources and criteria, as well as calculation methods, which are global in coverage with values for most countries, availability of documentation and literature references, and publication/dissemination by a recognized organization are reported in the literature [2]. In addition, spatial coverages were used for renewable flows to allow for calculations within a GIS environment [3] and future analysis at sub-national scales.

1.3 System boundary

Emergy evaluation of countries accounts for all major inflows and outflows crossing country boundaries, as well as internal production processes. The data used for accounting the emergy related to a Country's economy start from the use of official statistical databases. Flows include diffuse flows from the environment (i.e., sun, wind, rain), concentrated flows from mined materials (*i.e.* metals, fuels, minerals), and purchased materials and services imported from other countries. The physical boundaries defining a country are edge of the submarine continental shelf (200 m); 100 m above the earth and water surface; 2 m below the earth surface, or lake or sea floors. Data are collected to calculate the flows in energy or weight units.

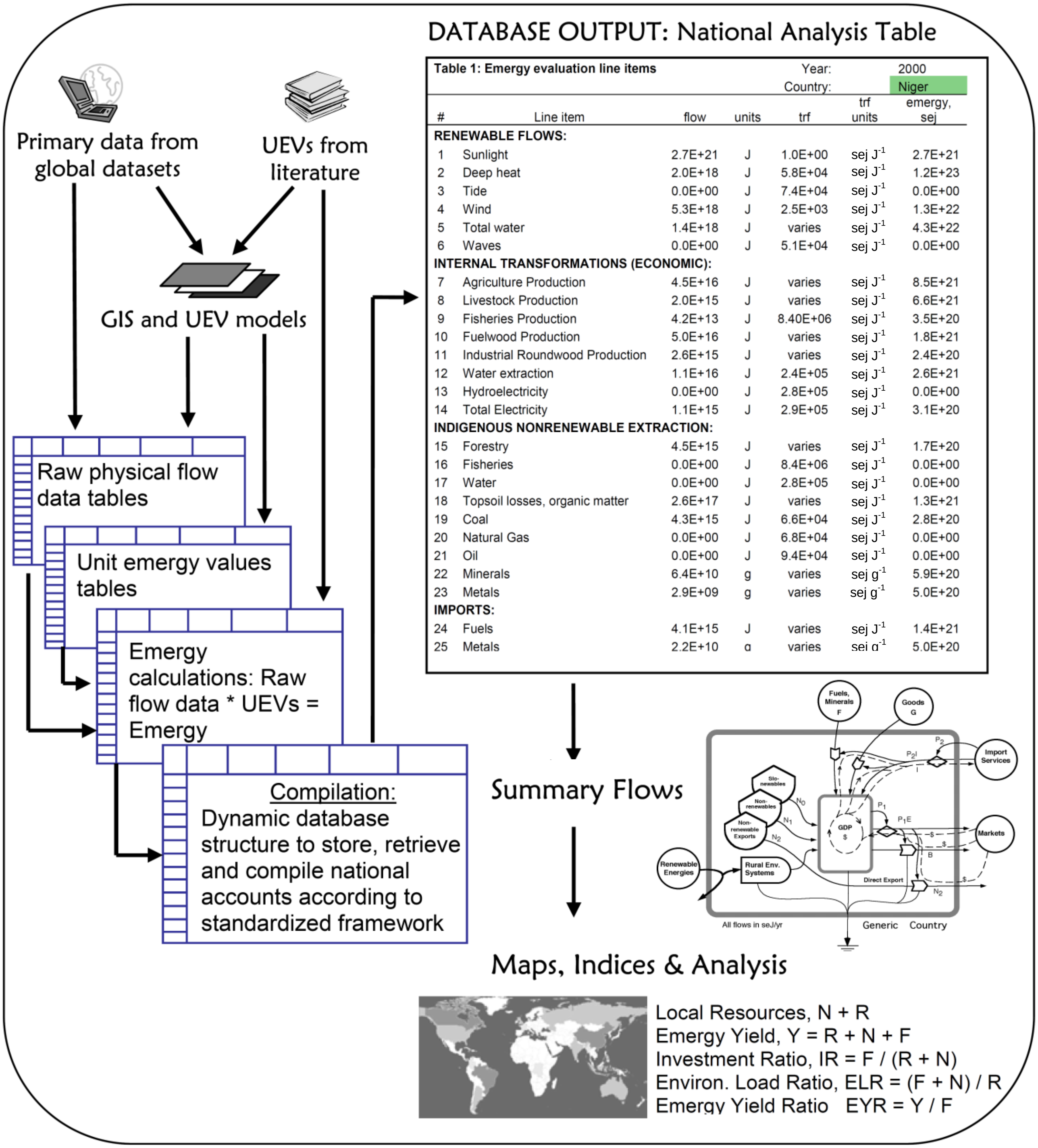

Fig. S1. Scheme of the National Environmental Accounting Database (NEAD) structure

2. Calculation of transformities and available energy

Table S1 lists transformities and available energy for renewable energy sources (green background), agricultural, forestry and fishery products (gray background), non renewable energy and materials (yellow background), industrial and manufactured products and energy (blue background). The data are from the NEAD and represent total available energy for the 100 non-missing-data countries for the year 2014. Available energy of each category is the sum of all flows within that category across all countries in the NEAD. Transformities, as defined by Odum, for each component included in

Table S1 were computed following the standard rules of emergy accounting [4]. Where more than one product was included in a flow category, the mean was computed for all transformities of that category, the details of the calculation method are shown in the Figure S2-S5, where E_i represents the emergy of product i; trf_i represents the transformity of product i; m_i represents the mass of product i. The calculation method of renewable energy sources trasnsformity is shown in Figure S2. The calculation method of the transformity for agricultural, forestry and fishery products are shown in Figure S3. The calculation method of the transformity for nonrenewable energy and materials is shown in Figure S4, in which the forest production transformity was computed as equation (2). The calculation method of the transformity for industrial and manufactured products and energy is shown in Figure S5.

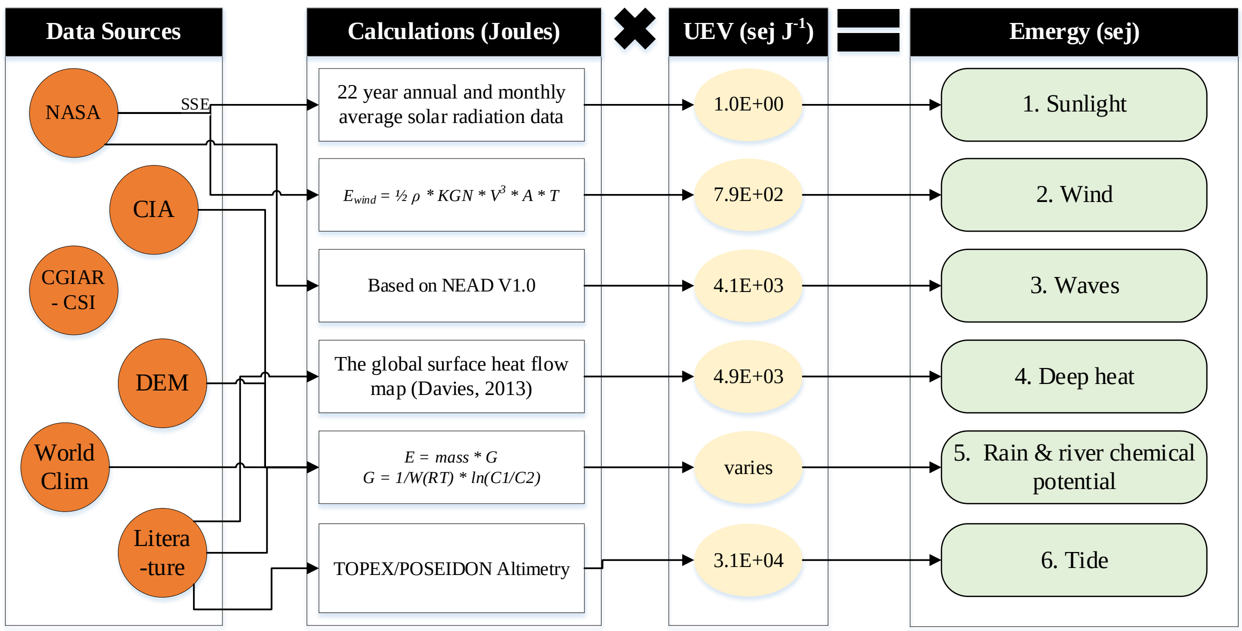

Fig. S2. The calculation method of renewable energy sources transformity

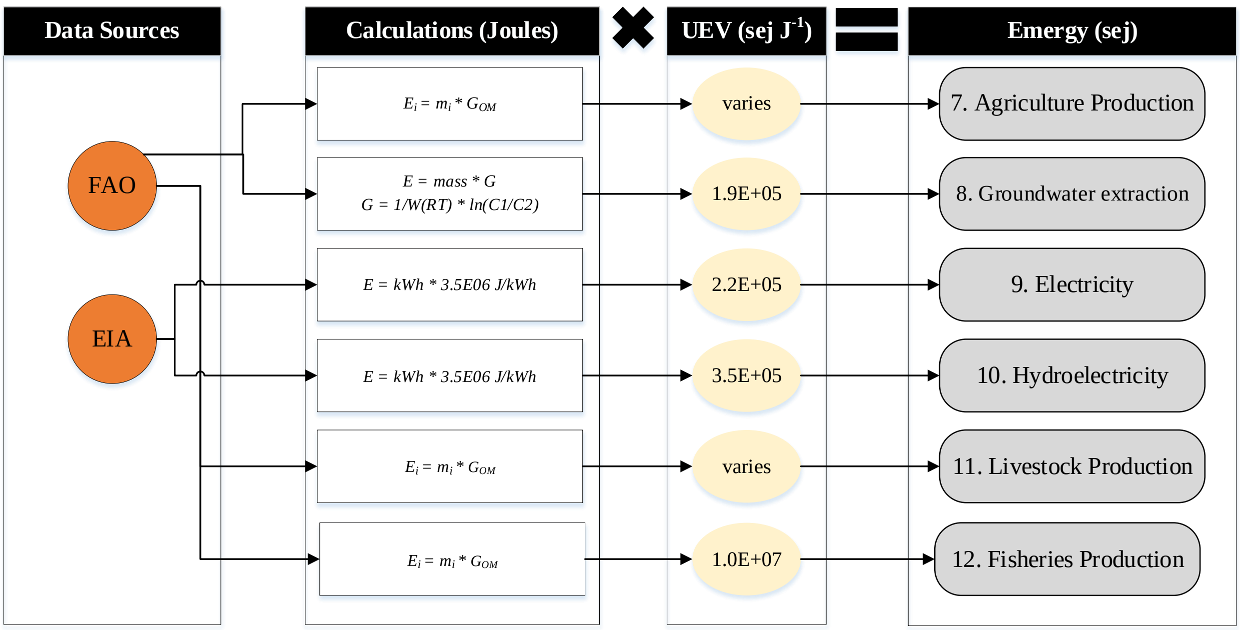

Fig. S3. The calculation method of renewable energy sources transformity

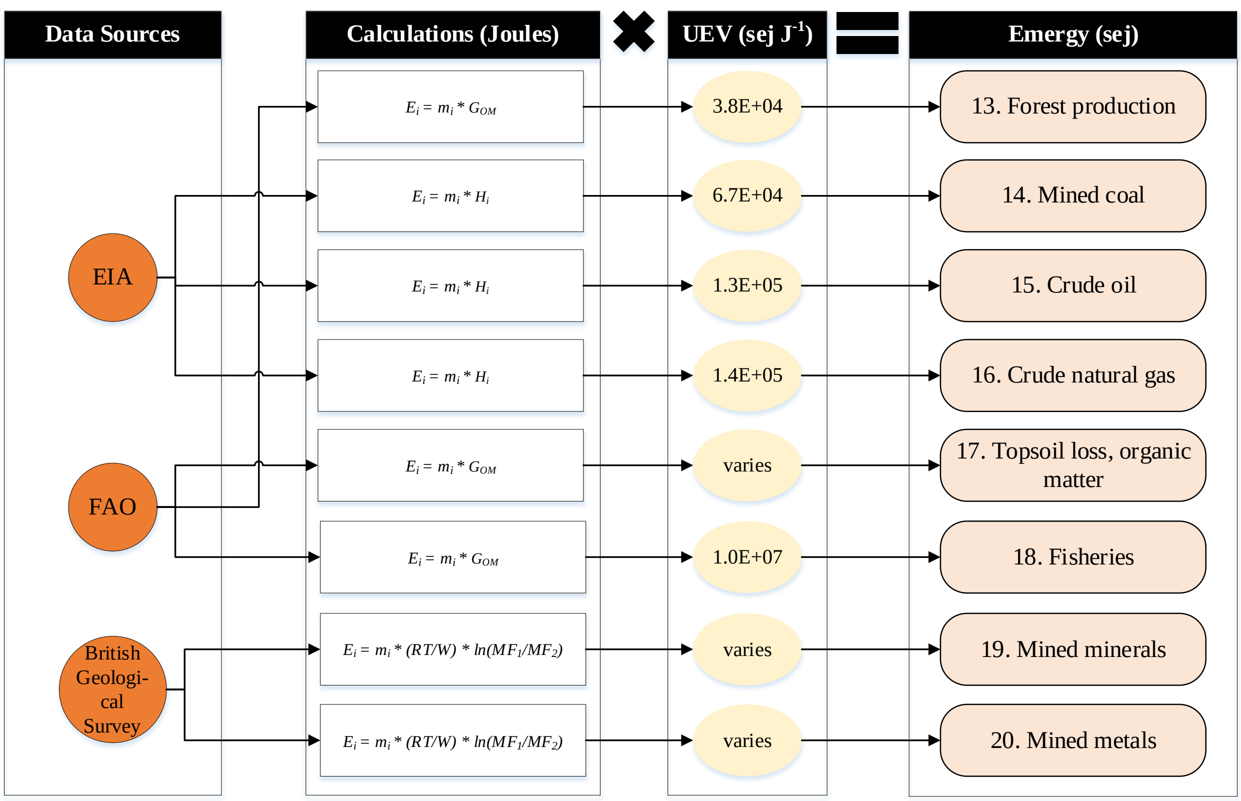

Fig. S4. The calculation method of industrial and manufactured products and energy transformity

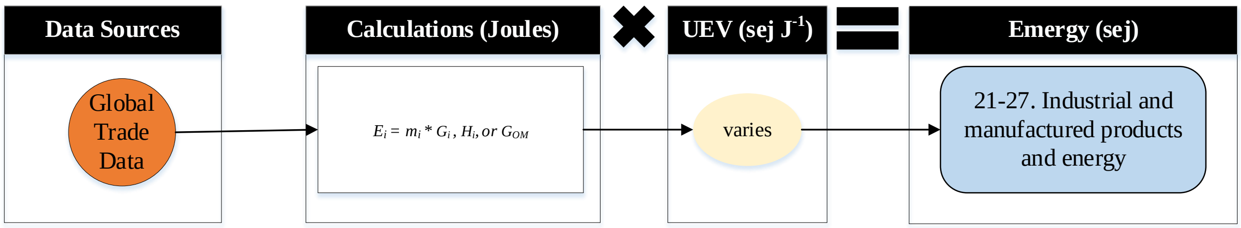

Fig. S5. The calculation method of industrial and manufactured products and energy transformity

Table S1. Transformities and available energy for flows of energy, materials and information supporting countries of the world.

	Ranking	Transformity (sej J^{-1})	Exergy input (J $year^{-1}$)	Log(Transformity)	Log(Exergy input)
Sunlight	1	1.00E+00	3.70E+24	0.00	24.57
Wind	2	8.00E+02	1.50E+22	2.90	22.18
Waves	3	4.13E+03	1.00E+21	3.62	21.00
Deep heat	4	4.90E+03	9.50E+20	3.69	20.98
Rain & river chemical potential	5	7.00E+03	5.30E+20	3.85	20.72
Tide	6	3.09E+04	1.10E+20	4.49	20.04
Groundwater extraction	7	1.85E+05	1.97E+19	5.27	19.29
Agriculture production	8	1.91E+05	1.07E+20	5.28	20.03
Electricity	9	2.21E+05	7.43E+19	5.34	19.87
Hydroelectricity	10	3.52E+05	3.73E+18	5.55	18.57
Livestock production	11	1.20E+06	5.68E+18	6.08	18.75
Fisheries production	12	1.01E+07	2.43E+17	7.00	17.38
Forest production	13	3.83E+04	1.52E+19	4.58	19.18
Mined coal	14	6.70E+04	2.00E+20	4.83	20.30
Crude oil	15	1.32E+05	2.09E+20	5.12	20.32
Crude natural gas	16	1.40E+05	1.32E+20	5.15	20.12
Topsoil losses, organic matter	17	6.99E+05	2.15E+19	5.84	19.33
Fisheries	18	1.01E+07	7.39E+16	7.00	16.87
Mined metals	19	1.03E+07	3.35E+17	7.01	17.53
Mined minerals	20	1.37E+07	6.80E+16	7.14	16.83
Finished products etc	21	1.50E+05	1.44E+19	5.18	19.16
Refined fuels	22	1.51E+05	2.18E+20	5.18	20.34
Food & agricultural products	23	1.85E+05	1.61E+19	5.27	19.21
Livestock, meat, fish products	24	1.36E+06	1.06E+18	6.13	18.03
Industrial chemicals	25	2.86E+06	7.81E+17	6.46	17.89
Refined minerals	26	1.10E+08	3.34E+16	8.04	16.52
Metals	27	2.52E+08	4.79E+16	8.40	16.68

	Ranking	Transformity (sej J^{-1})	Exergy input (J $year^{-1}$)	Log(Transformity)	Log(Exergy input)
Human information processing	28	3.16E+14	3.16E+09	14.50	9.50
Human DNA	29	3.98E+15	5.01E+06	15.60	6.70
Internet information processing	30	5.01E+23	1.00E+01	23.7	1

3. Calculation of work output and emergy intensity of Countries

Input data for 50 selected countries was derived from the NEAD. The 50 countries included developed and developing economies as defined by the UN [5]. The exergy and emergy of inputs were taken directly from the NEAD. Exergy input was converted to work output by applying the thermodynamic efficiencies given in Table S2. Emergy intensity (sej J^{-1}) of each economy was computed by dividing the emergy of the economic output (sum of the emergy inputs) by the work output. The emergy and exergy input data, work output, and emergy intensity as well as log work output and emergy intensity are given in Table S3.

Table S2. Thermodynamic conversion efficiencies

Item	Conversion Efficiency
Sunlight	0.01
Wind	0.475
Waves	0.045
Deep heat	0.356
Rain & river chemical potential	0.3
Tide	0.3
Groundwater extraction	0.86
Agriculture production	0.04
Electricity	0.3
Hydroelectricity	0.9
Livestock production	0.04
Fisheries production	0.04
Forest production	0.05
Mined coal	0.25
Crude oil	0.25
Crude natural gas	0.25
Topsoil and organic matter	0.04
Fisheries	0.04
Mined metals	0.2
Mined minerals	0.2
Finished products	0.999
Refined fuels	0.25
Food & agricultural products	0.04

Livestock, meat, fish products	0.04
Industrial chemicals	0.999
Refined minerals	0.999
Metals	0.999

Table S3. Emergy and exergy of inputs, work output Emergy intensities, and, log work output and log emergy intensity, for 50 countries derived from NEAD database

Name of Country	Emergy Input(sej year^{-1})	Exergy input (J year^{-1})	Work output (J year^{-1})	Emergy Intensity (sej J^{-1})	Log Work output	Log Emergy Intensity
Albania	4.50E+22	2.82E+20	2.86E+18	1.57E+04	1.85E+01	4.20
Argentina	3.17E+24	2.87E+22	2.90E+20	1.09E+04	2.05E+01	4.04
Australia	4.07E+24	1.33E+23	1.34E+21	3.04E+03	2.11E+01	3.48
Austria	1.60E+24	4.43E+20	4.95E+18	3.23E+05	1.87E+01	5.51
Belgium	4.56E+24	1.68E+20	3.26E+18	1.40E+06	1.85E+01	6.15
Botswana	1.74E+23	5.46E+21	5.55E+19	3.14E+03	1.97E+01	3.50
Brazil	7.47E+24	1.02E+23	1.03E+21	7.23E+03	2.10E+01	3.86
Canada	7.65E+24	7.30E+22	7.45E+20	1.03E+04	2.09E+01	4.01
Chile	7.77E+23	3.25E+22	3.29E+20	2.36E+03	2.05E+01	3.37
China	2.75E+25	7.17E+22	7.58E+20	3.63E+04	2.09E+01	4.56
Costa Rica	3.52E+23	5.21E+21	5.28E+19	6.67E+03	1.97E+01	3.82
Denmark	6.41E+23	7.01E+20	7.47E+18	8.58E+04	1.89E+01	4.93
Ecuador	5.63E+23	1.16E+22	1.18E+20	4.77E+03	2.01E+01	3.68
Egypt	1.67E+24	1.22E+22	1.24E+20	1.35E+04	2.01E+01	4.13
Estonia	1.42E+23	3.85E+20	3.97E+18	3.59E+04	1.86E+01	4.55
Finland	6.03E+23	1.76E+21	1.81E+19	3.34E+04	1.93E+01	4.52
France	6.35E+24	5.20E+21	5.50E+19	1.16E+05	1.97E+01	5.06
Germany	1.70E+25	1.95E+21	2.48E+19	6.84E+05	1.94E+01	5.84
Greece	6.71E+23	5.05E+21	5.16E+19	1.30E+04	1.97E+01	4.11
Hungary	1.50E+24	5.06E+20	5.49E+18	2.73E+05	1.87E+01	5.44
Iceland	8.72E+22	3.08E+21	3.16E+19	2.76E+03	1.95E+01	3.44
India	7.64E+24	4.63E+22	4.76E+20	1.61E+04	2.07E+01	4.21
Ireland	4.12E+23	2.29E+21	2.35E+19	1.75E+04	1.94E+01	4.24
Israel	4.03E+23	4.43E+20	4.75E+18	8.48E+04	1.87E+01	4.93
Italy	4.85E+24	6.14E+21	6.40E+19	7.57E+04	1.98E+01	4.88
Japan	6.63E+24	3.30E+22	3.37E+20	1.97E+04	2.05E+01	4.29
Latvia	1.58E+23	4.47E+20	4.58E+18	3.46E+04	1.87E+01	4.54
Lithuania	3.14E+23	3.36E+20	3.56E+18	8.82E+04	1.86E+01	4.95
Malaysia	2.36E+24	6.36E+21	6.59E+19	3.58E+04	1.98E+01	4.55
Mexico	8.45E+24	4.75E+22	4.82E+20	1.75E+04	2.07E+01	4.24
Netherlands	4.37E+24	4.94E+20	8.43E+18	5.18E+05	1.89E+01	5.71
New Zealand	4.41E+23	2.76E+22	2.79E+20	1.58E+03	2.04E+01	3.20
Norway	1.74E+24	4.54E+21	4.82E+19	3.61E+04	1.97E+01	4.56
Panama	3.68E+23	3.20E+21	3.24E+19	1.14E+04	1.95E+01	4.06

Peru	7.91E+23	1.77E+22	1.78E+20	4.43E+03	2.03E+01	3.65
Poland	3.04E+24	1.59E+21	1.76E+19	1.73E+05	1.92E+01	5.24
Portugal	1.02E+24	1.35E+22	1.36E+20	7.49E+03	2.01E+01	3.87
Singapore	2.28E+24	1.98E+19	2.01E+18	1.13E+06	1.83E+01	6.05
Slovakia	4.14E+24	2.46E+20	2.76E+18	1.50E+06	1.84E+01	6.18
Slovenia	4.01E+23	1.17E+20	1.32E+18	3.05E+05	1.81E+01	5.48
South Africa	1.86E+24	2.18E+22	2.22E+20	8.40E+03	2.03E+01	3.92
South Korea	2.20E+24	2.86E+21	2.95E+19	7.45E+04	1.95E+01	4.87
Spain	6.43E+24	1.16E+22	1.19E+20	5.41E+04	2.01E+01	4.73
Sweden	1.84E+24	2.61E+21	2.68E+19	6.88E+04	1.94E+01	4.84
Switzerland	8.71E+23	2.30E+20	2.60E+18	3.35E+05	1.84E+01	5.52
Thailand	2.96E+24	6.70E+21	6.90E+19	4.29E+04	1.98E+01	4.63
Turkey	2.74E+24	7.43E+21	7.59E+19	3.61E+04	1.99E+01	4.56
United Kingdom	6.50E+24	4.27E+21	4.72E+19	1.38E+05	1.97E+01	5.14
United States	2.96E+25	1.19E+23	1.22E+21	2.42E+04	2.11E+01	4.38
Vietnam	1.53E+24	7.83E+21	7.94E+19	1.93E+04	1.99E+01	4.29

4. Calculation of transformity and available energy of information

The general procedure for computing available energy in information is to evaluate the information content of the process or stock in bits and convert to Joules of information using a conversion ratio. The emergy of information is the emergy required to produce or maintain it, which is the available energy required multiplied by its transformity. In this study, we computed the available energy and transformity for three types of information: 1) human information processing; 2) human DNA; 3) WWW information processing. In addition, the available energy and transformity of human know-how. The exergy content of information is derived from literature data on the information flux from the Sun and the solar exergy driving the information flux. Details of the calculation are given in Table S4.

Table S4. Exergy content of solar information

Variable	Value	Reference
Information flux from the Sun	1.0E+38 bits s^{-1} = 3.1E+45 bits yr^{-1}	6
Solar exergy driving information flux	3.6E+24 J yr^{-1}	1
Solar exergy content of information	3.6E+24 J yr^{-1} / 3.1E+45 bits yr^{-1} = 1.14E-21 J bit^{-1}	

4.1 Transformity of human information processing

Solar transformity is computed as the ratio of solar emergy (sej) per joule of available energy. The transformity for human information processing is the ratio of the exergy of the information processed to the emergy per year of support (from NEAD database). Calculations are given in Table S5.

Table S5. Human information processing transformity

Variable	Value	Reference
Human brain information processing	3.2E+15 bits s^{-1} = 1.0E+23 bits yr^{-1}	[7]
Exergy of human brain information processing	1.0E+23 bits yr^{-1} × 1.1E-21 J bit^{-1} = 1.1E+02 J yr^{-1}	*From Table S3, line 3*
Human emergy per year (2014)*	6.4E+16 sej $capita^{-1}$ yr^{-1}	*NEAD*
Human metabolism	2400 kcal d^{-1} × 4186 J $kcal^{-1}$ × 365 d = 3.7E+09 J yr^{-1}	
Transformity	6.4E+16 sej $capita^{-1}$ yr^{-1} / 1.1E+02 J yr^{-1} = 5.8E+14 sej J^{-1}	*This work*
Log human metabolism	9.7	
Log transformity	14.8	

* mean for countries used in this study

Solar photons are primary carriers of information for any Earth process, which also support biogenesis [8]. Based on the calculations [9], explicitely mentioned by Odum[10], and Nicolis[11], Gorshkov et al. [12] reported the calculation of information flux from the Sun as 10^{38} bit/s, being derived through the definition of entropy flow. Consequently, the information flow from the Sun along 1 year is 3.15E+45 bit. A solar exergy value of 3.6E+24 was reported by Brown et al. [1] in the latest quantification of geobiosphere emergy baselines (GEB). In the case of Sun, the information UEV ($UEV_{info, Sun}$), being the ratio of the two above amounts, is 8.75E+20 bit/seJ. Its reciprocal, being 1.14E-21 seJ/bit, represents the amount of solar-equivalent energy contained in 1 bit of information.

4.2 Transformity of human DNA

Transformity of human DNA is computed as the ratio of solar emergy required to support viable human population per joule of information in the DNA of the population, based on quantity of DNA in average human, age of reproductive adult, emergy per year of support, and minimum viable population. The data are given in Table S6.

Table S6. Human DNA transformity

Variable	Value	Reference
Quantity of DNA per cell	7.0E-12 g DNA/cell	[13]
Number cells (adult)	3.7E+13 cells	[14]
Min. viable population	4.0E+04 p.	[15]
Emergy of human per year	4.4E+16 sej $capita^{-1}$ yr^{-1}	*NEAD*
Years to adult	13 yr	[16]
Energy of DNA	3.7E+13 cells × 7.0E-12 g DNA $cell^{-1}$ × 5.0 kcal g^{-1} DNA × 4186 J $kcal^{-1}$ = 5.4E+06 J DNA $adult^{-1}$	*This work*
Transformity human DNA	13 yr × 4.4E+16 sej $capita^{-1}$ yr^{-1} × 4.0E+04 p. / 5.4E+06 J = 4.3E+15 sej J^{-1}	*This work*
Log exergy DNA	6.7	*This work*
Log Transformity	15.6	*This work*

4.3 Transformity of Internet information processing

Solar transformity of internet is computed as the ratio of the emergy required by the world wide web (WWW) per joule of information being processed. Given in Table S7 are estimates of information flux and the exergy of the information processed as well as the exergy costs of information processing by internet worldwide.

Table S7. WWW information processing

Variable	Value	Reference
Data traffic	1.2 ZB = 9.6E+21 bits yr^{-1}	[17]
Energy	334 TWh = 1.2E+18 J yr^{-1}	[18]
Transformity of electricity	5.0E+05 sej J^{-1}	NEAD
Emergy of WWW	1.2E+18 J yr^{-1} × 5.0E+05 sej J^{-1} = 6.0E+24 sej yr^{-1}	*This work*
Exergy of information	9.6E+21 bits yr^{-1} × 1.14E-21 J bit^{-1} = 1.09E+01 J yr^{-1}	*This work*
Transformity	6.0E+24 sej yr^{-1}/1.09E+01 J yr^{-1} = 5.5E+23 sej J^{-1}	*This work*
Log information exergy	1.0	
Log Transformity	23.7	

4.4 Transformity of human know-how for selected Countries

Transformities for human know-how were calculated as the ratio of emergy use per capita, whose values are available from NEAD, and exergy of human brain information processing (see: Table S5). Exergy of information was computed by multiplying the population of a country by the average exergy content of human brain information processing per year (see: Table S5). Transformity and exergy values related to human know-how for selected countries are given in Table S8.

Table S8. Transformity and available energy values of human know-how for selected Countries

Country	$U_{Per\ capita}$	Population	Tr_{info} (sej J^{-1})	E_{info} (J $year^{-1}$)	Log Tr_{info}	Log E_{info}
			(= $U_{per\ cap.}$/1.1E+02)	(= pop × 1.1E+02)		
Albania	1.56E+16	2.89E+06	1.42E+14	3.18E+08	14.2	8.5
Argentina	7.38E+16	4.30E+07	6.71E+14	4.73E+09	14.8	9.7
Australia	1.73E+17	2.35E+07	1.58E+15	2.59E+09	15.2	9.4
Austria	1.87E+17	8.54E+06	1.70E+15	9.39E+08	15.2	9.0
Belgium	4.07E+17	1.12E+07	3.70E+15	1.23E+09	15.6	9.1
Botswana	7.85E+16	2.22E+06	7.13E+14	2.44E+08	14.9	8.4
Brazil	3.62E+16	2.06E+08	3.29E+14	2.27E+10	14.5	10.4
Canada	2.16E+17	3.55E+07	1.96E+15	3.91E+09	15.3	9.6
Chile	4.37E+16	1.78E+07	3.97E+14	1.96E+09	14.6	9.3
China	2.02E+16	1.36E+09	1.84E+14	1.50E+11	14.3	11.2
Costa Rica	7.39E+16	4.76E+06	6.72E+14	5.24E+08	14.8	8.7
Denmark	1.14E+17	5.64E+06	1.03E+15	6.20E+08	15.0	8.8
Ecuador	3.54E+16	1.59E+07	3.22E+14	1.75E+09	14.5	9.2

Egypt	1.86E+16	8.96E+07	1.70E+14	9.86E+09	14.2	10.0
Estonia	1.09E+17	1.31E+06	9.87E+14	1.44E+08	15.0	8.2
Finland	1.10E+17	5.46E+06	1.00E+15	6.01E+08	15.0	8.8
France	9.58E+16	6.63E+07	8.71E+14	7.29E+09	14.9	9.9
Germany	2.10E+17	8.10E+07	1.91E+15	8.91E+09	15.3	9.9
Greece	6.15E+16	1.09E+07	5.59E+14	1.20E+09	14.7	9.1
Hungary	1.52E+17	9.87E+06	1.38E+15	1.09E+09	15.1	9.0
Iceland	2.67E+17	3.27E+05	2.42E+15	3.60E+07	15.4	7.6
India	5.88E+15	1.30E+09	5.34E+13	1.43E+11	13.7	11.2
Ireland	8.91E+16	4.62E+06	8.10E+14	5.08E+08	14.9	8.7
Israel	4.90E+16	8.22E+06	4.45E+14	9.04E+08	14.6	9.0
Italy	7.97E+16	6.08E+07	7.25E+14	6.69E+09	14.9	9.8
Japan	5.22E+16	1.27E+08	4.75E+14	1.40E+10	14.7	10.1
Latvia	7.96E+16	1.99E+06	7.24E+14	2.19E+08	14.9	8.3
Lithuania	1.07E+17	2.93E+06	9.75E+14	3.22E+08	15.0	8.5
Malaysia	7.89E+16	2.99E+07	7.17E+14	3.29E+09	14.9	9.5
Mexico	6.76E+16	1.25E+08	6.14E+14	1.38E+10	14.8	10.1
Netherlands	2.59E+17	1.69E+07	2.35E+15	1.86E+09	15.4	9.3
New Zealand	9.79E+16	4.51E+06	8.90E+14	4.96E+08	14.9	8.7
Norway	3.39E+17	5.14E+06	3.08E+15	5.65E+08	15.5	8.8
Panama	9.52E+16	3.87E+06	8.65E+14	4.26E+08	14.9	8.6
Peru	2.55E+16	3.10E+07	2.32E+14	3.41E+09	14.4	9.5
Poland	7.99E+16	3.80E+07	7.26E+14	4.18E+09	14.9	9.6
Portugal	9.82E+16	1.04E+07	8.92E+14	1.14E+09	15.0	9.1
Singapore	4.17E+17	5.47E+06	3.79E+15	6.02E+08	15.6	8.8
Slovakia	7.63E+17	5.42E+06	6.94E+15	5.96E+08	15.8	8.8
Slovenia	1.95E+17	2.06E+06	1.77E+15	2.27E+08	15.2	8.4
South Africa	3.44E+16	5.41E+07	3.13E+14	5.95E+09	14.5	9.8
South Korea	4.36E+16	5.04E+07	3.96E+14	5.54E+09	14.6	9.7
Spain	1.38E+17	4.65E+07	1.26E+15	5.12E+09	15.1	9.7
Sweden	1.90E+17	9.70E+06	1.73E+15	1.07E+09	15.2	9.0
Switzerland	1.06E+17	8.19E+06	9.67E+14	9.01E+08	15.0	9.0
Thailand	4.38E+16	6.77E+07	3.98E+14	7.45E+09	14.6	9.9
Turkey	3.54E+16	7.75E+07	3.22E+14	8.53E+09	14.5	9.9
United Kingdom	1.01E+17	6.46E+07	9.14E+14	7.11E+09	15.0	9.9
United States	9.28E+16	3.19E+08	8.44E+14	3.51E+10	14.9	10.5
Vietnam	1.69E+16	9.07E+07	1.54E+14	9.98E+09	14.2	10.0

Table S9 The development changes from 2001 to 2014 in 50 countries

No.	COUNTRY	2001 log Transformity	2001 log Exergy input	2014 log Transformity	2014 log Exergy input	Types*
3	Australia	3.39	23.12	3.49	23.12	developed
8	Canada	4.01	22.86	4.01	22.86	developed
9	Chile	3.06	22.51	3.38	22.51	developed
17	France	5.05	21.72	5.08	21.72	developed
18	Germany	5.66	21.29	5.84	21.29	developed

25	Italy	4.81	21.79	4.89	21.79	developed
26	Japan	4.20	22.52	4.30	22.52	developed
42	South Korea	4.49	21.46	4.89	21.46	developed
43	Spain	4.68	22.07	4.74	22.07	developed
45	Switzerland	5.37	20.36	5.56	20.36	developed
48	United Kingdom	5.15	21.63	5.15	21.63	developed
49	United States	4.35	23.07	4.39	23.07	developed
1	Albania	4.10	20.45	4.20	20.45	developing
2	Argentina	3.82	22.46	4.04	22.46	developed
4	Austria	5.53	20.65	5.52	20.65	developed
5	Belgium	6.20	20.22	6.15	20.23	developed
6	Botswana	3.39	21.74	3.50	21.74	developing
7	Brazil	3.69	23.01	3.86	23.01	developing
10	China	4.18	22.86	4.56	22.86	developing
11	Costa Rica	3.66	21.72	3.83	21.72	developing
12	Denmark	5.07	20.85	4.96	20.85	developed
13	Ecuador	3.53	22.07	3.68	22.07	developing
14	Egypt	3.79	22.09	4.13	22.09	developing
15	Estonia	4.49	20.59	4.58	20.59	developed
16	Finland	4.55	21.25	4.56	21.25	developed
19	Greece	4.49	21.70	4.13	21.70	developed
20	Hungary	5.18	20.70	5.45	20.70	developed
21	Iceland	3.46	21.49	3.44	21.49	developed
22	India	3.85	22.66	4.21	22.67	developing
23	Ireland	4.40	21.36	4.27	21.36	developed
24	Israel	5.06	20.65	4.94	20.65	developed
27	Latvia	4.56	20.65	4.57	20.65	developed
28	Lithuania	4.63	20.53	4.96	20.53	developed
29	Malaysia	4.30	21.80	4.56	21.80	developing
30	Mexico	4.15	22.68	4.25	22.68	developing
31	Netherlands	5.65	20.69	5.72	20.69	developed
32	New Zealand	3.13	22.44	3.20	22.44	developed
33	Norway	4.57	21.66	4.57	21.66	developed
34	Panama	3.38	21.51	4.06	21.51	developed
35	Peru	3.63	22.25	3.65	22.25	developing
36	Poland	4.99	21.20	5.25	21.20	developed
37	Portugal	3.87	22.13	3.89	22.13	developed
38	Singapore	6.07	19.21	6.06	19.30	developed
39	Slovakia	5.42	20.39	6.18	20.39	developed
40	Slovenia	5.41	20.07	5.49	20.07	developed
41	South Africa	3.76	22.34	3.93	22.34	developing
44	Sweden	4.74	21.42	4.85	21.42	developed
46	Thailand	4.32	21.83	4.64	21.83	developing
47	Turkey	4.16	21.87	4.57	21.87	developing
50	Vietnam	3.75	21.89	4.29	21.89	developing

Note: * The classification of developed and developing countries mainly based on the Wikipedia.

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