Scenarios of Systemic Transitions in Energy and Economy

Gilbert Ahamer
Senior Researcher [a], Expert [b], gilbert.ahamer@uni-graz.at

[a] Institute for Economic History at the Graz University, Brandhofgasse 5, 8010 Graz, Austria
[b] Environment Agency Austria, Spittelauer Lände 5, 1090 Vienna, Austria

Abstract

For the energy economics sector, earlier forecasting approaches (e.g., a Kaya identity or a double-logarithmic function) proved too simplistic. It is becoming necessary to systemically include the emergence of new discrete evolutionary changes. This paper provides a novel quantitative forecasting method which relies on the Global Change Data Base (GCDB). It allows for the generation and testing of hypotheses on future scenarios for energy, economy, and land use on a global and country level.

The GCDB method envisages systemic variables, especially quotients (such as energy intensity), shares (such as GDP shares, energy mix), and growth rates including their change rates. Thus, the non-linear features of evolutionary developments become quantitatively visible and can be corroborated by plots of large bundles of time-series data. For the energy industry, the forecasting of sectoral GDP, fuel shares, energy intensities, and their respective dynamic development can be undertaken using the GCDB method.

Keywords: energy foresight; global modelling; Global Change Data Base; scenarios; heuristic modelling; fuel mix; trends extrapolation; dynamics-as-usual scenario; land use change; saturation; autopoietic systems

Citation: Ahamer G. (2022) Scenarios of Systemic Transitions in Energy and Economy. *Foresight and STI Governance*, 16(3), 17–34. DOI: 10.17323/2500-2597.2022.3.17.34

Paper type: Research Article

Introduction

Foresight methods and decision support systems are able to provide quantitative data material, analyze it suitably and derive conclusions for real-world economic decisions including energy (Lu et al., 2009; MacHaris et al., 2012; Mattiussi et al., 2014; Seuring, 2013). An earlier article in this journal (Ahamer, 2018) explained the functioning of the Global Change Data Base (GCDB) method, which maps trends from a system dynamics perspective. The GCDB detects country-wide dynamics of energy-related socioeconomic systems. Bundles of time series of per-country data can be plotted and visually analyzed by the GCDB analytical tool. From globally relevant public data, the GCDB provides re-computations, combinations, time derivatives, and their correlations with time, economic development (GDP/capita) and other structural variables in order to provide a consistent picture of global evolutionary trends (Castells, 1996; Christian, 2005). Such evolutionary trends can inform scenario-writing which further allows one to assess a country's room for maneuvering depending on various policy scenarios.

This article will apply the GCDB to energy and the economy and will detect "systemic transitions" — meaning the gradual restructuring within countries' institutions for energy economics and their rules of functioning along the evolution of the global systems of energy and economy. The GCDB and its analytical tool provides a more detailed scenario writing opportunities than current databases (e.g., the International Institute for Applied Systems Analysis, IIASA)[1] because it provides sector-specific and fuel-specific timelines for each country with much greater detail, as it includes several dozens of economic sectors and fuels.

Methods Used

The GCDB method consists of creating country-wide correlations not only of data points but of data series, and includes graphical representations which open themselves much better for interpretation than single mathematical numbers such as regression coefficients (r). GCDB's genesis and method was explained earlier (Ahamer, 2014, 2018, 2021) and the profits of combining often uncombined data sets such as FAO's land use data[2], IEA's energy data[3] and UNSTAT's economic data[4], after solving difficult compatibility questions regarding economic sectors and fuel types, which are defined differently in different data bases.

In practical work, the user selects the data sets to be correlated from a menu and displays them in either a logarithmic or linear manner on two axes of a coordinate system. The assumption of underlying "evolutionary trends" is more likely for such data correlations which show highly streamlined arrays of (averaged) lines than for those showing almost no correlation. For building theories, the most highly correlated plots are selected; and these are shown in the following chapters. Furthermore, building on such (graphical) trend extrapolations, options for policy making can be defined, especially in such cases where single states do not yet follow global trends or fall behind their structural potential. One example is the parameter of energy intensity which was lower by a factor of 5-10 in former communist countries (the former USSR, China) as compared to countries with free market economies. In this sense, the worldwide rising value of this parameter clearly correlates with human evolution proceeding from autocracies to democracies.

The factor formula using consecutive quotients

The GCDB allows for gaining more accuracy in the identification of long-term trends in the development of the global energy system based on detailed statistical analysis. For the above-mentioned target, an ordering structure for the parameters to be analyzed here is proposed as Figure 1, representing a well-known factor decomposition often referred to as the *Kaya identity* (Kaya, Keiichi, 1997; Peters et al., 2017; Feron, 2016), and including the key parameter population, economic activity (GDP), final energy demand (E_{final}), and primary (or raw) energy demand ($E_{prim.}$). All of these have to be analyzed as a time series on a per-country level.

The advantage of expressing recent historic development (and — in the case that reality can be projected at all — the near future) as a formula lies in the increased visibility of several distinct thematic areas within a logic chain, namely

- energy technology and fuels (described by the CO_2 emission factor CO_2 / E_p),
- energy conversion efficiency (described by the efficiency of converting primary to final energy, E_p / E_f),

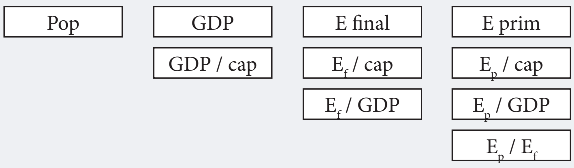
[1] E.g., the database supported by the International Institute for Applied Systems Analysis (IIASA). https://previous.iiasa.ac.at/web/home/research/researchPrograms/Energy/Databases.en.html, accessed 18.11.2021.

[2] The database supported by the Food and Agriculture Organization (FAO). https://www.fao.org/land-water/databases-and-software/ru/, accessed 18.11.2021.

[3] The database supported by the International Energy Agency (IEA). https://www.iea.org/data-and-statistics/data-browser, accessed 18.11.2021.

[4] The database supported by the United Nations Statistics Division (UNSTAT). https://unctadstat.unctad.org/EN/, accessed 18.11.2021.

Figure 1. **The Principal Set-up of the Statistical Analysis**



Note: Several sets of quotients of the key parameters are used such as population number, (final and primary) energy demand, and economic level (GDP).

Source: author.

- efficacity of an economy to provide output with a given amount of energy input, called "energy intensity" E_f / GNP),
- the economic level of a country described by per capita Gross Domestic Product GNP / capita) and
- the population.

This factor formula reads in the general notation as:

$$CO_2 = (CO_2 / E_p) \times (E_p / E_f) \times (E_f / GNP) \times (GNP / capita) \times population$$

where: CO_2 — level of CO_2 emissions; E_p — demand for primary energy (for a specific energy carrier); E_f — demand for final energy (for a specific energy carrier); GNP — gross national product (in a specific economic sector); P — population.

This same factor formula reads in the detailed notation, including sectors and fuels:

$$CO_2 (c, y) = \Sigma\, CO_2 (c, y, f, s) = [CO_2 (c, y, f, s) / E_p (c, y, f, s)] \times [E_p (c, y, f, s) / E_f (c, y, f, s)] \times [E_f (c, y, f, s) / GNP (c, y, s)] \times [GNP (c, y, s) / P (c, y)] \times P (c, y)$$

where: c = country, y = year, f = fuel, s = economic sector.

Unlike with simple correlations, the present theme of global evolution requires the careful handling of uncertainties and selective deviations from trends. Thus, the present article provides the most important of the above-mentioned quotients in a graphical manner in order to portray the levels, increase rates, trends, and statistical deviations of the presumed trends in an easily perceivable manner. Therefore, this article deems it more suitable to provide a graphical means of presentation as compared to a presentation of mere numbers representing the correlation factors.

Data and projections used

The present article uses past data only, and depending on their specific interest or the apparent correlation coefficient, the reader may extrapolate data into the long-term future, which will require personal paradigms on how world history is likely to function (Christian, 2018). Evidently, extrapolation by a few years might seem safer than by a few decades. In the following figures, for most cases this projection is not undertaken explicitly by using single lines because such line-drawing could create the false impression of safe assumptions regarding future trends. Therefore, the author refrains from explicitly "computing the future" by a regression formula. Actually, reality is far more complex than can be described by a handful of statistical parameters and includes innovation, saturation stages, political conflicts, and culturally produced deviations from seemingly stable trends (Ahamer, Kumpfmüller, 2013), among which recent decisive climate change policies which already visibly curb some countries' CO_2 emissions. Therefore, the continuation of trends represents rather mere hypotheses for structural change in many cases, which then still have to be counter-checked against their real-world likelihood.

Which Systemic Transitions Have already Taken Place in the Past?

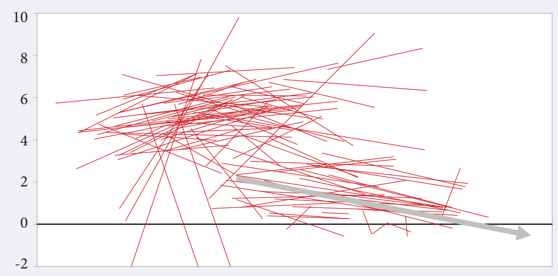
Additionally, to the mainly evolutionary character of historic development, distinct steps or leaps can be perceived in the structural-functional interplay between the techno-socio-economic parameters of the anthroposphere; thus leading to a stepwise, ever more complex self-creation of the noosphere (Jäger, Springler, 2012; Kondratieff, 1984; Christian, 2018; Raskin, 2016). During this co-creative evolution to a humanized world, "yet varieties of global disruption (barbarization) and progressive transformation (great transition) remain plausible alternatives"— as we especially witness currently.

On a more general level, we perceive a steady shift between those domains which exhibit virulent growth during some historic epochs while showing stagnation beforehand and afterwards (such as population, Gross Domestic Product GDP, final energy E_f, and primary energy E_p). In world history, there are transitions (Christian, 2005) visible which represent rather rapid systemic structural changes, including

- the population transition,
- the deforestation transition or land-use transition,
- the transition among several energy sources which have their corresponding main pollutants.

This stepwise "*evolution in transitions*" makes mere trend projection irrelevant as a scientific method and practically-minded foresight toolbox, but instead suggests a more inspired retrieval of crucial points determining the overall civilizational dynam-

Figure 2. **Population Growth Rates in All Countries of the World during the Last Few Decades**



Note: A possible path for industrialized countries such as Russia or Austria is shown in grey.

Source: author.

ics such as saturation points, turning points, and the seemingly unexpected creation of new phenomena. The GCDB method takes such complex dynamics into account by analyzing the 1st and 2nd time derivatives of data series (Ahamer, 2018).

Population explosion and population transition

One of the best-known structural transitions of the anthroposphere is the so-called *population transition* or demographic transition (Galor, 2012; Akaev et al., 2012). This first type of evolutionary transition is well documented and well explained in scientific literature based on several decades-long analyses (Chen, 2014; Fischer, 2008; Zhang, 2002; Du, Yang, 2014; Toft, 2007; Shen, Spence, 1996; Ssewamala, 2015; Jeníček, 2010; Nielsen, Fang, 2007) and therefore serves as the first example for how the GCDB illustrates global trends. As a function of increasing education, birth rates in many countries decrease (Kravdal, Rindfuss, 2008; Mills et al., 2011; Raymo et al., 2015; Upadhyay et al., 2014) while depending on several framework conditions; and as a function of increased medical support, death rates decrease in similar time periods.

The relevant aggregate change rate is population change (d pop/dt) which has already slowed down, as Figure 2 shows for the growth rates as a function of GDP/cap (each red line meaning the time average of a country during 1960–1991). Thus, our earlier global problem of a population explosion has already turned into our present problem of "population shrinkage", especially in countries of the "Global North".

Figure 3. **Deforestation (in percent of arable land area) as a Function of GDP/Capita**

Note: From left to right, along evolution, chronic deforestation even turns into afforestation in developed countries.

Data sources: FAO, World Bank, GCDB.

Deforestation in order to gain new arable land

The second type of transition is mentioned in literature and commonly named "land use transition" (Lambin, Meyfroidt, 2011, 2019; Hurtt et al., 2006, 2011; Macedo et al., 2012; Baumann et al., 2011; Grau, Aide, 2008; Rounsevell et al., 2012; Long, 2014; Long et al., 2014; Munteanu et al., 2014; Powers et al., 2011; Long, Qu, 2018; Meyfroidt et al., 2018; Nuissl et al., 2009)[5] including various shades of this global trend. To evaluate this massive trend, the GCDB provides long-term trends for countrywide averaged values.

The setting aside of agricultural areas has replaced the former pressing need for "*new agricultural land*", which earlier caused deforestation. This is becoming strikingly visible in Europe and countries with high GDP/capita and is displayed in Figure 3 as a function of GDP/capita.

The key message of this figure is that apparently with growing development, less deforestation is needed to maintain an economy. The more a country develops, the less deforestation activities become necessary and even reafforestation can be undertaken. At the same time, the limits are illustrated of a concept that attempts to portray the economic future as a mere function of the economic past. The principal necessity for a multi-paradigmatic methodology of foresight (Vester, von Hesler, 1980; Ahamer, Jekel, 2010) is already felt here.

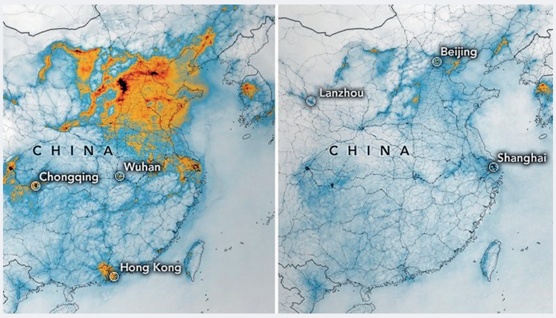
Epochal systemic changes in air pollution and the energy fuel mix

During recent environmental protection history, we can even observe a systemic and epochal change in the air pollutants considered the most relevant and these correlate with the evolutionary changes of en-

[5] Alternative term proposal is "deforestation transition" as chosen by the author (Fagua et al., 2019).

Figure 4. **The Concentration of Nitrogen Oxide in the Air above China**

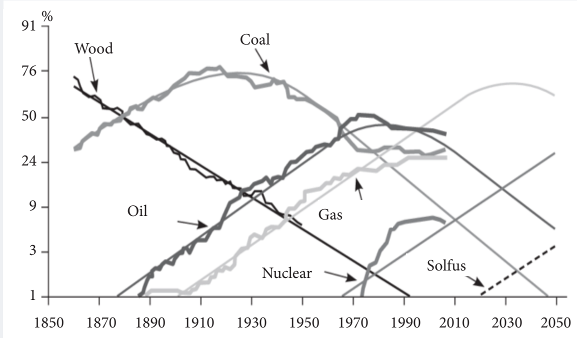
a) January 2020 ***b) February 2020***



Note: One can see strong decreases in concentration of nitrogen oxide as a result of the Corona virus pandemic and related economic limitations.

Source: https://www.zeit.de/2020/14/emissionen-corona-krise-klimaschutz-treibhausgase-co2, accessed 19.01.2022.

Figure 5. **The "Marchetti Curve"**



Note: The "Marchetti curve" had hoped to explain past and project future energy carrier percentages according to a logistic substitution model. As we see, earlier prognoses for growing nuclear shares did not come true (Ahamer, 2012), and the "solfus" (= solar or fusion, then still undecided) turned out to be renewable energy, not fusion energy. Seen from now, this curve is a historic document from a techno-optimistic era.

Source: adapted basing on (Marchetti, Nakićenović, 1979).

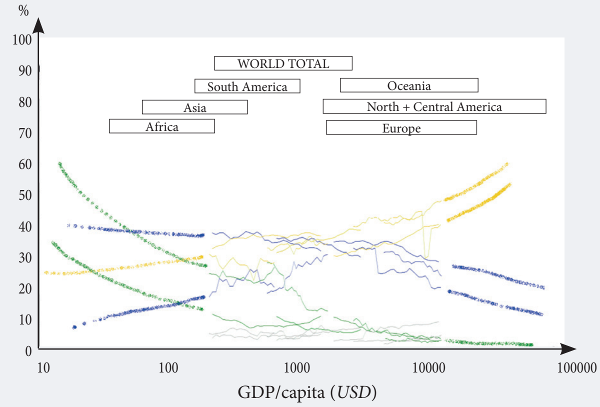
ergy sources "on the catwalk", i.e., in the perception of environmentally interested persons. First in the early days of environmental protection: these were dust, CO, and SO_2 which represent "classical pollutants". Later NO_x and hydrocarbons (often from traffic sources, see Figure 4) become relevant for ozone formation and causing respiratory diseases. Afterwards CO_2 and greenhouse gases (GHG) came to attention as systemic effects of any fossil-based society (Meadows et al., 1972; Lovelock, 1988).

Therefore, we can conclude: every time period has its mode of environmental pollution, ranging from small-scale coal dust and CO pollution to the globally relevant greenhouse gas CO_2, and this changes according to humanity's environmental understandings. Experience shows that these environmental problems were (at least partially) solved in this historic sequence: during the 1960s until the 1990s, dust, CO, and SO_2 were lowered considerably, mostly by (end-of-pipe) filter technologies, during the 1990s-2010s ozone precursors were reduced, and presently GHG are the focus of environmental action worldwide. In the same sense, there appears to be a trend from individual to systemic, namely from an individual case of a limited problem (e.g., from an individual, easily identifiable industrial chimney) to a pervasive *systemic* and structural problem with myriads of emitters (such as households and traffic) that includes a strong behavioral component. The crisis of COVID-19 coronavirus offers an unexpected insight that air emissions can actually be reduced from one month to another to such a considerable extent that it even suffices as a climate protection measure (Figure 4).

As a second example, the historic sequence of emphasis on changing market shares of energy sources seems to follow a regular pattern at first sight. This led early researchers to assume a double logarithmic curve as was propagated by Italian Cesare Marchetti who plotted relative market shares (f) against time (Marchetti, Nakićenović, 1979). The following image (Figure 5) emerges in his vision: after an early historic biomass era, there follows the coal era, then the oil era, currently the gas era and — in these authors' vision of the future — the nuclear era, which was even more desired at that time. These analysts remain partly undecided regarding the future: as an interpretation of the ambiguous abbreviation "solfus", every reader can make their own interpretation of what this abbreviation means: solar or fusion, depending on the preferences of any given reader. This example shows that in former decades, research tried to remain entirely value-free, according to the paradigm of "pure science" during these times. The so-called *Marchetti curve* represents successive epochs with different predominant energy sources according to their market shares f, which are plotted into a double-logarithmic horizontal scale (f/(1–f)), see Figure 5. This curve became well known, but still did not prove sufficiently correct, based on how the situation actually developed with the benefit of hindsight (i.e., 40 years later in this case) which proved the earlier presentation of this information to be partly incorrect.

In the author's view, this example underlines the fact that relying too much on an ideological paradigm might mislead forecasting activities and distort suggested scenarios.

Figure 6. **The Three Main Economic Sectors Plotted for Each Continent as a Function of GDP/Capita**



Note: Agriculture marked as green; industry — blue; services — yellow. In order to highlight possible "paths of development", sprayed colours suggest lines outside the actual scope of data.

Source: author, using data from (Ahamer, 2019) and GCDB.

Which Economic Sectors are Important during Evolution, and to What Extent?

This chapter presents the diagnosis of evolutionary shifts among sectors of an economy as a function of economic development and provides various graphic representations for this evolutionary analysis.

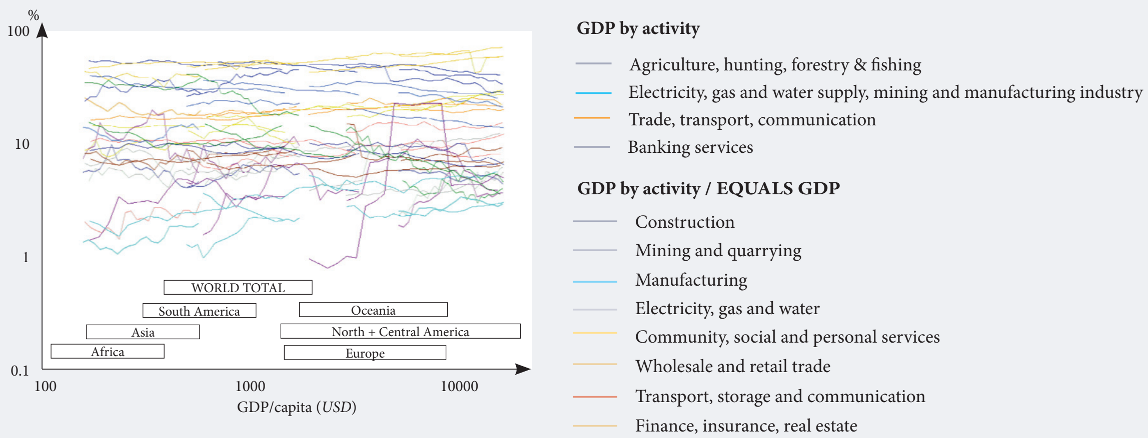
Graphically representing development paths for sectoral GDP by continents

One key interest of any forecasting activity is finding structural shifts within global economic systems (Sterman, 2000; Abler et al., 1971; Duraković et al., 2012). This means, to what extent do the sectors shift, and in which sequence? Expressed in other words, what is important to the population, by which economic activity is their attribution of importance expressed and by how much economic effort is their drive to express their preferences implemented in reality? What is essential for an economy is expressed to a large extent by the percentage share of the relevant economic sector; for example, the expenses and services that are made by these sectors. Existing gross national product data allow such a representation in a uniform manner through the value for all countries in past decades.

As a first step, continent-wide representations of the percentages of the three main GDP sectors as functions of these continents' economic levels (GDP/cap) are arranged in Figure 6, where each continent is shown by graphs allocated to this continent's GDP/cap levels. Sprayed lines in the three colors suggest a window width in which so-called "paths of developments" could continue on our planet, including a supposed history covering smaller GDP/capita levels. However, it should be kept in mind that assuming the existence of "paths of development" at all represents an act of implicitly subscribing to one of several possible opinions within the realm of developmental paradigms: the notion of development paths means identical pathways for any evolution, and that all countries would more or less follow the track of "the most developed" nations. Such developmental optimism (provided by internal growth theories), however is contrasted by dependence theories (Fischer et al., 2016; Ahamer, Kumpfmüller, 2013; Bader et al., 2013, 2014).

As a second step, continent-wide representations of the percentages of the ten GDP parts as functions of these continents' economic levels (GDP/cap) are shown in Figure 7, which provides more details but at the same time less easily traceable "paths of development", and more disturbance by potential changes in data coverage producing stepwise functions.

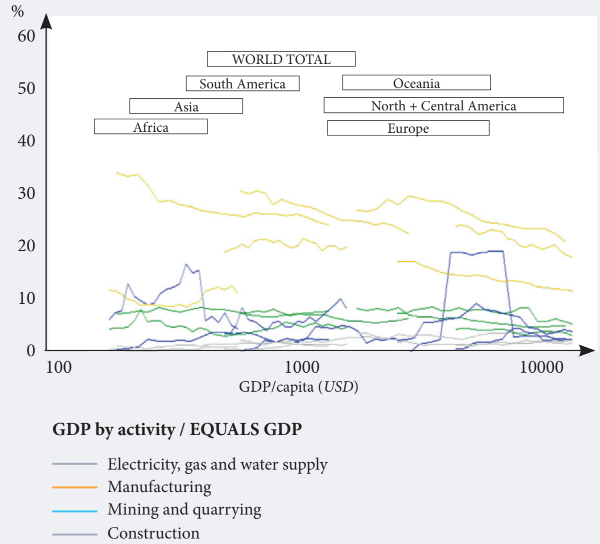
Figure 7. **The Ten Economic Sectors Plotted for Each Continent as a Function of GDP/Capita on a Logarithmic Vertical Scale**



Note: Agriculture marked as green; industry — blue; services — yellow.

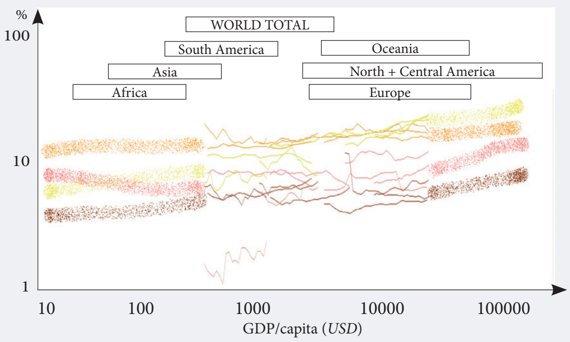
Source: author, using data from World Bank and GCDB.

Figure 8. **The Four Industrial Economic Sectors Plotted for Each Continent as a Function of GDP/Capita on a Linear Vertical Scale**



Source: author, using data from World Bank and GCDB.

Figure 9. **The Four Service Economic Sectors Plotted for Each Continent as a Function of GDP/Capita on a Logarithmic Vertical Scale**



Source: author, using data from World Bank and GCDB.

As a next step, Figure 8 explores the details of industrial sectors only while using a linear scale — in contrast to the logarithmic scale of Figure 7. It becomes clear that the dynamics of small values of a few percent only become more visible on a vertical logarithmic scale, which better complies with an implicit paradigm of "presumably constant relative change rates during development" (Estep, 2002), which thus will be kept in use in the future.

Better visibility of alleged "paths of development" can be achieved by logarithmic (as opposed to linear) plots, which is corroborated by Figure 9 showing the generally rising percentage shares of service sectors on any continent. The GCDB generally relies on graphic *pattern recognition* and tends to understand better pattern discernability as better explainability for an evolutive formula. Thus, any evolution tends to obey exponential building laws as opposed to linear building laws.

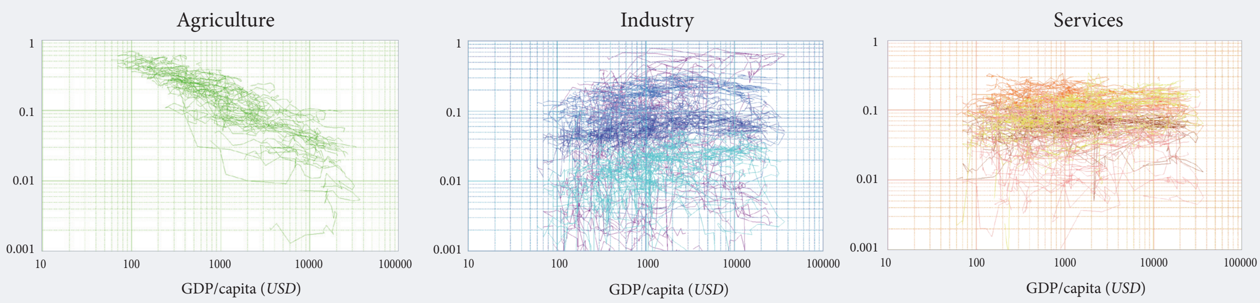
The methodological message of Figure 10 is that a plot of all single countries without using a time-average representation could likely provide a less clear picture as compared to using spatial or temporal aggregates, which is done in other figures.

The above-mentioned type of economic transition between sectors has known for a long time (Haggett, 2001), and the GCDB allows one to quantify its relative speed and periods of onset for all single sectors. By doing so, "economic transition" becomes a generalizable "natural law" for all countries.

Visualization of development paths for sectoral GDP by countries

This subsection shows how various manners of graphical representation (of one and the same data) allows for the recognition of various sub-aspects within the economic transition as a global phenomenon.

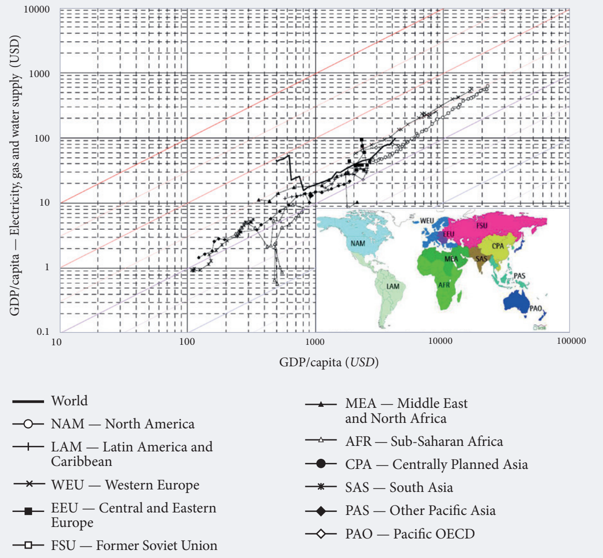
Figure 10. **The Three Main Economic Sectors as Composed by their Respective Single Sectors**



Note: Vertical axis reflects the ratio "GDP per capita / EQUALS GDP". Data plotted for each continent as a function of GDP/capita for each single country. Agriculture marked as green; industry — blue; services — yellow.

Source: author, using data from World Bank and GCDB.

Figure 11. **Development of the Sectoral GDP/Capita of the Electricity Generating Industry as a Function of GDP/Capita**



Legend for diagonal lines: red = 100% share of total GDP, pink = 10% share, violet = 1%, grey = 0.1%.

Note: Incomplete data supply by single countries may cause jumps in data curves. The eleven world regions equate IIASA modelling, as described by the map insert.

Source: author, using data from World Bank and GCDB.

Based on the above experiences with graphical representations depicting the *intra-sectoral shift* occurring during economic evolution (in possibly systematic manner, which is still to be analyzed), a new method of presenting is being developed now.

On the one hand, all evolutionary information is best plotted as a function of GDP/capita; on the other hand, the percentage rates of every single economic sector should be clearly visible. Additionally, appropriate (spatial and temporal) averaging is recommended in order to render the development paths visible.

As a first example of a type of presentation as well as of the variability between geographical regions, Figure 11 plots the development of GDP per capita for the energy-related sub-sector named "electricity, gas, steam"[6] as a function of GDP/cap. The definition of eleven regions complies with IIASA models (IPCC, 2002; Ahamer, 2008, 2014, 2015).

In the course of overall economic growth, the GDP of this single sub-sector also increases; and therefore, the curves of all continents point towards the top right. The percentage of total GDP can be read by comparison with the diagonals, which are therefore explicitly marked. Greater inclination upwards in Figure 11 means a positive rate of increase in Figure 13.

Figure 12 shows the same information as Figure 11 for the entirety of all nine economic sectors, plus for the aggregates industry, services, and statistical adjustments. The sequence of diagonal lines is the same as in Figure 11, only in blue color.

It becomes visible that a few sectors do not seem to follow a "development path" but rather obey local geographical circumstances; the most visible sector being mining – which becomes clear when understanding geographic and geologic criteria for mining activities which do not depend on a country's economic level. Other sectors' development seems to exhibit a rather clear "evolutionary path".

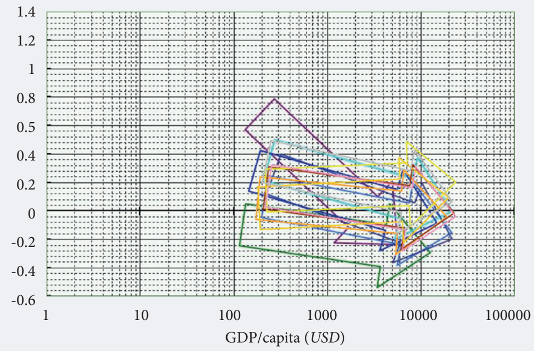
In a next step, the change rates of the percentages of all nine sectors are displayed in an explicit manner.

Figure 12. **Development of the GDP/Capita of All Nine Economic Sectors as Function of GDP/Capita**

Note: Legend for the sequence of diagonal lines as in Figure 10
Source: author, using data from World Bank and GCDB.

[6] According to UN economic categories. See: https://unstats.un.org/unsd/trade/classifications/SeriesM_53_Rev.5_17-01722-E-Classification-by-Broad-Economic-Categories_PRINT.pdf, accessed 14.01.2022.

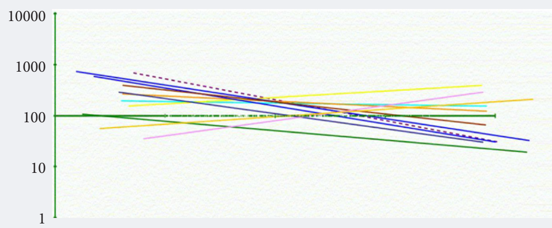
Figure 13. **Arrows for the Change Rates for All Nine Sectorial Percentages as a Function of GDP/Capita**



Note: Legend for the sector colours see in Figure 11.

Source: author, using data from World Bank and GCDB.

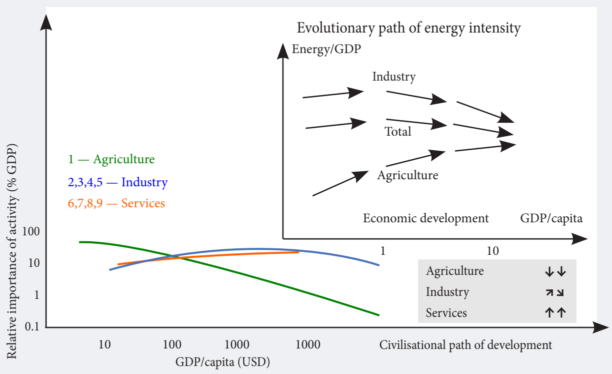
Figure 14. **Change Rates (in %) for All Nine Sectors as a Function of GDP/Capita**



Note: Legend for the colours of the sectors as in Figure 11.

Source: author, using data from World Bank and GCDB.

Figure 15. **The Resulting Presumed Development Path for the Three Main Economic Sectors Plotted Globally as a Function of GDP/Capita**



Note: Agriculture marked as green; industry — blue; services — yellow. The insert provides yet more detail by suggesting a path for the related energy intensity in agriculture and industry.

Source: author, using data from GCDB.

Figure 13 shows arrows which equal roughly the trends for change rates when averaging across all countries worldwide. In another type of depiction, Figure 14 provides the averaged change rates for all nine economic sectors, again measured as percentage points.

Conclusions for the shift in sectoral GDP

Based on analysis of the previous figures and by selecting those economic sectors with growing increase rates, the following conclusions can be made regarding sectors promising further expansion of their economic activities in the medium and long term (i.e., showing positive rates of increase in the right part of Figure 14):

- Technological infrastructure, i.e., electricity, gas, water: currently has a low level, but very high growth rates,
- Transport and communication,
- Financial services and insurance,
- Community and social services.

It is essential in this analysis that rates of increase themselves are viewed as variables. Passing the zero line in Figure 14, hence changing the sign mathematically, marks a transition process similar to the well-known population transition.

The grand picture is delivered by Figure 15 showing the hypothesized path for agriculture, industry, and services as a function of the economic level. As an interpretation, economic levels (sectoral GDP/cap) translate to the "perceived importance" of the related societal activity.

Which Overall Trends Exist in the Energy Sector?

Let us go to the analysis of the energy transition, which explicitly offers huge opportunities for Russia (IRENA, 2017a, b; IRENA, 2022; Grechukhina, 2021). Conventional projections of energy demand mostly conceive the demand for energy as linear or growing slightly exponentially (IPCC, 2002; IIASA, 1998). Often, this is on the basis of earlier research at IIASA assuming a worldwide and uniform *constant* numerical value for the improvement of energy intensity (E/GDP), namely –0.8%. Are there better ways to map global dynamics?

Rate of increase for final energy

First of all, this article presents the rates of change for energy demand over time (Figure 16). In this and the following figures, only the red average line is shown but not the strongly oscillating actual values. It is striking that the rates of increase converge to about 1% in the right-hand side of the figure, which means the economically more developed countries — and secondly, those rates start to sink; in some cases, they already seem to have become negative. If one continues the development mentally, the negative growth of the energy requirements means an expected reduction of energy demand in the developed nations.

This self-organizing dynamic behavior ultimately might regulate the entire global energy problem and the greenhouse effect problem. *This is the energy transition*. It is obviously caused by negative feedback cycles in the global energy system.

Per capita final energy demand and its rate of increase

In this subsection we perceive that across all political systems and economic levels, the growth of per-capita energy consumption levels off and thus represents one of the most stable and most characteristic trends of the worldwide "energy transition". For the individual countries, according to Figure 17, the per capita final energy demand is initially positively correlated with GDP/capita. This is in line with the widely known fact that economically developed countries have higher per capita consumption; and additionally, such consumption increases over time. Both facts together lead to very pessimistic assessments about the increase in energy demand being unavoidable.

We also see that historically dramatic "learning effects" are possible, namely that economies with previously lower GDP/capita (e.g., China) may already hit the path toward decreasing E/cap. Figure 18 provides the data for the rates of change for E/cap, (which further adds to the clarity that E/cap growth actually saturates).

Energy intensity (E final / GDP) and its rate of increase

In general, viewing the quotient energy intensity (= final energy / GDP) characterizes entire economies. As a fundamental strategy against global warming, decoupling energy demand from economic growth has great potential — but must be filled with practical measures on a concrete pragmatic level. Viewing Figure 19 may even lead one to consider the decrease of energy intensity natural law.

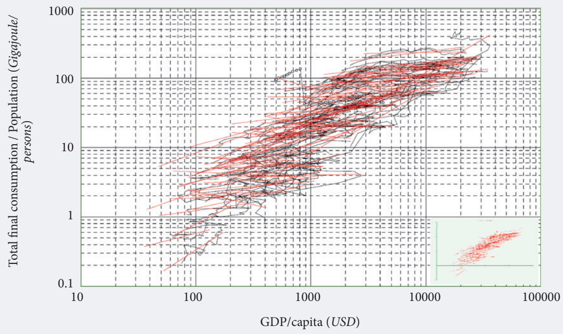
A finer picture of the (possibly inherent) dynamics of reducing E/GDP is perceivable from Figure 20: in a medium phase (around a GDP/cap of 1000–2000$/cap), economies show almost no improvement in energy intensity, while afterwards strong gains in energy intensity become possible (at bottom in Figure 20).

When identifying components within the global "energy transition", the partial effect of ever more ef-

Figure 16. **Development of the Rate of Increase in Final Energy Consumption in Petajoules PJ (E final) as a Function of GDP/Capita**

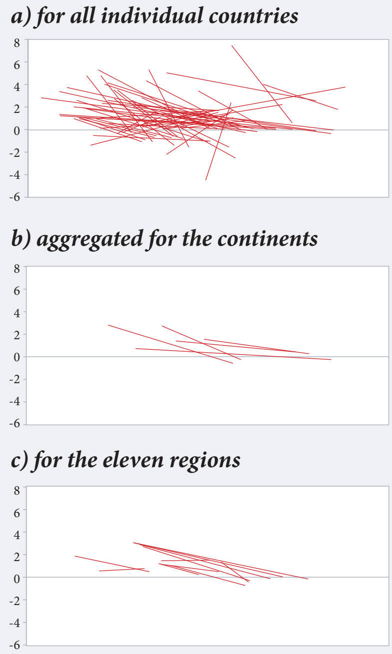
Note: This rate obviously decreases in the course of evolution.
Source: author, using data from IEA and GCDB.

Figure 17. **Illustration of the Final Energy Consumption per Capita as a Function of GDP per Capita**



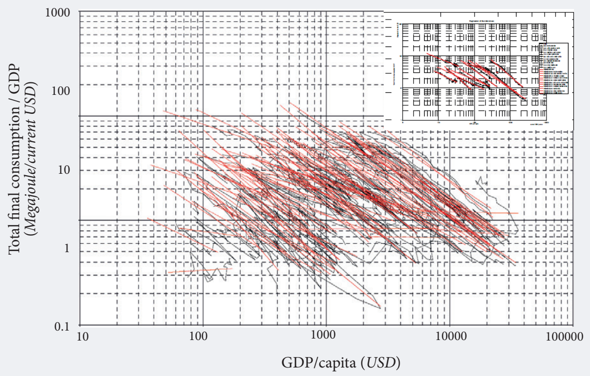
Note: In the insert only the red trend lines are made visible. This variable seems to approach a state of saturation.
Source: author, using data from IEA and GCDB.

Figure 18. **Rate of Change in Final Energy Consumption per Capita as a Function of GDP per Capita**



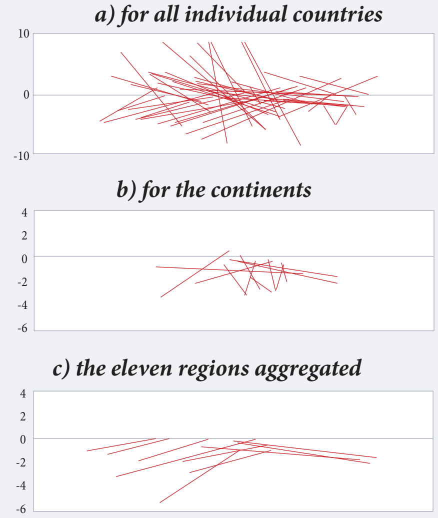
Source: author, using data from GCDB.

Figure 19. **Energy Intensity for Producing a Unit of Value Added (Energy Consumption per Capita) as a Function of GDP per Capita**



Note: In the insert only the eleven regions are shown.
Source: author, using data from IEA and GCDB.

Figure 20. **Rate of Change in Energy Intensity as a Function of GDP per Capita**



Source: author, using data from GCDB.

ficient provision of economic output per energy input is revealed as a key contributing factor by means of the GCDB's quantitative data.

Which sectoral trends exist in energy demand?

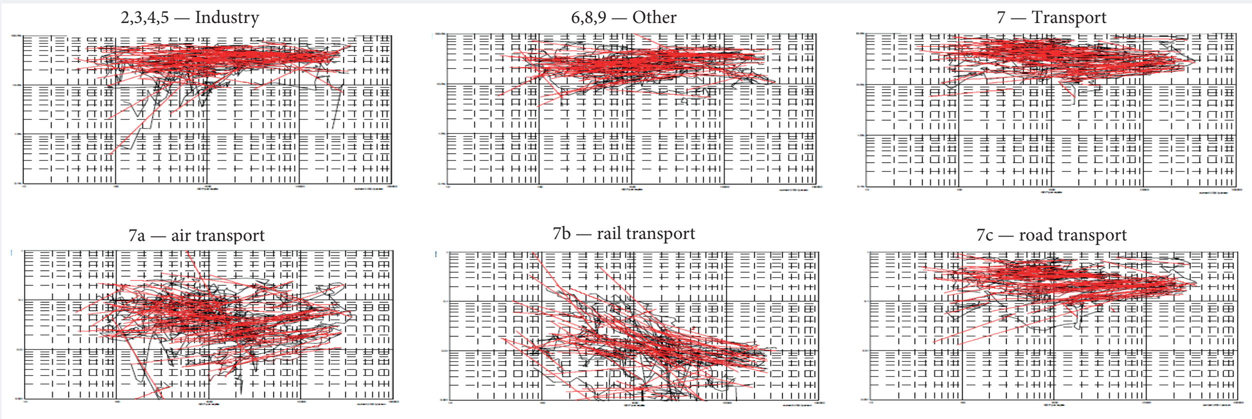
Percentage of final energy consumption in some main sectors

The approximately 30 economic sectors of the IEA database[7] are unfortunately different from those in UN economic statistics and therefore the (principally seemingly easy) quotients from Figure 1 cannot be computed in all cases, especially when sectoral data for both energy and GDP data are required.

In order to provide a reasonable and feasible illustration, Figure 21 shows some telling examples of the percentage of final energy consumption, including in industry, service, and transport, while using the earlier colors of the headings.

The evolutionary and developmental processes described in the previous chapters are widely known and statistically clearly corroborated. In contrast to the GDP-related breakdowns in the earlier chapters,

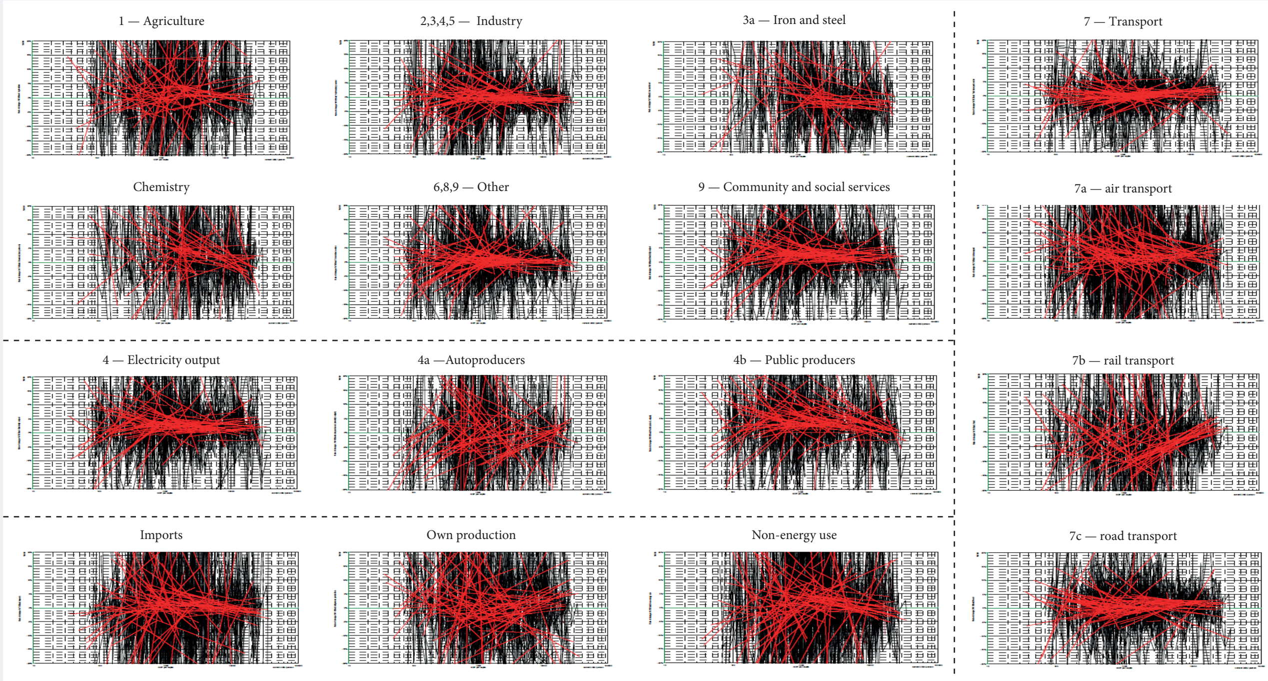
Figure 21. **Share of Energy Use in Three Main Sectors**



Note: Roughly the same size of energy use (above), and, as a detail, the breakdown within the transport sector (below), using red trend lines for all countries.
Source: author, using data from GCDB.

[7] Its position within the GCDB is integrated within Figure 17 in (Ahamer, 2018).

Figure 22. **Growth Rates in the Shares of Energy Use in Individual Sectors**



Note: Includes details of the breakdown within the electricity sector (centre) and its supply modes (bottom). Again here, a red trend line is shown for each country, and the zero percent line is situated in the image centre.

Source: author, using data from GCDB.

this chapter provides shares of energy consumption (as part of total energy demand), according to various domains of usage of this energy, as depicted in Figure 21. As one example, the *transport* sector (brown) comprises a strikingly large percentage of energy consumption. In addition to the classical service sector, the "*other*" sector (yellow) also includes households, which are not associated with the generation of sectoral GDP. Detailed quotients (E_i/GDP_i) are therefore not always clearly possible.

Rates of change of percentages of energy use by sector

This section shows change rates of variables shown in the previous section. The country-by-country representation of the sectoral growth rates (Figure 22) enables the better perception of dynamics, especially for developed countries at the right in the images. According to visible trend lines and correlations, data are interpreted as follows:

- The constant increase in the energy demand share for road traffic is likely to continue in the short and long term.
- The previous growth rates for the share of energy demand in aviation remain high, but in the medium-term in economically very developed countries this may increase even further, in the moderately-developed countries, it should slow down.
- The relative decline in energy consumption share for the railways remains constant for the time being, but in the medium term can turn into a noticeable increase in highly developed countries.

Other observations are summarized at Table 1.

Percentage of final energy differentiated by energy sources

This chapter deals with the development of the percentages of each (one of over twenty) energy sources. The graphical representation of the energy carrier shares uses a more concise form of representation (namely by region, not by country as before) (Figure 23) and this is done again in the medium and long term.

The following energy sources are declining: coal and heavy oil in the medium term, all oil products (after their expiring short-term increase) such as diesel and gasoline in the long term. In the medium term, growth is expected for natural gas, electricity, while in the long-term this growth is expected for biomass, heat, and jet fuel.

Table 1. **Interpretation of Some Trends Identified within Figure 21**

Perspective	Trends
Short-term (5-10 years)	• The (low) share of energy consumption in agriculture tends to increase • The (already high) energy share of industry is falling, particularly strongly in the iron and steel sector • The electricity generated as a share of total energy consumption continues to rise significantly, mainly generated by public electricity producers • The domestic production of energy sources is increasing. • The share of energy consumption for the service sectors is continuously increasing slightly
Medium-term (10-20 years)	• In the long term, the proportion of electricity generated at companies themselves ("own production") begins to increase • The proportion of non-energy use that has risen to date begins to fall in the long term • Imports, which have risen so far, are beginning to decline again • The previously high rate of increase in the share of energy consumption for the chemical industry begins to decline in the long term • The previously high rate of increase in the share of energy consumption for the transport sector remains high and is growing
Source: author.	

Rates of change in percentages of final energy differentiated by energy sources

More striking information and thus more insight into global dynamics is provided by plots of the increase rate of energy carrier shares. These are displayed in Figure 24.

This diagnosis results in statements about possible long-term shifts in the energy mix:

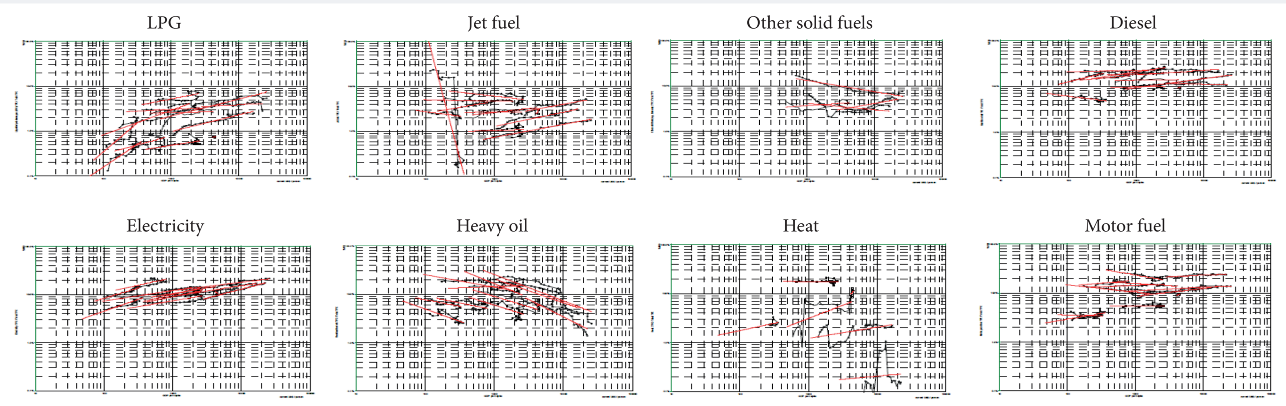
- a slowing down in the decline of coal,
- an acceleration of the decline of oil products,
- the cessation of gas growth,
- a steady increase in electricity use,
- the beginning of an increase in other solid fuels such as biomass,
- a very strong slowdown in the increase of heat use;
- an acceleration of heavy oil consumption for oil products,
- the moderate continuation of petrol and (lower) diesel growth,
- a strong slowdown in LPG growth in more developed countries,
- a decrease in growth for jet fuel everywhere.

Conclusions

Global change is a long-term and complex evolutionary procedure. Given that, it is welcome to find any reliable quantitative orientation, namely a corroboration of systemic long-term trends with global relevance. Such trends can support any of the existing methods for scenario writing, independent of the underlying assumptions, for example, such methods include:

- a cyclic or exponentially growing economy,
- a steady or transition-driven historic development,
- a paradigm leaning toward ever widening or narrowing economic gaps between population groups,
- a narrative versus formulaic style for expressing historiographic and futuristic convictions.

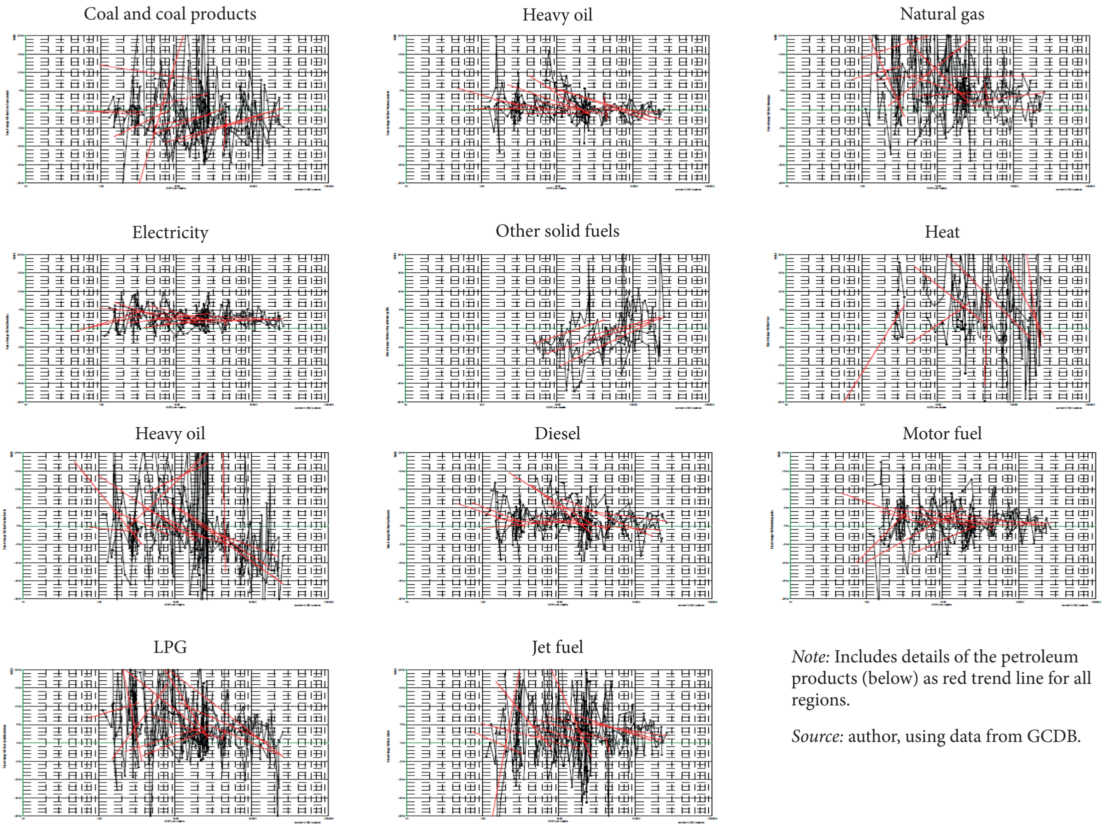
Figure 23. **Share of Energy Use by Individual Energy Sources**



Note: Includes the detailed breakdown of petroleum products (below) as red trend line for all regions.

Source: author, using data from GCDB.

Figure 24. **Rate of Increase in the Share of Energy Use by Individual Energy Sources**



Note: Includes details of the petroleum products (below) as red trend line for all regions.

Source: author, using data from GCDB.

In this wide existing paradigmatic context, the GCDB method (on the quantitative basis of the Global Change Data Base with its expandable 2,500 primary data sets for all countries) sets out to provide an analysis of multiple, non-linear, unpredictable, and stunning trends in economy, energy and land use on a per-country level. This article suggested several trends in the domains of energy demand and supply, energy efficiency and the intensity of its use, change in the fuel mix, economic sector composition, sectoral energy demand and supply, and, finally, changes in all of the above-mentioned change rates. Detailed trends were presented as images and texts.

At first glance, we see that growth rates of global energy demand will decline. This result is stable with regard to all energy types: the peaks of coal, oil, and gas seems to be over soon — in this sequence of energy types. Today already "peak oil" is a well-known phrase.

A suitable counterstrategy against the detected megatrends which threaten the fossil economic basis of any country strongly relying on oil, gas, and coal (such as Russia or some Central Asian countries), is to promote the production of decisively renewable energy and its integration into national grids — namely biomass, solar,and wind.

A second look, however, brings us beyond the mere contemplation of "trends" which tacitly rely on the assumption that world history proceeds in a linear or exponential manner. A thorough analysis of evolutionary paradigms (Ahamer, 2019) shows that many combinations between cyclic and trend-oriented exist and that history does not at all flow in the direction which could ever be expressed by stringent formulae, not even by exponential or sinus curves. Rather, the CEBM diagnosis suggests transitions as governing dynamic pattern in techno-socio-economic evolution. Examples are, starting with already well-known transitions:

- the *population* transition,
- the *deforestation* transition or land-use transition,
- the transition among several *energy sources* which have their corresponding main pollutants, and
- with regard to *economy* as a whole, a steady historic shift away from the agricultural sector towards industrial sectors and onwards to service

sectors in various types of graphic representations

As to the *energy transition*: which is the main focus of our article, steady lowering of the increase rate of final energy consumption (E_{final}) along historic evolution; this is one of the strongest existing trends overall. This diagnosis is corroborated by the variable "final energy consumption per capita (E_{final}/cap)" coming into saturation which can be still better visualised by its growth rates. The most striking diagnosis is found for the strongly decreasing variable *energy intensity*, i.e., the required final energy consumption for producing a unit of value added (E_{final}/GDP; and its growth rate). This energy transition (in the sense of a strategic retraction from fossil fuels and reorientation towards renewable energies) is actually the focus of all country's present climate strategies, and is still more speeded up by the worsening geo-political issues, calling from energy supply independence from incalculable authoritarian regimes.

As to *transitions within energy sectors* and *fuels*, among a complex overall picture, several general trends can be identified, including: (i) away from (dirty, emission-rich) primary fuels such as coal and crude oil) toward consumer-oriented and refined fuels such as electricity, heat, LPG and jet fuel and (ii) away from heavy sectors, such as (especiallye steel) industry and agriculture toward service sectors.

All these transitions are observable principally in all countries, while the historic time of their onset varies considerably, which can even be several centuries. In order to 'normalize' these effects, the historic time is often replaced by a country's economic level (GDP/capita) in order to depict a proxy variable for 'evolutionary time'.

Therefore, evolution is seen here as a sequence of transitions, and was called "*blossoming evolution*" by this author earlier (Ahamer, 2019). This paradigm means that (additionally to a mainly evolutionary dynamic) state transitions between distinct socioeconomic systems take place in world history (Christian, 2018) while each of them maintains a steady-state equilibrium (until it becomes systemically unstable) while functioning on the basis of a set of "natural laws" (e.g., those of power vertical as opposed those of democratic respect and self-responsibility). Each such socioconomic system produced its own characteristic rationality, laws and ethics, as could be perceived throughout history (Küstenmacher et al., 2010). According to long-term historical observations, despite some (and large-scale) deviations, the world is evolving towards a more democratic structure based on dialogue and mutual respect, which is consistent with the provisions of the theory of "*blossoming evolution*".

To sum up, the Global Change Data Base (GCDB) method is a suitable tool for detecting trends and changes in trends in the global energy system, thus providing a better understanding of its global dynamic behaviour.

References

Abler R., Adams J.S., Gould P. (1971) *Spatial organisation. The geographer's view of the world*, Englewood Cliffs, NJ: Prentice-Hall.

Ahamer G. (2008) Virtual Structures for mutual review promote understanding of opposed standpoints. *The Turkish Online Journal of Distance Education*, 9(1), 17–43.

Ahamer G. (2012) Geo-Referenceable Model for the Transfer of Radioactive Fallout from Sediments to Plants. *Water, Air, and Soil Pollution*, 223(5), 2511–2524. DOI: 10.1007/s11270-011-1044-x

Ahamer G. (2014) Kon-Tiki: Spatio-temporal maps for socio-economic sustainability. *Journal for Multicultural Education*, 8(3), 206–223. DOI: 10.1108/JME-05-2014-0022

Ahamer G. (2015) Applying student-generated theories about global change and energy demand. *International Journal of Information and Learning Technology*, 32(5), 258–271. DOI: 10.1108/IJILT-01-2015-0002

Ahamer G. (2018) Applying Global Databases to Foresight for Energy and Land Use: The GCDB Method. *Foresight and STI Governance*, 12(4), 46–61. DOI: 10.17323/2500-2597.2018.4.46.61

Ahamer G. (2019) *Mapping Global Dynamics. From Local Pollution to Global Evolution*. Heildelberg, Dordrecht, London, New York: Springer. DOI: 10.1007/978-3-319-51704-9

Ahamer G. (2021) Can we synthesise different development theories? *Social Evolution and History*, 20(2), 79–108. DOI: 10.30884/seh/2021.02.04

Ahamer G., Jekel T. (2010) Make a Change by Exchanging Views. In: *Cases on Transnational Learning and Technologically Enabled Environments* (eds. S. Mukerji, P. Tripathi), Hershey, PA: IGI Global, 1–30. DOI: 10.4018/978-1-61520-749-7.ch001

Ahamer G., Kumpfmüller K.A. (2013) Education and literature for development in responsibility: Partnership hedges globalization. In: *Handbook of Research on Transnational Higher Education* (eds. S. Mukerji, P. Tripathi), Hershey, PA: IGI Global, 526–584. DOI:10.4018/978-1-4666-4458-8.ch027

Akaev A., Sadovnichy V., Korotayev A. (2012) On the dynamics of the world demographic transition and financial-economic crises forecasts. *European Physical Journal: Special Topics*, 205(1), 355–373. DOI: 10.1140/epjst/e2012-01578-2

Bader L., Bereuther T., Deutsch E., Edlinger J., Füreder S., Kaspar E., Köttstorfer M., Mautner C., Rossegger C., Samonig A., Samonig S., Schuster C., Witz G., Zotter V., Ahamer G. (2013) Quality Improvements in Curricula for Global Studies. *Multicultural Education and Technologies Journal*, 7(2/3), 113–126, DOI: 10.1108/17504971311328035

Bader L., Bereuther T., Deutsch E., Edlinger J., Füreder S., Kaspar E., Köttstorfer M., Mautner C., Rossegger C., Samonig A., Samonig S., Schuster C., Witz G., Zotter V., Rozanov A., Ilyin V., Ahamer G. (2014) Multiparadigmatic Humanities: Curricula for Global Studies. *International Journal of Humanities and Social Science*, 4(6), 314–337. http://www.ijhssnet.com/journals/Vol_4_No_6_1_April_2014/34.pdf and also https://istina.msu.ru/workers/6530980/, accessed 11.04.2021.

Baumann M., Kuemmerle T., Elbakidze M., Ozdogan M., Radeloff V.C., Keuler N.S., Prishchepov A.V., Kruhlov I., Hostert P. (2011) Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. *Land Use Policy*, 28(3), 552–562. DOI: 10.1016/j.landusepol.2010.11.003

Bertalanffy L. (1968) *General System Theory: Foundations, Development, Applications*, New York, NY: Braziller.

Brans J., Mareschal B. (1994) The PROMCALC & GAIA decision support system for multicriteria decision aid. *Decision Support Systems*, 12(4–5), 297–310. DOI:10.1016/0167-9236(94)90048-5

Castells M. (1996) *The Information Age: Economy, Society and Culture*, Cambridge, MA: Blackwell.

Chen R., Ye C., Cai Y., Xing X., Chen Q. (2014) The impact of rural out-migration on land use transition in China: Past, present and trend. *Land Use Policy*, 40, 101–110. DOI: 10.1016/j.landusepol.2013.10.003

Christian D. (2005) Macrohistory: The Play of Scales, *Social Evolution & History*, 4(1), 22–59.

Christian D. (2018) *Origin Story: A Big History of Everything*, New York, Bostion, London Little: Brown and Company.

Du Y., Yang C. (2014) Demographic transition and labour market changes: Implications for economic development in China. *Journal of Economic Surveys*, 28(4), 617–635. DOI: 10.1111/joes.12072

Duraković E., Feigl B., Fischer B., Fleck C., Galler L.-M., Heinrich J., Kulmer K., Kurzweil B., Scholze M., Sperl R., Unterköfler R., Matzenberger J., Remele K., Ahamer, G. (2012) Dialogic Global Studies for Multicultural Technology Assessment. *Multicultural Education & Technology Journal* 6(4), 261–286. DOI: 10.1108/17504971211279527

Estep D. (2002) Constant Relative Rate of Change and the Exponential. In: *Practical Analysis in One Variable. Undergraduate Texts in Mathematics* (eds. S. Axler, F.W. Gehring, K.A. Ribet), Heidelberg, Dordrecht, London, New York: Springer. DOI: 10.1007/0-387-22644-3_30

Fagua J.C., Baggio J.A., Ramsey R.D. (2019) Drivers of forest cover changes in the Chocó-Darien Global Ecoregion of South America. *Ecosphere*, 10(31), e02648. DOI: 10.1002/ecs2.2648

Feron P.H.M. (2016) Introduction. In: *Absorption-Based Post-combustion Capture of Carbon Dioxide* (ed. P.H.M. Feron), Sawston (UK): Woodhead Publishing, pp. 3–12. DOI: 10.1016/B978-0-08-100514-9.00001-9

Fischer A.M. (2008) "Population invasion" versus urban exclusion in the Tibetan areas of Western China. *Population and Development Review*, 34(4), 631–662. DOI: 10.1111/j.1728-4457.2008.00244.x

Fischer K., Hauck G., Boatcă M. (eds.) (2016) *Handbuch Entwicklungsforschung*, Berlin: Springer. https://www.springer.com/de/book/9783658047894, accessed 18.04.2022.

Galor O. (2012) The demographic transition: Causes and consequences. *Cliometrica,* 6(1), 1–28. DOI: 10.1007/s11698-011-0062-7

Grau H.R., Aide M. (2008) Globalization and land-use transitions in Latin America. *Ecology and Society*, 13(2), 16. DOI: 10.5751/ES-02559-130216

Grechukhina I. (2021) Socio-economic and environmental effects of renewable energy policy in Russia. *International Journal of Foresight and Innovation Policy*, 15(1–3), 157–170.

Haggett P. (2001) *Geography – A global synthesis,* Harlow: Pearson Education.

Hurtt G.C., Chini L.P., Frolking S., Betts R.A., Feddema J., Fischer G., Fisk J.P., Hibbard K., Houghton R.A., Janetos A., Jones C.D., Kindermann G. (2011) Harmonization of land-use scenarios for the period 1500-2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change*, 109(1), 117–161. DOI: 10.1007/s10584-011-0153-2

Hurtt G.C., Frolking S., Fearon M.G., Moore B., Shevliakova E., Malyshev S., Pacala S.W., Houghton R.A. (2006) The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Global Change Biology*, 12(7), 1208–1229. DOI: 10.1111/j.1365-2486.2006.01150.x

IIASA (1998) *Global Energy Perspectives in 1998* (IIASA/WEC Report), Cambridge (UK): Cambridge University Press. http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py, accessed 26.03.2022.

IPCC (2002) *Special Report on Emissions Scenarios (SRES),* Geneva: International Panel on Climate Change (IPCC). https://www.ipcc.ch/report/emissions-scenarios/, accessed 14.01.2022.

IRENA (2017a) *Russia Can Nearly Quadruple Share of Renewable Energy by 2030 Tweet,* Abu Dhabi, Bonn, New York: International Renewable Energy Agency. https://www.irena.org/newsroom/pressreleases/2017/Apr/Russia-Can-Nearly-Quadruple-Share-of-Renewable-Energy-by-2030, accessed 19.04.2022.

IRENA (2017b) *Renewable Energy Prospects for the Russian Federation* (REmap working paper), Abu Dhabi, Bonn, New York: International Renewable Energy Agency. https://www.irena.org/publications/2017/Apr/Renewable-Energy-Prospects-for-the-Russian-Federation-REmap-working-paper, accessed 16.04.2022.

IRENA (2022) *World Energy Transitions Outlook: 1.5°C Pathway*, Abu Dhabi, Bonn, New York: International Renewable Energy Agency. https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022, accessed 16.04.2022.

Jäger J., Springler E. (2012) *Ökonomie der internationalen Entwicklung - Eine kritische Einführung in die Volkswirtschaftslehre* (Series "Geschichte – Entwicklung – Politik", GEP14), Wien: Mandelbaum.

Jeníček V. (2010) Population problem in the future - Challenges, questions. *Agricultural Economics*, 56(3), 97–107. DOI: 10.17221/91/2009-AGRICECON

Kaya Y., Keiichi Y. (1997) *Environment, energy, and economy: Strategies for sustainability,* Tokyo: United Nations University Press. https://archive.unu.edu/unupress/unupbooks/uu17ee/uu17ee00.htm

Kondratieff N. (1984) *Long Wave Cycle*, Boston, MA: E.P. Dutton.

Kravdal Ø., Rindfuss R.R. (2008) Changing relationships between education and fertility: A study of women and men born 1940 to 1964. *American Sociological Review,* 73(5), 854–873. DOI: 10.1177/000312240807300508

Küstenmacher M., Haberer T., Küstenmacher W.T. (2010) *God 9.0*, Gütersloh (Germany): Gütersloher Verlagshaus. http://gott90.de/god-9.0-english, accessed 17.02.2022.

Lambin E.F., Meyfroidt P. (2011) Global land use change, economic globalization, and the looming land scarcity. *PNAS*, 108(9), 3465–3472. DOI: 10.1073/pnas.1100480108

Lambin E.F., Meyfroidt P. (2019) Land use transitions: Socio-ecological feedback versus socio-economic change. *Land Use Policy*, 27(2), 108–118. DOI: 10.1016/j.landusepol.2009.09.003

Liao S. (2005) Expert system methodologies and applications-a decade review from 1995 to 2004. *Expert Systems with Applications,* 28(1), 93–103. DOI: 10.1016/j.eswa.2004.08.003

Long H. (2014), Land consolidation: An indispensable way of spatial restructuring in rural China. *Journal of Geographical Sciences*, 24(2), 211–225. DOI: 10.1007/s11442-014-1083-5

Long H., Qu Y. (2018) Land use transitions and land management: A mutual feedback perspective. *Land Use Policy*, 74, 111–120. DOI: 10.1016/j.landusepol.2017.03.021

Long H., Liu Y., Hou X., Li T., Li Y. (2014) Effects of land use transitions due to rapid urbanization on ecosystem services: Implications for urban planning in the new developing area of China. *Habitat International*, 44, 536–544. DOI: 10.1016/j.habitatint.2014.10.011

Lovelock J. (1988) *The Ages of Gaia. A Biography of Our Living Earth*, New York, London: W.W. Norton & Co.

Lu C., Lee T., Chiu C. (2009) Financial time series forecasting using independent component analysis and support vector regression. *Decision Support Systems*, 47(2), 115–125. DOI: 10.1016/j.dss.2009.02.001

Macedo M.N., DeFries R.S., Morton D.C., Stickler C.M., Galford G.L., Shimabukuro Y.E. (2012) Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *PNAS*, 109(4), 1341–1346. DOI: 10.1073/pnas.1111374109

MacHaris C., Turcksin L., Lebeau K. (2012) Multi actor multi criteria analysis (MAMCA) as a tool to support sustainable decisions: State of use. *Decision Support Systems*, 54(1), 610–620. DOI: 10.1016/j.dss.2012.08.008

Marchetti C., Nakicenovic N. (1979) *The Dynamics of Energy Systems and the Logistic Substitution Model* (Report RR-79-13), Laxenburg: Austria International Institute for Applied Systems Analysis. http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, accessed 23.01.2022.

Mattiussi A., Rosano M., Simeoni P. (2014) A decision support system for sustainable energy supply combining multi-objective and multi-attribute analysis: An Australian case study. *Decision Support Systems*, 57(1), 150–159. DOI: 10.1016/j.dss.2013.08.013

Meadows D., Meadows D., Randers J., Behrens III W. (1992) *The Limits to Growth*, New York: Universe Books.

Meyfroidt P., Roy Chowdhury R., de Bremond A., Ellis E.C., Erb K.-H., Filatova T., Garrett R.D., Grove J.M., Heinimann A., Kuemmerle T., Kull C.A., Lambin E.F. (2018) Middle-range theories of land system change. *Global Environmental Change*, 53, 52–67. DOI: 10.1016/j.gloenvcha.2018.08.006

Mills M., Rindfuss R.R., McDonald P., te Velde E. (2011) Why do people postpone parenthood? reasons and social policy incentives. *Human Reproduction Update,* 17(6), 848–860. DOI: 10.1093/humupd/dmr026

Munteanu C., Kuemmerle T., Boltiziar M., Butsic V., Gimmi U., Lubos Halada K.D., Király G., Konkoly-Gyuró É., Kozak J., Lieskovský J., Mojses M. (2014) Forest and agricultural land change in the Carpathian region – A meta-analysis of long-term patterns and drivers of change. *Land Use Policy*, 38, 685–697. DOI: 10.1016/j.landusepol.2014.01.012

Nielsen I., Fang C. (2007) Demographic shift and projected labour shortage in China. *Economic Papers*, 26(3), 231–236. DOI: 10.1111/j.1759-3441.2007.tb00432.x

Nuissl H., Haase D., Lanzendorf M., Wittmer H. (2009) Environmental impact assessment of urban land use transitions – A context-sensitive approach. *Land Use Policy*, 26(2), 414–424. DOI: 10.1016/j.landusepol.2008.05.006

Peters G.P., Andrew R.M., Canadell J.G., Fuss S., Jackson R.B., Korsbakken J.I., Le Quéré C., Nakicenovic N. (2017) Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Climate Change,* 7, 118–122. DOI: 10.1038/nclimate3202

Powers J.S., Corre M.D., Twine T.E., Veldkamp E. (2011) Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. *PNAS*, 108(15), 6318– 6322. DOI: 10.1073/pnas.1016774108

Raskin P. (2012) Scenes from the Great Transition. *Solutions*, 3(4), 11–17. https://archive.ph/20130620204841/http://thesolutionsjournal.anu.edu.au/node/1140#selection-209.0-233.11, accessed 16.02.2022.

Raskin P. (2016) *Journey to Earthland: The Great Transition to Planetary Civilization*, Boston, MA: Tellus Institute.

Raskin P., Banuri T., Gallopín G., Gutman P., Hammond A., Kates R., Swart R. (2002) *Great Transition: The Promise and Lure of the Times Ahead* (A Report of the Global Scenario Group), Boston, MA: Tellus Institute.

Raymo J.M., Park H., Xie Y., Yeung W.-J. (2015) Marriage and Family in East Asia: Continuity and Change. *Annual Review of Sociology,* 41(1), 150504162558008. DOI: 10.1146/annurev-soc-073014-112428

Rounsevell M.D.A., Pedroli B., Erb K.-H., Gramberger M., Busck A.G., Haberl H., Kristensen S., Kuemmerle T., Lavorel S., Lindner M., Lotze-Campen H., Metzger M.J. (2012) Challenges for land system science. *Land Use Policy*, 29(4), 899–910. DOI: 10.1016/j.landusepol.2012.01.007

Rubenstein-Montano B., Liebowitz J., Buchwalter J., McCaw D., Newman B., Rebeck K. (2001) A systems thinking framework for knowledge management. *Decision Support Systems*, 31(1), 5–16. DOI: 10.1016/S0167-9236(00)00116-0

Sayamov Y. (2013) Education as a Global "Soft Power" for Sustainable Development. *Campus-Wide Information Systems*, 30(5), 346–357.

Seuring S. (2013) A review of modeling approaches for sustainable supply chain management. *Decision Support Systems*, 54(4), 1513–1520. DOI: 10.1016/j.dss.2012.05.053

Shen J., Spence N.A. (1996) Modelling urban-rural population growth in China. *Environment and Planning A*, 28(8), 1417–1444. DOI: 10.1068/a281417

Ssewamala F.M. (2015) Optimizing the "demographic dividend" in young developing countries: The role of contractual savings and insurance for financing education. *International Journal of Social Welfare*, 24(3), 248–262. DOI: 10.1111/ijsw.12131

Steiniger S., Bocher E. (2009) An overview on current free and open source desktop GIS developments. *International Journal of Geographical Information Science,* 23(10), 1345–1370. DOI: 10.1080/13658810802634956

Sterman J. (2000) *Business Dynamics: Systems thinking and modelling for a complex world*, New York: McGraw Hill.

Toft M.D. (2007) Population shifts and civil war: A test of power transition theory. *International Interactions*, 33(3), 243–269. DOI: 10.1080/03050620701449025

Upadhyay U.D., Gipson J.D., Withers M., Lewis S., Ciaraldi E.J., Fraser A., Huchko M.J., Prata N. (2014) Women's empowerment and fertility: A review of the literature. *Social Science and Medicine,* 115, 111–120. DOI: 10.1016/j.socscimed.2014.06.014

Vester F., von Hesler A. (1980) *Sensitivitätsmodell. Umweltforschungsplan des Bundesministers des Innern: Ökologie und Planung in Verdichtungsgebieten*, Frankfurt am Main: Regionale Planungsgemeinschaft Untermain.

Zhang J. (2002) Urbanization, population transition, and growth. *Oxford Economic Papers*, 54(1), 91–117. DOI: 10.1093/oep/54.1.91