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A method of assessing in units of exergy the costs of depleting the supply, from planet Earth, of mineral ores and fossil fuels

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ABSTRACT

This paper describes the most basic aspects of a method, devised in recent years at the University of Zaragoza by Antonio and Alicia Valero, of assessing, quantitatively and in discriminating detail, depletions of nonrenewable natural stocks of notable abiotic (i.e. not living) substances that have market value: the minerals which are mined and the fossil fuels. Certain graphic aspects of the description, and certain refinements of the Valeros' terminology, are, with the Valeros' approval, provided by the author. The assessments are in units of exergy (kilowatt hours or joules).

In regard to the economically useful minerals that are mined, to assess in terms of exergy the economic damage of the depletions entails assessing (likewise in terms of exergy) the "natural bonus" of humankind having, at any one moment, access or potential access to an estimated quantity of concentrated natural deposits of each of them, i.e., ores. If the mineral in question were diffused 100% evenly – or nearly so – in the economically accessible parts of the planet, the cost of separating it out from the other stuff (in order to produce it in sufficiently pure form for use in manufacturing commodities) would be impossibly high. In regard to every economically valuable kind of mineral provided to humankind by the Earth, the Valeros apply the term "thanatia" to a condition approaching to such an extent toward theoretical 100% diffusion that no one would mine it.

Keywords : *exergy economics, depletion of non-renewables, ores, natural bonus, thanatia.*

1. Introduction:

There are many notable facets of the current swift decline of the capacity of humankind's natural environment on Earth to provide material support to humankind at an adequate per-capita rate. Among the various notable facets – such as: nonrenewable natural stocks tending to become exhausted; renewable flows of natural resources being used up faster than they flow; ecologically destructive dislocations of some very plentiful and, when not dislocated, ecologically vital chemicals (think of H_2O and SiO_2); many kinds of pollution (e.g. of water, soil, food, and air); global warming; earthquakes becoming more frequent; mass extinction of biological species; and yet a flourishing of super-bacteria and of more and more virulent viruses – the first facet mentioned in the above list, namely, nonrenewable natural stocks tending to become exhausted, may be the most irreversibly relentless. It merits careful study. Some basic aspects of the method of study which is the topic of the present article are described in Section 2 below. Two widely accepted concepts which need to be understood in order to understand the method of study are "Hubbert curves" and "exergy".

1.1 Hubbert curves :

Hubbert curves were originally a way of predicting, graphically, how soon this or that particular batch of sources of petroleum extracted from the crust of the planet (oil wells) would become exhausted. Marion King Hubbert (1903-1969) was a geophysicist in Texas who devised in the 1950s the kind of graph of which an idealized version is shown in Fig.1. [1] The area under the curve represents the total amount, past and future, of the nonrenewable natural stock that is being considered. Time (notched in, say, quarter-centuries or half-centuries in this idealized model of a graph) is plotted from left to right. The height of the curve at any given moment represents the momentary rate of extraction.

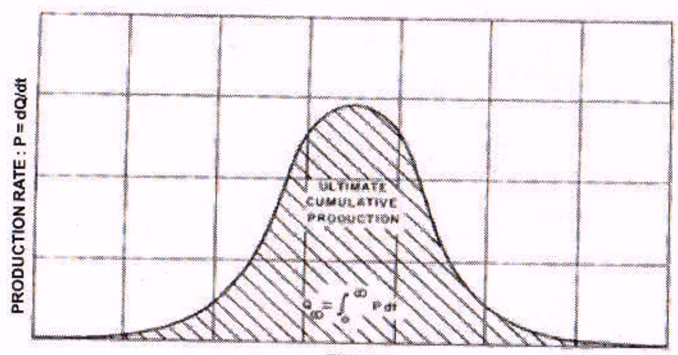

Fig.1. Hubbert's graph of the relation between historic rates of production and historic time (e.g. quarter-centuries) in the complete history of production of an exhaustible resource [1]

Hubbert's prediction method entailed using on the one hand an estimate, represented by the area under the curve, of the total natural stock beneath the ground for those oil wells, and on the other hand an assumption, based on some historical observations which he had made, that after half of the stuff has been used up, the rate of extraction slows down symmetrically in reverse to the way it had increased. The validity of the assumption has, in very recent decades, not been borne out 100% by data. More about this will be said in Section 3 below. What is not speculative is that when the bucket is half empty it's only half full.

(Elucidation of this "empty bucket" metaphor when applied to ores will be provided, in Section 2.1 below, by the discussion of the terms "Grave" and "thanatia").

The first part of an applied version of a Hubbert curve is based on actual production data and is therefore jagged. Fig.2 shows how he predicted – accurately – in 1962 that "peak production" (i.e., the historically fastest rate of annual production, barrels-wise) from oil wells in the USA would occur in 1970. [2]

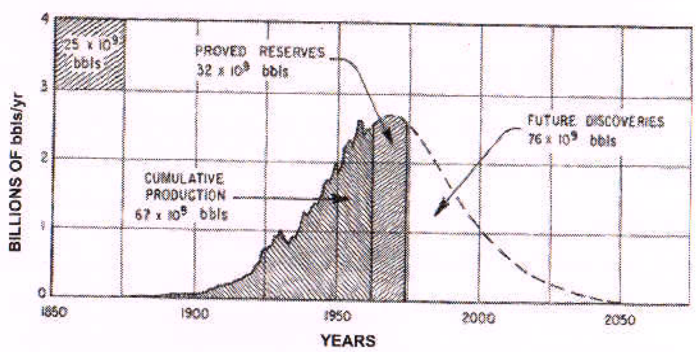

Fig.2. A prediction, re: oil wells in USA, arrived at by Hubbert in 1962 [2]

Hubbert curves have been taken seriously by relevant corporations and governments.

1.2 Exergy :

The term "exergy" is synonymous with the terms "available energy" and "available work", and so the unit of measure for it can readily be kilowatt hours (or, for that matter, joules). The following explanatory paragraphs are for readers unfamiliar with this standard concept of physics.

Every increase of "entropy" (a term meaning that the whole system is, alas, 'winding down') is due to expenditure of exergy – that is, of energy of such a quality that it can, at least potentially, yield work (in the physicist's sense of the term "work": i.e., affecting the momentum of big or little things and thereby making them move faster or slower or change direction) because of some kind of disequilibrium in the physical system (disequilibrium in regard, for instance, to temperature or pressure or electric charge). The energy in question can potentially yield work if it is not currently "kinetic" (not physically active) but is nevertheless subject to kinetic release under the right conditions. The relation between exergy and entropy is thus always reciprocal; but it is not steady: the higher the temperature(s), the less is the increase of entropy is entailed by a given amount of exergy expenditure. In any given isolated physical system, however, zero exergy (whereby no further work could possibly occur in that isolated system) would amount to maximum entropy; there would be 100% equilibrium throughout.

Energy exists in many forms (e.g., kinetic, chemical, gravitational, electro-magnetic, nuclear; a famously concentrated form is mass, as $e = mc^2$). Exergy is, by definition, convertible (to some extent – i.e., this can happen more or less efficiently) into energy of a kinetic or potentially kinetic form; but not all energy is of such a quality as to be convertible into exergy. An example of energy not convertible into exergy is that the heat in the air which makes us sweat on a warm day (even if no work is being done at the moment) is due to the "thermal energy" of molecules zigzagging aimlessly here and there in the air and bumping into each other. The amount of thermal energy in the aimless movements of air molecules at 20° (centigrade) in a 4-by-5-metre office is more (if the ceiling isn't *very* low) than the amount of chemical energy stored in three standard 12-volt car batteries. (The batteries store chemical energy for conversion into electric current.) However, the only possible use of the thermal energy in the air is to keep the room warm, whereas the electric current from the batteries could be used to run a computer, to cook a lunch or even to make an electric car go. While the two quantities of energy may be the same in the two cases illustrated in Fig.3 (Case A and Case B), the quality or potential kinetic usefulness of the electrical energy from the batteries differs from that of the thermal energy in the air. In the air, the energy is randomly distributed, not readily accessible and not easily used for diverse purposes, whereas the electrical energy from a battery is far more concentrated and is available for a variety of potential uses. The significant difference between these two cases is qualitative, and it accounts for why exergy is expended in Case A but not in Case B.

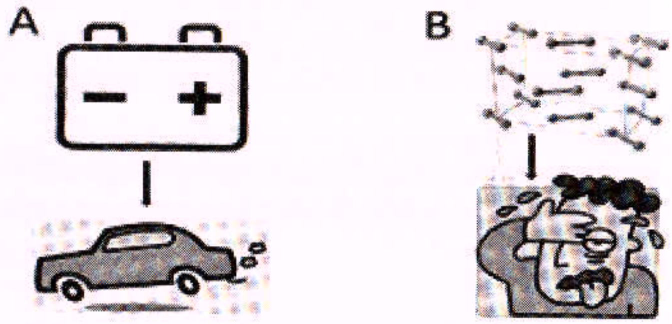

Fig.3. Some effects of (A) exergy stored in the battery of an electric car and (B) thermal energy dissipated (e.g. from cars) into an urban outdoor atmosphere on an uncomfortably warm day

The term "exergy cost" is customarily used to mean "cost reckoned in terms of exergy" (e.g. kilowatt hours), not "monetary cost of 'consumable energy'". If a car goes 50 km on a litre of gas, that level of efficiency in terms of exergy is the same regardless of the price per litre of gas. Efficiency in terms of exergy is a material fact, whereas the monetary cost of the fuel may depend to a considerable extent on (*a*) hoarding by OPEC, on (*b*) flooding of the petroleum market by the USA (with the produce of its fracking) and on (*c*) the presence or absence of wars for control of oil wells. The price tends to be higher during such a war.

Charles A. Hall, an ecologist, has devised the following well-known equation for "Energy Returned on Energy Invested" (EROEI): [3]

$$EROEI = \frac{\text{Energy Delivered}}{\text{Energy Required to Deliver that Energy}}$$

A professionally trained physicist would present the issue in terms of "Exergy Returned on Exergy Invested":

$$EROEI = \frac{\text{Exergy Delivered}}{\text{Exergy Required to Deliver that Exergy}}$$

A big difference between energy and exergy is that whereas energy cannot be destroyed but can only be transformed from one kind to another (this is the "First Law of Thermodynamics"), every such transformation entails some loss of exergy. This latter fact is the "Second Law of Thermodynamics". An example of it is that a car doesn´t just *go* when the gas in it is burned up (or when the chemical energy stored in the batteries of an electric car is used up), it also gets hot, and that heat making the city's air too warm for comfort (if the air would be already plenty warm without the cars) represents a net loss of exergy. The greater the amount of useless heat generated as a "by-product" of the physical work that is being done, the more exergy has thereby been wasted (and the more entropy has been created).

2.0 Exergy economics :

No matter how much the monetary prices of "consumable energy" (produced by burning fossil fuels, or from hydroelectric dams or nuclear power plants or wind-turbines etc.) may fluctuate from time to time, to waste lots of exergy in our economic activities is bound to entail big monetary costs sooner or later. So, wise economists and business-men are beginning nowadays to pay attention to "exergy economics": economic reasoning based on calculations in terms of exergy.

2.1 The exergy-cost basis of the Valeros' theoretical contribution to exergy economics :

Given this background information in regard to the terms "exergy" and "exergy economics", the main purpose of the present article is to describe the gist of the contributions which Prof. Dr. Antonio Valero and his daughter Prof. Dr. Alicia Valero have made (often in collaboration with students and colleagues) to the theory of exergy economics [4 - 60 etc.].

(It is worth mention that they engage also in its practice. Antonio Valero has helped render remarkably profitable, for certain corporations, the extraction and pre-manufacture processing of minerals; the American Society of Mechanical Engineers awarded him in 1996 its top prize in thermodynamics, "for advancing the theory of thermodynamics to a new level, and clarifying the basic concepts of exergetic costs (i.e. exergy costs), as well as providing methods which integrate costing and system simulation in order to optimize the design and operation of energy-conversion and processing plants, including numerous real-world applications"; and he is an honorary professor at North China Electric Power University [61]).

The Valeros make quantitative assessments of each kind of mineral commodity ("commodities" are, by definition, products marketed for money) in terms of a concept which one might describe as its "thermo-dynamic value" but which they call (when writing in English) its "thermodynamic rarity". They define it as the amount of exergy which would have to be expended, using the best currently available techniques, to extract the desired mineral from ordinary, average-Earth-upper-crust rock (i.e., not from ore) and to purify it to the level of purification needed for its use in industrial manufacturing, in craftsmanship, etc.

This concept is used to reckon, together: (1) a theoretical "natural bonus" of having the ore (i.e. a naturally concentrated mineral deposit) in the first place, plus (2) the exergy costs (i.e. the expenditures of consumable energy) of the mining, of the "beneficiation" (physically sorting out the stuff near the mine; this may entail a lot of grinding etc.) and then of the necessary chemical transformation and purification processes, as well as (3) economically applicable theoretical allocations, to different useful mineral elements in one and the same ore, of their respective natural-bonus values and exergy costs.

The Valeros calculate the second item in that list of three items – the exergy cost of producing a batch of marketable abiotic industrial or agriculturally or medically useful material (such as, for instance, iron or copper or lithium or zinc or phosphate) – via reckonings of how much consumable energy (i.e. purchased inanimate exergy) has been expended for its production. If trustworthy data for that kind of reckoning are lacking, they revert to a so-called "embodied-energy" estimate ("embodied energy" is a familiar notion in ecological economics) as a surrogate for a proper exergy-cost calculation. Embodied-energy estimates are based on published market-economics "material flow analysis" (MFA) data. They are, however, dogged by analytical vagueness. For instance: When a piano tuner tunes a piano in somene's house, how much of the cost of the consumable energy that was paid for in order to manufacture the vehicle in which (s)he traveled to the house – where (s)he had to come in order to do the work – is "embodied" in the tuning? Assessments like that are absurdly difficult to sort out.

2.2 The Valeros' concepts of "cradle to cradle", of "exergy replacement cost", of a "crepuscular" phase of macroeconomic depletion, of "thanatia" and of a theoretical "Grave" :

The Valeros' calculations of exergy cost are based on accounts of the relevant humanly directed extraction- and purification-processesas represented by the two bold-font items in Fig.4, where the arrows represent economic decisions.

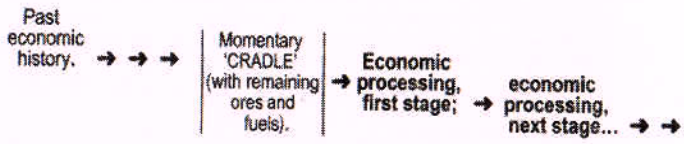

Fig.4. Meaning of the term "cradle" in the Valeros' theory

The information in Fig.5 puts this in a broader context and shows how an imagined "replacement exergy cost" (by means of which the "natural bonus" is assessed) fits into the Valeros' theory. In this figure, most of the thin arrows represent "natural" expenditures of exergy, i.e., expenditures not due to human decisions but due instead to the cosmic Big Bang and all that. (The fact that thick arrows are used here to represent our forth-coming purposeful expenditures of exergy doesn't mean that those expenditures are bigger than the ones represented by thin arrows; it just means that they are due to human decisions and that they postdate the moment of the present "cradle".)

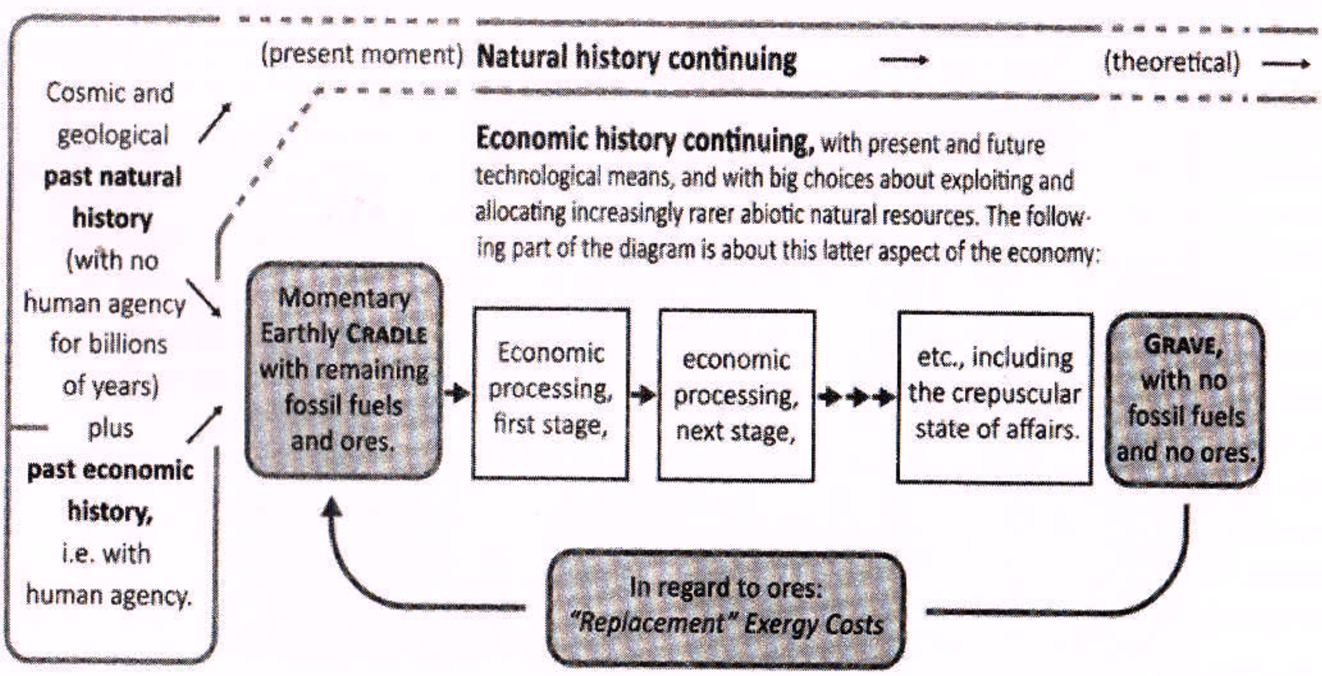

Fig.5. Uses of the terms "Grave" and "Replacement exergy costs" in the Valeros' theory

(Figs. 4 and 5 are of my design. Please don't lose any sleep about increase of entropy due to long-term accumulated cosmic expenditures of exergy. The Sun will swell up and engulf the Earth long before the Universe might approach a condition of "heat death", i.e. of uniform temperature, pressure etc. throughout, i.e. of physical equilibrium.)

The word "Grave" in the Valeros' theoretical terminology refers to an imagined demise, not of humankind, but just of any possibility whatever of ores (since each economically useful mineral would, at that point, be diffused 100% into the Earth's crust or oceans or atmosphere). Such a geological condition never did and never will exist. This "Grave" is a theoretical construct devised to provide an objective baseline for assessing the "replacement exergy costs" of mineral resources, without speculating as to how much exergy Nature had expended, millions or billions of years ago, to create this or that part of our natural endowment.

(An analogy is with economist William Stanley Jevons's famous rejection, in 1871, of the classical economists' "labour theory" of market value. Labour is an aspect of the history of a commodity up to the moment when it is put on sale to consumers. Jevons said that "labour once spent has no influence on the future value of any article". [62] He was relying on the fact that the market value of a commodity is how much money people are willing to pay for it, regardless of how much or how little labour may have gone into producing and delivering it.)

Ordinarily, the word "crepuscular" – in Fig.5 just before the box with the word "Grave" in it – means "at twilight" (i.e., in the morning *or* the evening); but here, the metaphor is not with the historical "dawn" of the prosperity which industrial capitalism has bestowed on millions of people, but with a gradually creeping "dusk" due to gradually worse and worse shortages of economically viable abiotic raw materials.

The "Grave" is defined as 100% dispersion (into either the upper crust or the atmosphere or hydrosphere) of each kind of economically valuable mineral resource. However, a mere approach to that unattainable theoretical condition – say, 70%-80% dispersion – would suffice to render the mineral economically inaccessible. The Valeros have devised a term for such a predicament: "thanatia" (derived from the ancient Greek name, *Thanatos*, for the personified spirit of death).

(The Valeros have, in their writings, occasionally confused the meanings of their three terms "thanatia", "grave" and "crepuscular". They appreciate my distinction of the three meanings described above).

We are now in a "crepuscular" phase. This is indicated by the fact that we are beginning to worry about these concerns.

2.2 Some examples of application of the Valeros' theory.

Consider, for a first example, gold as a mineral. Mining companies are nowadays routinely grinding up some 5 - 70 tonnes of gold ore in order to get an ounce of "24-karat" gold (i.e. as pure as possible, normally taken as 99.9%). [63] The Valeros have told me that if all the gold in the world were 100% dispersed, then some 15000 tonnes of rock would have to be ground up in order to extract from it an ounce of pure gold. For all practical purposes, however, the economic result would be the same if, say, 10000 tonnes had to be ground up for just one ounce: no one would do it. The condition would be thanatia (with reference to gold) although the dispersion would be less complete than at the baseline level of the theoretical "grave".

Partha Dasgupta, a very eminent 21st-century economist [64], regards "natural capital" (eco-systems, sources of fresh water, greenery, the atmosphere etc.) as one of four aspects of an economy's "capital assets", the other three being (1) "manufactured capital" (roads, ports, machinery etc.), (2) "human capital" (people capable of working), and (3) "knowledge". (He also warns that "If institutions [governments, for example] are weak or simply bad, then the social worth of those [various kinds of capital] assets would be small"). [65]

Reasonably undogmatic economists admit that market price is an inadequate guide to values in ecological economics, while all ecological economists are quite aware that the people most affected by the current rates of environmental degradation – the children and the presently unborn – cannot bid in the current market. And one could well, with an analogous focus on the future, set aside "embodied energy" assessments as being based on essentially silly estimates of how much exergy has somehow been expended in the past, whereas the Valeros' "replacement exergy cost" assessments are conducive to clarity as to some of the material aspects of the difficulties which are now being bequeathed to the children and to the as-yet-unborn people whom we will love later on in our lives.

The overarching issue of environmental degradation can arouse such strong fears and hopes (for mitigation) that some intellectually important points may get lost in the shuffle. One such point can be the rudimentary distinction between depletions of natural resources and various kinds of pollution. The Valeros' notion of thanatia has to do with depletions only. However, humankind's "crepuscular" approaches to thanatia may sometimes happen to entail serious pollution problems.

Here is an example. In the middle of Fig.6, the tall bar tagged "Mercury" means that the Valeros have calculated that nearly 90% of the original natural endowment (i.e., as of the birth of modern industry) of ores for mercury had been exhausted by 2008. And meanwhile, most of the mercury which humankind had somehow extracted from ores had, sometime in the last couple of centuries, been discarded in one way or another, and a lot of it has ended up in fish which humans like to eat, and so some species of fish are now dangerous to eat because you may get a poisonous amount of mercury from them. [66] A long book could describe various ways in which some particular kind of depletion and some particular kind of pollution are 'two sides of the same coin'. But they are not the same type of problem. Many kinds of pollution can be countered by hygienic procedures (there is, for instance, a viable chemical way to remove mercury from fish oil, and fish for eating can be cultivated in mercury-free ponds), whereas depletion of nonrenewable natural resources is relentlessly irreversible.

Here is another example of how the Valeros apply their theory of thermodynamic rarity. They estimate that exergy-wise, some two-thirds of the current rate

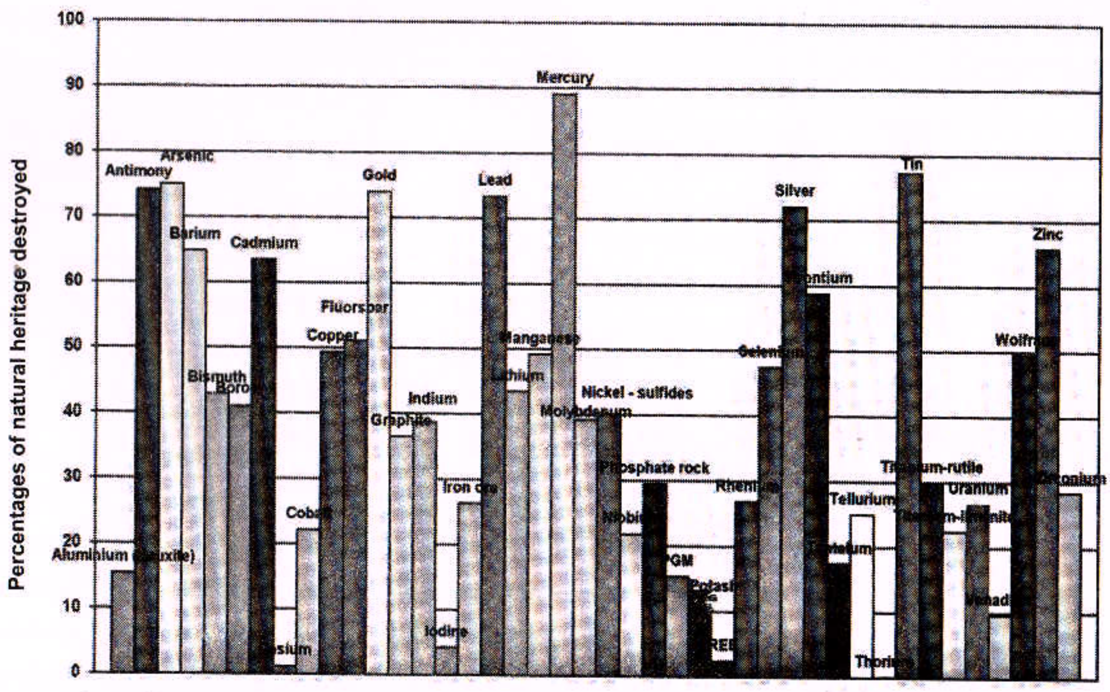

Fig.6: Bar-graph estimates of percentages of the total amounts various economically valuable minerals once available from Planet Earth to humankind for mining, that had already been mined as of 2008 [5]

of depletion of abiotic non-renewables is due to converting fossil fuels into smoke and ashes, while the other one-third is due to using up the natural bonus of having (non-fossil-fuel) ores still at our disposal. Fig.7 shows their estimate of the extent to which the overall "rate of exergy countdown" was, as of 2008, due to losses of fossil-fuel reserves, and to what extent they consider it to have been due to ongoing losses of the natural bonus of having mineral ores. (Please understand clearly that Fig.7 is only about rate of depletion, not at all about the horrendous problems of pollution and of global warming.)

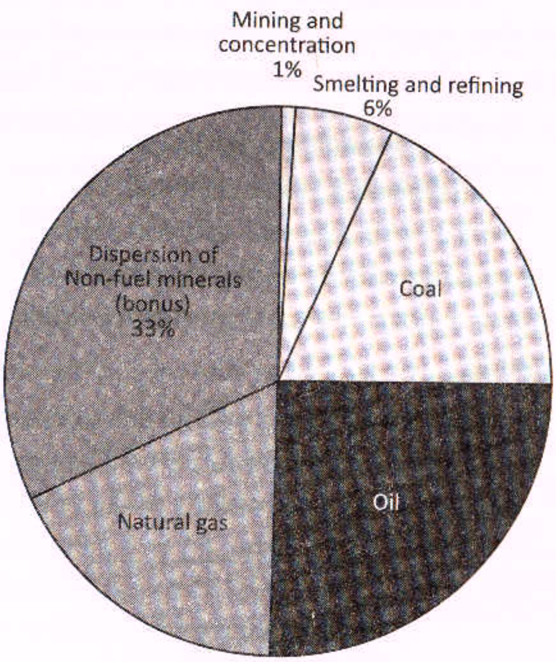

Fig.7. Relative portions, percentage-wise, of the ongoing worldwide rate of "exergy countdown" (as of 2008) due to ongoing losses of fossil-fuel reserves (of three kinds) vis à vis ongoing losses of the natural bonus of having non-fuel mineral ores for mining [5]

A century or two ago, when the quantity and quality of the ore in any then-current cradle were better than in its modern counterpart at the same location, the theoretical value of the natural bonus was accordingly more; and, the exergy cost of extracting the ore from the cradle and purifying the stuff enough to render it marketable to manufacturers etc. for use in making their products (such as, for instance, vehicles or pharmaceuticals or jewelry) was correspondingly less. The difference is charted schematically in the pair of graphsshown in Fig.8 (adapted from graphs designed by the Valeros).

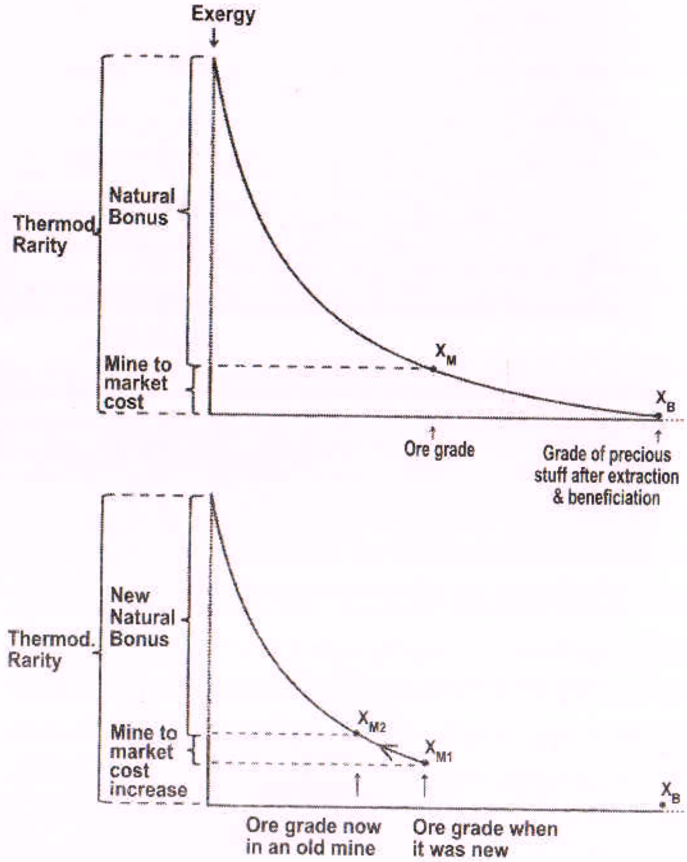

Fig.8. How the value (assessed in terms of exergy) of a mine declines in the course of its history

The "grade" of the ore – which has, of course, a big effect on its economic value – is plotted horizontally. "Zero quality" is set arbitrarily at the imaginary Grave level. "x_M" refers to the potentially useful stuff (useful for producing some kind or kinds of commodities) in the ore, and "x_B" refers to the economically "precious" stuff inasmuch as it is, after the mining and necessary subsequent processing, marketable to manufacturers and artisans. (In the market under consideration here, the buyers are those manufacturers and artisans.) The mine-to-market cost is represented in the first graph as being about 1/5th of the natural bonus – which is assessed with a dotted vertical line because it's not based on any actual exergy expenditures but on those which would theoretically have to be made to revert from theoretical 100% dispersion to the momentarily current amounts and grades of ore(s).

In the second graph, the mine-to-market cost with regard to the older and therefore semi-exhausted mine(s) is represented as being nearly 1/3rd of the remaining natural bonus.

These are schematic representations. The smoothness of the curve is analogous (in its way) to the smoothness of the line in Fig.1. The curve here goes from upper left to lower right because all improvements of quality are due to expenditures of exergy. (The converse is not true. The explosion of a destructive bomb in war, for instance, is an exergy expenditure which reduces quality.)

In the second graph, the curve is truncated at x_{M1} in order to indicate that the abscissa axis (the horizontal one) is a schematic generalization just of the ore-grade down in the mine, and not of the grades of materials that have processed after being taken out of it. In both graphs x_B is placed slightly higher than the bottom of the graph, and the abscissa is represented as continuing further rightward than x_B, in honour of the fact that the last possible stages of refining – for instance from, say, 23 karat to 24 karat gold – are always less efficient exergy-wise than all the previous stages (for instance, from 12 to 13 karat; and indeed, total purification/decontamination is technically unfeasible; this is actually an application to separation processes of the Third Law of Thermodynamics). The far right part of this kind of graph would resemble Fig.9 (which Prof. Valero has kindly sent to me for use in this article) if it were to cover such economically unfeasible procedures, and would thus become symmetric vis à vis the far-left part.

The mine-to-market cost increase represented in the second graph in Fig.8 could in some cases be mitigated momentarily by clever improvements in the techniques for various aspects of the mining and refining. Such improvements would, however, soon tend to aggravate the exhaustion of the natural bonus. All the mines *will* become so exhausted as to be useless, and you can readily infer, by pondering intelligently Fig.6, that for certain invaluable minerals (copper, for instance) the year is in a proximate future, not a distant one.

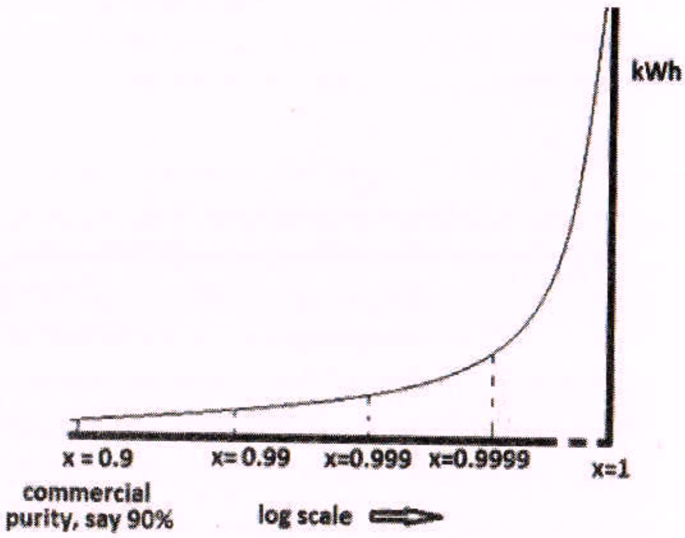

Fig.9. Why manufacturers wouldn't pay for (and so, mining companies don't sell) 99.99% pure copper, iron etc. (Here, "**kWh**" means kilowatt hours, a unit of measure for exergy).

It is, however, sane to want such things to happen later rather than sooner.

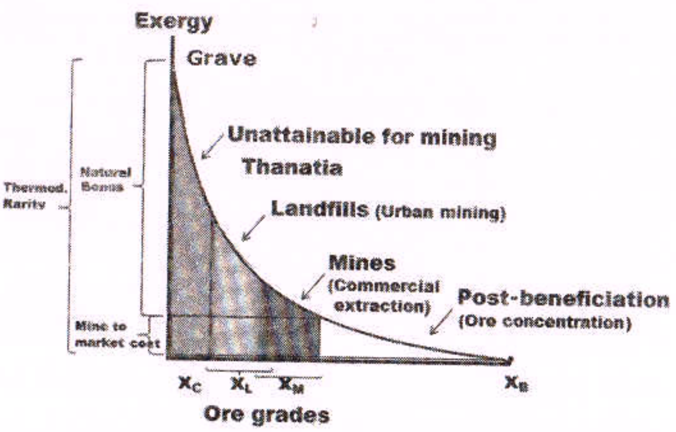

Fig. 10. Landfills as a hallmark of the 21st-century transition to thanatia

Fig.10 (also based on a graph sent to me by Prof. Valero) represents a macro-economic understanding of the issues and brings out the importance of sorting waste as soon as possible so that as much of it as possible can be recycled instead of being dumped into landfills.

3.0 Reconsideration of Hubbert's premise as to how the rate of extraction declines after the "peak-production" year

Section 1.1 of this article referred to Hubbert's theoretical assumption that the moment when a natural "bucket" of economically useful stuff is half empty (and therefore only half full) is the "peak production" moment, i.e. when the rate of economic removal of the stuff from the Earth's crust is the highest; and in that section of the article it was suggested that this assumption might be invalid with regard to some of the Earth's stocks of non-renewable natural resources. There has indeed been some recent evidence, data-wise, that it has been invalid to some extent. It is to be hoped that a considerable amount of each nonrenewable stock will be deliberately "left in the ground" in the proximate future, and that much of the last part of each curve will therefore slope down for, say, a century or so longer than Hubbert would have supposed – as suggested graphically in Fig.11. (Please recall that in such a graph, time is plotted horizontally, whereas rate of extraction is plotted vertically.) The dotted line in Fig.11 is the right-hand part of a symmetrical Hubbert curve. On the asymmetrical curve, the peak-production year ("Point A") is represented as occurring before the bucket is half empty. During the time represented as being between (1) where, say, the two curves cross and (2) the extreme right part of the graph, some radically different techniques might be devised for doing either whatever the stuff is now used for, or for some other developments which to some extent could obviate, in a way that is beneficial to humankind, the need for that service.

It is conceivable that humankind might meanwhile develop, to a necessary new level, some relevant modes of cooperation in the face of "Stingy Mother Nature". Unless there are wisely prolonged crepuscular phases, there will be in store for humankind a lot of simultaneous steep downward trends of availability (down to nearly null) of natural resources for which there are strongly felt economic needs, and then acute social troubles are bound to ensue. This is beginning already to happen. Engineers (as well as various other people) ought to take the problem seriously.

4.0 "Composite thermodynamic rarity" in electric and electronic equipment

While defining a "thermodynamically rare" chemical element as one that is naturally scarce and/or costly exergy-wise to process, the Valeros have begun to study, in collaboration witha German colleague, Nadja von Gries, the "composite thermodynamic rarities" of the sets of materials used in this and that kind of electric and electronic equipment (EEE). Such assessments could be used to help set some priorities in the design of such equipment and in regard to recycling the various materials when the consumers are ready to discard the equipment.

This entails finding out how much of each of the following metallic elements is contained in various kinds of EEE: cobalt, gallium, gold, indium, palladium, silver, tantalum, tin, yttrium, and the rare-earth elements. (A typical mobile phone, for instance, might contain nearly 10 micrograms of palladium, nearly 25 of gold, up to 250 of silver, up to 3½ grams of cobalt in its battery, etc.) The Valeros define the

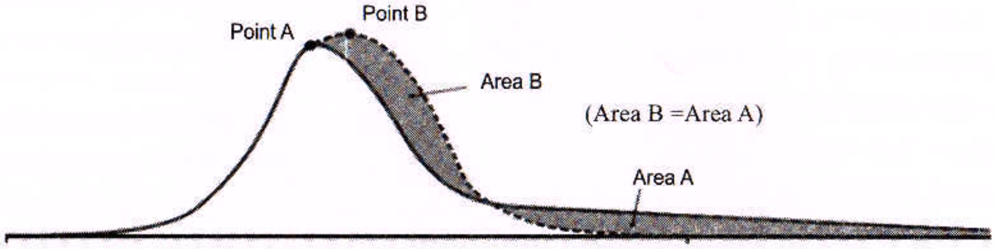

Fig. 11. An asymmetric alternative to a Hubbert Curve

composite thermodynamic rarity of an EEE as the weighted arithmetic mean of its components' thermodynamic rarities x_i. In the defining equation, w stands for mass:

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

The "rareness intensity" of each kind of equipment is defined as its composite thermodynamic rarity divided by its average duration of use and multiplied by its sales volume. This gives an objective message as to the "materials scarcity risk" of using critical metals for a given technology. The higher the "rareness intensity" estimate, the higher could well be the future supply-disruption risk of the technology.

This project has entailed estimating the composite thermodynamic rarities of dozens of kinds of EEE sold in Germany in 2010. Nadja von Gries estimated carefully in terms of weight the typical content, in each unit of some specific kind of EEE, of each of the metals listed above. Then, on the basis of available data for the number of units of that particular kind of EEE sold that year in Germany, an estimate was made of the total weight of the appliances of that kind that had been sold. Fig.12 shows the gist of some of the findings. [67] The further to the right an icon is located, the more units of that kind of EEE had been sold. (For instance, the least popular kind had been old-fashioned TV sets, represented by the icon the furthest to the left; only some 12,000 of them had been sold.) If an icon is located in the upper part of the graph, there tended to be, relatively speaking, a lot of critical raw materials (as assessed in terms of thermodynamic rarity) in each such unit. For each sample kind of product, the estimate (re: the total of all the products of that kind that were sold) is represented by the area of the rectangle from the lower left corner of the graph to the icon representing the product. Fig.12b shows the relative locations of

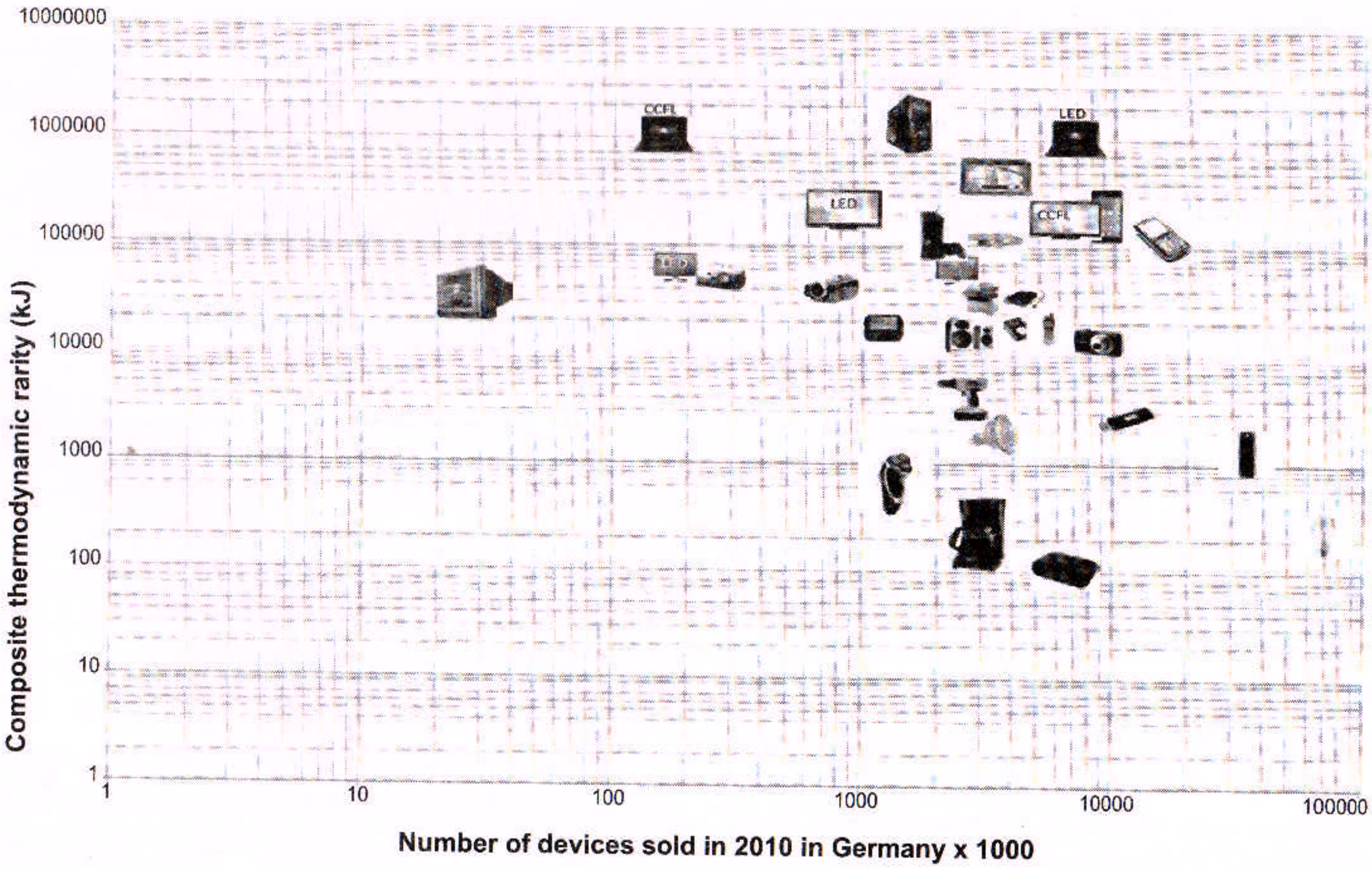

Fig.12a. Relative "composite thermodynamic rarity" estimates (approximate) for aggregated numbers of each of various kinds of EEE sold in 2010 in Germany [67]

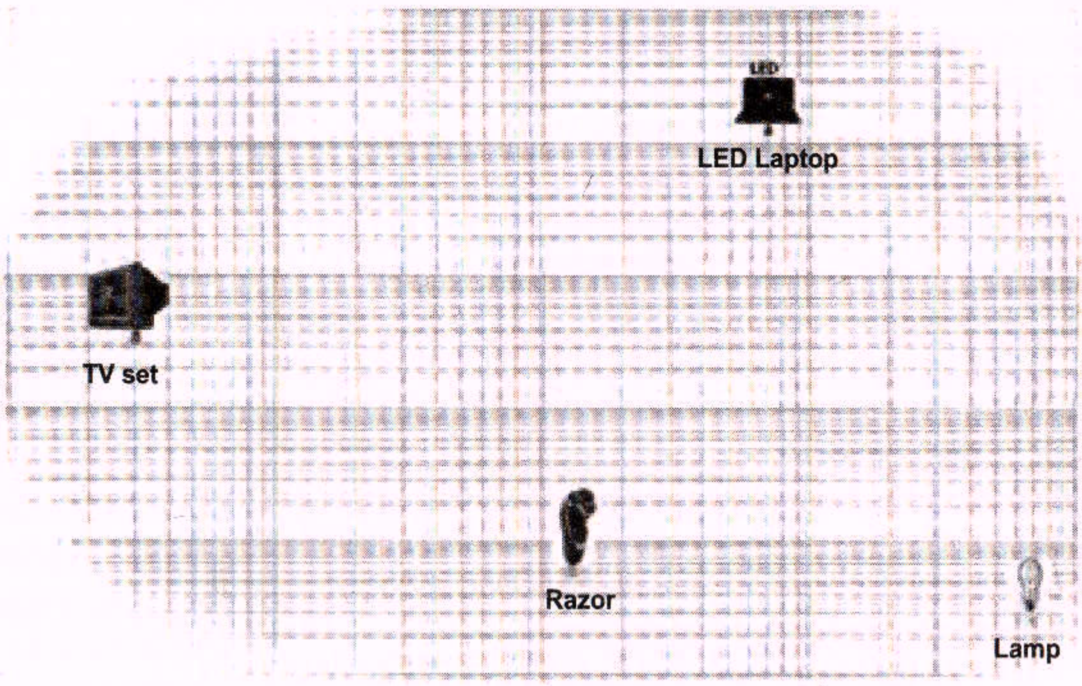

Fig.12b. Four icons excerpted from Fig. 12a.

the icons for four types of EEE: old-fashioned TV sets, electric razors, LED laptops, and vapor-discharge lamps (represented here by an image of an old-fashioned light bulb).

Studies of this kind may be of use for setting priorities with reference to recycling of various kinds of EEE, and may show that new and in some ways notably more efficient devices are not necessarily "green" from a materials point of view, since the metals contained in them may be or may become very scarce and/or difficult to extract.

5.0 Phosphate

Phosphorus is, along with nitrogen and potassium, one of the three chemical elements most rapidly removed by plants from the soil where they are growing. The three elements – nitrogen, phosphorous, potassium – are the "macro-ingredients" of artificial fertilizer.

Nitrogen from the atmosphere (of which it comprises more than 75%) can readily be "fixed" chemically (i.e., compounded with oxygen to produce nitrates) in order to make up a useful portion of the fertilizer. A well-informed 21st-century writer on planetary science, Oliver Morton, has remarked that "industry [nowadays] fixes over a hundred million tonnes [of nitrogen] a year, comfortably more than [do] all the earth's nitrogen-fixing soil bacteria put together. This extraordinary industrialization of the planet's metabolism changed the conditions under which the human race lives. It adapted the Earth-system to a quadrupling of the human population [in less than 100 years!] and gave humans a dominant role in one of the earth-system's basic biochemical cycles." [68]

As for phosphorus, Higdon et al. (2014) explain that it "is an essential [nutritional] mineral that is required by every cell in the [human] body for normal function. Bound to oxygen in all biological systems, phosphorus is found as phosphate (PO_4^{3}) in the [human] body. Phosphorus is found in most food because it is a critical constituent of all living organisms." [69]

Schröder et al. (2010) have pointed out that humankind's main source of phosphorous for fertilizer etc. is "phosphate rock – a non-renewable resource", that there is "general consensus that the quality of remaining reserves is in decline", both in terms of phosphate content and in terms of the presence of poisonous heavy metals and other contaminants, and that the phosphate layers of the relevant mines are becoming "more physically difficult to access". "At the same time, the global demand for phosphorus is expected to increase – primarily due to an increasing demand for food from a growing world population [of humans]. The increasing popularity of meat and dairy products (which require more phosphorus to produce) in developing economies, and phosphorus demand for non-food uses, may further increase global demand. [And meanwhile,] the uneven geological distribution of phosphate rock means that [a very small number of countries] control 85% of global reserves." [70]

(India will continue to use lots of artificial fertilizer in the next three decades. Two reasons for this are that the number of residents needing to be fed will increase from less than 14 thousand million in 2020 to some 16 thousand million or more by 2050 [71] and that the quality [72] and quantity [73] of arable land in the Indian countryside will meanwhile decrease.)

In regard to availability of phosphorous for use in artificial fertilizer, the problem is not any dire overall lack of it in the parts of Nature that are accessible to humankind. It is one of the dozen or so most plentiful elements in the of the Earth's crust and amounts weight-wise to something like a tenth of a percent of it [74] – almost entirely in phosphates since the chemical element itself is very strongly reactive (unlike nitrogen). However, the various phosphate ores are of many quite different qualities, and some of the differences have to do, as mentioned above, with potentially poisonous levels of pollution of one kind or another. The Valeros' thermodynamic-rarity concept could, conceivably be put to use for figuring out (1) how to estimate the natural-bonus losses due to mining the phosphate (losses entailing, eventually, economic dependence on the few countries where the ore is mainly to be found) and also (2) how best to reduce the amounts of exergy required (and hence the monetary costs which are of course a big concern of the mine owners) to extract the phosphate while also sorting out and disposing properly of the poisons.

In a comprehensive survey of natural economic resources "in a planetary perspective", Harald Sverdrup and Kristín Vala Ragnarsdóttir have remarked that "There is no substitution option available for phosphorus in food", and that "this fact is beyond any discussion". "The world cannot support a population at the present order of magnitude without closing the phosphorus cycle. Today, it is open." [75] By "closing the phosphorus cycle" they mean bringing about a situation where humankind is no longer dependent for its nourishment, as it now is, on phosphate mining. A good reason for insisting that there is no "substitution option" for phosphorus in food is that the U.N. has publicized widely, ever since the mid-1990s, the gravely mistaken view of Sudhir Anand and Amartya Sen that "The fact of substitutability (in both production and consumption) implies that what we are (morally) obligated to leave behind [for children and future humankind] is *not* [my italics] any particular thing or any particular resource." [76]

6.0 Brief concluding remarks

Here is a list of five ways to slow down the currently swift march toward thanatia:

- Devising and habitually using, in the daily lives of affluent folks, various ways of making do with less of the nonrenewable resources still available to humankind from the Earth. (Some opportunities for innovative, small-is-beautiful engineering may lurk here).
- Finding some more ores. (Maybe in the moon? How about the shipping costs?)
- Recycling discarded stuff better than is now done. This is technologically feasible and ripe for social acceptance.

- Lowering the rate of increase of the human population. (The number might thus increase by 2050 to only 9 billion rather than the 9½ or 10 which the U.N. estimated in 2019 to be likely [71]; see Fig.13).
- Apropos the forthcoming exhaustion of fossil fuels: developing more and more new ways to generate economically applicable exergy. (It is doubtful whether controlled thermonuclear fusion will prove feasible. Quite a few other ways are being explored – each one with its strong and its troublesome or weak aspects.)

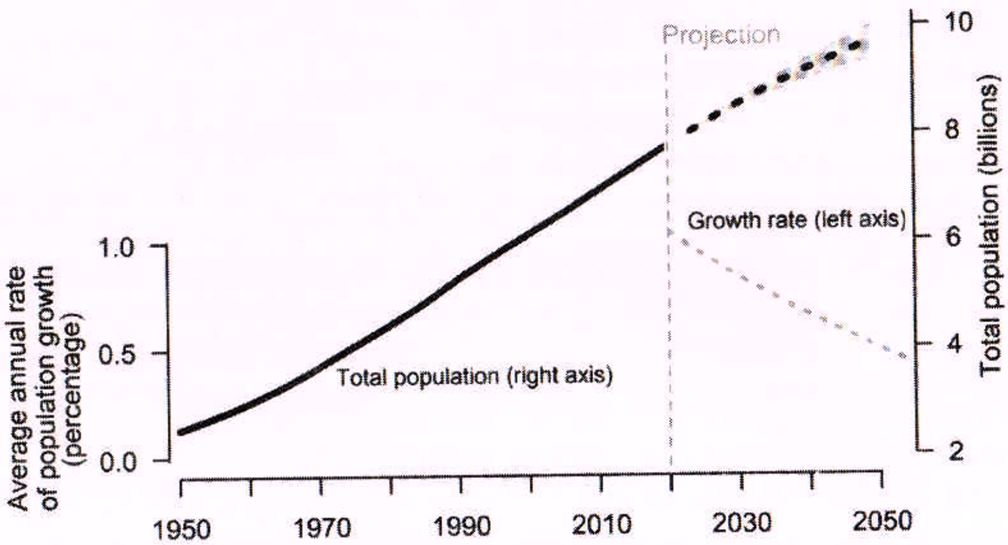

Fig.13. Estimates of worldwide human population 1950-2050 [71]

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(In this list, "Ao." and "Aa." are abbreviation for "Antonio" and "Alicia". Web addresses were accessed on 25/02/2021.)

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