Chapter 4

Accounting for Mineral Depletion Under the UN-SEEA Framework

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.77290

Abstract

The scarcity factor of non-renewable resources is absent in conventional accounting methodologies. This chapter proposes an approach for accounting for abiotic resource depletion through the second law of thermodynamics. It is postulated that each chemical element has associated a cycle that should be closed either naturally or technologically. Once a mineral is extracted from the Earth, the cycle starts. The overall process from mining to dissipation is the cradle-to-grave path and is generally well characterized and accounted. However, to close the cycle, we need to account for an imaginary path through the "grave-to-cradle" approach. This semi-circle is a debt we acquire with future generations. It represents the effort that we should invest in returning minerals from a dispersed state to the initial conditions found in nature, and hence, it is a measure of depletion. This is calculated through exergy replacement costs, which indicate the energy effort required to close the cycle from the grave with prevailing technologies. The grave is the model of degraded Earth (called "Thanatia"), which was developed previously. This chapter concludes proposing the inclusion of this approach in the System of Environmental-Economic Accounts (SEEA), converting it into a "Global System of Environmental-Thermo-Economic Accounts" (SETEA).

Keywords: exergy, SEEA, economic accounting, minerals, depletion, SDG12

1. Introduction

Mining, smelting, and refining processes have important environmental impacts: they deplete natural resources, minerals and fossil fuels that cannot be replaced; they use land that affects landscapes and their ecosystems; they discharge wastes into air, waters, and soil; and they can influence in the depletion of renewable natural resources such as biota or ground waters.

These activities have accompanied the development of man from the early stages of civilization. To such an extent that the stages of civilization have been named by the prominent resource that supported the era: bronze, iron, coal, and oil Ages. When nature was abundant, the side effects were not taken into account. However, the intense technological development of the twentieth century has forced society to realize them.

In this ambition, environmental economists have developed methods to evaluate the economic effect that has the use of natural resources to support our economic activities. They convert physical assets and impacts on ecosystems into monetary accounts, which are added or subtracted from the aggregated accounts, and finally, from the gross domestic product (GDP). The advantage of using monetary units is that it allows comparing among other environmental assets and aggregating them to look for their contribution of the wealth of a country.

However, as an agreement among economists is difficult to attain, and it is of paramount importance to yearly account for the human appropriation and use of nature, the United Nations proposed to develop a System of Environmental-Economic Accounts (SEEA). It consists of a satellite account system for reflecting the environmental deterioration proposed to adjust the System of National Accounts (SNAs). This is an optimum reference framework to follow in the description of economic valuation methods.[1] In fact it is an important tool to manage appropriate resources and thus ensure sustainable consumption and production as advocated by the UN Sustainable Development Goal Number 12.

This chapter explains the capabilities and drawbacks of the system of environmental and economic accounts. Subsequently, we describe an alternative approach for assessing abiotic resource depletion through the second law of thermodynamics. Finally, a proposal for accounting depletion based on the organized structure of the SEEA is provided.

2. SEEA accounts

"The System of Environmental-Economic Accounts (SEEA) is the United Nations statistical framework that provides internationally agreed concepts, definitions, classifications, accounting rules and standard tables for producing internationally comparable statistics on the environment, and its relationship with the economy. The SEEA framework follows a similar accounting structure as the 'System of National Accounts' (SNAs) and uses concepts, definitions, and classifications consistent with the SNA in order to facilitate the integration of environmental and economic statistics."[2] The international community agreed to elevate the SEEA-2003 from a manual of best practices to an international statistical standard on par with the System of National Accounts. For attaining this objective, an iterative revision process was initiated by the United Nations Statistical Committee, relying on a broad global experts' consultation. The revised SEEA is organized into three main parts: the Central Framework, Experimental

[1]See https://www.un.org/sustainabledevelopment/sustainable-consumption-production/ [Accessed: June 2018].
[2]See http://unstats.un.org/unsd/envaccounting/seea.asp [Accessed: June 2018].

http://dx.doi.org/10.5772/intechopen.77290

Ecosystem Accounts, and Extensions and Applications. The Central Framework, consisting of the internationally agreed standard concepts, definitions, classifications, tables, and accounts was completed in 2013.

2.1. General considerations about the SEEA

In particular, the Central Framework of SEEA intends to be a universal single measurement system information on water, energy, minerals, timber, soil, land, ecosystems, pollution and waste, production, and consumption of all interactions that society makes with nature. It recommends presenting the yearly accounts for these interactions in an organized manner parallel to the System of National Accounts. The basis consists of defining and systematically accounting the concept of "environmental assets," which are defined as "the naturally occurring living and non-living components of the Earth, together comprising the biophysical environment that may provide benefits to humanity." These assets are presented in both physical and monetary data. The Central Framework claims that it facilitates comprehension of data by scientists and economists and brings a bridge between them.

Universally organized statistics is perhaps the main value of the SEEA, and economists have developed well established procedures to rely on them. To start with, the economists define flows and stocks.

Natural inputs are physical flows moving from the environment to production processes. They are mineral, energy or timber resources, also renewable energy resources and finally inputs from soil, water, and air resources. At the same time we produce products, we produce wastes. These are flows discarded, discharged or emitted in the production processes, and absorbed by the environment in the form of solid, liquid or gaseous materials and energy.

Stocks, in physical terms, refer to the total quantity of individual environmental assets at a given point in time. "These assets are defined by their material content without specific reference to their constituent elements." This is a major drawback since tons of a given metal do not tell about its wealth. Its mineral composition, ore grade, accompanying minerals or burden for instance can be very variable.

The physical units of these flows and stocks vary with their type and are measured according to the System of International units, mass, length, volume, joules, etc.

The way the physical flow is accounted follows the structure of monetary and use supply tables that are used to show transactions in products between different economic entities like industries, households, government, and the rest of the world. The structure of the physical supply and use tables (PSUT) adds another entity: the environment. This is made by adding columns and rows that consider the flows going into and leaving from it. In addition, the tables show separate accounts for materials flows, water and energy sub-systems.

Energy and water flows are accounted in physical units in a cradle-to-grave way. The physical flow accounts for materials are a complex subject for SEEA; this is because of its diversity as compared to energy and water flows. The SEEA uses the mass basis for each type of material.

Insofar as materials can react and mix with other materials to produce new materials, the trace of physical flows may be very complex in its cradle-to-grave description. In some cases, it is possible to track flows of elements such as mercury because of their hazardous nature.

To provide an aggregate overview in tons, the economy-wide material flow accounts (EW-MFA) are used. These accounts describe the materials input-output of an economy including the environment and the rest of the world as subsystems.

Converting these units into money allows, in theory, comparison among different assets. The preferred approach of SEEA to the valuation of assets is the use of market values. "Strictly, market prices are defined as amounts of money that willing buyers pay to acquire something from willing sellers."

However, valuating assets at market prices have an important problem since there are "few markets that buy and sell the assets in their natural state and hence determining an asset's economic value can be difficult." Therefore, the central framework recommends using the net present value (NPV) approach for estimating market prices for non-marketed assets. This approach also named as the discounted value of future returns approach, "uses projections of the future rate of extraction of the asset together with projections of its price to generate a time series of expected returns."

2.2. Asset accounts for mineral and energy resources in the SEEA

Mineral and energy resources are non-renewable resources whose extraction leads to depletion, and subsequently, the end of the industrial activity. Therefore, their asset accounts must organize the information about stocks, flows of extraction, depletion, and discoveries, as well as of monetary estimates of the value added, operating surplus of the extracting companies, and depletion adjusted value-added measures. This is briefly described here.

Known deposits of mineral and energy resources are classified by SEEA according to the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009)[3]. The UNFC-2009 classifies deposits with triple dimension criteria: economic and social viability (E), field project status and feasibility (F), and geological knowledge (G). The first criterion (E) establishes the commercial viability of the project. The second criterion (F) indicates where the technical extraction project is on the road from exploration to market. The third criterion (G) designates the level of certainty in the geological knowledge and potential recoverability of the quantities. Each criterion is further numbered as high (1), moderate (2), and low (3) or very low (4).

Besides of that, known deposits are categorized into three classes: class A for commercial projects with recoverable Resources, i.e., the case of E1 deposits and projects F1; class B for potentially commercial projects with recoverable resources when deposits fall in the category E1 or E2 and projects in F2; and class C for non-commercial, and other known deposits. In these three classes, the geological knowledge may be G1, G2, or G3.

[3]See http://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/UNFC2009_ECE_EnergySeries39.pdf [Accessed: June 2018].

http://dx.doi.org/10.5772/intechopen.77290

The SNA limits its scope to commercially exploited deposits, whereas SEEA opens the scope for having a broader picture on the availability of the stock of these resources.

Notwithstanding this, these criteria consider the mining wealth in an economically simplified and present-day view. It misses the fact that geology is more complex than what statistics reflect. Consequently, there is no internationally agreed detailed classification for mineral and energy resources suitable for statistical purposes. For instance, there are many types of minerals and combinations of them with specific geological structures. In addition, the exploitation may result in recovering burden, tailings, and residues that were previously discarded as a function of market demand, for instance.

Thus SEEA simply proposes a compilation of the physical asset accounts for mineral and energy resources by type of resource including estimates of the opening and closing stock and changes in the stock over the accounting period. The type of measuring units indicates the roughness of the accounting system. They are measured in tons, cubic meters, or barrels. There is neither homogeneity in units nor specificity in the type of mineral. In fact, "it is noted that a total for each class of deposit across different resource types cannot be meaningfully estimated due to the use of different physical units for different resources. For certain sub-sets of resources, for example, energy resources, an aggregate across certain resource types may be possible using a common unit such as joules or other energy units."

As explained previously, all mining activities, either for extraction of mineral or energy resources impact on environment. Their effects are on air, waters and soils in form of pollution and degradation of environmental reservoirs. They also affect the landscapes, the ecosystems, and the local human settlements. The SEEA tries to organize these costs into a framework that allows valuating and yearly trace these impacts. In theory, the revenues caused by mining should overcome the temporal or permanent loss of environment. The only way to know that is by monitoring and accounting all these impacts in an organized and standardized way. This is the highest contribution of SEEA. Unfortunately, the loss of (i) landscapes, (ii) ecosystems supporting particular biotas, or (iii) local communities, might not be captured by these impassive accounting systems. Another problem is the lack of single and universal measuring units.

The structure of the monetary asset accounts largely parallels the structure of the physical asset accounts. "The valuation of the stocks uses of NPV approach at the level of each individual resource type, and ideally for specific deposits of the resource, and then summed over the range of different resources in order to obtain a total value of mineral and energy resources."

The application of NPV approach requires specific considerations in the estimation of the resource rent. First, the resource rent should be limited to the extraction process itself excluding the refinement and processing of the extracted resource. Accordingly, the extraction process includes the typical mining activities like mineral exploration, evaluation, mining, and beneficiation. Commonly, the mineral deposit contains several types of resources. For example, an oil well containing gas or, nickel sulfide deposits often found with copper ores, where cobalt is also obtained as a by-product. In that case, the resource rent should be allocated by commodity.

An important problem in valuation is the frequent fluctuation of the market price of mineral commodities while operating costs are quite foreseeable. Consequently, the resource rent may be composed of a quite volatile time series. Mineral exploration and evaluation costs are treated as a form of gross fixed capital formation. Moreover, decommissioning costs reduce the resource rent earned by the extractor over the operating life of the extraction site.

The physical extraction rate is usually constant along the life of the resource if there are no reappraisals. However, as resources approach depletion, there will be a decline in the ore grades and the environmental and energy costs associated with extraction will increase, thus avoiding extraction of yearly constant quantities. Even the central framework of SEEA warns that there is no reason why the extraction rate should necessarily be constant. In practical terms an important physical fact is ignored: the extinction of the mine is not constant along the extraction period but follows the law of diminishing returns.

2.3. Final comments on the SEEA

We find two main objections to the SEEA. First, dividing nature into assets does not reflect all interactions among natural systems themselves. For instance, converting a forest into a stock of timber does not reflect other benefits coming from it, like floods protection, clean air, being a life-supporting system, or even its recreational purposes. Numbers will never reflect causality and may provoke greed for rapid exploitation of natural resources. For the SEEA central framework, the whole is exactly the sum of its parts. It resigns holism in favor of reductionism.

Second, SEEA and SNA are firmly based on market price methods. Even if money has the power of easy comparisons among different issues, it reflects social values rather than objective values. They vary with time and from nation to nation. Money reflects the purchasing power of man in society. We pay people, not nature, and if nature claims nothing for its services, the monetary accounting system will only reflect present man´s interests. The implicit paradigm behind is: if we could extract and use all present environmental capital and convert it into money, it would be better than having physical assets not yet exploited. This is an absurd reductionism, and only the impossibility of having enough money to extract and convert nature into money inhibits that insanity. On the other hand, if everything is converted into money, the value of money itself would depreciate. Therefore, those that have retained their resources would become the wealthiest. The willingness to pay weakens with abundance and strengthens with scarcity. Yet the lack for a better numéraire excuses the use of money.

In fact, an important problem in SEEA is that it uses physical accounts without homogeneity in units or specificity in the type of mineral/material. This makes very confusing the trace of physical flows throughout its life cycle since materials react, mix, and decompose. Converting these units into exergy values would facilitate materials trace analyses through Sankey diagrams.

That said, the SEEA constitutes an impressive initiative for putting numbers to the man-nature interactions in a rational and global way. Universally organized statistics is perhaps the main value of the SEEA, and economists have developed well established procedures to rely on them.

In what follows, we present an alternate method for assessing natural non-renewable resources from a thermodynamic perspective.

http://dx.doi.org/10.5772/intechopen.77290

3. Closing material's cycles: the view "down the rainbow" (DTR)

We have seen in the previous section that SEEA accounts for physical flows in a cradle-to-grave perspective. However, in the cradle-to-grave path, there is information that these accountancy systems will never supply: depletion. Neither the economic nor physical accounting systems are efficient enough to assess the depletion of natural resources.

Something lacks in a global view: the mineral endowment and the non-renewable resources of the Earth are constantly decreasing. Each time non-renewable resourcesare extracted and not replaced we lose them irreversibly. And the only thing we can measure is its yearly decrease, not its lost value. There is no way of appraising what valuable things mankind is losing forever. Scarcity and the effort needed to replace non-renewable resources is absent in conventional accounting methodologies. Indicators for Materials recycling, substitution and consumption decrease also lack in the credit list. It could be argued that having an indicator of scarcity per chemical element could be enough to solve the problem. However, the myriad of inorganic products we can extract from mine Earth and the huge amount of chemical products that these materials can be converted into, makes impossible to have a decent accounting of the material cycles of all chemical elements.

In our view, there is a lack of theory rather than a lack of indicators. Partial or total cradle-to-grave assessments are the half part of the cycle. We name them "over the rainbow" (OTR) accounting methodologies. They lack the other side: the grave-to-cradle assessment. In the same way that imaginary numbers can hardly be explained in the real space, some phenomena like depletion may be better explained in the "down the rainbow" (DTR) approach [1].

The planet works in cycles driven by solar energy: carbon, oxygen, nitrogen, phosphorus, sulfur, and water have their cycles but, to our knowledge, there are no postulated cycles for metals and chemical elements in general. Those elements related with life have short closing cycle times even if they have reset times measured in geological scale times. However, such elements that do not form part of biological life will hardly be reset. They are constituents of our exosomatic organs, and they are in danger of being scarce for future organs because of dispersion. In practical terms, both types of chemical elements must have their own cycle. And the human being must allocate a major effort to close and accelerate their closure. Sustainable development requires the closing of all chemical elements in the planet either for endo or for exo-somatic organs. Their closing cycle velocity, and the effort required must be a function of how intense is their use with respect to their physical scarcity. If man alters the cycles, closing them corresponds to man.

By extracting the ore from a mine, the exergy (i.e. physical utility) of the ore increases, even though we spent a lot of exergy (i.e. useful energy) to remove it. From the standpoint of future generations having the raw material in a store instead of having it in a mine would be a good inheritance. All environmental costs would be a matter of the past. This is something similar to leaving for the future the pyramids or the cathedrals. Clearly, if we use this raw material and then recycle it, we would be using it temporarily.

The problem arises with dispersion. What is dispersed and, of course, the increase in demand needs to be replaced with more extraction. That increases the size of the cycle to be closed, and the energy debit increases over and down the rainbow. The over the rainbow part is a real consumption, and the down the rainbow is a debt we acquire with future generations. Anything that reduces the new extraction is positive: substitution, miniaturization, recycling, the efficient use of materials, and indeed the extraction efficiency.

Dispersion of raw materials has not been sufficiently considered in economic analyses. It has been ignored as a materials availability loss, but rather it is seen as a pollution problem. As it happens with heat in energy balances, it is obtained by difference. The dispersion is thus accounted by material balance: what is extracted minus what is recycled is equal to what is dispersed. But in reality there is no universal care in having a systematic accounting of the cycles of elements.

Dispersion is the key for understanding the phenomenon of raw materials. The raw material backpack has two components: one is the overall impact of its extraction and the other, the acquired debt for avoiding dispersion. Each particular raw material has an environmental cost for dispersal. Under this light, substitution of a raw material for another would make sense if both parts of the backpack decrease. These assessments must be essentially physical. It is important to highlight that while the OTR side can be restored directly by nature in timespans of several generations - provided that our wastes should not exceed the assimilative capacity of the biosphere; the DTR side needs geological eras to naturally closing the cycle for each particular element. Restoring the planetary mines as they were before civilization would only be possible with the internal heat of Earth through volcanism. It is something beyond imagination. The “easiest” mineral resources to restore would be fossil fuels. However, fossil fuels have a formation time of the order of million years. Giampietro and Pimentel [2] gave a value for fossil energy productivity of the Earth as low as 0.016 MJ/m^2/day or 1000 kcal/0.7 m^2/year.

4. Thermodynamic approach for accounting the Earth’s mineral capital

Ecological economists have learned that entropy is closely related to economics [3, 4]. It tells us about the direction to which economical fluxes (as part of the natural environment) go. However, entropy is a very difficult property to understand, and it is often used and “misused” in a metaphorical manner. In this way, we can find statements such as “mines of low entropy become mines of high entropy.” However, the latter assert even if correct, does not provide much information. How can we overcome this deficiency? The answer is with exergy. Through this property, we are able to convert metaphors into real numbers. A good management of our finite concentrated mineral deposits needs to be based on reliable, objective and strong information sources, and removed away from market subjectivities.

This has been the motivation for the development of the Exergoecology approach [5, 6]. The fundamental instrument of the latter is the calculation of exergy replacement costs as a way for evaluating the “effort” that nature put into play for concentrating substances from a completely dispersed state to the concentrated conditions of the minerals found in the deposits. As the ore grade tends to zero, the exergy required to extract a mineral from the mine tends to infinity. Thanks to the fact that nature provides us with mines, the exergy needed to produce minerals is infinitely lower than if we would need to obtain them from the “bare rock.” However, as extraction continues, the state of the deposits approaches to the bare rock, and future generations will have to deal with very low-grade ores, needing increasing amounts of energy for their

http://dx.doi.org/10.5772/intechopen.77290

exploitation [7]. Therefore, if we add an additional asset in the accountancy of minerals, namely the replacement costs in a "down the rainbow" view, we will consider the scarcity factor. This way, depleting high-grade ores is penalized since the exergy required to replace them with current technology would be very large. It should be noticed, that this point of view goes in the opposite direction of current practices: the larger the ore grade, the more cost-effective is its exploitation since production costs are much lower. However, this criterion enhances the depletion of high-grade ores since the future scarcity is ignored. Both aspects, replacement costs and conventional processing costs give a broader and more equilibrated vision of "sustainability" in the mining sector and closes the cycle of materials, covering the OTR and DTR paths.

Note also that these two indicators do not need speculations about the remaining mineral capital on Earth. No matter how much mineral remains to be exploited and the level of depletion, what we can assess is the "avoided" cost humanity had for exploiting the mine instead of doing it in the bare rock. These indicators also provide the exhaustion and the speed of exhaustion of all minerals we are extracting today in the planet. It is done in fully additive energy units instead of money units. Besides of that, the exergy replacement cost can easily be converted into money units since the price of each actual operation is available. That said, converting the replacement exergy into money units is senseless since the reversible processes to convert the bare rock into the mineral as in the mine are purely theoretical.

4.1. Thanatia: a model of the dispersed Earth

Exergy measures the quality of systems with respect to a reference. When the system under analysis reaches the conditions of the reference, then it loses completely its distinction, i.e., its exergy [8, 9]. Therefore, the more separated the system from the reference, the more exergy it has. In the case of a mineral deposit, the more concentrated the mine, the more "quality" it has. Therefore, which should be the reference for the assessment of the mineral capital? In the end, when a mine has been completely depleted, its concentration would have theoretically reached that of the average crust. Hence, it is clear that our reference should be an Earth, where all minerals have been depleted, and all fossil fuels have been burnt. That model of Earth, that we named the "Crepuscular Planet" or "Thanatia" (from the Greek Thanatos, death), was developed by the authors and is extensively described in [10, 11]. Basically, it consists of a degraded atmosphere, hydrosphere, and continental crust. The atmosphere of Thanatia is obtained assuming that all conventional fossil fuels are burnt and all CO_2 is released. As a result, it has a CO_2 concentration of 683 ppm and a mean surface temperature of 17°C. The degraded hydrosphere was assumed to have the current chemical composition of seawater at 17°C (poles and glaciers melted). And for the upper continental crust, we proposed a model of bare rock defined by the composition and concentration of 324 substances in which 292 are minerals, and the remaining are mainly diadochic elements included in the crystal structure of other minerals.

As explained in [11], Thanatia should not be mixed up with the reference environment (RE), such as the one proposed by Szargut [12] for the calculation of chemical substances. In fact, both concepts constitute a reference for calculating exergies, but there are determinant differences. The assumption of assuming one substance per chemical element, which is common for all global RE, radically invalidates the use of the RE as a substitute of the model of crepuscular planet. We need a model of dispersed Earth where all commonly found substances appear.

The former only provides the chemical composition of the environment. The concentration factor is very important for assessing the mineral capital on Earth since as we explained before, the exergy of a mineral deposit increases exponentially with its ore grade. The greater the difference between the concentration of the mineral in the mine and in the dispersed crust, the more exergy (the greater value) will have the deposit. Hence, not only the composition of the "dead environment" is required, but also the concentration at which the substances are found in it.

That said it should be stated that conventional REs are still needed and constitute a tool for calculating chemical exergies. In fact, Thanatia has chemical exergy with respect to a defined RE. And as Szargut's approach is the most internationally recognized, we have adopted it with some improvements.

4.2. Methodology

Exergy measures the minimum (reversible) work required to extract and concentrate the materials from a RE to the conditions found in nature. The approach named Exergoecology [13]. allows to assess natural resources taking advantage of both thermodynamics and thermoeconomics principles. When minerals are extracted from Earth through the separation of it from the ore by means of different process like mining, beneficiation, roasting, smelting, refining, etc., the exergy associated to the mineral increases but this process requires the consumption of fuel, and other materials, whose exergy is destroyed after use.

The concentration exergy b_c, represents the minimum amount of energy associated with the concentration of a substance from an ideal mixture of two components and is given by the following expression:

$$b_c = -\overline{R}T_0\left[\ln(x_i) + \frac{(1-x_i)}{x_i}\ln(1-x_i)\right] \tag{1}$$

where R is the universal gas constant (8.314 kJ/kmol K), T_0 is the temperature of the reference environment (298.15 K), and x_i is the concentration of the substance i. The exergy accounting of mineral resources implies to know the ore grade, which is the average mineral concentration in a mine x_m as well as the average concentration in the Earth's crust (in Thanatia) x_c. The value of x in Eq. (1) is replaced by x_c or x_m to obtain their respective exergies, whilst the difference between them represents the minimum energy (exergy) required to form the mineral from the concentration in the Earth's crust to the concentration in the mineral deposits.

This approach includes the irreversibility factor through the so-called exergy cost, which is defined as the total exergy required concentrating the mineral resources from the Thanatia with prevailing technologies.

The concentration of a mineral from the ore grade of the deposit to its commercial grade implies energy consumption completely different to that of concentrating the mineral from the dispersed state of Thanatia to the mine. The exergy cost of concentrating a mineral would require k_c times the minimum concentration exergy (Eq. (2)).

$$b^*_{ci} = k_c \cdot b_{ci} \tag{2}$$

http://dx.doi.org/10.5772/intechopen.77290

where k_c is a constant called unit exergy cost and is the ratio between the real energy required for the real process to concentrate the mineral from the ore grade x_m to the refining grade x_r and the minimum thermodynamic exergy required to accomplish the same process (Eq. (3)).

$$k_c = \frac{E_{realprocess}}{\Delta b_{mineral\,x_m \to x_r}} \tag{3}$$

Since the energy required for mining is a function of the ore grade of the mine and the technology used, so it is the unit exergy cost. Then, the exergy cost of concentrating a mineral from the Earth's crust is named exergy replacement cost. Note that fossil fuels are different from non-energy minerals in that once burnt, they cannot be replaced because they have been converted mainly into CO_2 and water. The exergy of fossil fuels is commonly accounted for through their High Heating Value (HHV). Pollutant abatement costs in exergy terms can be substracted from the HHV to account for the clean fossil capital on Earth [14].

4.3. Case studies

Table 1 show results from [16] when the methodology is applied to several commodities. It has been assumed a world average ore grade for each metal shown. As can be seen, the exergy replacement costs are not insignificant and have at least the same order of magnitude than conventional mining and metallurgical costs. This way, we can give numbers to the whole cycle of materials: the over the rainbow path, through conventional mining and metallurgical costs, and the down the rainbow path, through the exergy replacement costs.

4.4. Summary of the theory

Physical measures fall within science, and a few of them transcend and become socially relevant. To cross this boundary, both the object of measurement and the units must have a set of consistent properties that facilitate understandability, universality, and measurement capability of social evolution.

In this context, the object of measurement is our global depletion of mineral resources at the planetary level. And we postulate exergy as its measurement unit. For doing that we need a theory supporting how this can be accomplished. The fundamentals of such a theory are:

(1) There can be postulated an imaginary degraded Earth planet in which the crust, the hydrosphere, and the atmosphere reached a maximum level of dissipation of all its materials compatible with the Sun´s energy and the internal heat of the Earth. We name this planet Thanatia and is a crepuscular Earth where no mines exist and thus all materials are dispersed and have the composition of bare rocks commonly found in the crust; the hydrosphere contains no poles and is nearly composed by standard salt water; and the atmosphere reached the state predicted by long-term climate change models, with a high concentration of greenhouse gases coming from the complete combustion of fossil fuels. Thanatia is by no means in an equilibrium state, but in a conceivable geological steady state that can be characterized by a reasonable short set of physicochemical parameters. Thanatia is postulated as the ultimate state of the present evolutionary man-induced degradation path of the Earth.

(2) Exergy measures the minimum work needed to convert a thermodynamic state of a system characterized by a constant mass of constituent chemical elements into any other state of that system. Therefore, any state of the planet between the present one and Thanatia can be measured with the knowledge of the physicochemical parameters characterizing the two states. This general definition allows calculating the exergy distance between any two states of any specific mine, no matter what its chemical composition is likely to be. The same occurs when the mineral is converted into a raw material, smelted, refined, manufactured, transported, used, recycled, disposed of in a landfill, and/or dispersed.

(3) Once any two states of the system are characterized, it is possible to calculate the current exergy cost we need to invest with prevailing technologies to reach a final state from an initial one. As our technology is far from being reversible, exergy cost and minimum exergy differ in many cases in several orders of magnitude. History tells us that mining and chemical technologies have changed rather slowly over decades and hence, the exergy costs can be assumed to be constant over a not too short period of time (for some cases over decades). Exergy may be a better indicator for pure scientific purposes. In turn, exergy cost is prone for social interpretations because even if it depends on the state of technology, it is closer to societal perception of value. Both indicators are equally valid on a thermodynamic basis.

(4) We postulate that each chemical element must have its own cycle either naturally powered by direct or indirect Sun´s energy, or geologically powered. Man-made technology can accelerate or decelerate these cycles. Thus metallic elements can be viewed to be somewhere in the geosphere or in the technosphere. One element in mine has not initiated its cycle. Once it is mined, the cycle starts. The more mineral is mined, the larger its cycle. And the shorter the residence time in the technosphere is, the greater it's dissipation. Recovering what was dispersed would require significant amounts of exergy and ingenuity that makes in many cases almost impossible closing the cycle. However, humanity will need to recover more and more elements from bare rock because of its profligate use of previously mined ones. Many rare earths and scarce elements are already obtained from nearly bare rocks. Technology exists accordingly.

(5) Under this light, we propose measuring depletion of a given mineral as the exergy cost needed to close the cycle between the compositions of the constituents in the Thanatia´s dispersed state, and the mineral in the mine at its present state. In addition, its exergy is also a complementary measure of this depletion. We named these parameters exergy replacement cost and replacement exergy, respectively. The overall process from mining to dispersion and dissipation is the well known cradle-to-grave process. This is the part everybody sees, that is why we name it as the "over the rainbow" part. However, there is an imaginary part, "down the rainbow" or grave-to-cradle approach, which can aptly explain and measure how much depletion is going on with all man activities. We have seen that all the attempts to measuring depletion "over the rainbow," either in monetary or in physical terms, collide with the impossibility to put an objective value to physical scarcity. The depletion of the mineral capital on Earth must be measured on a grave-to-cradle basis.

http://dx.doi.org/10.5772/intechopen.77290

Values in GJ/ton of metal if not specified	DTR path Exergy replacement costs, GJ/ton	OTR path Mining and metallurgical costs, GJ/ton
Aluminium-Bauxite (Gibbsite)	627	54
Antimony (Stibnite)	474	13
Arsenic (Arsenopyrite)	400	28
Barite	38	1
Beryllium (Beryl)	253	457
Bismuth (Bismuthinite)	489	56
Cadmium (Greenockite)	5898	542
Cerium (Monazite)	97	523
Chromium (Chromite)	5	36
Cobalt (Linnaeite)	10,872	138
Copper (Chalcopyrite)	292	57
Fluorite	183	1
Gadolinium-Monazite	478	3607
Gallium (in Bauxite)	144,828	610,000
Germanium (in Zinc)	23,749	498
Gold	553,250	110,057
Graphite	20	1
Gypsum	15	0
Hafnium	21,814	11,183
Indium (in Zinc)	360,598	3320
Iron ore (Hematite)	18	14
Lanthanum-Monazite	39	297
Lead (Galena)	37	4
Lime	3	6
Lithium (Spodumene)	546	433
Magnesite (from ocean)	136	447
Manganese (Pyrolusite)	16	58
Mercury (Cinnabar)	28,298	409
Molybdenum (Molybdenite)	908	148
Neodymium-Monazite	78	592
Nickel (sulphides) Pentlandite	761	115
Nickel (laterites) Garnierite	167	414
Niobium (ferrocolumbite)	4422	360
Palladium	8,983,377	583,333
Phosphate rock (Apatite)	0.35	5

Values in GJ/ton of metal if not specified	DTR path Exergy replacement costs, GJ/ton	OTR path Mining and metallurgical costs, GJ/ton
PGM (average value for all PGM)	2,695,013	175,000
Platinum	4,491,688	291,667
Potassium (Sylvite)	665	2
Praseodymium-Monazite	577	296
REE (Bastnaesite)	348	384
Rhenium	102,931	156
Silicon (Quartz)	1	77
Silver (Argentite)	7371	1566
Sodium (Halite)	17	41
Strontium	4.2	72
Tantalum (Tantalite)	482,828	3091
Tellurium-Tetradymite	2,235,699	589,405
Tin (Cassiterite)	426	27
Titanium (Ilmenite)	5	135
Titanium (Rutile)	9	258
Uranium (Uraninite)	901	189
Vanadium	1055	517
Wolfram (Scheelite)	7429	594
Yttrium-Monazite	159	1198
Zinc (Sphalerite)	1627	56
Zirconium (Zircon)	654	1372

Updated from Valero and Valero (2015); [15].

Table 1. Total exergy costs of selected metals: the OTR and DTR paths.

5. Do exergy measures accomplish the standards for a good environmental indicator?

With exergy replacement cost we cannot measure the progress to sustainability but the progress to depletion, ultimate to Thanatia. It can be like a watch measure to death. We can decelerate death, but we cannot avoid it. Nevertheless, it can be a good policy guide since it can quantify the annual depletion of the mineral capital and explain crystal clear, what are the needed measures to stop it or at least to slow it. The only question is to prove that the indicator undertakes the requirements for a good one.

The Organisation for Economic Co-operation and Development (OECD) [17, 18] proposed a set of criteria for having a good environmental indicator: policy relevance, analytical soundness, and measurability.

http://dx.doi.org/10.5772/intechopen.77290

Concerning policy relevance, a good indicator must be: (a) easy to interpret, (b) show trends over time, (c) be responsive to changes in underlying conditions, and (d) have a threshold or reference value against, which conditions can be measured.

Exergy as the available energy is easy to interpret since it is what laypeople call energy. As a matter of fact, we pay exergy not energy. The exergy replacement cost and the exergy cost indicators can show either aggregated or disaggregated trends over time just being responsive to any kind of variation in amounts of extraction, improvements in processes efficiency, substitution, recycling, and whatever changes in the element cycle. Finally, Thanatia as a threshold is the best provider of reference values to which evolutions on depletion can be measured. Therefore, our indicators are policy relevant according to OECD.

Concerning analytical soundness, indicators should be well supported in technical and scientific terms. It is obvious that exergy indicators are well based on the second law of thermodynamics.

Concerning measurability, indicators should be: (a) calculated from data that are readily available or available at reasonable cost, (b) data should be documented and of known quality, and (c) data and indicators should be updated at regular intervals.

The data for calculating exergy replacement costs must come from data provided from the physical SEEA tables. Assets providing amounts of extracted material, composition, ore grades, amounts of processed, smelted, refined chemicals, amounts of recycled material with its composition, etc., available in the PSU tables are what exergy costs need for their calculations. The data obtained for exergy replacement costs will be as reliable as the data provided by SEE accounts. And the calculations required are easily available with adequate computer programs. International agreements could be reached in order to update both data and indicators as well as improve interpretations and act accordingly. As exergy is an additive property, it has the capability of integrating and aggregating a large variety of causes of variation including how substitution, recycling, and nanotechnologies positively improve our global management of the mineral capital. Conversely, each country, company or mine could use the exergy replacement cost to account for the attained depletion level. And this cost can easily be converted into money units just by multiplying it by some previously agreed energy price. Money accounts are useful at the micro level from companies to countries, but at a global scale and throughout time, exergy accounts may give a clearer picture far removed from economic vagaries.

Finally, the proposed indicators are complementary with others, especially with cradle-to-grave indicators that close the cycles of elements. All together could provide an overall measure of "unsustainability" and its yearly variation, which could be used as a policy lever.

6. Concluding remarks: from SEEA to a global system of environmental-thermo-economic accounts

The depletion of a mineral should not be anymore the difference between its world price and its economic cost of production as economists propose. On the contrary, it should be assessed as the loss of reserves quantified through its replacement cost with prevailing technologies, from the bare rock to the ore grade conditions of the mine. This depletion indicator can be used for all fossil fuels, and minerals no matter their chemical composition and concentration. Fossil fuels must be replaced with renewable energy sources and need to be accounted for such progress. In the same way, stopping depletion of metals will largely come from techniques such as designing for recyclability, reducing the number of alloys used, avoiding the design of monstrous hybrids, designing for disassembly, symbiosing industrial complexes, increasing the efficiency of smelters to avoid metal losses in slags, increasing the throughput of scrap, etc., (see [19, 20]). All these techniques decrease depletion and must be accounted for too.

The idea of replacement, restoration, remediation or repair exergy could easily be extended to indicate the depletion of many other non-renewable resources of biogeological origin like the loss of forests, landscapes, fertile soil, subsoil waters, fisheries, climate change, etc. The amount of work needed to restore what was degraded should be accounted for, even if it will hardly be restored. It is like a debit account for future generations. Each time we learn how to accomplish replacements or recycling or how to live with less, is like slowing the time machine toward Thanatia.

If "prevailing technologies" are a reflection of embodied knowledge, we will see to what extent they decrease our debt with future generations. Nevertheless, it is not clear that any new technology that directly or indirectly improves efficiency in production processes decrease our debt. The rebound effect goes always in the opposite direction; the more efficient we are the more consumption is promoted (see, for instance, [21]).

Valuing our technological improvements is as important as conservation of resources. Conservation is something else than repair, restoration, or replacement. It requires a change in our lifestyle through education. Education is an indispensable tool for technological innovation and conservation. And it is not clear yet, which of both are more important at any historical moment in man´s life on the planet. Conservation and technological improvement can be accounted for with the proposed theory. Consequently, the second law of thermodynamics ought to be placed at the core of economists' literacy.

If replacement can be calculated and registered for almost any action of man on the planet, we need an international framework to provide concepts, definitions, classifications, accounting rules and standard tables for all countries. The System of Environmental-Economic Accounts (SEEA) of the United Nations may well provide such statistical framework. As explained previously, the System of National Accounts (SNA) is an established system for producing internationally comparable economic statistics, which imposes the organization and standardization of domestic accounts. It is widely accepted and established worldwide. Bureaus of statistical office (BSO) for data recovering and economic accounting exist in almost any country. Companies and countries report economic and physical data following the established accounting procedure, and BSOs integrate them. It is a huge infrastructure. From households to companies and to countries, these accounts are presented in money values. SEEA follows the accounting structure of the SNA thus facilitating the integration of environmental statistics with economic accounts. Thus, each national BSO needs to take the responsibility for the environmental data recovery and environmental-economic accounting too. However, these offices are mainly composed by economic statisticians, which are used to convert their assets into money values. When describing the physical tables needed for SEEA, we have seen

http://dx.doi.org/10.5772/intechopen.77290

that the information recovered is rather poor since tons of materials are not sensitive enough for qualifying most of the physical phenomena. Therefore, at the countries level, both monetary accounts and physical accounts are concurrently needed. Monetization runs well from households to companies. At the countries level the money yardstick is proved insufficient for economic-environmental accounts, and at the aggregated global level accounts, money losses weight in favor of physical accounts. To see the planet´s evolution, monetary accounting is not only insufficient but inappropriate. The aggregation level of accounting determines the numéraire to be used in the accounts.

We propose "replacement" as the keyword for re-producing the planetary global accounts, from households to the whole planet in a comprehensive way. Using the exergy cost measured in international. units as a numéraire. The cost of replacement of non-renewable resources and the cost of restoring deteriorated renewable resources may be used just to account how much effort we should need to close the natural and man-made cycles. Some efforts will be done as we pay our debt, but many others will remain as a debt to future generations. Future generations will need to know this. As the former Deputy Secretary-General of OECD, Ásgeirsdóttir [22] said "the luxuries of one generation are often the needs of the next," and "We need to achieve more sustainable consumption and production patterns, to increasingly decouple environmental pressure from economic growth, to ensure sustainable management of natural resources, and to work together in partnership to reduce poverty." This is in effect, achieving UN Sustainable Development Goal No. 12. For achieving it, SEEA must be the starting point and its framework. SEEA would need a step forward to convert them into a SETEA. A major intellectual effort needs to be done from the concepts stated here. At the end, the real overall accounting unit will be the residence time of the human species on the planet.

Acknowledgements

This chapter has been financed by the TRIDENTE project from the Spanish Ministry of Industry and Science.

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