GLOBAL EXERGY ACCOUNTING OF NATURAL RESOURCES

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Keywords: Energy, exergy, environment, exergy replacement cost, exergy abatement cost, renewable, energy resources, reserves, mineral capital, water, fuel, analysis, pollution

Contents

Summary

This chapter presents a methodology for a systematic and rigorous answer to the question: what is the mineral capital on earth? The second law of thermodynamics is used to answer this question and, thus, to evaluate the physical value of the natural mineral capital, the world's renewable water resources and Antarctica and Greenland ice sheets. This involves the *Exergy Replacement Cost*, defined as the energy required by the best available technologies to return a resource to the same conditions as it was delivered by the ecosystem. In the case of fossil fuels, a new concept called *Exergy Abatement Cost* is proposed as a physical way of measuring the exergy cost of the best available technology for avoiding the environmental externalities associated with the use of fossil fuels. A *clean ton* of fossil fuel is defined as the difference between its exergy and its actual exergy abatement cost. Energy reserves can then be expressed in

terms of clean tonnes of oil equivalent, *ctoe*, instead of the conventional measure expressed as toe.

1. Introduction

An analysis of the natural capital of the earth can tell us our current state of affairs with the planet, i.e. how much we owe and how much we have to give back to nature. This information is critical for responsible management of natural capital. Understanding that this capital is finite and measurable will help create a new economy that will integrate sound management practices with our desire to acquire and consume more things since all of us have a right to personal and social development. This accounting should consider fossil fuels and all minerals and materials including air and water. Resources are not objects we can put in a savings account, since each time we use them we damage nature. We must, therefore, discount the effect of environmental impact of natural resource use.

A rational accounting also demands that everything be in the same units, which makes the task more complicated. They cannot be monetary units since we do not know the long-term value or purchasing power of any currency. The most obvious and universal unit is mass, which can be estimated in tonnes for all mineral resources. But this has several methodological complications. On the one hand, there is the diversity of the minerals (we cannot mix apples and pears) and the lack of information about properties such as resource quality and relative concentration. The amount of tonnes of a specific metal (e.g., copper) does not provide information about the type of mineral, its places of availability, its distribution throughout the planet, countries, regions, or within different layers of the same mine.

Several authors led by Costanza, have already made an economic evaluation of some ecosystem functions and have determined a value range with an average that exceeds national GDPs by billions of dollars. However, ecosystems are only a part of the earth that is offered for free, and, thus, minerals should also be included in an accounting methodology. How do we measure the capital mineral of the earth?

One solution is to use the second law of thermodynamics and the concept of *exergy*. Exergy is the maximum useable energy that can be obtained from a material with respect to a predetermined reference environment. For example, not all of the energy in a heat flow can be used to move a mass or make electricity. The higher the temperature with respect to the environment, the easier it will be to convert into more usable forms of energy. The same concept can be applied to materials. Their composition and concentration with respect to a reference system of completely degraded (oxidized) and dispersed materials have a thermodynamic minimum of useful energy (equivalent). This is the definition of minimum energy with respect to the equivalent exergy of the material. We can imagine a completely degraded and dispersed earth where all the minerals have undergone chemical reaction to reach their most inert conditions and are completely dispersed: a homogeneous crust with all elements are present at an average concentration and evenly mixed and where all water is a solution of all soluble salts at their lowest chemical reactivity uniformly distributed throughout the crust. Under these hypothetical conditions, the crust has zero exergy. This means that we would always need to use work to extract a certain metal or fuel or to gather and/or desalt water. From this point of view, any mineral with a relatively higher concentration in this dead state environment, would have a natural exergy that can be evaluated and counted as mineral capital. Once the dead reference state environment is chosen, exergy equivalence can be used as a universal measure that does not depend on social contingencies and can be obtained in the same physical units (e.g., kWh) for all substances, independently of whether they are minerals, rocks, fossil fuels, water, or air. Since exergy is the minimum work needed for producing something from a given environment, it is indirectly expressed that all the hypothetical producing processes are reversible (i.e. without inefficiencies). For this reason, the exergetic values of different materials are not equally significant.

A better indicator should measure the *real* exergy used to extract a material and not the minimum useful energy or exergy. One alternative would be to use the *exergetic replacement cost* to assess materials. This concept expresses the "*quantity of exergy needed, using the best available technology, to replace a material from its surrounding environment and original composition and concentration before extraction*". However, the definition of the surrounding environment can be quite ambiguous. It is also unclear why we would want to return a mine to its original condition. Nonetheless, the key point is that the exergetic replacement cost can be used as an evaluating and accounting tool. It is based on generalized formulas that allow a simple and reasonable estimation of values based on thermodynamics.

Two problems need to be solved to accomplish this. First, the identification of resources according to quantity, concentration, and location is needed. A resource is the natural concentration of a solid, liquid, or gas in the earth's crust, with specific physical characteristics and quantities that can be exploited. At the same time, resources are normally classified as demonstrated or inferred. The demonstrated ones can be measured or simply indicated. From the point of view of exploitation, only a part of these resources obeys the minimum physical and chemical specifications (including grade, quality, thickness and depth). These resources are base reserves, which are further classified into economic, marginal economic and sub-economic reserves. The probability of undiscovered reserves can range from the hypothetical to the purely speculative, which further complicates the problem. It is predictable that new deposits could be found and the exploitation of previously unprofitable wells will continue to occur if oil prices increase. The end result is an enormous uncertainty in the measurement of the earth's resources, which is quite surprising since our development, progress and future depends on knowing and managing this finite wealth.

The second problem is the accounting methodology. Extracting minerals always requires exergy, while fossil fuels are exploited in order to use their exergy. Although both are measured in the same units, the data associated with the former indicate the amount of exergy saved by finding these minerals in appropriate concentrations and compositions. The exergetic cost of replacement measures something similar to their natural cost. In the case of fossil fuels, we are interested in exergy which has a biological origin. Replenishing a fossil fuel makes no sense so they are not assessed by their replacement cost but by their exergy content. Their combustion damages the environment. We should and can avoid emissions of carbon dioxide and nitrogen oxides of sulfur and particulate material. Apart from this necessary investment, we should also use the necessary energy and materials (exergy) to capture harmful gases from combustion. For this reason, any thermal electric plant should discount the exergy used to clean emissions from its total exergy production. The net exergy produced is then its exergy minus the exergy needed to clean the gases using the most advanced technology.

Thus, our assessment is an overestimate because we do not use cleaning technologies in cars, thermoelectric plants, or direct combustion to avoid contaminating emissions. Nor do we fix CO_2 or spend money and energy on planting trees. We should not use fossil fuels if we cannot alleviate their use or eliminate their harmful effects on the environment, which should be done at the beginning of the process since doing it after dispersion implies even higher costs.

2. The Exergy Replacement Cost

As mentioned above, a new concept called exergetic replacement cost is proposed as a physical way of evaluating the earth's natural wealth: mineral, renewable water and fossil fuel resources. The developed model has been applied to the reserves and production of these resources and a first estimate of their physical value have been made.

2.1 The Exergy Replacement Cost of the Natural Mineral Capital

The thermodynamic value of a mineral is defined by its physical and chemical conditions (scarcity and composition), which differentiate it from the conditions of the reference environment (a hypothetically degraded earth at zero exergy level where all materials have reacted, dispersed and mixed). These same degrading processes make them useful to humans. That is, human use of the materials implies subjecting them to processes that degrade exergy content. According to the second law of thermodynamics, the minimum amount of energy (exergy) needed to concentrate a mineral from the conditions in the reference environment to the conditions in a mine is given by the following expression:

$$b_c = -RT_n\left\{\ln x_1 + \frac{(1-x_1)}{x_1}\ln(1-x_1)\right\} \qquad (1)$$

where
b_c = Concentration exergy (J/mol)
R = Gas constant (8.3147 J/mol K)
T_n = Standard normal temperature (298.15 K)
x_1 = Resource concentration (N_1/N) (dimensionless); N_1: Number of molecules from a certain resource in a mineral deposit; N: Total number of molecules in the mineral deposit (mol)

Thus, the lower the concentration, the greater the exergy needed to extract the resource. As opposed to fossil fuels, mineral deposits are not commonly valued for their chemical exergy. Instead, their concentration in the mine saves exergy when they are extracted, as compared to the rest of the earth's crust where their concentration is normally hundreds of times lower.

In addition, the thermodynamic value of a mineral is not only physical. Nature also has had to use some chemical exergy to make mineral compounds from which we extract the mineral element in the required purity using metallurgical processes. The chemical exergy can be calculated using the following expression:

$$b_{\mathrm{ch}} = \sum \nu_k b^0_{\mathrm{ch\ el}-k} + \Delta G_{\mathrm{mineral}} \qquad (2)$$

where
b_{ch}= *C*hemical exergy (J/mol)
ν_k = Number of molecules of the additional element in the molecule of the reference species (dimensionless)
$b_{\mathrm{chel}\text{-}k}{}^0$ = standard chemical exergy of element k(J/mol)
$\Delta G_{\mathrm{mineral}}$ = Free energy of formation of the mineral (J/mol)

This approach can be added to methods proposed by others who have attempted to establish the use of thermodynamics to assess exergy resources. This ultimate application for assessing global resources has demonstrated that we are now able to develop an objective methodology for establishing an appropriate value for natural wealth. However, previous assessments of exergy requirements which focused on the process “from mine to market” were never able to allocate the value of mineral resources “from a degraded earth to the mine”. This is because the second law concept of a degraded earth as a reference point was lacking.

To begin with, exergy is the minimum energy required to replenish a resource from its most degraded state or, in other words, to remake it from the reference environment via a reversible process. However, the real processes designed by humans are far from the ideal condition of reversibility and the exergy requirements to obtain a resource are always greater than those dictated by the second law. For this reason, we should not evaluate natural resources solely in terms of reversible processes since this would ignore technological limits, which impose more costs from a physical point of view.

Therefore, we must include real physical unit costs in the thermodynamic evaluation of resources. These are defined as the relationship between the exergy invested in the real process of obtaining the resource and the exergy required if the process was reversible. It has a dimensionless value and measures the number of exergy units needed to obtain one unit of exergy of the product. Generally, the exergetic unit cost is tens or even hundreds of times greater than its exergetic content. The real thermodynamic value of a resource is determined by its exergy multiplied by the real physical unit cost of the process to obtain it, as in Eq.(3):

$$k \quad = b_{\mathrm{c}} * k_{\mathrm{c}} + b_{\mathrm{ch}} * k_{\mathrm{ch}} \qquad (3)$$

where
k =Real physical unit cost (dimensionless)

k_c = actual physical unit cost of the concentration process (dimensionless)
k_{ch} = Chemical unit cost of converting the reference species into the mineral (dimensionless)

2.2. The Exergy Replacement Cost of the World's Renewable Water Resources

In the case of water, its thermodynamic value has two basic components; its composition makes it useful for different human and agricultural activities and its potential energy can be used to perform mechanical work and generate electricity. These two conditions should be returned to the water from its more thermodynamically degraded state (the ocean in this case). Some authors have already proposed physical models to determine the thermodynamic value of a river, and to physically and economically calculate water resource values in a country or region. Nevertheless the models may not be very practical since they require a lot of informational inputs.

For this reason, we propose to thermodynamically evaluate the world's renewable water resources using the concept of *Exergy Replacement Cost* (*ExRC*). The first component of this replacement cost of water resources is the exergy needed to return the quality characteristics back to the water and is represented by the desalination exergy which is given by Eq.(4)

$$b_{\mathrm{des}} = \frac{vRT_{\mathrm{H2O}}}{R_c}\frac{x_{\mathrm{1H2O}}}{1-x_{\mathrm{1H2O}}}\ln\left[\frac{1}{1-R_c}\right] \qquad (4)$$

where
b_{des} = Desalination exergy (J/mol)
v = Molar partial volume of the solvent in the solution
T_{H2O} = Absolute temperature of water (K)
R_c = Recuperation ratio (N_0/N_1) (dimensionless). N_1: number of moles of water at the input flow of the desalination plant (mol)
x_{1H2O} = Molar fraction of the salt in water at the input flow of a desalination plant

The second component is the minimum exergy needed to return the resource to its conditions of physical disequilibrium (or potential) with the chosen reference level (the ocean). This exergy can be calculated using the following equation:

$$b_{\mathrm{phys}} = 9.8Qh \qquad (5)$$

where
b_{phys} = Physical exergy (kW)
Q = Volumetric flow of water (m^3/s)
h = Height (m)

2.3 An Assessment of the Earth's Clean Fossil Exergy Capital based on Exergy Abatement Costs

We could replenish fossil fuel exergy by using the same process that provided them: photosynthesis. Unfortunately, the net conversion output does not exceed 0.3 %, which, after considering global conditions, averages to 0.023 %.

The unit physical cost (defined as the ratio of exergy obtained to the invested exergy) of replacing each joule of fossil fuel varies between 300 and 5,000. So, the natural replacement cost of these reserves (814,811 Mtoe – according to the U.S. Department of Energy) amounts to between 244 x 10^6 and 4.07 x 10^9 Mtoe. If the net carbon fixation in terrestrial ecosystems is approximately 2 Gton C/year, the current energy reserves of fossil fuels could be replaced in 320 years (assuming they are 80 % carbon).

Although we are unable to replace fuels, we are spending them 3 or 4 times faster than they can be fixed by photosynthetic processes. This causes significant distortions in global material cycles but the demand is estimated to continue to increase by almost 2 % annually until 2020. In the light of our limited technologies and energy dependence, the least we can do is use these resources cleanly without adverse effects on ecosystems. We propose a new approximation to measure the environmental externality caused by the use of fossil fuels called the *Exergy Abatement Cost* (*ExAC*) defined as "*the quantity of exergy needed to reduce the emissions of a specific contaminant to innocuous levels for the environment, using the best available technology*".

The *ExAC* is a physical and anticipated way to internalize most external environmental effects. It can be used to decrease the exergy contained by any fossil fuel (the exergy needed to decrease its associated emissions), and express its remaining exergetic content as *clean tonnes of oil equivalent*, *ctoe*, instead of the traditional equivalent tonnes of oil, *toe*. The new unit of exergy content *ctoe* represents the fuel exergy that does not represent a risk for the environment.

Clean fossil fuel exergy reserves can be calculated as:

$$CEx_R = R_i * CEx = R_i \left[HHV_i - \sum \left(EF_j * ExAC_j \right) \right] \qquad (6)$$

CEx_R = Clean exergy [The value of the HHV is approximately equal to the fossil fuel exergy] contained in the specific fuel reserves (ctoe)

R_i = Fuel reserves i (t)

CEx = Clean exergy contained in the specific fuel (ctoe)

HHV_i = High heating value of the ith fuel (kJ/t)

EF_j = Emission factor of pollutant j (kg/t) (depends on the fuel type and the technology used to transform the chemical exergy)

$ExACj$ = Exergetic cost of reducing pollutant j (kJ/kg)

Both CEx and CEx_R are expressed in ctoe.

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Biographical Sketches

Antonio Valero, Chair in Thermal Systems at the University of Zaragoza, Spain.

Since 1982, Dr. Valero has been involved in the fundamentals of thermoeconomics relating the idea of irreversibility with that of cost. He has searched the physical roots of the process of cost formation. He has applied thermoeconomics to the optimization, design, diagnostics and operation of conventional and advanced power plants, cogeneration systems, bio-mass plants, sugar factories and dual power and water production plants. Dr. Valero is also involved in the applications of Second Law of Thermodynamics to environmental problems and global resources assessments. Second Law outcomes of the greenhouse effect, Second Law assessment of the Earth's mineral reserves, fresh water and fossil fuels are some of his relevant contributions.

He currently serves as a director of CIRCE, a research institute for Energy Resources and Consumption comprised of 60 researches. Circe is devoted to developing and disseminating the rational use of energy through the integration and extensive use of renewable energies and cost efficient measures.

Dr. Valero received the James Harry Potter Gold Medal (1996) established by the American Society of Mechanical Engineers in recognition of an eminent achievement in the application of the science of thermodynamics in mechanical engineering. He also received three Edward F. Obert Awards for the Best Paper in ASME Advanced Energy Systems.

He is honorary professor of the North China University of Electric Power, China, and several other universities worldwide.

He is the Vice-president of the ISGWES, the International Study Group for Water and Energy Systems, and he holds memberships in the American Association for the Advancement of Sciences, the American Society of Mechanical Engineers and the International Association for Hydrogen Energy, among other distinctions.

Edgar Botero, Mechanical Engineering, Ph. D. in Thermal Systems and Energy Optimization of Zaragoza University (Spain).

He is the director of the Integrated Center for Research Develop of the Pontifical Bolivariana University of Medellín, Colombia. He has worked in the environmental field and has applied the thermodynamic second law to calculate the physical cost of natural resources, using methodologies like life cycle assessment and the exergetic cost developed by Valero et. Al.

He currently develops some projects in Colombia to apply the exergy concept as valuation method of environmental impacts in the life cycle assessment and processes optimization.

He was recognized in 2003 by JCI as outstanding young person in the environmental field. He is member of the ISGWES, the International Study Group for Water and Energy Systems.

Alicia Valero received her degree in Chemical Engineering from University of Zaragoza, Spain, in 2002. In addition to University of Zaragoza, Spain, she studied in the Technical University of Berlin and the "Institute National de Sciences Appliquées" in Toulouse.

She is currently working in the Center of Research for Energy Resources and Consumption (CIRCE), working on energy efficiency and renewable energies.

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