Bio-products: A new way to calculate fossil fuels in the grave to cradle exergy assessment

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Abstract:

The current grave to cradle exergy assessment of natural resources considers that fossil fuels are non-substitutable. Yet, technology allows for the replacement of fossil fuels by bio-products. The key contribution of this paper is to apply the life cycle assessment to fossil fuel bio-equivalents thus tying together the cradle to grave to the grave to cradle approach, which enables comparisons between fuel and non-fuel mineral depletion. The methodology developed gives an improved estimate of the exergy required to replace fossil fuels, not in terms of their composition or origin but with regards to the role they play in society and Nature. The current procedure of using the chemical exergy of fossil fuels to represent the cost of their replacement, sub-estimates the exergy replacement cost twenty-eight fold, on average. This difference in magnitude occurs due to the omission of the exergy bonus that is created when plants concentrate solar energy and convert it into biomass. This forges a paradigm shift towards looking at the function of a mineral, rather than its chemical composition, which has questionable relevance in the sustainable development discourse.

Keywords:

exergy replacement cost; photosynthesis; bioenergy; Thanatia; exergy replacement cost

1. Introduction

The concept of exergy can be explained by the Orwellian idea that whilst all energies are equal, some are more equal than others. This is because energy from heat is not the same as energy from work, even if they both measure one joule. This is because energy from heat does not hold the same
value, or have the same usefulness of that of work. In other words, exergy can be used as an efficiency gauge to state energy’s real value. This concept lends itself well to irreversibility and the practice of using exergy accounting to measure natural resource scarcity, through the use of an appropriate reference baseline. This supports a better understanding, and ultimately can be used to tackle the issue of resource depletion, given that natural resource consumption, by definition, implies the destruction of organised systems and the creation of entropy.

As Carmona and Whiting (2015) state any given mineral will possess exergy, and the higher a mineral’s grade, the more exergy it will have when compared to that same mineral at a lower grade. Once an element is extracted from a mine, that same mine will begin to look more and more like standard bedrock and will experience a significant drop in exergy, which is measured relative to what Valero and Valero (2014) refer to as Thanatia and model in the Crepuscular Earth Model. Thanatia is a commercially dead, theoretical, planet where all commercially viable fuel and non-fuel mineral deposits have been extracted and then burnt or used to meet non-energy societal demands. It is a theoretical baseline, via the exergy replacement cost (ERC), used to measure the sustainability of mineral policy, environmental accounting practices and economic development within a thermo-economic framework.

The exergy cost of reversing the extractive process (i.e. going from standard bedrock concentrations to that found in a natural mineral deposit) can be determined through exergy replacement cost calculations. Such calculations quantitatively evaluate the effort, or energy, needed to re-concentrate extracted mineral wealth via reversible processes or current best available technology (Carmona et al., 2015). Since high grade ore deposits have a greater exergy replacement cost associated with them, the ERC is an objective way of assessing the impact of future consumption, with one universal unit.

The method of calculating exergy replacement costs, as a means to evaluate mineral capital and the thermodynamic cost of closing the material cycle comes under the umbrella of grave to cradle assessments, put forward by Valero and Valero (2013) and discussed at length in Valero and Valero (2014). Whilst it does bear resemblance with aspects of emergy, given that emergy assessments are an alternative thermoeconomic quantitative analysis, that provide a common basis for integrating economic and ecological sciences and which likewise evaluate resources, goods or services in common units (in this case solar emergy), the two are not the same (Amaral et al., 2016. Jamali-Zghal, et al., 2014). This is because Odum’s proposed “6th energy law” relies on transformities, a fundamental method within emergy, and one that losses rigour for minerals (but works well with renewables) when one considers those mineral resources (iron and gold, for example) which are not
currently, and will not be in the future, affected by solar energy quantities (Valero and Valero, 2014).

Returning to the ERC, this approach is useful in that with a reference baseline, one can determine the exergy “bounty” that humanity freely enjoys when the extractive industry finds and can exploit naturally concentrated minerals from deposits, when the alternative would be the highly economic cost and energy intensive process of obtaining and concentrating the very same minerals, as completely dispersed elements within the Earth’s crust. One key characteristic of this approach is that, currently, it is only used for non-fuel minerals because according to Valero and Valero (2014, p280):

*It makes no sense to apply exergy replacement costs to fossil fuels, due to the impossibility of reproducing the photosynthetic process that once created the resource.*

This has led the “Zaragoza school” to either ignore fuels or calculate their exergy replacement cost using chemical exergy, through the high heating value (Valero et al 2014; Valero et al 2015; Calvo et al 2015; 2016; Carmona et al 2015). We, the authors, whilst in concordance with the application of exergy replacement costs as a means measure the sustainability of extraction, believe, that the photosynthetic processes that created fossil fuels can be reproduced. The problem is that the geological processes that transformed the organic material into fossil fossils cannot be reproduced, within a human lifetime. Furthermore, and the probable reason why Valero and Valero (2014), amongst others, ignore ERC for fossil fuels is that it is currently impossible, using best available technology, to reverse the combustion process, as indicated in Figure 1. In other words, society cannot convert carbon dioxide back into its fossil fuel source. And, as Valero and Botero (2002) state, the only way to replenish fossil fuel energy is by using the same process that provided them; photosynthesis.

This present paper looks at the role of photosynthesis and the creation of bioproducts, as a means to calculate the ERC of fossil fuels (Figure 1). In doing so, it also creates a paradigm shift towards looking at the function of a mineral, rather than its chemical composition, which has questionable relevance in a sustainable development discourse anyway. Since the publication of Valero and Valero (2014), as can be seen by our reference section, there has been increasing evidence to demonstrate that current technology can and has recuperated the functions of fossil fuels through biological equivalents, and in some cases on a commercial scale.
2. Replacing Fossil Fuel functions

The substitution of fossil fuels with biomass, biofuels, biogas and biopolymers is becoming an increasingly promising option for power technologies and synthetic fuel production. Notably they are a renewable and a relatively clean feedstock for producing modern energy carriers, such as electricity and transportation fuels (Piekarczyk et al. 2013). Furthermore, energy crops can recuperate, through photosynthetic processes, in their early life stages, the carbon dioxide released upon the burning of fossil fuels to create fuel alternatives within a short enough timeframe for the resource to be considered renewable. Given that bio alternatives are derived from plant or microbial sources, which use carbon dioxide as their feedstock in photosynthesis, an additional benefit is that the carbon cycle can be closed.

Biomass can replace coal and biogas can replace natural gas. Coal in commercial pig iron production has been successfully substituted for charcoal in smaller furnaces (Fick et al. 2014) whilst the coal/coke employed in basic oxygen steelmaking has been swapped in pilot tests (Jahanshahi et al. 2013). Multiple trials using biochar, a type of charcoal yielded in pyrolysis, have provided positive results for medium sized recycled steel production via an electric arc furnace (Reichel, 2014). Such furnaces account for half of the European Union’s steel production. Biogas produced in conjunction with biochar has not been tested due to storage difficulties. Model simulations do imply however that the natural gas used in EAFs could be replaced by biogas (European Commission, 2014).

Biofuels can be exploited instead of oil, whereby the gasoline fraction is substituted for bioethanol, whilst diesel can be switched for biodiesel. For aviation fuel alternatives the case is less clear cut. There have been various successful tests, mostly with blends, although also with neat, that show that one can replace jet fuel with biodiesel obtained from algae, and non-edible energy crops such...
as camelina and jatropha (Hari et al, 2015). The commercial aircraft carrier Lufthansa, for example operated, in 2011, 1,187 domestic flights between Frankfurt and Hamburg using a 50/50 blend of regular fuel and bio-kerosene, derived from jatropha, in one of the plane's two engines, before tests were stopped due to a lack of biofuel supplies (Deutsche Welle, 2012). Whilst, certain technical compatibility issues, agricultural and policy/legal complications slow the technological development and industrial acceptance required for biofuel to completely replace kerosene commercially (Gegg et al 2014; Kick et al, 2012), given that it is now technically possible, means that in a world approaching a situation where energy demand can no longer be meet by viable fossil fuel deposits, there will be a greater incentive to solve these existing issues, and hence the inclusion of kerosene substitutes (biodiesel, waste cooking oil) in the ERC calculations. In any case, and in all fuel substitutions presented in this paper, the neat concentration is assumed i.e. B100 or E100, given that all commercially viable oil deposits would have presumably already been extracted and burnt or used in non-energy goods, such as plastics.

Plastics, currently derived from either gas or oil, could be produced through the use of plant or microbial produced biopolymers. Although wastes may also be used to create bio crude, via the thermal depolymerisation of waste plastics or the pyrolysis of tyres, these technologies were not included in the calculations. Such possibilities are still very much in the experimental stage, as indicated by review papers such as Osayi et al (2014). Any assumptions, as to their widespread use into the future are weak at best. In addition, the recycling process is not a renewable one and waste is always produced, making 100 percent conversion rates impossible. Consequently, and even if all the input material (plastic or tyres) could be converted into bio crude, for instance, there will always be, as long as demand continues to grow, a need for fresh non-recyclate. Biological sources are the obvious exception to this hence the inclusion of sewage sludge, as a means to create biogas and waste cooking oil, used to replace aviation fuel in the calculations (Mash, 2008).

Bitumen replacement with biochar is deemed possible and has been researched. Zhao et al (2014) studied the physio-chemical properties of biochar used as an asphalt cement modifier. Kolokolova (2013) looked at pyrolysis optimisation for the eventual development of a commercial bio-bitumen. The most practical example, to date, is that of low net traffic Icelandic roads. In 2006 the Icelandic Road Administration started to promote and use bio-oils such as fatty acid methyl ester from rapeseed oil and ethyl ester from fish oil for binder modification in road surface dressing. The main problems have resulted from a lack of standards/guidelines for the bio-oil modification of bitumen, which can be addressed (Guarin et al 2016).
3. Fundamental Theory

3.1. Exergy cost and Exergy Replacement Cost

The exergy cost is calculated as the quantity of exergy necessary to obtain something. To correctly evaluate exergy costs within a system, a clearly defined energy and material inventory is required, as are well stated boundaries, operations, processes, final products, sub-products and wastes. The value of unit exergy cost, \( \kappa \), correlates to efficiency, meaning that it can decrease, if operational efficiency improves.

\[
\kappa_j = \frac{\sum_i E_{xij}}{P_j} \quad (1)
\]

Equation 1 can be used to determine the unit exergy cost of any resource, whether it is renewable or not, a fuel or non-fuel, where, \( E_{xij} \) is the exergy consumption of natural resource, \( i \), required to generate product, \( j \). \( P_j \) is the exergy of the system’s output. The latter refers to the amount of mass or exergy of a given resource (e.g. the chemical exergy of a fuel, which is similar to its HHV).

In addition, ERC can be determined according to Equation 2, where \( \kappa \) is a dimensionless variable that represents the unit exergy cost, defined as the ratio between the resources (e.g. energy or exergy) invested in the real obtaining process, and the minimum theoretical amount of resources required if the process from the grave to the final product was reversible. \( B \) represents the exergy require to create (chemical), concentrate or comminute a given amount of any resource, depending on its nature. For non-fuel minerals, \( B \) normally refers to the difference between the concentration exergies of a mineral deposit and that of average concentration in the Earth’s crust, while for fossil fuels the value of their chemical exergy is more suitable.

\[
ERC_j = \sum_j^n \kappa_j \cdot B_j \quad (2)
\]

3.2. Cumulative Exergy Consumption and its variants

The aforementioned concept of exergy consumption (\( E_{xij} \)) can be expanded through the concept of cumulative exergy consumption (CExC), to account for the totality of exergy cost. This method, and its various forms below, is the most commonly used approach in exergy cost analysis because it allows for a comprehensive global view of exergy flows through a system.

The CExC is the sum of exergy for all stages within a production process. The CExC application and use will depend on a study’s scope. Originally proposed by Szargut (2005a), it is the origin of various related evaluations including:

- Cumulative Exergy Demand (CExD): This is utilised to differentiate the exergy analysis of a system with that of a specific process which forms part of that same system. Examples for
biofuels include Liao et al. (2011), Liao and Heijungs (2015) and Martin and Parsapour (2012). It has also been incorporated into the LCA software SimaPro, where the exergy referred to is that of the primary resources that enter the system (Bosh et al. 2007).

- **Cumulative Exergy Extracted from the Natural Environment (CEENE):** This method uses CExD to also include aspects relating to land use and atmosphere (Dewulf et al. 2007).
- **Cumulative Net Exergy (CNEx):** This is where product exergy is discounted from the CExD, e.g. HHV of fuels. The method has been applied to biofuels in Berthiaume et al. (2001) and Patzek (2004).
- **Thermo-Ecological Cost (TEC):** This is used only to evaluate the consumption of non-renewable resources and the avoidance of the release of substances harmful to the environment (Szargut 2005b, Stanek 2006). When the TEC is applied throughout the entirety of a product’s or service’s life cycle it is referred to as the Thermo Ecological Cost Life Cycle (LC-TEC). It has been applied to biofuels in Piekarczyk et al. (2013).
- **Exergy Cost:** According to Lozano and Valero (1993), the exergy cost refers to the exergy necessary to produce a product, from fuel. To analyse the interactions between various processes that constitute a system one can make use of input-output analysis and apply it to the exergy cost theory. The result is a fuel-product matrix that facilitates irreversibility allocation. Font de Mora et al (2012; 2015) used this method for their research into biofuels.
- **Other CExC:** some researchers use the term in a more generic way. Talens Peiró et al (2010) and Sorguven and Ozilgen (2010) are two examples of where CExC methods were applied to biofuels. They used it to identify the scope of their respective analysed systems, and did so by declaring and defining clearly entry and exit flows and technological considerations (e.g. pollution treatments).

### 4. Method

A means to calculate the ERC of fossil fuels can be undertaken by applying cumulative exergy consumption, through the use of the life cycle assessment, to the life stages of fossil fuel bio-equivalents, thus tying together the grave to cradle and the cradle to grave approach. On burning, and excluding water vapour, between 80 to 99 percent of a fossil fuel is carbon dioxide, in mass terms (Dupre 1968, Dincer & Rosen 2012). It is this carbon dioxide which forms the critical component of bio-product equivalents. Other types of contaminants, principally carbon monoxide, nitrous oxide, sulphur dioxide, volatile organic compounds and particular matter are also released.
Yet, and whilst they are important emission factors when looking at say, atmospheric pollution issues, their role within an exergy analysis may be ignored.

We undertook an extensive literature review of the different bioproduct substitutes that support the way that society functions today, paying specific attention to CExD calculations. In total 127 data entries, eighty two percent from SimaPro, and the rest from eleven references, (Font de Mora et al. 2012; Talens Peiró et al. 2010; Sorguven and Ozilgen 2010; Jungbluth et. al. 2007; Liao et al. 2011; Patzek, 2006; Berthiaume et al. 2001; Parsapour, 2012; Piekarczyk et al. 2013 and Frenzel et al. 2014a; 2014b), were identified and standardised under one unit to allow for comparison. Table 1 summarises the studies evaluating the exergy cost of biofuels considered as part of this paper’s literature review. This exergy analysis gives an improved estimate of the exergy required to replace fossil fuels, not in terms of their composition or origin but with regards to the role they play in society and Nature. In other words, whilst no technology exists that can reconvert carbon dioxide back into fossil fuels (emphasizing origin and composition), as we pointed out biofuels can be produced from (in part) atmospheric carbon dioxide and can fulfil all the societal functions required of oil, coal and gas.

The bio-product breakdown is shown in Table 1. The large number of entries illustrates the difficulty involved in replacing certain fossil fuel products and the research bias towards petroleum, and its substitutes.

<table>
<thead>
<tr>
<th>Mineral Product</th>
<th>References information</th>
<th>Data entries*</th>
</tr>
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<tbody>
<tr>
<td><strong>Bio-Equivalent</strong></td>
<td><strong>Bio-sources</strong></td>
<td><strong>NR+R</strong></td>
</tr>
<tr>
<td>Fuel Gasoline</td>
<td>Bioethanol Corn, brewer, sweet sorghum, sugarcane, sugar beets, rye, whey, potatoes, grass, NE biomass**</td>
<td>22</td>
</tr>
<tr>
<td>Diesel Biodiesel</td>
<td>Rapeseed, sunflower, palm oil, microalgae, soy bean</td>
<td>13</td>
</tr>
<tr>
<td>LPG Bio-SNG</td>
<td>Wood, NE biomass</td>
<td>3</td>
</tr>
<tr>
<td>Kerosene Used cooking</td>
<td>Cooking oil</td>
<td>3</td>
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Figure 2 shows the variability of the identified studies. Box plots were drawn to show median, maximum and minimum values. It is evident that when a product is evaluated only considering non-renewables that the exergy cost drops substantially, indicative of the eco-efficiency of the process (which is the conceptual basis of TEC), but not the real exergy cost. Unsurprisingly, exergy cost increases when the scope is extended from “crop to fuel” to “crop to storage”. “NR+R” values are always higher than one, by definition.
The scope of our study was from “sun to fuel”. Whilst we would have preferred to have referenced a secondary data value for “sun to fuel”, in order to represent the full lifecycle of a biofuel (or biopolymer or biochar), there are no known studies that have evaluated the process within that scope. Accordingly, we revised the literature for the exergy of photosynthesis and bio-production independently, and came up with an appropriate value. “Crop to tank”, “crop to gate,” and “crop to energy” were all considered to be beyond the scope of this paper, as we only sought to demonstrate that the exergy replacement cost for fossil fuels could be accounted for through bio-equivalents.

The exergy cost of bio-production values was obtained as the average of those entries that had the scope “crop to fuel” and which evaluated “NR+R” resources using CExD and CExC methodology (Figure 2, values in green). Exergy cost allocation was done according to the results and procedure in Jungbluth et al (2007), because biofuel production results in by-products that could be used for road construction or livestock feed. Exergy allocation was assigned according to market price.

For the ERC of bio-oil substitutes the authors took into account the breakdown of all the sub-products that comprise an average barrel of oil, in order to calculate a weighted exergy cost as shown in equation 3.

$$\kappa_j = \frac{\sum_n f_n \kappa_i}{\sum_n f_n}$$

(3)

Where $\kappa_j$ is the ERC of fuel $j$, $f_n$ is the fraction of product $n$ that can be obtained from fuel $j$, and $\kappa_i$ is the exergy cost of the bio-equivalent of product $n$.

4.1. Photosynthesis: From sun to crop calculation

Photosynthetic efficiency represents the energy from the sun which is converted into chemical energy during plant and algae photosynthesis. It is estimated that biomass produced on Earth occurs at around 37 TJ per second (Szargut, 2005a). The process is usually described by the chemical reaction of equation 4 and the change in standard Gibbs free energy per mole of glucose, as stated by Albarrán-Zavala and Angulo-Brown (2007):

$$6\text{H}_2\text{O} + 6\text{CO}_2 + \text{energy “light } \lambda \text{[nm]}=680\text{”} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \Delta G^\circ=2880.31 \text{ kJ/mol}$$

(4)

Photosynthetic efficiency may be calculated as the energy content of the glucose produced during photosynthesis, divided by the incident radiant energy. This value is different from the overall energy efficiency of growth, which includes metabolism, that is to say the cost of living, and includes everything from the degradation of sugars and biomass to produce high energy molecules (such as ATP), to the repair, maintenance, and manufacture of the complex proteins in the photosystems and the enzymes used in the Calvin Cycle (Beal et al 2012; Silva et al 2015).
A scan of available academic literature shows a wide range of plant photosynthetic efficiencies from anywhere between 2 and 41 percent (Zhou et al 1996; Lems et al 2010; Silva et al 2015; Keller, undated), due to the considerable methodological differences that exist. The value from Silva et al (2015) was obtained from their comprehensive analysis of various papers and all the photosynthetic processes that occur within the chloroplast and those that affect the organism as a whole. Their results state that the exergy cost of photosynthesis is 25.44 MJ/MJ of glucose. This is an overall efficiency of 3.9 percent, and is calculated following allowances for the plant’s metabolic exergy cost. It highlights the full extent of exergy bonus provided in having a plant or algae concentrate and transform solar energy into glucose. In other words, for every 1 MJ of biomass produced, approximately 25 MJ of exergy is consumed. The rigour of Silva and his co-authors, and the study’s inclusion of exergy cost is why this value, and not others within the range, was taken for the basis of this present paper.

Sorguven and Ozilgen (2013) state that photosynthetic microalgae, after taking into consideration their metabolic exergy costs, are able to convert 3.8 percent of solar exergy into chemical exergy, which they store as an algal lipid biomass. Beal et al (2012) state that algal photosynthetic efficiencies, in a highly productive case scenario, are 2.95 percent, after factoring in metabolic exergy costs.

In this paper only plant-based photosynthetic efficiency was used because no exergy cost calculation for algal based biofuel production exists that may be worked into the parameters established within this methodology. Once more algal data becomes available, this ERC calculation can be refined.

### 5. Results and their Application

The unit MJ/MJ states how much exergy is consumed by either Nature and/or society in order to obtain 1 MJ of fuel. Table 2 presents the ERC of fossil fuels, taking into account the entire lifecycle from “sun to fuel”. Considering the 3.9 percent efficiency of photosynthetic conversion of sunlight to biomass, 85 to 99 percent of all ERC for bio-products is incurred at this stage (Figure 3).
Table 2. ERC of fossil fuels and comparison with other non-fuel minerals ERC. Source: Authors

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<tbody>
<tr>
<td>Coal</td>
<td>25.44</td>
<td>1.52</td>
<td>25.96</td>
<td>589.0</td>
</tr>
<tr>
<td>Oil</td>
<td>25.44</td>
<td>3.96</td>
<td>28.40</td>
<td>1,296.9</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>25.44</td>
<td>5.56</td>
<td>30.00</td>
<td>1,066.0</td>
</tr>
<tr>
<td>Phosphate Rock</td>
<td>-</td>
<td>-</td>
<td>0.4 (Lowest value of 36 minerals)</td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>-</td>
<td>-</td>
<td>583,668 (Highest value of 36 minerals)</td>
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Note: If you break down a system into its component parts (i.e. photosynthesis and bio-production), it would seem that you have an extra MJ in the second process because you have to include the 1 MJ of biomass derived from the first process as an input. This is not the case if you calculate globally.

The inclusion of bio-equivalents in the exergy assessment broadens the exergy replacement cost, as a concept, beyond its current scope, of the energy required by best available technology to concentrate a mineral deposit, to include the energy required to capture and concentrate solar energy and create biomass. This enables the approach’s focus of non-fuel mineral scarcity to be extended to fuel and non-fuel minerals and allows for a quantitative comparison between them both. In the second column of Table 2, the unit MJ/MJ is transformed into GJ/tonne, using the HHV of
each conventional fossil fuel. This allows for a comparison of the 54 non-fuel minerals calculated by Valero and Valero (2014) with the fossil fuel calculations presented here. The average HHV of coal, oil and natural gas is assumed to be 22,692, 45,664 kJ/kg and 39,394 kJ/Nm$^3$.

The non-fuel minerals evaluated by Valero and Valero (2014) constitute 19.8 percent of the total ERC of the extractive sector and fuels 80.2 percent. Our calculations show that when compared against the values for fossil fuels calculated via a bio-product alternative pathway (Figure 4), their method sub-estimates, on average, the ERC twenty-eightfold. This is because the HHV does not consider the huge exergy bonus provided by Nature in concentrating sunlight into biomass, which can be burned, or converted into non-energy products, to provide society with the functions it needs to operate now and into the future. Even if one does not consider photosynthesis as part of the scope, the ERCs of fuels calculated via the alternative pathway, are still underestimated by between 1.52 and 5.56, as shown in Table 2. Furthermore, when the ERC of fuels are re-calculated using the alternative pathway, the ERC of non-fuel minerals account for only 0.9 percent of the total, whilst fuels rise to 99.1 percent.

![Figure 4. Comparison of methods for Worlds mineral capital depletion 1900 to 2008](image)

The same calculation can be applied to the findings in Calvo et al (2016), where the ERC concept was employed in the material flow analysis for mineral trade in those countries constituting the European Union (EU-28) and published in the form of a Sankey diagram. Calvo et al states that “in the case of fossil fuels, it makes no sense to use the concept of exergy replacement costs” and consequently only perform an analysis for non-fuels. Once again, as with Valero and Valero (2014), when the ERCs of fuel minerals are calculated via the alternative pathway we developed in this present paper, any comparison between fuels and non-fuels (measured with the same indicator and unit of measure) shows that the exergy costs of the latter to be negligible (Figure 5). Consequently, any mineral policy drawn up would, in ignoring the weight of fossil fuels, gravely miss the
significance of reducing fossil dependency and investing in alternative technologies and innovative practices.

Furthermore, using chemical exergy to depict a fuel’s ERC, instead of the method presented here, apart from being unsuitable and misleading, especially for heavily fuel dependent economies in the EU-28, leads to the erroneous conclusion that more exergy is required to re-concentrate non-fuel minerals than fuels and thus most political effort should be focused on these resources. It is worth stating that the specific ERC (MJ/MJ) for some non-fuel minerals, such as gold (583,668 GJ/tonne) is higher than coal, gas and oil but that the exergy required to replace all the fossil fuels consumed globally between 1990 and 2008 is higher than that for all non-fuels, due to the quantities involved.

6. Discussion

We provide an accurate exergy replacement cost for fossil fuels by calculating the exergy replacement cost of their bio-equivalents. The use of biofuels as a measure of fuel’s ERC, instead of other energies (such as renewables) ties the grave to cradle to the cradle to grave concept. To clarify, whilst renewable energy sources can replace some of the functions of fossil fuels, thus
prolonging Thanatia conditions further into the future, by reducing pressure on fossil fuel reserves, they cannot capture and re-concentrate atmospheric carbon dioxide into a hydrocarbon that can be burnt or stored in non-energy products. The same holds true for the electricity used by hybrid vehicles. Neither can be used to substitute fossil fuels in the exergy replacement cost calculations because they do not adhere to the method, which requires that the life cycle is closed.

The chemical composition of a resource is irrelevant to a meaningful discussion on sustainability. Using biofuels, as a means to create an alternate pathway within the ERC concept, forces a paradigm shift towards looking at function. The importance of considering function stems from the fact that current generations do not have to fulfil the tenants of sustainable development by providing future generations with oil. Oil is only as useful as the services that it provides. For current generations to leave future ones with at least the same quality of life they must ultimately leave them with a healthy natural environment along with technological developments and the technical capabilities required to obtain a resource that enables them to experience the privileges enjoyed today because of fossil fuels (Lomborg, 2001). If ERC is a measure of sustainability, and an indicator to be used by politicians and industry to take hard line decisions, it is important that sustainability is seen in those terms. The rationale behind the creation of the theoretical commercially dead Earth, Thanatia, as a metaphor and the Crepuscular Earth Model, as its quantitative representative, is not to ensure the preservation of a chemical element or compound but rather a means to ensure sustainable decision making and planetary wellbeing, so to increase the distance between current Earth and the conditions of a commercially dead planet. The fact that bio-equivalents offer the prospect of fossil fuel replacement, either completely or in blends (even if not on the same scale and at the expense of the environment) means that commercial death is prolonged into the future, especially as these substitutes for fossil fuels are renewable. Refining biomass to produce different end products also presents a major opportunity for market diversity and growth and can prevent losses in thermodynamic efficiency (De Meester et al 2011).

Substituting fossils fuels with renewable alternatives enables economic growth to continue by reducing their consumption, allowing more time for technological innovation to lead humanity towards a long term solution to meet their energy needs (fission technology could be one example), until no substitute is found for a different critical resource (that may or may not be related to energy needs). Furthermore, if upon exhaustion of commercially viable fossil fuel deposits, alga could generate biodiesel on a commercial scale (current tests are at trial stages), some issues such as land space, competition with food production and water criticality may become less critical. In addition, alga could mean that the mass utilisation of electric vehicles which demand rare earth elements could be avoided. Such elements would then be diverted to other applications such as
telecommunications and IT, thus reducing, although not removing, rare earth scarcity and again prolonging the distance between that of current Earth conditions and those of Thanatia.

We would like to make clear that this paper is not stating that fossil fuel burning and any subsequent replacement with biological equivalents is sustainable or a desirable end point. The use of biomass and biofuels, particularly, is already linked to notable drawbacks. These include threats to biodiversity, water scarcity and contamination and the utilisation of fertile soils currently sustaining food production (Ajanovic, 2011; Pedroli et al, 2013; Rathmann et al, 2013). As the World Resources Institute points out even if all the world’s harvested biomass was used for energy, this would provide just 20 percent of the world’s energy needs in 2050 (Searchinger and Heimlich, 2015). In other words, there is not enough fertile land to sustain current energy demand and even if only five percent were met, there would be severe implications on food production and societal equity. This is just one of the ethical issues surrounding first, and some second generation, biomass and biofuels that are already being raised and discussed in the mainstream media and at policy level (Steer and Hanson, 2015). This may change, however, if alga were used and able to produce commercial quantities of biodiesel. Second generation biofuels derived from cooking oil and agro-waste should also be promoted to meet energy needs without affecting food supply (Ackrill and Kay, 2014). Any further discussion of these issues, although poignant, is beyond the scope of demonstrating physical feasibility and the fulfilling of fossil fuel function, as a technical issue within the exergy replacement cost calculation.

It is important to clarify that the ERC of biofuels and bio-products, as calculated in this paper, corresponds to the availability of the resources at present Earth conditions. If the ERC were calculated based on the conditions present in Thanatia, this figure would increase significantly. The CExC for biofuel production in Thanatia, would need to be re-calculated to take into consideration that the fossil fuels currently used in such production in 2016 would be substituted by biofuels, given that all viable fossil fuel deposits have been excavated. Furthermore, a great part of this rise would be attributed to the exergy required to desalinate water, through inverse osmosis, in order to provide energy and bio-product crops with the freshwater they need, given that the Crepuscular Earth Model, shows that all water available in the hydrosphere, except for a tiny 2.5% due to the hydrological cycle as it is now, is saline due to all freshwater and saltwater having mixed (Valero and Valero 2014; p23). This is not applicable to algae, however, which do not require fertile soils, in which to grow, hence their likely growing importance, where a lack of land, or commercial fertilisers, pesticides, insecticides etc would severely inhibit plant growth and place restrictions on humanity. The increased concentrations of carbon dioxide in Thanatia, at 640 ppm, is thought, by many researchers, to stimulate plant growth through an, on average, 40 percent increment in carbon
fixation by leaves. Carbon dioxide also influences stomatal openings and higher levels reduce stomatal conductance, and thus water loss through the stomatal pores, by 22 percent on average, potentially combating some of the acute water pressures that may be faced in light of global warming (Ainsworth and Rogers 2007). Leakey et al (2009) showed that overall water requirements may drop by 5 to 20 percent. It is worth stating however that other researchers have found that elevated carbon dioxide only enhances plant growth when nitrogen, precipitation and temperature remain unchanged (Shwartz 2002), which is not the case in Thanatia.

7. Conclusion

We looked at the role of photosynthesis and the development of bioproducts, as a means to calculate the exergy replacement cost of fossil fuels within the grave to cradle mineral assessment. Since the publication of Valero and Valero (2014), the key text on the subject, there has been increasing evidence to demonstrate that current technology can and has recuperated the functions of fossil fuels through biological equivalents, such as biofuels and biopolymers.

The inclusion of bio-equivalents in the exergy assessment extends the concept of the exergy replacement cost, beyond its current scope to include the exergy involved to capture and concentrate solar energy and create biomass. For a specific fuel, the ERC is the exergy cost required by the best available technology (photosynthesis in plants) of bringing a carbon source (CO₂) from dispersal in the atmosphere back to a form of biomass that can replace fossil fuels. Photosynthesis embodies the largest exergy replacement cost and ignoring it will sub-estimate the ERC twenty-eight fold on average. In addressing the issue of non-substitutability of fossil fuels in the grave to cradle exergy assessment, we provide an exergy replacement cost of fossil fuels that is much more consistent with the exergy replacement cost calculation for non-fuel minerals.

This paper enables the approach’s focus of non-fuel mineral scarcity to be extended to fuel and non-fuel minerals and allows for a quantitative comparison between them both. It also creates a paradigm shift towards looking at function, instead of chemical composition. This means that any policy and corporate decisions made, as a result of the ERC method, would focus on sustainable development as a way to ensure that future generations can meet their own needs. It is worth reiterating that these needs do not necessarily have to be met with fossil fuels, but equivalents, such as, but not limited to, biofuels. The key thing at stake is whether, or not, current generations can provide future society with the services that, say oil, currently provides, at the same cost, if not more cheaply, easily and efficiently. The idea of preserving a chemical composition is not relevant
and is a redundant barrier to the further development of the ERC calculation and its role in shaping environmental debates.

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