Raugei, M, Carbajales-Dale, M, Barnhart, C and Fthenakis, V

Rebuttal: "Comments on 'Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants' – Making clear of quite some confusion"

Raugei, M, Carbajales-Dale, M, Barnhart, C and Fthenakis, V (2015) Rebuttal: "Comments on 'Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants' – Making clear of quite some confusion". *Energy*, 82. pp. 1088-1091

doi: 10.1016/j.energy.2014.12.060

Rebuttal: "Comments on 'Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants' – Making clear of quite some confusion"

Marco Raugei [a,b,c], **Michael Carbajales-Dale** [d], **Charles J. Barnhart** [e], **Vasilis Fthenakis** [c,f]

[a] *Faculty of Technology, Design and the Environment, Oxford Brookes University, Wheatley, Oxford, UK*

[b] *UNESCO Chair in Life Cycle and Climate Change, Escola Superior de Comerç Internacional (ESCI) – Universitat Pompeu Fabra, Barcelona, Spain*

[c] *Center for Life Cycle Analysis, Columbia University, New York, NY, USA*

[d] *Environmental Engineering & Earth Sciences, Clemson University, Clemson SC, USA*

[e] *Department of Environmental Sciences, Huxley College of the Environment, Western Washington University, Bellingham, WA, USA*

[f] *Photovoltaic Environmental Research Center, Brookhaven National Laboratory, Upton, NY, USA*

Tel.: +44 7553 811 759, *E-mail address:* marco.raugei@brookes.ac.uk

Keywords: EROI (energy returned on invested); EROEI (energy returned on energy invested); Energy intensity; EPBT; Energy payback time; Life cycle assessment

In Weißbach et al.'s reply [1] to Raugei's comments [2] on their original paper [3], the former persist in attempting to defend their flawed claims, and describe Raugei's efforts to add methodological clarity as "allegations" based on "sophisms", and even coin the phrase "fuel feedstock deception (FFD) method".

Under careful scrutiny, though, their attitude appears to stem from a lack of understanding of (1) the inherently different viewpoints of Life Cycle Assessment (LCA) *vs*. Net Energy Analysis (NEA), and (2) the widely-accepted rationale for the definition of Primary Energy Sources (PES). We shall therefore make a further attempt here to carefully identify the origin of these misunderstandings, as well as to explain why the arguments put forth by Weißbach et al. in their reply are (still) wrong and a potential source of confusion. We shall then also address the points that they make in support of their "buffered" EROI calculations.

1. EROI and CED

As Weißbach et al. correctly state in their reply piece [1], for EROI caluculations, "the thermal energy content of an energy carrier, the "fuel feedstock", is in fact not part of the energy invested E_I". This is undisputed, as is the definition of EROI as the ratio of the usable energy E_R returned during a system's lifetime to all the invested energy E_I needed to make this energy usable [3]. Such definitions are firmly rooted in the viewpoint offered by the discipline of Net Energy Analysis (NEA), which, as the name implies, is concerned with how much *net* (i.e. surplus) energy is left over of the gross energy extracted (and processed and delivered) from a Primary Energy Source (or a mix of PES), after the energy required to sustain the extraction, processing and delivery processes has been subtracted [4].

Where the authors are wrong, though, is in claiming that the energy investment E_I is the same thing as the Cumulative Energy Demand (CED, sometimes also referred to as 'embodied energy'). The latter is among the most commonly employed energy performance metrics in Life Cycle Assessment (LCA), and responds to a different, yet arguably complementary, logic.

While NEA seeks to understand how effective is a system at exploiting societal uses of energy to upgrade environmental stocks and flows into societally useful forms, in contrast, LCA seeks to understand the full environmental impacts of a product or production process. Accordingly, the CED of an energy system describes the total primary energy that must be extracted from the environment in order to deliver a given product or support a given process. This is done by summing the energy inputs to each of processing stage in the production chain (or more accurately network). This method of calculating CED is well defined within the computational structure of LCA as outlined in Heijungs and Suh [5] and used by every LCA software tool on the market.

Using the example outlined by the authors [1] of a network of processes producing coal, electricity and aluminium, we can define this network using the LCA methodology as:

$$\left|\frac{\mathbf{A}}{\mathbf{B}}\right| = \begin{array}{r|cccc|} & \text{Coal} & \text{Elec.} & \text{Oil} & \text{Alu.} \\ & \text{extr.} & \text{prod.} & \text{prod.} & \text{prod.} \\ \text{Coal [MJ]} & 1 & -10 & 0 & 0 \\ \text{Elec. [kWh]} & 0 & 1 & 0 & -20 \\ \text{Oil [MJ]} & 0 & -0.125 & 1 & 0 \\ \text{Alu. [kg]} & 0 & 0 & 0 & 1 \\ \hline \text{WH [MJ]} & 0 & 6.525 & 0 & 72 \\ \text{Coal Earth [MJ]} & -1 & 0 & 0 & 0 \\ \text{Oil Earth [MJ]} & 0 & 0 & -1 & 0 \end{array} \qquad (1)$$

Where **A** represents the technology matrix and **B** the interventions matrix.

Columns represent processes: coal extraction, electricity production, oil production (the 'other energy' that the authors discuss in their example), and aluminium production. Rows represent 'products', both within the economy (coal, electricity, oil and aluminium) and between the economy and environment (waste heat, coal from the earth and oil from the earth). Note that the **A** matrix is in mixed units. Positive values represent outputs from a process and negative values represent inputs. In order to represent the authors network, we have had to assume that both the coal and oil extraction processes are 100% efficient and require no energy inputs. We'll ignore that physical impossibility in order to work through the example. The vector of environmental inventories, **g**, from our network, due to some final demand vector, **f**, is given by:

$$\mathbf{g} = \mathbf{B}\mathbf{A}^{-1}.\mathbf{f} \qquad (2)$$

So, for a final demand of 1 kg of aluminium from our network (a final demand of $f^{T}_{1kg\ Al}$ = [0, 0, 0, 1]) the associated environmental inventory would be, $g^{T}_{1kg\ Al}$ = [202.5, -200, -2.5] from which the CED may be easily found by summing the energy extractions (coal and oil) from the environment to give $CED_{1kg\ Al}$ = 202.5 MJ.

Making the same calculation for a final demand of 20 kWh of electricity, $f^{T}_{20kWh\ elec}$ = [0, 20, 0, 0] gives $g^{T}_{20kWh\ elec}$ = [130.5, -200, -2.5] and a corresponding $CED_{20kWh\ elec}$ = 202.5 MJ. This should not be surprising, since we are assuming that the only energy inputs to the aluminium production process come from electricity; therefore, $CED_{20kWh\ elec}$ *must* equal $CED_{1kg\ Al}$. It cannot be otherwise. There is no definition by which $CED_{20kWh\ elec}$ could not include the energy content of the coal and yet $CED_{1kg\ Al}$ does, because they are connected only via the electricity generation process. Contrary to the authors' contention that this leads to "multiple counting in energy statistics" [1, p.1004], in fact it is the only means to ensure that all energy is accounted for, as demonstrated by the balance between waste heat output and energy inputs for $g^T_{1kg\ Al}$.

Weißbach et al. argue that including the energy of the feedstock fuel in the calculation of the CED is "completely arbitrary" as well as "biased" [1]. These allegations are completely unfounded. In fact, for both the specific cases of e.g. a conventional thermal power system (A) and of a power system harvesting renewable energy such as PV, wind or hydro (B), the CED consistently includes both the energy investments E_I (to extract, process and deliver the feedstock – required for system A - and to produce, maintain and decommission the power plant – required for both systems A and B), and the energy flow itself that is converted into electricity (respectively, the feedstock fuel for system A, and the captured renewable energy for system B). These definitions and calculations are corroborated by a plethora of published LCAs, and are common practice to the extent that one need only open an LCA software package of choice, select a suitable process out of any commercial LCI database, and click on "CED" to find out.

It should be made clear, though, that, unlike Weißbach et al., we are not arguing that either the NEA logic (underpinning EROI) or the LCA one (underpinning CED) is in any way superior or inferior to the other, nor that the concept or operational definition of EROI should be altered at all. What we are concerned about, though, is the repeated spreading of incorrect information and the arbitrary re-definition of widely employed and accepted metrics.

2. Primary Energy Sources

Weißbach et al. also raise the question of what primary energy "weighting factor" should be used for renewable technologies such as hydro power [1]. This is clearly intended as a rhetorical question, since their thesis is that no such "weighting factor" are to be employed, and all calculations should instead be performed on the basis of the straight exergy content of the inputs, regardless of the type of energy that they consist of (such as e.g. thermal or electric or solar radiation) [3]. As already argued before [2], this is rather questionable reasoning that results in units of 'apples and oranges' being casually tossed together. In fact, the exact same argument is made by Giampietro and Sorman [6] (within a section headed "The importance of NOT summing apples and oranges") used by the authors in support of their argument for not using a weighting factor [2, p.210], suggesting that they did not read the cited article very carefully. After careful consideration, it now appears clear to us that Weißbach et al.'s failure to accept the soundness of employing appropriate 'primary energy-equivalent' (PE-eq) factors to account for the varied nature of a system's energy inputs likely stems from their misunderstanding of what such factors actually stand for.

As similarly stated countless times in the scientific literature, and recently reprised clearly and concisely by Murphy and Hall, "a primary energy source is an energy source that exists in nature and can be used to generate energy carriers (e.g., solar radiation, fossil fuels, or waterfalls). An energy carrier is a vector derived from a primary energy source (e.g., electricity, gasoline, or steam)" [7].

These definitions directly support the following statements:

i. Each successive transformation from one type of energy to the next (starting from the PES itself and along an often long chain of different energy carriers) entails some of the previously available forms of energy (chemical, gravitational potential, etc.) being downgraded into heat dispersed into the environment (2nd law of thermodynamics).

ii. Each energy transformation also requires some additional investment of energy to make it happen.

iii. As a result of (i) and (ii), at each energy transformation (i.e. for each successively generated energy carrier) progressively higher PE-eq factors may be calculated, which take into account both (i) and (ii) above, and which are *specific* to the employed transformation pathway.

Thus, the PE-eq "weighting factor" of e.g. hydro electricity is no mystery, but simply ensues from the application of the definitions of CED and E_R given in section 1 above, and is in fact numerically equal to the CED of one unit (e.g. MJ) of delivered hydroelectricity. The exact same logic is then applicable to any other energy system, be it 'renewable' or 'non-renewable', thermal or otherwise, and without arbitrarily invoking any "alleged average efficiency of thermal power plants", as Weißbach et al. mistakenly assume [3]. Furthermore, by the same token, the PE-eq of a country's grid mix may also be directly computed as the overall CED of one unit of electricity delivered (or alternatively as the weighted average of the PE-eq of the electricity production systems that comprise it).

Also, contrary to Weißbach et al.'s non-standard definition of Energy Pay-Back Time [3], which results in non-externally comparable results, the commonly accepted definition [8] *is* EPBT = $E_I/[(E_R/T)/\eta_G]$ (where T = system's lifetime). This definition *does* include the average 'life cycle efficiency' (η_G) of the grid. EPBT is an intrinsically comparative, rather than absolute, metric, to be interpreted as "how many years it will take for a system to produce as much electricity as could be produced by the current grid mix, using the same amount of primary energy" [9].

According to the same logic, the notation of a primary energy-weighted EROI as $EROI_{PE-eq}$ = T/EPBT = EROI/η_G [10] is perfectly valid, and clearly preferable to Weißbach et al.'s misleading "EMROI" acronym [3], since money has absolutely nothing whatsoever to do with the way it is calculated.

Weißbach et al. are of course right when they argue that the choice of how far back to go when defining what constitutes a 'primary' energy source entails a degree of subjectivity, since e.g., even fossil fuels reserves came into existence through a chain of ancient energy transformation processes (starting with biomass production by photosynthesis, and then proceeding with its anaerobic degradation and fossilization) [1]. Incidentally, estimates of the additional energy demands of these natural processes leading to the formation of fossil energy resources, and of the associated 2nd law energy conversion efficiency factors, are available in the scientific literature [11]. However, it is widely accepted in both NEA and LCA that such initial energy transformations (up until the formation of the exploitable reserves of fossil fuels, as well as of other mineral ores) fall outside of the scope of most analyses, and should therefore be disregarded. In other words, by almost universal convention, the decision is made to define 'primary energy sources' as those which are readily available for human exploitation at the present time, including both 'renewable' and 'non-renewable' sources "(e.g., solar radiation, fossil fuels, or waterfalls)" [7].

3. Buffering and the grid mix

In their reply [1], Weißbach et al. misinterpret Raugei's remark that their original storage scenarios [3] only provide "a theoretical ceiling value" to the "additional energy demand" due to the requirement for energy storage

[2] (i.e., a theoretically maximum E_I and therefore minimum EROI), and instead misquote him as stating that their scenarios provide "(optimum) ceiling EROI values". In fact, the opposite is true. While we understand and accept that the analysis of complete grid mixes was outside of the intended scope of Weißbach et al.'s original study, their dismissal of the very real and documented benefits of combining different renewable energy systems such as PV and wind in terms of their relative offsetting of each individual system's intermittency is unjustified and untenable. Once more, a fundamental lack of understanding (both of Raugei's arguments and of those put forth by the studies he cites in their support [12-14]) appears to lie at the core of this refusal to accept any criticism. For instance, Weißbach et al. refer to the unrelated reduced EROI of gas power plants when these are used as back-up for renewables [1] (incidentally, quoting an unreferenced "about 20"), while Raugei's claim referred to the reduced requirement for storage resulting from "the intermittent pattern of electricity generation by one technology" being "largely compensated by the out-of-phase production by other technologies" [2].

This viewpoint speaks to a larger issue regarding the goal of making an EROI calculation. Is it to examine a technology's ability to make use of existing societal energy resources when plugged into the current electricity supply mix, or to examine that technology's ability to supply all eletricity needs on its own? It seems that the authors are trying to do the former, however statements regarding the wind resources at Germany's coast being "too sparse to supply the society" [3, p.214] or the statement that "significant buffering efforts are indispensable for a grid only consisting of renewables" [1, p. 1006] suggest the latter. If the latter is the goal, then why are the same demands not made of gas-fired or nuclear electricity? The EROI of natural gas supplies would almost certainly decline if these resources were required to supply all of society's electricity needs. Similarly, base-load generators that are unable to follow demand loads, such as nuclear, are equally reliant on other flexible generation or storage (or must make the "unrealistic assumption that all electricity is usable" [3, p.213]), if their electricity output is to be completely "useable" at all times, a point that seems to have escaped the authors' attention.

Additionally, Weißbach et al.'s statement that "exergy supply should be completely adaptable to the society's demand to provide flexible usage, not vice versa" [1] not only arbitrarily and single-handedly dismisses the well-documented potential benefits to be gained from demand-response grid management, but is an indication of their likely subscription to a politically motivated ideal that our current societal patterns of consumption should be non-negotiable, irrespective of how irrational, unnecessarily wasteful or intrinsically unsustainable they may be. Of course, if one were to buy this rather questionable argument, then, unsurprisingly, conventional energy technologies such as e.g., nuclear would appear to have an intrinsic advantage *vs.* renewables such as PV or wind.

4. Conclusions

In conclusion, we cannot help but reiterate here Raugei's previous conclusions that "in the light of all of the above, there appears to be ample reason to question the reliability of the authors' numerical results, and, most importantly, their internal as well as external comparability to those produced by previously published studies." In addition, the authors make a number of physically impossible statements, such as "only exergy is generated and destroyed" [3, p.212] (exergy can only be destroyed, never created), which could be forgiven as a typographical error (though suggesting a lack in methodological rigour) were it not for the fact that it was compounded four sentences later with discussion of ”generated exergy” suggesting (perhaps even worse) that the authors lack a fundamental grasp of basic thermodynamics, further underlining the need to question the original analysis. Finally, Weißbach et al.’s defence of their untenable assertions by setting up straw man arguments and misinterpreting and misquoting Raugei’s comments comes across as a worrying indication of their seeming lack of familiarity with scientific standards and widely accepted methodological conventions.

References

[1] Weißbach D, Ruprecht G, Huke A, Czerski K, Gottlieb S, Hussein A. Reply on “Comments on ‘Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants’ - Making clear of quite some confusion”. Energy 2014; 68:1004-1006.

[2] Raugei M. Comments on ‘Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants’ - Making clear of quite some confusion. Energy 2013; 59:781-782.

[3] Weißbach D, Ruprecht G, Huke A, Czerski K, Gottlieb S, Hussein A. Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. Energy 2013; 52:210-21.

[4] Carbajales-Dale M, Barnhart CJ, Brandt AR, Benson SM. A better currency for investing in a sustainable future. Nature Climate Change 2014; 4:524-527.

[5] Heijungs, R, Suh, S (2002). *The computational structure of life cycle assessment* (Vol. 11). Springer.

[6] Giampietro M, Sorman AH. Are energy statistics useful for making energy scenarios? Energy 2012; 37:7-12.

[7] Murphy DJ, Hall CAS. Energy return on investment, peak oil, and the end of economic growth. Annals of the New York Academy of Sciences 2011; 1219:52–72.

[8] Fthenakis V, Frischknecht R, Raugei M, Kim HC, Alsema E, Held M, de Wild-Scholten M. Methodology guidelines on life cycle assessment of photovoltaic electricity, 2nd edition. Report IEA-PVPS T12-03:2011. Available at http://www.iea-pvps.org.

[9] Raugei M. Energy Pay-Back Time: methodological caveats and future scenarios. Progress in Photovoltaics: Research and Applications 2012; DOI: 10.1002/pip.1249

[10] Raugei M., Fullana-i-Palmer P., Fthenakis V. The Energy Return on Energy Investment (EROI) of Photovoltaics: Methodology and Comparisons with Fossil Fuel Life Cycles. Energy Policy 2012; 45:576-582

[11] Brown MT, Protano G, Ulgiati S. Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas. Ecological Modelling 2011; 222(3):879-887.

[12] Gross R, Heptonstall P, Anderson D, Green T, Leach M, Skea J. The Costs and Impacts of Intermittency: An assessment of the evidence on the costs and impacts of intermittent generation on the British electricity network. UK Energy Research Centre 2006; ISBN 1-90314-404-3.

[13] Vitolo T, Keith G, Biewald B, Comings T, Hausman E, Knight P. Meeting Load with a Resource Mix Beyond Business as Usual. Synapse 2013; available at: http://www.civilsocietyinstitute.org.

[14] Nikolakakis T, Fthenakis V. The optimum mix of electricity from wind- and solar-sources in conventional power systems: Evaluating the case for New York State. Energy Policy 2011; 39:6972–80.