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COMMENT

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Comment on "Powering sustainable development within planetary boundaries" by I. M. Algunaibet, C. Pozo, A. Galán-Martín, M. A. J. Huijbregts, N. Mac Dowell and G. Guillén-Gosálbez, *Energy Environ. Sci.*, 2019, 12, 1890

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Algunaibet *et al.* (2019) reported an important and novel study linking planetary boundaries to individual sectors—in their case, electricity generation in the US—and explored designs that could keep the sector operating within a safe space. In determining the total emissions associated with electricity generation in the US, the authors multiplied electricity's life cycle emission intensities by the total generation. This method, however, commits an accounting error that can lead to overestimation. First, I use an example to illustrate, theoretically and conceptually, why it is incorrect to multiply the total output of an intermediate product, by its life cycle emission intensities. Then, I show that this overestimation error in the specific case of US electricity sector can range from 5% to 200% across different environmental impacts, using the environmentally extended input-output model of the US (USEEIO). Given the novelty and importance of their work, I encourage Algunaibet *et al.* to revisit their analysis using correct accounting methods.

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In a recent article,[1] Algunaibet *et al.* presented an important and novel study that downscaled planetary boundaries to electricity generation and analyzed how sustainable design of energy mix may help the electricity sector keep, or close to keeping, operating within a safe space. Another recent study applied a similar approach and linked planetary boundaries with the global food system.[2] Such work opens new frontiers of research in industrial ecology and sustainability science at large, and thus is commendable, and the ideas behind should be further explored.

However, in quantifying the total emissions of electricity generation, Algunaibet *et al.* made an accounting error. Correcting this error may substantially change their results and major conclusions. While Algunaibet *et al.* developed complicated modeling, it is clear that they calculated the total emissions associated with electricity generation in the US by multiplying the life cycle emission intensities of electricity, taken from the ecoinvent LCA database,[3] by the total electricity generation. This calculation is erroneous. It double-accounts or overestimates the actual contribution of electricity in the total emissions of an economy.[4]

Why is it incorrect to multiply the life cycle environmental intensities of electricity (or any intermediate product) by the total generation (or gross output)? The problem lies in the latter. The way the life cycle emission intensities of electricity (*e.g.*, CO_2e per kW per h)—or, more precisely, cradle-to-gate emissions—are calculated is basically the sum of (1) direct emissions from electricity generation per kW per h and (2) indirect emissions embodied in the input materials used (*e.g.*, coal, natural gas, capital investment).[5] And the indirect, or embodied, emissions are simply a result of attributing a fraction of the output of other products, traced through the supply chain,[6] and associated emissions to electricity generation. When we multiply the life cycle emission intensities of electricity by the total generation, the results would include part of the total output and emissions of other products. And if we were to do the same calculation for all products (from electricity to data center, electric cars, chemical manufacturing, *etc.*) and sum them up, we would end up with a total that requires more electricity than is actually generated in the economy. This is because electricity is also part of the embodied emissions of other products. In fact, we would end up with a total amount of emissions which requires more output of any product than is actually produced in the economy, and which is greater than is actually emitted by the entire economy.

Here, I use a fictitious example to further illustrate this error. Suppose an economy consists of 5 productive processes

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A

	coal	electricity	machinery	service	bus
coal (kg)	1	-2	0	0	0
electricity (kwh)	-0.01	1	-0.25	-0.15	-1.5
machinery (item)	-0.2	-0.003	1	-0.012	-0.7
service (item)	-0.05	-0.04	-0.01	1	-0.08
bus (item)	0	0	0	0	1

y

final demand
0
405
251
336
200

B

CO_2 (kg)	0.1	2	0.4	0.05	0.2

x

total output	2000	1000	800	500	200

Fig. 1 An example of a 5-process economy, where **A** is the technology matrix showing process input (–) per unit of output (+), **B** is the environmental matrix showing direct emission intensity, **x** indicates the total gross output of each process, and **y** indicates final demand by households.

(coal, electricity, machinery, service, and bus), and they emit CO_2 only. Data on each process's input use (**A**) and direct emissions (**B**) per unit of output, total output (**x**), and final demand (**y**) that is consumed by households are presented in Fig. 1.

Given the data in Fig. 1, we can calculate the total CO_2 emissions released by the entire economy using (T indicates transpose):

$$\mathbf{Bx}^{\mathrm{T}} = 2585 \text{ kg} \tag{1}$$

And we can calculate the life cycle CO_2 intensity of each product (**E**), using the standard matrix inversion method,[7,8] which is also widely used by LCA software programs,[9]

$$\mathbf{E} = \mathbf{BA}^{-1} \tag{2}$$

which gives

$$\mathbf{E} = [0.4 \quad 2.8 \quad 1.1 \quad 0.5 \quad 5.2] \tag{3}$$

Compare this with direct emissions,

$$\mathbf{B} = [0.1 \quad 2.0 \quad 0.4 \quad 0.05 \quad 0.2] \tag{4}$$

it is clear that the life cycle emission intensity of each product is greater than their direct emission intensity because of, as discussed above, the emissions embodied in the inputs used in each process. For electricity, the direct emission intensity is 2.0 kg kW^{-1} h^{-1} and life cycle emission intensity is 2.8 kg kW^{-1} h^{-1}.

To calculate the total CO_2 emissions of electricity, what Algunaibet *et al.* did was basically multiply the life cycle emission intensity by the total output:

$$2.8 \text{ kg kW}^{-1} \text{ h}^{-1} \times 1000 \text{ kW h} = 2800 \text{ kg} \tag{5}$$

But if we were to calculate this for all products, we would end up with a total of

$$\mathbf{Ex}^{\mathrm{T}} = 5651 \text{ kg} \tag{6}$$

which is 2.2 times of the actual total amount of CO_2 emissions (2585 kg) released by the entire economy (eqn (1)).

Conventionally, the two methods to account for emissions associated with a product or a sector are production-based and consumption-based,[10]

$$\mathbf{Bx}^{\mathrm{T}} = \mathbf{BA}^{-1}\mathbf{y} \tag{7}$$

where the left-side of the equation is production-based and the right-side consumption-based. Each method has its own meanings and implications, but when summed up they would yield the same total of 2585 kg of CO_2 emissions.

Using the production-based accounting, emissions from electricity generation are simply the direct emission intensity multiplied by total output:

$$2 \text{ kg kW}^{-1} \text{ h}^{-1} \times 1000 \text{ kW h} = 2000 \text{ kg} \tag{8}$$

Using the consumption-based accounting, emissions caused by final consumption of electricity are calculated by the life cycle emission intensity multiplied by the final demand:

$$2.8 \text{ kg kW}^{-1} \text{ h}^{-1} \times 405 \text{ kW h} = 1119 \text{ kg} \tag{9}$$

What Algunaibet *et al.* attempted to quantify is closer to the production-based accounting (eqn (8)). In this case, the method employed by the authors (eqn (5)) would overestimate the emissions associated with electricity by 40% (from dividing the life cycle emission intensity, 2.8 kg kW^{-1} h^{-1}, by direct emission intensity, 2 kg kW^{-1} h^{-1}).

This simple 5-process example is meant to give a theoretical or conceptual explanation of the overestimation error. Using the Environmentally Extended Input–Output model of the US (USEEIO),[11] which is based on real-world data of the US economy, the life cycle impact of electricity generation is greater than its direct impact by 5% to 200% across different environmental impact categories (Table 1). In other words, the overestimation error of Algunaibet *et al.* could range from 5% to 200%, depending on the particular impact category. And correcting this error may substantially change their results and major conclusions. Note that USEEIO is an input–output (IO) based LCA model developed by the US Environmental Protection Agency (EPA) to support their Sustainable Materials Management program.[11] IO-based models are another major

Table 1 Environmental impacts per kW h of electricity generation in the US in 2013. (Results from USEEIO,[11] available at data.gov;[17] N – nitrogen, CTUe – Comparative Toxic Unit for Ecotoxicity,[18] and CTUh – Comparative Toxic Unit for Human toxicity.[18])

Impact category	Unit	Direct impact	Life cycle impact	Overestimation error (%)
Acid rain	kg SO_2-eq.	1.71×10^{-2}	1.81×10^{-2}	6
Eutrophication	kg N-eq.	1.41×10^{-3}	2.10×10^{-3}	49
Freshwater ecotoxicity	CTUE	1.23×10^{-2}	2.70×10^{-2}	119
Global climate change	kg CO_2-eq.	6.16×10	6.48×10	5
Human health noncancer	CTUH	5.58×10^{-10}	1.69×10^{-9}	203
Human health respiratory	kg $PM_{2.5}$-eq.	1.47×10^{-3}	1.61×10^{-3}	10
Human health cancer	CTUH	9.20×10^{-11}	2.68×10^{-10}	191
Ozone layer depletion	kg CFC_{11}-eq.	1.11×10^{-7}	1.74×10^{-7}	58
Smog formation	kg O_3-eq.	1.44×10^{-1}	1.76×10^{-1}	22

approach of LCA.[12] Compared with process-based models (the one used in the example above), IO-based models are at a more aggregate sector level with the entire economy covered. The two approaches share the same theoretical foundation, though.[13] IO-based LCA models are widely applied, notably, to estimate environmental impacts embodied in international trade.[14–16]

It is beyond question that Algunaibet *et al.* did seminal work by linking planetary boundaries to individual sectors. Given the importance of their work, I would encourage the authors to revisit their analysis, using correct accounting methods. Besides the production- and consumption-based accounting mentioned above, a mixed approach[4] that allocates burdens between suppliers and consumers is also an option. Whichever method is used, however, emissions from individual products or sectors must add up to the total.

Conflicts of interest

There are no conflicts to declare.

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