I have divided the review into two parts. First, it appears what I consider to be the main limitation of the methodology. I do not intend to overcome this limitation, as I believe that it is not the objective of this paper, but it could be noted for possible future work. I would be glad to collaborate on this in the future if you consider it of interest. Second, I provide the review of the paper, in which the limitations mentioned in the first part is contextualized, along with other comments.

**1. First Part**

The paper presents a robust methodology that has already been successfully applied before, but in my view, it could be improved even further (in future work).

The main point for improvement lies in the calculation of electricity. If I understood correctly, electricity exergy is assumed to be 1. However, the exergy of the materials required for its production is not considered. In this paper (<https://doi.org/10.1016/j.energy.2024.133987>), we performed an estimation of the exergy cost (also considering material exergy) of electricity and found that it can vary significantly, ranging from 3 MJ/MJ to barely 1.06 MJ/MJ. This is because electricity may come from renewable sources (with high material exergy, e.g., steel, silicon, rare earths…) or from fossil fuels (with high fuel exergy). I think, this first estimation could be improved by using the methodology of your paper.

Including more detailed calculations for electricity is key in the context of the energy transition. The exergy of materials used in renewable technologies is not negligible. However, through these materials it becomes possible to capture renewable exergy (e.g., solar radiation, wind kinetic energy) from nature. This is the true nature of the energy transition: shifting from *direct* use of fossil fuel exergy to *indirect* use of material exergy. Furthermore, electricity can also be used to produce hydrogen (<https://doi.org/10.3390/en18061398>) or ammonia (<https://doi.org/10.1016/j.renene.2025.123891>).

Considering potential changes in the energy mix (i.e., the increased use of renewable electricity and hydrogen), we have published several papers examining their impact on the material exergy of certain metals (<https://doi.org/10.1016/j.jclepro.2025.145978>) or of a PCB (<https://doi.org/10.3390/en17194973>). Another key advantage of this approach is that it allows differentiation between renewable exergy (e.g., solar radiation, wind kinetic energy) and non-renewable exergy (e.g., coal, oil, natural gas, iron ore…). In this way, it becomes possible to assess the real progress of the energy transition.

Nevertheless, none of the aforementioned articles include as robust a calculation as the one presented here. For this reason, I believe that in the future we could try to combine these perspectives.

**2. Second Part**

Aside from the limitation mentioned above, I believe the paper has potential, as it can serve as a reference calculation for future work. Below, I provide line-by-line comments.

* **Line 18:** In addition to “declining ore quality,” I think it is important to mention the decline in the EROI of fossil fuels. (For example, cite: <https://doi.org/10.1016/j.enpol.2013.05.049>)
* **Line 51:** Be cautious when referring to “critical materials,” as this term is usually reserved for minerals that are geopolitically sensitive and therefore not necessarily scarce from a geological or environmental perspective. To refer to the latter, I prefer the term “scarce materials.”
* **Lines 58-64:** Be careful here, since some authors could argue the following: if the *function* or *purpose* of a material is not to perform work, to what extent is its exergy representative of efficiency? It is clear that for an energy product its *purpose* is to produce energy, but this is not the case for a material. Moreover, there are very clear examples of this. For instance, the exergy of aluminum is very high (it reacts strongly with the environment) compared to gold. This might suggest that aluminum production processes are more efficient than those of gold, which does not necessarily hold true. Therefore, I think it is important to retain mass-based values alongside exergy so as not to lose this perspective.

Regarding the relationship between exergy and *value* concepts (such as price or geological scarcity): the following graphs show for 51 metals (data points) that *value* is related to Exergy Cost (a; the amount of exergy destroyed to produce a product; equivalent to concepts such as *embodied exergy* or *exergy footprint*) and not to Exergy (b; chemical exergy). Thus, the more expensive and scarce a metal is, the higher its exergy cost. This makes sense, since more energy and materials must be invested in its extraction. On the other hand, with chemical exergy the opposite trend is seen: the scarcer and more expensive a metal is, the lower its chemical exergy. Furthermore, in this case no clear relationship is observed between the two aspects. With this, I aim to emphasize the importance of exergy losses and irreversibilities when analyzing material exergy.

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This might go beyond the purpose of the introduction, but it could be mentioned that there are exergy-based indicators (exergy cost, embodied exergy, cumulative exergy, etc.) to evaluate the *value* of materials from an exergy perspective (perhaps this could be included in Section 1.3). If you are interested in including this, I can provide further information and references.

* **Line 74:** Explain “comminution exergy” more clearly. Does it refer to the exergy required for ore comminution?
* **Lines 75-76:** The definition of material and energy exergy is identical, so they could be defined together.
* **Lines 83-90:** Same comment as for lines 58-64.
* **Lines 184-187:** This is key: everything has at some point been a material (except for renewable exergy, which ultimately comes from the Sun). Even electricity itself. Therefore, it is important to consider the material exergy required for the generation of electricity. Infrastructure (material exergy) is always required to harness free exergy from nature (the renewable exergy), such as building a waterwheel.
* **Line 226:** The definition of “comminution exergy” is unclear.
* **Line 254:** For mineral chemical exergy, I think it is important to cite Szargut’s work (<https://doi.org/10.1016/0360-5442(86)90013-7>).
* **Lines 285-286:** I believe concentration exergy is miscalculated, as it cannot be negative. The equation used in reference [5] is as follows (note that it has a negative sign at the beginning that does not appear in equations 9 and 10).



Although this will modify the results, I do not think it will affect the conclusions due to the low weight of concentration exergy.

* **Lines 307-310:** Here it is stated that electricity exergy is 1. However, this could be improved by including the materials (infrastructure) required for electricity production and the source of exergy (renewable or non-renewable), as discussed in the first part. This could be pointed out as a limitation in the text.
* **Table 3 (Lines 336-337):** “Non-energy materials include limestone, iron ore, and combustion air.” Silicon or the iron itself needed to produce the electricity used in the process should also be included. It is important to account for all materials involved in production (including indirect ones). Moreover, this provides a key advantage for exergy analysis: the differentiation between renewable and non-renewable resources, which is impossible from a purely mass-based perspective.
* **Line 425:** Indicate which section of the supplementary information is being referenced.
* **Lines 427-440:** Instead of recalling the equations used to obtain the results, a discussion of those results could be provided. For example, explain why some values are higher than others. The exergy of SiO₂ is negative in Table 4 — this should be reviewed.
* **Table 4 (Lines 440-441):** Are concentration exergies negative? What percentage of “material exergy” is “chemical exergy”? In my experience, chemical exergy is the most representative compared to concentration, physical, or comminution exergy. This is important because in future work, chemical exergy alone might be sufficient, which would simplify calculations.
* **Equation 15 (Lines 467-468):** The equation seems to be incomplete.
* **Table 9 (Lines 492-493):** Why are there negative irreversibilities? Why is the irreversibility of iron ore extraction 0? If mining is included, many fuels are burned in this process, such as truck diesel, which should result in high irreversibilities.

I have a question here: is embodied exergy equal to the sum of material exergy and all irreversibilities generated in the process? I think it is important to report the value of embodied exergy, since this result could be compared with those obtained by other authors for pig iron, thereby confirming the calculations. The embodied exergy result is also important because it is related to the concept of metal *value*, as mentioned earlier.

* **Lines 569-579:** This confirms what was previously stated about the importance of chemical exergy. It might be useful to indicate the percentage contribution of chemical exergy to the total. I think this would be better discussed in the results section (close to Table 4), as it seems somewhat out of place here.

**Other Comments:**

In general, I miss better contextualization of the numbers in sections 3 and 4. For example, indicating which industries have the highest exergy losses and why. What could be done to minimize these exergy losses in those industries? Which type of efficiency is preferable? Why it is important to use the exergy analysis for materials compared to other methodologies such as Life Cycle Assessment?

I also think it is important to compare the results obtained in this work with others in the literature. For instance, it could be stated how many MJ are used to produce 1 kg of pig iron (embodied exergy?) and compare this with other papers analyzing energy or exergy footprints in Life Cycle Assessment (LCA) studies.

Another general question I have about the methodology concerns the lifetime of materials. The exergy of energy products is consumed/destroyed instantly, so this is not an issue. However, materials can last for years or decades. If social annual calculations are made, how is the temporal variable of infrastructures/materials considered? This consideration is key when calculating the exergy of electricity, since power plants have lifetimes on the order of decades.