Including exergy irreversibilities caused by environmental impacts in the exergy cost of products

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Abstract:

Forty years after the introduction of the exergy cost concept, thermoeconomic analysis has evolved from simple manufacturing boundaries to comprehensive "cradle-to-grave" assessments. While the exergy cost of resource scarcity and depletion is well-documented through models like the Exergy Replacement Cost and the reference state of Thanatia, a significant gap remains regarding the irreversibilities caused by emissions throughout a product's life cycle. This paper addresses this gap by establishing a methodological framework to quantify the environmental exergy destruction associated with CO_2 emissions. The research focuses on three primary environmental impacts: the loss of mountain glaciers, the degradation of coral reefs, and the deforestation driven by climate-induced crop yield reductions. Glacier loss is quantified by accounting for both the "purity" exergy (concentration exergy relative to seawater) and potential energy, resulting in a destruction of approximately 1198 MJ per ton of CO_2 emitted. Marine eco-exergy loss, focusing on the decline of half the global coral reef area since 1950, contributes an additional 529 MJ per ton of CO_2. Finally, the study models the terrestrial eco-exergy loss resulting from the need to expand agricultural land into tropical forests as global yields for staple crops (wheat, rice, maize, and soybean) decline due to rising temperatures. This deforestation component represents the largest impact, estimated at 1909 MJ per ton of CO_2. The synthesis of these factors yields a total environmental exergy irreversibility of 3636 MJ per ton of CO_2 (or 3.636 MJ/kg). To demonstrate the practical utility of this value, the study applies it to the exergetic cost of concrete. Results show that incorporating environmental irreversibilities increases the total exergy cost of concrete from 0.594 MJ/kg to 1.085 MJ/kg, highlighting that for carbon-intensive materials, the exergy destroyed in the environment can be as significant as the embodied exergy of the material itself. This framework provides a bridge between thermodynamics and ecology, offering a more holistic metric for sustainability in the ECOS community, and aims to serve as base from where future studies can propose a strict method to integrate the environmental damage of emissions into exergy cost.

Keywords:

Thermoeconomic analysis; Irreversibility; Carbon footprint; Sustainability.

1. Introduction

Forty years ago, Valero *et al* [1] introduced the concept of exergy cost. It quantifies the total amount of exergy that enters the process to obtain a product, accounting for both the exergy in the final product and the exergy destroyed during the processes (irreversibilities). The scope to calculate the exergy cost of a product can be direct (only manufacturing process as the limit boundaries) or life-cycle, considering all materials and irreversibilities upstream. This approach also considers the exergy cost of the scarcity created by the depletion of resources extracted to obtain the product, the irreversibilities created during the use and the exergy needed for recycling or final disposition. This scope, from the cradle to the grave, has been studied for several products using life-cycle inventories, while the exergy cost of depletion has been modelled for minerals through the Exergy Replacement Cost and the reference state of Thanatia [2].

There is, however, a gap concerning the exergy related to emissions during the life cycle. These emissions do not only contain physical and chemical exergy, but they also impact the environment, which can destroy the exergy of natural resources. These emissions can be abated, in which case, the exergy costs of the emissions abatement should be incorporated to the exergy cost of the product. In the case that emissions are not abated, the loss of exergy in the environment caused by the emissions should be considered.

To illustrate this situation, the emission of 1 ton of carbon dioxide from cement production process (in the kiln) is studied. There are several ways in which carbon dioxide affects the environment, being the two most important its contribution to climate change and ocean acidification. Both of these phenomena have intricate implications, unknown effects, feedback loops and other ramifications that make it complicated to calculate the impacts in terms of exergy. Because of these reasons, this research paper does not attempt to obtain an exact calculation of the irreversibilities created in nature by the emission of CO_2, but to establish a methodological a methodological framework to evaluate them.

There are, however, some irreversibilities that can be calculated. For example, global warming is directly linked to glacier retreat. Glaciers serve important ecological services, such as local climate regulation, freshwater for rivers through dry seasons, erosion prevention, among others [3,4]. Furthermore, ice is almost pure water, and so it has concentration exergy relative to sea water, the ground state; and continental glaciers usually are located at high altitudes [5–7], meaning they also have potential energy, which contributes to its total exergy [8].

Other irreversibility of the environment that can be estimated is the loss of eco-exergy due to conditions change. For instance, both ocean acidification and warming impact the ability of calcifying organisms to build and maintain their exoskeletons [9], including the ability of corals to build coral reefs [10]. Coral reefs provide home for 4000 fish species and more than one million other species of animals and other organisms [11]. This great diversity and biomass can be measured in terms of exergy, as Jorgensen showed [12]. The loss on coral reef area will, thus, mean that eco-exergy is lost. A similar case can be proposed for the other habitats, like rainforests.

In this article, the exergy impacts associated with climate change and ocean acidification are assessed and quantified, in order to estimate the exergy irreversibility impact in the environment of emitting 1 ton of CO_2 to the atmosphere. As stated previously, it must be reminded that this is not a comprehensive list of impacts.

2. Methodology

2.1. Estimation of the exergy irreversibilities from ice loss in glaciers

Mountain glaciers have shown mass and area loss since the beginning of 20th century, mainly due to anthropogenic climate change, and that trend has accelerated rapidly in the last decades [13]. To estimate the impact of each ton of CO_2 emitted over the glaciers, a past trend was considered. According to Zemp *at al.* [14], 8300 Gton of ice were lost in continental glaciers (*i.e.* not including Antarctica and Greenland) between 1961 and 2016. The ice loss rate is different for every glacier (due to size and local climate conditions), and also glacier altitude differs in every case. The data, grouped by region, is summarized in Table 1.

Table 1. *Ice loss and representative altitudes of glaciers of different regions of the world.*

Region	Ice loss (ton)	Representative altitude (m)	Altitude specifications	Altitude Ref.
Southern Andes	1.22E+12	1500	Southern Patagonia ice field ELA	[7]
Low latitude	6.81E+10	4500	Peru and Kilimanjaro glaciers typical altitude	[15]
Alaska	3.02E+12	1500	Alaskan glaciers average ELA	[16]
Russian Arctic	1.05E+12	600	Mainly on islands	[17]
Northern Canadian Arctic	1.07E+12	1200	Queen Elizabeth Island glaciers ELA	[18]
Svalbard & Jan Meyer islands	6.87E+11	560	Austfonna glacier's dome mean altitude	[19]
Western North America	4.27E+11	2600	Rocky Mountains glaciers	[20]
Southern Canadian Arctic	4.15E+11	1300	Mean ELA	[21]
Iceland	1.32E+11	1100	Mean Snowline altitude in Iceland	[22]
Central Asia	4.49E+10	5000	Mean ELA of Tibetan Plateau galciers	[23]
Scandinavia	3.91E+10	1400	Jostedal Glaciers ELA	[24]
Northern Asia	2.18E+10	2250	Kodar range glaciers ELA	[25]

As explained in the introduction, the exergy destroyed when glaciers lose ice mass is composed by a "purity" term and a potential energy term, as shown in Eq. (1)

$$B_g \approx B_{g,c}^{*} + B_{g,h}, \qquad (1)$$

Where B_g is the exergy of the glacier that was destroyed throughout the period, $B_{g,c}$ is the exergy cost of pure water relative to seawater and $B_{g,h}$ is the potential exergy of the ice mass due to its altitude. The exergy cost of pure water is obtained using an LCA perspective from the Ecoinvent database. The LCI inventory of oil, natural gas and coal consumption were considered for the tap water production from seawater reverse osmosis – the standard and most used process for desalination – and of ultrapure water from tap water. That way, exergy cost of obtaining 1 ton of ultrapure water was calculated according to Eq. (2)

$$B_{g,c} = m_{oil} * \Delta H_{comb,oil} + m_{coal} * \Delta H_{comb,coal} + m_{NG} * \Delta H_{comb,NG}, \qquad (2)$$

Where m is the sum of the mass of each fuel consumed for both steps – desalination and purification – and ΔH_{comb} is the specific higher heating value of each fuel. The potential exergy of ice was calculated using the definition of potential energy, as shown in Eq. (3)

$$B_{g,h} = m_{ice} * g * h, \qquad (3)$$

Where g is the gravitational acceleration on Earth (9.81 m s^{-2}) and h is the representative altitude of each glacier. This altitude must be the now lower than the altitude of the glacier nor the Equilibrium Line Altitude (ELA) of a given zone – the altitude at which the snow accumulation rate equals the ice melt rate. Finally, to estimate the exergy cost incurred by the emission of 1 ton of CO_2, the total irreversibility created during the period was divided by the cumulative CO_2eq emissions during the period.

2.2. Estimation of the eco-exergy irreversibilities of coral habitats losses

Jorgensen *et al* [26,27] established that organisms contain exergy related not only to their chemical exergy, but also to the information they contain (eco-exergy), as information directly related to entropy. This information is written in genes and expressed in amino acid chains synthesized by those genes [28]. That way, ecosystems also contain exergy, which can be calculated as the sum of the eco-exergy of organisms present in said ecosystem.

For warmwater corals, the eco-exergy per unit of area is in the range of 2900-6700 MJ m^{-2} [29], which is exceptionally high. According to Eddy *et al* [30], half the global area of warmwater corals has been lost since 1950 (considering up to 2016). As the main driver of coral reefs death has been global warming – through marine heatwaves and steady temperature increase – and ocean acidification, the eco-exergy destroyed per ton of CO_2 is estimated dividing the eco-exergy destroyed in the period by the GHG emissions (CO_2eq) of the period.

2.3. Estimation of the eco-exergy irreversibilities from land ecosystems losses

Just as marine ecosystems, land ecosystems also act as exergy storage due to the eco-exergy of the organisms that live in them. Climate change can affect ecosystems in a large number of ways: droughts, intensification of wildfires, sea-level rise, among others. In this section, the analysis will be centred around the decline in crop yields and its impact in deforestation. As Zhao *et al* [31] have shown, each degree-Celsius increase in global mean temperature would, on average, reduce global yields of wheat by 6.0%, rice by 3.2%, maize by 7.4%, and soybean by 3.1%. Leaving aside all other parameters that affect the area of cultivated land – *i.e.* world population, market preferences, increases in yield due to technical advances – it is fair to assume that a reduction in crop yields will be offset by a larger area cultivated. In some countries, that increase in cultivated area carries the clearance of forests, such is the case of soybean in Brazil or Argentina [32], rice in India and Bangladesh and maize in China [33]. It is assumed that each country will produce the same fraction of each of world's crops as today. The production of soybean in Brazil and Argentina and maize in China were considered, as data was available for these crops in said locations. Maize in Brazil and Argentina was not considered, as it is used mainly as a rotation crop for soy.

Using map data of biomass [34] and deforestation [32], the eco-exergy of tropical forests cleared for plantations was estimated, using Eq. (4)

$$B_{eco} = \sigma_{bio} * A * \beta * 18.7\ MJ\ kg^{-1}, \qquad (4)$$

Where B_{eco} corresponds to the eco-exergy of a surface, σ_{bio} is the biomass density, A is the area of woodlands cleared, β is the characterization factor of biomass eco-exergy relative to detritus [29] − which is higher the more complex an organism is − and 18.7 MJ kg^{-1} is the standard chemical exergy of detritus (dead organic matter). To obtain the area additional forest cleared for each crop for every ton emitted, the equivalence in Eq. (5) [35] and the derivative of temperature to carbon dioxide atmospheric concentration at current temperature and concentration [36] – shown in Eq. (6) – were used.

$$1\ ppm_{CO_2} = 7.81\ Gton_{CO_2}. \qquad (5)$$

$$\frac{\partial \mathrm{T}}{\partial c_{\mathrm{CO}_2}} \approx \frac{0.1\ ^{\circ}\mathrm{C}}{10\ ppm}. \qquad (6)$$

3. Results

3.1. Irreversibilities from exergy destruction in mountain glaciers loss

Table 2 shows the exergy destroyed in each region's glaciers in the 1950-2016 period, separated by the exergy cost of obtaining ultrapure water from seawater ($B_{g,c}$) and the exergy cost of elevating the water to the glaciers altitude ($B_{g,h}$). From ecoinvent database [37,38], it was determined that the consumption of oil, coal and natural gas to produce 1 ton of ultrapure water from seawater are 0.44 kg, 3.83 kg and 1.11 Nm^3, respectively, resulting in an exergy cost of 167 MJ/ton. 167 MJ is the energy needed to lift more than 17000 m 1 ton of water, so, it is no surprise that the purification component of the exergy destroyed in glaciers loss is one order of magnitude higher than the potential energy component. Still, the potential energy component accounts for around 7.5 % of the total exergy, being especially relevant in high-altitude glaciers, like the ones in low-latitudes and central Asia.

***Table 2.** Exergy cost of ice lost in each (B_g) region divided in cost of puryfing water ($B_{g,c}$) and potential energy of ice due to its altitude ($B_{g,h}$)*

Region	$B_{g,c}$ (MJ)	$B_{g,\mathrm{h}}$ (MJ)	B_g (MJ)
Southern Andes	2.04E+14	1.79E+13	2.22E+14
Low latitude	1.14E+13	3.00E+12	1.44E+13
Alaska	5.05E+14	4.44E+13	5.50E+14
Russian Arctic	1.75E+14	6.15E+12	1.81E+14
Northern Canadian Arctic	1.79E+14	1.26E+13	1.91E+14
Svalbard & Jan Meyer islands	1.15E+14	3.77E+12	1.19E+14
Western North America	7.14E+13	1.09E+13	8.23E+13
Southern Canadian Arctic	6.95E+13	6.51E+12	7.60E+13
Iceland	2.20E+13	1.94E+12	2.40E+13
Central Asia	7.51E+12	2.20E+12	9.71E+12
Scandinavia	6.54E+12	3.83E+11	6.92E+12
Northern Asia	3.65E+12	4.81E+11	4.13E+12
TOTAL	**1.37E+15**	**1.10E+14**	**1.48E+15**

The total GHG emissions in the period were 1.47 · 10^{12} ton CO_2eq, indicating a destruction of exergy of 1198 MJ/ton$_{CO2}$, or 1.2 GJ ton^{-1} of carbon dioxide emitted to the atmosphere, assuming trends continue.

3.2. Eco-exergy destroyed

3.2.1. Corals

Coral reefs cover around 348000 km^2 of ocean surface, however, around 80000 km^2 are coral living habitat [39]. As half the global coverage of living coral has declined by half since the 1950s, this means that, approximately, 80000 km^2 of living corals habitat have been lost. Considering the provided range for coral reef eco-exergy storage per surface area, the eco-exergy destroyed since the 1950s is in the range of 4.69 · 10^{14} – 1.08 · 10^{15} MJ, with a central value of 7.75 · 10^{14} MJ. Dividing by the emissions of the period, a value of irreversibility of 529 ± 209 MJ per ton of CO_2 emitted is obtained.

3.2.2. Deforestation due to crop yields reduction

Employing Eqns. (5) and (6), it was calculated that every ton of CO_2 released to the atmosphere should account for 1.28 · 10^{-10} ppm of concentration increase. However, since around 50 % of anthropogenic CO_2 emissions are absorbed by the ocean and plants [40], the increase in atmospheric concentration per emitted ton is actually ~6.4 · 10^{-11} ppm. That increase in atmospheric CO_2 concentration correlates with an increase in temperature of ~6.4 · 10^{-13} °C.

The biomass density in the cleared forest areas was estimated to be 150 ton ha^{-1} [34], and β was estimated to be 180, as suggested by [12]. That way, the obtained eco-exergy of forest lost to deforestation for crops was 50490 MJ m^{-2}. Note that this value is even higher than the high-end estimate for coral reefs. A total irreversibility of 1.9 GJ ton^{-1} due to deforestation was obtained for CO_2 emissions, as shown in Table 2.

Table 3. *World cultivated area of maize and soybean, and exergy destroyed per CO_2 ton emitted.*

Crop	World land use area (ha)	Yield loss per ton CO_2 (%)	New cultivated area per ton CO_2 (ha)	Fraction produced by Br, Ar and Chn (%)	Exergy destroyed by deforestation per ton CO_2 (MJ)
Maize	2.10E+08	4.736E-12	9.95E-06	24.2	1217
Soybean	1.43E+08	1.984E-12	2.83E-06	48.5	693
TOTAL					**1909**

4. Discussion

4.1. Application to the case of concrete

The obtained value of exergy irreversibilities related to CO_2 emissions to the atmosphere in this study was 3636 MJ per ton, or 3.636 MJ kg^{-1}. According to Torrubia *et al* [41], concrete has a low exergy cost (or embodied exergy), of 0.594 MJ kg^{-1}. Considering concrete is around 15 % cement, and the production of cement has a carbon footprint of *ca.* 0.900 kg CO_2eq kg^{-1}, 0.490 MJ kg^{-1} should be added to the aforementioned 0.594, resulting in a value of 1.085 MJ kg^{-1}. In concrete, as it is a material with a high carbon footprint and low exergy cost, irreversibilities created by emissions become significant, as shown in Figure 1. It is evident that, for a material with a much higher embodied exergy or negligible carbon footprint, the relative contribution of the exergy destruction by emissions would be negligible.

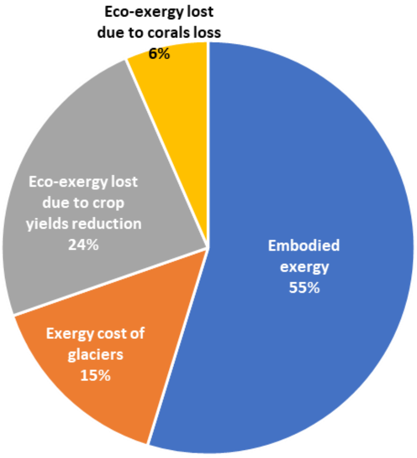

Figure 1. *Contributions of exergy components to the exergy cost of concrete in the analysed case.*

4.2. Evolution of exergy cost of water to replenish glaciers

In section 2.1, the exergy cost associated to the altitude of lost ice in glaciers is defined as the potential exergy of said ice. However, a more precise perspective would be to consider the exergy cost of pumping the water upwards to the needed altitude. It was considered that all pumps run on electricity, with an efficiency of 90 %. Since electricity is not primary energy, but an energy vector, the exergy cost of electricity must be taken into account. For this matter, LExCOE methodology was considered [41], however, since solar radiation and wind are “free” and constantly replenish, they were not considered for the calculation – the exergy cost of the Renewable Energy infrastructures, on the other side, were accounted, as well as fossil exergy. That way, the exergy cost of the potential energy of lost ice can be expressed according to Eq. (7).

$$B^*_{g,h} = \frac{B_{g,h}}{\eta} * LExCOE_{Ren}. \qquad (7)$$

The same reasoning applies to desalination, as an important part of the exergy cost of desalination and purification of water comes from electricity generation.

And Eq. (1) can be rewritten as Eq. (8).

$$B_g = B^*_{g,c}(t) + B^*_{g,h}(t), \qquad (8)$$

Where t is the year of analysis. Applying these equations, the following trend of glaciers-replenish exergy cost is obtained (Fig. 2).

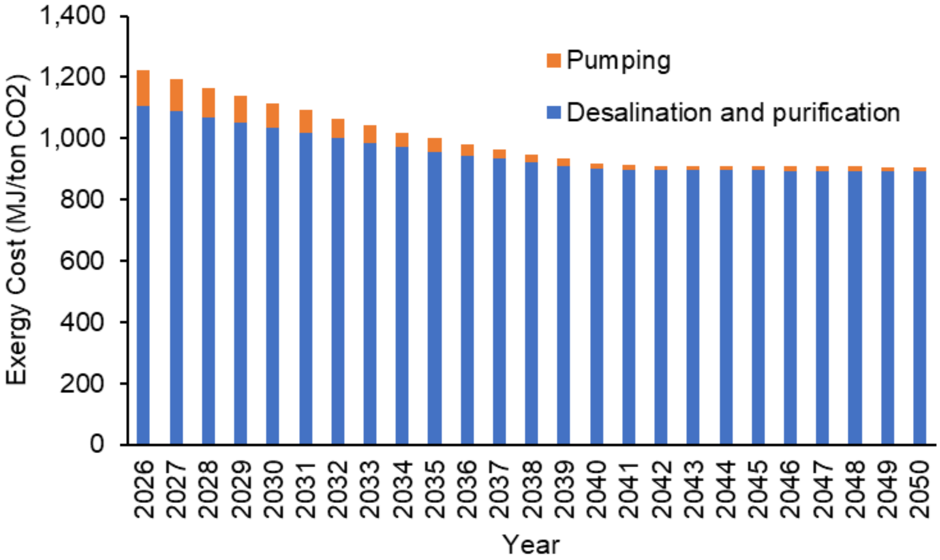

Figure 2. *Evolution of the exergy cost of replenishing glaciers.*

The exergy cost of pumping the water upwards decreases faster than the cost of purifying water, as the former one is more dependent on electricity than the latter one, which also relies on chemicals. Two important remarks must be made: the first one is that ELA of glaciers will increase in altitude as the planet warms up, but his effect was not considered, as it is difficult to predict how much the ELA will change in each world area. Also, the exergy cost of the infrastructures needed to move the water from the sea to the location of the glaciers was not accounted. This exergy cost might be important in the case of glaciers that are far inland, like Central Asia, Western North America and low-latitude glaciers.

4.3. Other non-considered exergy losses caused by CO_2 emissions and future work

As previously mentioned, this work does not aim to provide a definitive value for the exergy cost, but to show that the emissions can be accounted as exergy irreversibilities and establish a methodology for the calculation. Besides the three mentioned mechanisms by which CO_2 emissions to the atmosphere cause environmental exergy losses. Three of them are analysed in this section:

4.3.1. Aridification and desertification

By today, it has been well established that anthropogenic climate change can cause drylands to expand and turn into desert in some areas of the world, with more than 5 million dryland hectares converted into deserts that can be directly attributable to climate change [42]. This tendency is expected to continue as climate change accelerates [43]. This way, every ton of carbon dioxide emitted to the atmosphere will contribute to eco-exergy loses as of both soil and the biomass that inhabits it see their exergy destroyed as soil is degraded [44]. It must be reminded that CO_2 has a fertilizing effect, and so, overall, the increase in carbon dioxide concentration in the atmosphere could result in an increase in world plant coverage [45], but, in ecology, the destruction of an ecosystem cannot be justified by growth of a different one.

4.3.2. Fish biomass loss

Recent research has shown that both long-term ocean warming and marine heatwaves can significantly reduce the fish population [46,47]. Although this effect is well-documented, it is hard to quantify or predict, so it was not included in the calculations.

4.3.3. Feedback loops

Several of the mentioned effects in this article have positive feedback loops with climate change, which can amplify the exergy irreversibilities. For instance, the loss of glaciers can diminish the albedo and increase global warming. The Amazon Rainforest and Coral ecosystems are carbon sinks, which means that their loss or decline will result in an increase in carbon dioxide concentration in the atmosphere, increasing the exergy irrversibilities related to it. A system dynamics approach to assess this feedback loops and study their effects could increase the precision of the calculations.

4.3.4. Future work

5. Conclusions

The quest for a truly sustainable industrial metabolism requires an accounting system that reflects the physical accounting by proposing a methodological framework to evaluate the "unseen" irreversibilities that CO_2 emissions create within natural ecosystems. By translating complex environmental phenomena – such as cryosphere retreat and biodiversity loss – into the common language of exergy, we can now integrate environmental damage directly into the thermoeconomic cost of products.

Our analysis reveals that the impact of CO_2 on the environment is multi-faceted and significantly higher than previously estimated in simplified models. Mountain glaciers are not merely water storage; they represent a high-quality exergetic resource due to their chemical purity and elevated potential energy. We found that the purification component (167 MJ/ton) is an order of magnitude higher than the potential energy component, although the latter remains significant in high-altitude regions like Central Asia. The total impact of 1198 MJ per ton of CO_2 emitted underscores the immense "exergy debt" we are creating by accelerating glacier retreat.

The destruction of coral reefs represents a loss of "information exergy" that is far more difficult to replace than physical materials. With half of the global coral living habitat lost since 1950, the resulting irreversibility of 529 ± 209 MJ per ton of CO_2 reflects the high complexity and biological density of these ecosystems. Furthermore, the reduction in crop yields (ranging from 3.1% to 7.4% per degree of warming) forces a geographical expansion of agriculture into carbon- and exergy-rich tropical forests. This indirect deforestation accounts for 1909 MJ per ton of CO_2, making it the largest single contributor to the environmental irreversibilities studied here.

While this study establishes a robust framework, it is by no means an exhaustive list of environmental impacts. We have focused on quantifiable irreversibilities where data—such as ice loss rates, eco-exergy densities, and crop yield sensitivities—are available. Many other ramifications of climate change, such as ocean acidification's full impact or feedback loops of permafrost thawing, remain excluded due to their high complexity. The linear approximation used for the relationship between CO_2 concentration and temperature increase serves as a conservative starting point. As climate models become more sophisticated, these values can be refined.

The results presented here (3636 MJ per ton of CO_2) allow for a more rigorous comparison between "dirty" technologies and their "clean" alternatives by internalizing the environmental exergy destruction that was previously ignored. This paper marks a necessary step toward a thermodynamics-based environmental economics that respects the limits of our planet. Future work is needed to assess the exergy cost of environmental impacts and link them to Planetary Boundaries Framework.

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