ACCEPTED MANUSCRIPT

The unaccounted-for climate costs of materials

Paikea Colligan, Elisabeth Van Roijen, Seth Kane, Frances Moore, Sabbie A Miller

Environmental Research Letters

Received April 9, 2024
Accepted September 11, 2024
Published October 24, 2024

The unaccounted-for climate costs of materials

Paikea Colligan [a], Elisabeth Van Roijen [a, †], Seth Kane [a], Frances Moore [b], Sabbie A. Miller [a]
[a] Department of Civil and Environmental Engineering, University of California, Davis
[b] Department of Environmental Science and Policy, University of California, Davis
[†] Corresponding Author: E evanroijen@ucdavis.edu

Abstract:
Materials production is a primary driver of anthropogenic greenhouse gas (GHG) emissions; yet the externalized costs of these emissions on society are not reflected in market prices. Here, we estimate the externalized climate costs from materials production in the United States at approximately 79 billion USD per annum, and we highlight disparities in materials pricing. Proper accounting for such disparities can be leveraged to drive breakthroughs in technologies used for our material resources and manufacturing.

Introduction:

The industrial production of materials is a primary source of global anthropogenic greenhouse gas (GHG) emissions, accounting for an estimated 11 Gt of CO_2 in 2015 or ~23% of global GHG emissions[1]. Emissions from materials production are expected to grow in coming decades, driven by factors such as continued build out of infrastructure, particularly in developing economies[2]. Methods to mitigate GHG emissions from materials production, such as through the implementation of renewable energy have been well studied in most cases. The Department of Energy's roadmap for net-zero emissions in the industrial sector (specifically for the production of steel, cement, plastics and food products) highlights the ability for renewable electricity, low-carbon fuels and energy efficiency to lead to a 60% reduction in GHG emissions by 2050 (compared to 2015 GHG emissions).[3] Yet, to achieve net-zero emissions on a global scale, GHG emissions reductions are also required for process emissions, and economic barriers are regularly cited as a hindrance to low-emissions technology implementation[4].

Simultaneously, the external costs to society associated with climate damages, including effects on human health, infrastructure, and ecosystems, are not typically accounted for in the valuation of material production. The social cost of carbon (SCC) - defined as the estimated cost of the damages caused by a ton CO_2 – is a measure of the quantifiable damages associated with a ton of CO_2 emissions. This concept of internalizing the externalized costs of carbon has been introduced in policies around the world. In 2021, carbon was priced on 26% of global CO_2 emissions through the incorporation of carbon tax and carbon trading systems[5]. The level of implementation of and pricing used in these schemes varies by country and over time, with over 50% of emissions being priced in 17 countries in 2021[5]. Meanwhile, only 7.5% of CO_2 emissions in the United States (US) were covered by a carbon tax or trading scheme[5] in 2021. However, the incorporation of SCC into US policies has been gaining traction; a SCC has been used in roughly 60 regulatory analyses in the US between 2008 and 2019[6], summing to 1 trillion USD in total estimated benefits[7]. Previous studies have applied the SCC to determine the economic benefit of various GHG mitigation strategies[8,9]. However, a comprehensive analysis of the climate damages from materials manufacturing has not been conducted. Such analysis can provide critical insights into policy mechanisms that drive mitigation efforts for this significant contributor to GHG emissions.

In this work, we conduct a systematic analysis of the CO_2 emissions from materials production and estimate associated external climate costs. Other externalities, such as human health impacts from particulate matter emissions, were not considered. To ensure consistent and robust data, we focus on production within a confined geographical scope, the US, and on nine of the most produced materials: asphalt, plastics, brick, glass, cement, lime, gypsum, steel, and aluminum. Common biogenic materials (e.g., wood, paper) were omitted from our analysis due to their role in carbon uptake[10] and debate surrounding biogenic emissions accounting[11]. We use production quantity and recycling rates, energy consumption statistics, national energy-related emissions factors, and stoichiometric values for chemical-conversion-driven emissions for the US material industry in 2018 (the most recent year for which comprehensive data was available[12,13]). Estimates of the SCC with a 2% discount rate were based on the US Environmental Protection Agency's (EPA) recent analysis, and adjusted to 2018 USD [14] (see Methods). We use these inputs to assess the climate-related externalized cost of each material's production, these costs as a share of market value (referred to herein as the fractional change in market price), and the contribution of both chemical and energy emissions, which can be used to inform various economic and policy mechanisms to mitigate emissions.

Methods:

Scope

In this work, we focus on the CO_2 emissions from the production of nine of the most produced materials in the US. These materials were: asphalt (North American Industry Classification System (NAICS) 324121 and 324122), plastics (325211, 325212, and 326), brick (327120), glass (327211, 327212, and 327213), cement (327310), lime (327410), gypsum (327420), iron and steel (331110), and aluminum (33313). NAICS material categories were combined because of the lack of precise process emissions (CO_2 emissions that result from chemical decomposition) and production data for the individual categories. In this study, all data for material mass produced as well as production energy and emissions used are from the year 2018. Emissions reported include Scope 1 and 2 emissions. The mass values of material production and recycling used are inclusive of all US production. However, due to some variation in raw material resources, chemical conversion, and final material composition, the values for process emissions are representative of typical US production methods. It is important to note that due to synergistic production, the total values for materials production, energy emissions, process emissions, and social cost may result in double counting (e.g., some lime or gypsum is used in cement). The US dollar (USD) value referred to here is the 2018 US dollar. The total production (in kt), the market price, as well as the process and energy emissions per kg of material are reported in Table 1.

Table 1. Referenced production, cost, and emission values for all materials.

Material	Production mass (kt)	Market price (USD/kg)	Process emissions (kg CO_2/kg)	Energy emissions (kg CO_2/kg)[12]
Aluminum and alumina	4601[15]	2.53[15]	0.31[16]	4.15
Asphalt	16052[17]	0.48[18]	0 (assumed)	0.33
Brick	26400[15]	0.06[15]	0[16]	0.12
Cement	86368[15]	0.12[15]	0.53[16]	0.32
Glass	14983[13] *	4.17[19]	0.25[16]	0.59
Gypsum	38600[15]	0.02[15] †	0.08[16]	0.09
Iron and steel	110700[15]	1.17[15]	0.5[16]	0.88
Lime	18100[15]	0.15[15] †	0.81[16]	0.52
Plastics	54231[20]	2.29[21] †	0.98[22]	1.38

* Calculated by summing all reported mineral flows into glass as shown in Kane and Miller (2024) [23].
† Mass weighted average of multiple reported values for types.

Energy emissions

To determine energy-derived emissions, fuel types, quantities of fuels used, and emissions factors from US national databases were considered. Fuel consumption data, broken down by fuel type and quantity, was sourced from the US Environmental Information Administration's (EIA) *Material Energy Consumption Survey* (MECS)[12]. With two exceptions, the emissions factors used to find the CO_2 emissions for each of these fuels were sourced from the US EIA[23]. The two exceptions for emissions factors were for electricity demands reported and the "Other" fuel category reported in MECS. For electricity, emissions factors were modeled based on 2018 data reported by the US EPA[24]. For the "Other" fuel category, an emissions factor was approximated as an average of the other fuel types (a sensitivity analysis of different emissions factors for the "Other" fuel category are presented in the Supplemental Data, Sheet 4). In general, the "Other" fuel category contributed to less than 10% of overall energy-derived emissions, even when assuming a high carbon-intensity fuel. However, for plastics and lime, the contribution of "other" fuels ranged from being a negligible contribution to contributing 22% and 16% of overall energy-derived emissions, respectively, depending on the fuel type. For each material, energy-derived emissions for each material were calculated as:

$$EE = \sum_{i} (FC_i \times EF_i) \tag{1}$$

where *EE* represents the energy-derived emissions to produce a material (calculated herein in Mt of CO_2 emissions), *FC* represents the quantity of fuel consumption (trillion BTU), *EF* represents the emissions factor (Mt CO_2 emissions / trillion BTU), and *i* reflects each fuel type (reported by MECS in terms of distillate fuel oil, residual fuel oil, hydrocarbon gas liquids, coal, coke, natural gas, electricity, other fuel). Calculated total CO_2 emissions were divided by the mass of material produced in 2018 to assess energy-derived emissions per kg of material.

Process emissions

Process emissions, i.e., the emissions derived from resource decomposition and release of gaseous CO_2, were based on typical US production methods. For mineral-derived materials (brick, glass, cement, lime, gypsum, steel and iron, and aluminum), process emissions were determined from work calculating stoichiometric flows of emissions based on reactions necessary to achieve desired final material products[16]. The process emission factors (i.e., the quantity of chemical emissions per kg of material produced) used in this work are reflective of mineral resources and processing methods typical for US production in 2019. These data were selected as these were the most representative values that could be determined for all materials considered in this work and production methods between 2018 and 2019 did not vary greatly enough to cause significant changes in chemical emission factors between these years. Noting the variety of iron and steel products, process emissions reported herein represent mass-weighted-average emissions from carbon steel, alloy steel, stainless steel, and cast iron that were manufactured in 2018. For plastic production, there can be notable variations in emissions depending on the type of plastic that is being produced. In this work, process emissions for plastic production are modeled as 44% of total CO_2 emissions, which is a factor derived based on non-energy related fuel consumption from a global study of plastics production by Zheng and Suh[22].

The effects of recycling

We integrate US recycling statistics into this assessment. Namely, 2018 recycling rates are accounted for in the process and energy-derived emissions for each material. The MECS provides industry data for energy-derived emissions, which already include the impacts of recycling processes. To account for recycling in process emissions, the recycled fraction of material was assumed to have no process emissions and process emissions were assigned only to the mass of primary production.

The Social Cost of Carbon

The social cost of carbon (SCC) reported by the EPA[14] was used to determine the externalized climate costs associated with CO_2 emissions from materials production. Namely, an SCC factor for 2018 was determined using the most recently reported 2020 SCC (reported in 2023) by accounting for inflation, using the same method as the EPA[14]. We used the 2% discount rate SCC value of 184 USD/t CO_2 unless otherwise noted. Distributions of SCC values were obtained from the EPA analysis[25]. When examining sensitivity to discount rates, we calculate externalized costs using SCC for each discount rate provided by the EPA (Table 2).

Table 2. The social cost of carbon values for each discount rate in 2018 USD[14].

Discount Rate	2.5%	2%	1.50%
USD / t CO_2	116	184	330

For the nine materials considered in this work, externalized costs were assessed per kg of material production, and accounting was scaled for total material production in the US. Total US material production data was based on 2018 statistics. For iron and steel, aluminum, cement, lime, and gypsum, these production statistics were as reported in the US Geological Survey Mineral Commodity Summaries [15]. The determination of plastic, glass, brick, and asphalt production masses were based on other statistical reporting (see Table 1). Externalized costs were calculated as follows:

$$EC_{per\ kg} = \left(EE_{per\ kg} + CE_{per\ kg}\right) \times SCC \quad (2)$$

or

$$EC_{total} = \left(EE_{per\ kg} + CE_{per\ kg}\right) \times Q \times SCC \quad (3)$$

where *EC* is the externalized cost (USD) either per kg (Eq 2) or for the total production of the material in the US (Eq 3), *CE* is the chemical emissions, *Q* is the quantity of material, and all other terms are as previously defined.

Comparing externalized costs to market price

Representative 2018 material market prices were used to draw comparisons with the externalized costs from climate damages from materials. For iron and steel, aluminum, cement, lime, and gypsum, market price was based on values reported by the US Geological Survey Mineral Commodity Summary[15]. For glass, brick, asphalt, and plastic, market prices were determined based on available statistics (see Table 1).

Results:

The total mass of US production of the nine materials examined was 370 Mt in 2018, resulting in a total of 427 Mt of CO_2 emissions, which includes 22% of production being recycled material (Figure 1). For each of these nine materials, except cement and lime, energy resources were the primary driver of production CO_2 emissions. Process emissions made up approximately 42% of total emissions, and a majority of the emissions for cement and lime. Due to the combination of large mass produced and high emissions, iron and steel had the highest cumulative emissions of any material examined. The emissions per kg of material produced varied, ranging from 0.1 kg CO_2 for brick to 4.5 kg CO_2 for aluminum.

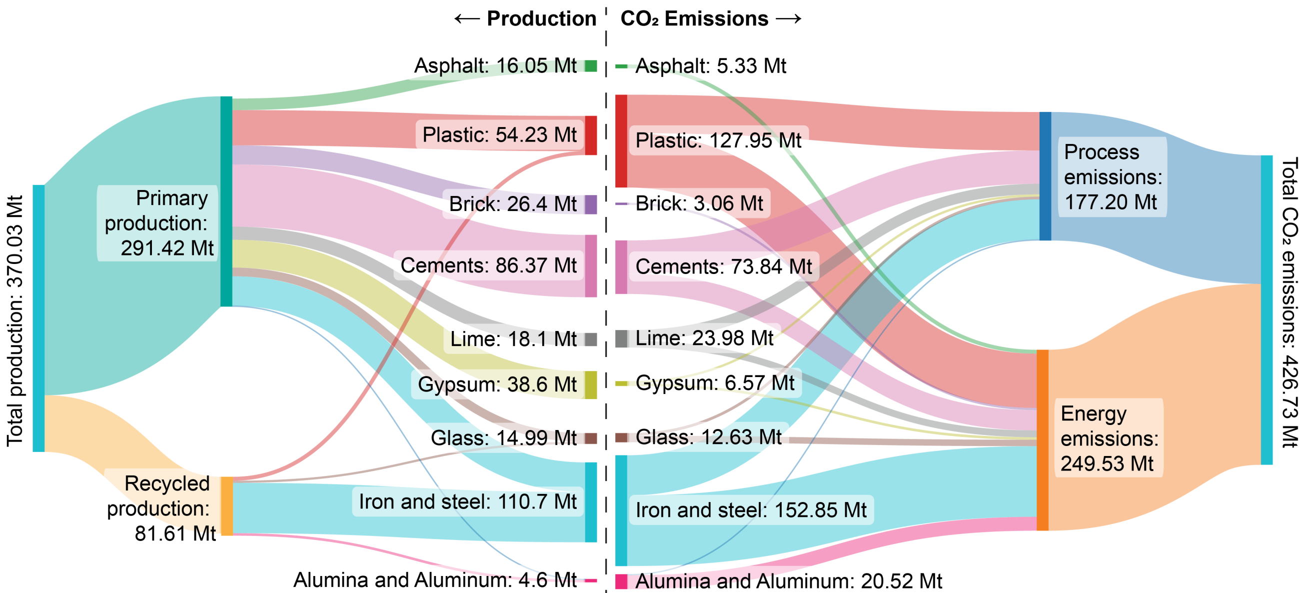

Figure 1. Mass flows of material mass production (left) and production CO_2 emissions (right) for the nine materials examined in the US, as of 2018.

As a result of these CO_2 emissions, the 2018 production of these nine materials resulted in approximately 79 billion USD of externalized climate costs. For each material, the externalized climate costs range from 4-163 % of the material's market price, with variations being driven both by the magnitude of emissions and the current market price. For example, externalized cost relative to market price for aluminum is a relatively low despite high CO_2 emissions per kg of material because current market drivers yield a high price for this commodity. Materials such as plastic, asphalt, glass, and steel, would also have a relatively small fractional change in market price, < 22%, if externalized costs were addressed in valuation. However, the materials with the largest contribution of process-derived emissions, specifically gypsum (47%), lime (61%), and cement (62%), have almost triple the externalized cost to market price ratio of any other material (Figure 2a). These materials have a relatively low market price partially due to low feedstock costs and less energy-intensive processing. Using energy has inherent costs, whereas CO_2 emissions derived from chemical reactions (i.e. process emissions) do not currently influence costs given that CO_2 emissions today remain largely unpriced. Introducing a pricing scheme that reflects the externalized cost of CO_2 emissions could incentivize changes in production methods or consumer practices that would address such emissions, which are particularly pronounced in industry (including materials production) relative to other sectors.

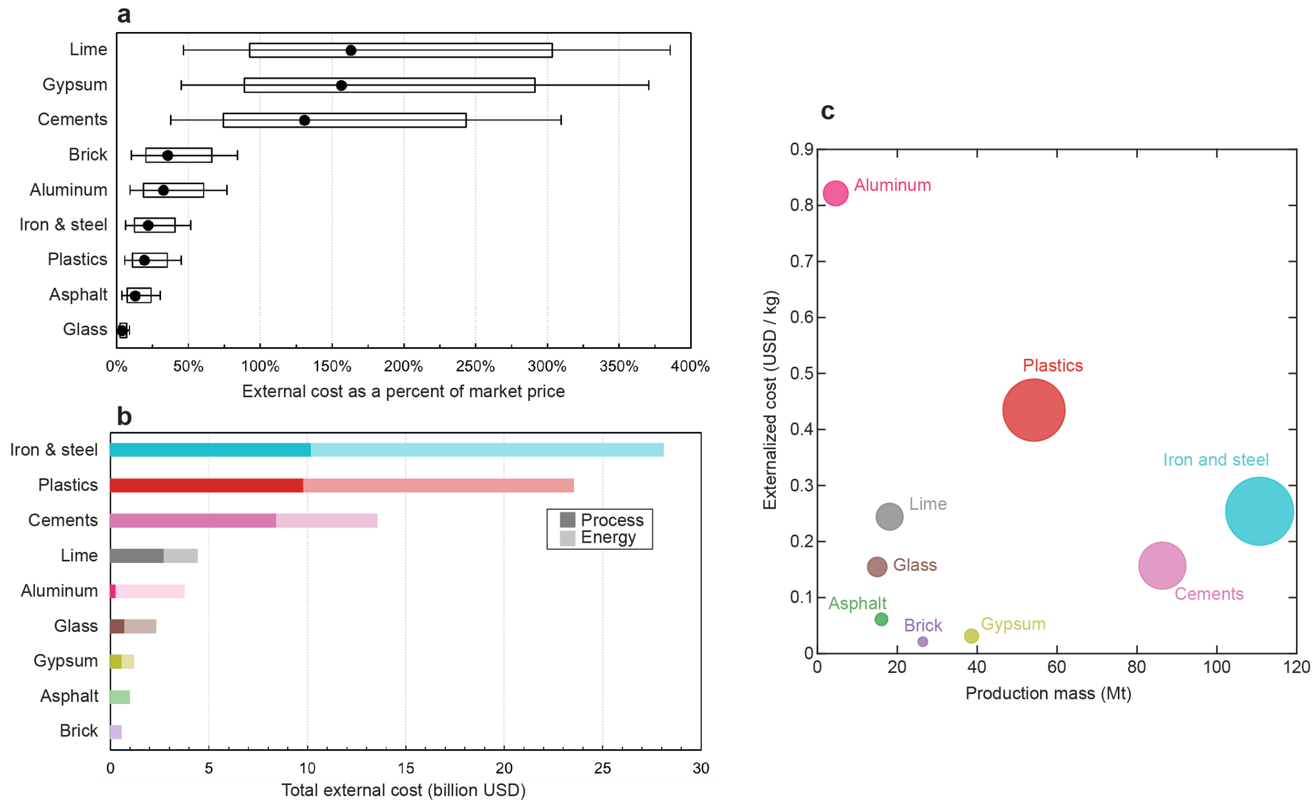

Figure 2. Summary of the externalized costs of materials and main drivers (a) Box plot of externalized climate costs as a percentage of the 2018 material market price for the EPA SCC 2% discount rate (indicated by the circle), 25^{th} and 75^{th} percentiles (box upper and lower limits) and 5^{th} and 95^{th} percentiles (error bars) [14]. (b) Total externalized climate costs for each material considered, broken down by process and energy contributions. (c) Comparison of production mass and externalized cost for each material, with the area of the circle indicating relative total externalized cost.

The total externalized climate costs from production of each material are driven by demand for these materials as well as their per kg emissions. For example, steel and plastics, despite their low fractional change in market price of 22% and 19%, respectively, each result in double the externalized damages as cement, and they result in nearly five times the externalized damages than any other material examined. These high externalized costs are because of both the extensive use of steel and plastics and their high emissions per unit mass.

Long-standing economic theory recommends internalizing the externalized costs of CO_2 emissions using carbon pricing or emissions trading. Such a policy would alter the relative prices of more carbon intensive materials, providing appropriate incentives for both conservation and technological mitigation strategies. For some materials, CO_2 emissions could be mostly or entirely mitigated by transitioning fully to net-zero energy sources. For example, the total externalized cost of aluminum and steel would decrease by 95% and 79%, respectively, if wind and biogas energy are used as the energy sources (see Supplemental Data 1, Sheet 3). However, the process emissions, which total 33 billion USD or 42% of total externalized costs across all materials, would not be addressed by a shift to zero-carbon energy sources and need to be addressed separately (e.g., via changes to process chemistry or through recycling to reduce the total amount of raw material produced). It is important for future policies to target these process-based emissions to minimize the need for new energy-intensive technologies such as carbon capture and storage. For example, recycling meaningfully reduces emissions relative to primary production for materials such as aluminum and steel, where recycling makes up 75% and 63% of total production. If aluminum and steel materials were not recycled, we could expect an additional 5 and 128

Mt of CO_2 emitted per year from those industries, respectively, just from the process emissions. Policies that could help improve recycling rates of materials include extended producer responsibility laws, and minimum recycled content targets[26]. While recent studies have explored the recyclability of cement from waste concrete,[27,28] it is still an energy-intensive and expensive process. Therefore, for materials like cement, which have significant process emissions and are challenging to recycle, introducing a carbon tax or creating an embodied carbon material standard could help accelerate the development and demand for alternative, low-carbon cement binders[4]. Further, policies could incorporate material efficiency standards to minimize the overuse of materials like cement and steel, particularly in the building industry.

While this study focused on US materials production, it is important to note that as some materials production is highly globalized, a carbon pricing scheme would be most effective if it were implemented globally or alongside other policies such as carbon tariffs[29]. Otherwise, incorporating carbon costs into materials pricing in the US could result in increased importation of lower-cost but possibly higher carbon-emitting materials, also known as carbon leakage. Therefore, future research on potential policy solutions such as border carbon adjustments or carbon tariffs is needed to understand how carbon pricing can best be leveraged to reduce the emissions of materials production globally[30].

For gypsum, lime, and cement, the externalized costs from CO_2 emissions are greater than their market value, highlighting another set of factors that may inform decision-making. These non-alloy mineral commodities are commonly locally sourced and have been reported to have closer ties to local economies and poverty reduction than more heavily traded commodities[31]. Yet for many commodities, the populations being most adversely affected by industrial processes are not necessarily those benefiting from manufacturing[32], and climate change is affecting specific populations more than others and driving increased inequalities [33]. Here, we focus on US materials production, but it is important to note that the US emits only 9% of global material production-driven GHG emissions [34]. Current investments, such as those being made in the US to encourage lower-GHG emissions materials production and use, likely do not reflect the localized burdens tied to the production of materials, particularly imported materials, which potentially result in environmental damages to one region while providing economic benefits to the importing nation. Further, it is pertinent to incorporate developing economies into climate mitigation strategies and carbon pricing schemes given that 90% of additional material production by 2050 is expected to occur in developing economies[35].

While externalized damages can be a significant fraction of total costs, we note that SCC is an accounting system with significant uncertainty and is continuously being revised. The lack of an internationally standardized method for internalizing climate costs has led to the development of 64 individual carbon schemes globally[35]. However, most of these mechanisms undervalue the cost of carbon, with only 9 using a carbon price above 40 USD/t CO_2 [35]. According to the Intergovernmental Panel on Climate Change (IPCC), although introducing carbon pricing schemes has generally resulted in a reduction in CO_2 emissions, to reach net-zero emissions by 2050, the carbon price needs to be meaningfully higher[35]. The SCC value of 184 USD/t CO_2 used in this study could be considered a conservative estimate. Other analysts estimate the social cost of carbon can be up to 1000 USD/t CO_2, with a literature average from 2018-2021 of 379 USD/t CO_2 (with a 5^{th}-95^{th} percentile range of 3.57-850 USD/t CO_2) [36,37]. The total externalized climate costs from the US production of the nine materials considered would increase to 141 billion USD if the EPA 1.5% discount rate were used, and it would exceed 160 billion USD if an average SCC value from the 2018-2021 literature was used (with a 5^{th}-95^{th} percentile range of 1.5-362 billion USD). At the upper range of these values, only glass, asphalt, and plastic have higher market prices than their externalized costs.

Other environmental externalities, such as human health or ecosystem damages, have been considered low relative to climate damages for some sectors; however, materials production can have notable burdens for such externalities[38,39], which should be considered in future work. Further, future work should expand to encapsulate a broader range of material types, industrial processes, and other geographical areas. Cumulatively, the damages estimated for US materials production alone are expected to be a small fraction of global climate externalities from industrial manufacturing, suggesting that appropriate valuation of emissions from this critical sector of society would likely warrant rapid investments to lower emissions and reduce damages.

Conclusion:

This work unveils the significant, yet often unaccounted for, climate costs of materials production in the US, estimated at approximately 79 billion USD. These findings highlight the true cost of materials production and addresses the disparities in market pricing which fail to reflect these externalities. Further, by examining the breakdown of emissions sources, this work serves as a foundation for the identification of relevant policy drivers to help mitigate emissions from materials production. Policies to integrate the externalized costs of climate change into market prices can align the incentives of all economic actors to lower emissions and limit climate change costs. High price point is a common reason why low emission alternative materials are not adopted voluntarily by industries. Accounting for the externalized cost of emissions could provide an economic basis for driving innovation and implementation of alternative material production methods. Additionally, carbon pricing may increase the viability of recycling, avoiding damages associated with waste disposal or shift demand to existing materials with lower emissions. Presenting the externalized climate costs for various materials quantifies the impact that an economic policy focused on carbon pricing may have in removing these externalities to incentivize more sustainable materials production and create a more fair, sustainable market.

Acknowledgments: The authors acknowledge funding provided by the United States National Science Foundation (CBET-2143981) and the United States Department of Energy's Advanced Research Projects Agency-Energy (DE-AR0001625). This work represents the views of the authors, not necessarily those of the funders.

Data availability: The data used to perform this work can be found in the Methods. Any further data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration: The authors declare no competing financial interests.

References:

1. Hertwich, E. G. Increased carbon footprint of materials production driven by rise in investments. *Nat. Geosci.* **14**, 151–155 (2021).
2. Cheng, D. *et al.* Projecting future carbon emissions from cement production in developing countries. *Nat Commun* **14**, 8213 (2023).

3. United States Dept. of Energy. *Industrial Decarbonization Roadmap*. https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf (2022).
4. Rissman, J. *et al.* Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy* **266**, 114848 (2020).
5. Ritchie, H., Rosado, P. & Roser, M. Which countries have put a price on carbon? *Our World in Data* (2024).
6. Aldy, J. E., Kotchen, M. J., Stavins, R. N. & Stock, J. H. Keep climate policy focused on the social cost of carbon. *Science* **373**, 850–852 (2021).
7. Nordhaus, W. D. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences* **114**, 1518–1523 (2017).
8. Rode, A. *et al.* Estimating a social cost of carbon for global energy consumption. *Nature* **598**, 308–314 (2021).
9. Acar, C. & Dincer, I. Comparative assessment of hydrogen production methods from renewable and non-renewable sources. *International Journal of Hydrogen Energy* **39**, 1–12 (2014).
10. Churkina, G. *et al.* Buildings as a global carbon sink. *Nature Sustainability 2020 3:4* **3**, 269–276 (2020).
11. Giuntoli, J. *et al.* Carbon accounting of bioenergy and forest management nexus. A reality-check of modeling assumptions and expectations. *Renewable and Sustainable Energy Reviews* **134**, 110368 (2020).
12. US Dept. of Energy Advanced Manufacturing Office. *Manufacturing Energy and Carbon Footprints (2018 MECS)*. (2021).
13. United States Geological Survey. Minerals Yearbook - Metals and Minerals. (2019).

14. United States Environmental Protection Agency. *Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf (2023).
15. United States Geological Survey. *Mineral Commodity Summaries 2019*. 23 https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries (2019).
16. Seth Kane & Sabbie A. Miller. Mass, enthalpy, and chemical-derived emissions flows in mineral processing. *Journal of Industrial Ecology* **Under Review.**,.
17. U.S. Energy Information Administration. *U.S. Refinery Net Production of Asphalt and Road Oil*. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=maprx_nus_1&f=a (2023).
18. National Asphalt Pavement Association. *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage 2018*. https://www.asphaltpavement.org/uploads/documents/IS138/IS138-2018_RAP-RAS-WMA_Survey_Final.pdf (2019).
19. RSMeans. *Green Building Cost Data*. (2010).
20. Madhumitha Jaganmohan. Total plastics production in the United States from 2010 to 2022. Statista (2024).
21. Madhumitha Jaganmohan. Market size of the plastic and resin manufacturing industry in the United States from 2012 to 2023. Statista (2024).
22. Zheng, J. & Suh, S. Strategies to reduce the global carbon footprint of plastics. *Nature Climate Change* **9**, 374–378 (2019).
23. United States Energy Information Administration. Carbon Dioxide Emissions Coefficients. (2022).
24. United States Environmental Protection Agency. Emissions & Generation Resource Integrated Database (eGRID). (2023).

25. Parthum, B. & Davis, W. The Social Cost of Greenhouse Gases. U.S. Environmental Protection Agency (2024).

26. Tumu, K., Vorst, K. & Curtzwiler, G. Global plastic waste recycling and extended producer responsibility laws. *Journal of Environmental Management* **348**, 119242 (2023).

27. Gastaldi, D. *et al.* An investigation on the recycling of hydrated cement from concrete demolition waste. *Cement and Concrete Composites* **61**, 29–35 (2015).

28. Dunant, C. F., Joseph, S., Prajapati, R. & Allwood, J. M. Electric recycling of Portland cement at scale. *Nature* **629**, 1055–1061 (2024).

29. Larch, M. & Wanner, J. Carbon tariffs: An analysis of the trade, welfare, and emission effects. *Journal of International Economics* **109**, 195–213 (2017).

30. Böhringer, C., Fischer, C., Rosendahl, K. E. & Rutherford, T. F. Potential impacts and challenges of border carbon adjustments. *Nat. Clim. Chang.* **12**, 22–29 (2022).

31. Franks, D. M., Keenan, J. & Hailu, D. Mineral security essential to achieving the Sustainable Development Goals. *Nat Sustain* **6**, 21–27 (2023).

32. Tessum, C. W. *et al.* Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences* **116**, 6001–6006 (2019).

33. Islam, S. N. & Winkel, J. *Climate Change and Social Inequality*. https://www.un.org/esa/desa/papers/2017/wp152_2017.pdf (2017).

34. Matos, G. R. *Materials Flow in the United States—A Global Context, 1900–2020*. *Materials flow in the United States—A global context, 1900–2020* vol. 1164 23 http://pubs.er.usgs.gov/publication/dr1164 (2022).

35. Intergovernmental Panel on Climate Change. Chapter 11: Industry. in *IPCC Sixth Assessment Report, Working Group 3: MItigation of Climate Change*.

36. Tol, R. S. J. Social cost of carbon estimates have increased over time. *Nat. Clim. Chang.* **13**, 532–536 (2023).

37. Rennert, K. *et al.* Comprehensive evidence implies a higher social cost of CO2. *Nature* **610**, 687–692 (2022).

38. Miller, S. A. & Moore, F. C. Climate and health damages from global concrete production. *Nat. Clim. Chang.* **10**, 439–443 (2020).

39. David Azoulay *et al. Plastic & Health: The Hidden Costs of a Plastic Planet*. https://www.ciel.org/wp-content/uploads/2019/02/Plastic-and-Health-The-Hidden-Costs-of-a-Plastic-Planet-February-2019.pdf (2019).