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EXTERNAL PEER REVIEW OF EPA'S DRAFT WASTE REDUCTION MODEL (WARM) METHODOLOGY

FINAL PEER REVIEW REPORT

December 2022

Submitted to:
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1. INTRODUCTION

In the second half of 2022, ERG, a contractor to the U.S. Environmental Protection Agency (EPA), organized an independent external peer review of EPA's Waste Reduction Model (WARM) version 16 methodology, developed by EPA's Office of Resource Conservation and Recovery (ORCR). This final report provides an overview of ERG's peer review process (Section 2), a summary of reviewer comments (Section 3), the technical charge to reviewers (Appendix A), and the peer reviewers' individual written comments (Appendix B). Section 3 and Appendix B provide individual reviewer comments exactly as submitted, without editing or correction of typographical errors (if any).

2. PEER REVIEW PROCESS

2.1 Reviewer Search and Selection

For this review, ERG identified, screened, and selected five reviewers who had no conflict of interest in performing the review and who collectively met the following selection criteria provided by EPA:

- Experience in life cycle assessment modeling
- Experience in solid waste management modeling
- Experience in modeling greenhouse gas emissions and other environmental impacts
- Experience in modeling carbon storage in landfills, forests, and/or soils

ERG screened the pool of interested and available candidates against these selection criteria. From the set of candidates who met those criteria, ERG proposed six candidates to EPA. Upon EPA confirmation that the proposed candidates met the selection criteria, ERG contracted with the following five experts to perform the review:

- Malak Anshassi, Ph.D.; Assistant Professor of Environmental Engineering, Florida Polytechnic University
- Richard D. Bergman, Ph.D.; Supervisory Research Wood Scientist, United States Department of Agriculture Forest Service
- Brandon Kuczenski, Ph.D.; Associate Researcher, University of California, Santa Barbara
- Matthew Realff, Ph.D.; Professor, Chemical and Biomolecular Engineering, Georgia Institute of Technology
- Thomas Theis, Ph.D.; Director, Institute for Environmental Science and Policy, University of Illinois at Chicago

2.2 Conducting the Review

ERG provided each reviewer with the WARM model v16 Excel tools, users guide, documentation chapters, and miscellaneous background documentation, as well as EPA's charge to reviewers (Appendix A). Each reviewer then developed written comments in response to EPA's nine charge questions. Per ERG instructions, reviewers did not share the review materials or consult with anyone else during the review process as they each worked individually to develop written comments.

ERG received a question of clarification about a charge question from one reviewer and provided EPA's response to all reviewers. All five reviewers submitted their written comments to ERG, and two reviewers provided additional editorial comments in the form of annotations to the review materials. ERG provided reviewer comments to EPA and confirmed that the Agency has no questions of clarification for reviewers.

3. REVIEWER COMMENTS SUMMARIZED AND ORGANIZED BY CHARGE QUESTION

For each charge question, this section presents a summary of reviewer comments followed by a table with each reviewer's complete response to that question. See Appendix B for reviewer comments organized by reviewer.

3.1 Are the assumptions made in WARM regarding biogenic carbon emissions scientifically sound and in line with common modeling best practices?

Three reviewers explicitly indicated that WARM's assumptions are generally consistent with common modeling best practices. One reviewer stated the model was scientifically sound on the basis that the biogenic carbon emissions modeling approach is consistent throughout WARM, and emissions are modeled in the same manner when waste components are landfilled or biologically treated. A second reviewer acknowledged the model assumptions were consistent with Intergovernmental Panel on Climate Change (IPCC) guidance, and a third noted alignment with International Organization for Standardization (ISO) 21930 (2017) standard for developing biogenic carbon emissions for wood building products. Several reviewers discussed concerns with specific model assumptions that relate to the soundness of the model:

- One reviewer was concerned that most of the data supporting estimation of biogenic emissions are more than 10 years old and said there may be updated sources for measurements of biogenic carbon that reflect new technology for measuring biogenic carbon content. This reviewer and another reviewer noted more recent data related to changes in waste stream composition over time may be available. However, as noted by the first reviewer, it's possible these updates may not result in significant changes to the existing biogenic carbon contents, given that inherent material makeup and manufacturing processes have likely not significantly changed.

- A reviewer was concerned that the current WARM methane emissions modeling stems from dated decay rates used as part of the 2014 Landfill Gas Monte Carlo simulations. While the values are within reasonable ranges when compared with other LCA tools, more recent data[1] have shown varying annual decay rates in different climates. Although the 100-year modeling timeframe does mitigate some of this concern, not updating these values may result in underreported estimates for current U.S. landfill gas generation, which has been become a mainstream topic.[2,3] Another reviewer suggested updating methane emission factors to those used in the 2021 IPCC report.

- A reviewer noted that EPA uses high default collection efficiencies of 75% for all years. In Anshassi et al. (2022)[4], when following 40 CFR 60 Subpart XXX regulations, the average minimum required collection efficiency ranged from approximately 20% to 65%, depending on the decay rate and concentration of nonmethane organic compounds. The results from the study were for the lifetime total gas efficiency (total gas collected divided by total gas generated), and although this is not directly comparable, it still suggests EPA's value is high.

[1] Jain, P., Wally, J., Townsend, T.G., Krause, M., Tolaymat, T., 2021. Greenhouse gas reporting data improves understanding of regional climate impact on landfill methane production and collection. PLOS ONE 16, e0246334.

[2] Duren, R.M., Thorpe, A.K., Foster, K.T., Rafiq, T., Hopkins, F.M., Yadav, V., Bue, B.D., Thompson, D.R., Conley, S., Colombi, N.K., Frankenberg, C., McCubbin, I.B., Eastwood, M.L., Falk, M., Herner, J.D., Croes, B.E., Green, R.O., Miller, C.E., 2019. California's methane super-emitters. Nature 575, 180–184.

[3] Bruggers, J., McKenna, P., Green, A., Benincasa, R., 2021. Your Trash Is Emitting Methane In The Landfill. Here's Why It Matters For The Climate. NPR.

[4] Anshassi, M., Smallwood, T., Townsend, T.G., 2022. Life cycle GHG emissions of MSW landfilling versus Incineration: Expected outcomes based on US landfill gas collection regulations. Waste Management 142, 44–54.

- One reviewer suggested that EPA discuss the 100-year timescale for the global warming potential (GWP) factors. IPCC and general consensus hold that 100 years is the common standard. This is important because it justifies ignoring biogenic carbon dioxide (CO_2), which has a cycling time of less than 100 years. Saying temporal dynamics are "inconsequential" is not supportable but, based on the consensus approach, EPA could say that they are "not considered." Also, the timescale should be applied consistently throughout the model; the soil carbon model discussed in Chapter 4 uses a 10-year timescale, which weakens its legitimacy.
- A reviewer suggested that EPA consider reporting GWP on a 20-year time scale where methane has a much higher GWP. EPA could present both 20-year and 100-year GWP, as it could be that landfill methane emissions would have a bigger impact in the short term as a management option. This reviewer also noted that the timeframe of biogenic emissions is particularly important because we can no longer assume that we are managing for 100-year timeframes; it is the next 25 to 50 years that will be critical to avoid potential tipping points in climate phenomena. Therefore, a state-of-the-art approach could be to spread out emissions over the growth and harvest cycles of biomass. See the approach presented in this paper where the specific timing of biomass harvest and use is considered.

Reviewer	Comments
Anshassi	In WARM, biogenic carbon emissions are expressed for paper products, food waste, wood products, yard trimmings, and other organic sources when they are biologically treated (composted, anaerobically digested) and landfilled. The current sources of biogenic carbon yields used for these modeling is from Barlaz (1998), Wang et al. (2011, 2013), and Levis et al. (2013), and when data was unavailable for specific solid waste components a proxy was used. Most of the data is greater than 10 years old which does suggest newer updated sources for measurements of biogenic carbon is needed, especially since the technology available to measure the biogenic carbon content has improved and that the waste stream components have changed (e.g., how has increased recycled content and biodegradable/compostable products effected biogenic carbon content). On the other hand, the improvements to the instrumentation and the changes in the waste stream are likely not going to result in tremendous changes to the existing biogenic carbon contents since the inherent material makeup and manufacturing processes are likely to not have changed greatly. The practices for balancing carbon vary amongst waste management approaches (see Christensen et al. 2009) and influences the overall greenhouse gas (GHG) emissions factors used in WARM. For example, for landfill modeling it is appropriate to assume that the biogenic CO_2 entering the waste system is stored, and its emissions is a climate positive impact (adverse) and that carbon (CO_2) storage is a neutral impact. However, it is also appropriate to assume that emitting biogenic CO_2 in the short term is neutral and storing CO_2 is beneficial. WARM currently models the later assumption for both landfilling and composting biogenic carbon waste sources. This modeling approach is common amongst lifecycle assessment (LCA) studies of solid waste management and is scientifically sound on the basis that the biogenic carbon emissions modeling approach is consistent throughout WARM; the emissions are modeled in the same manner when waste components are landfilled or biologically treated. When biogenic carbon sources are combusted, they are also assumed to be CO_2 neutral, further matching the consistency of the modeling approach. As biogenic carbon containing materials degrade, they release methane, one of the primary greenhouse gases (GHG) accounted for in WARM. When comparing the predicted methane

Reviewer	Comments

potential yields for some waste components in WARM to other commonly used LCA tools, the values are within reasonable ranges (Table 1). One concern for the current WARM methane emissions modeling stems from the dated decay rates used as part of the 2014 Landfill Gas Monte Carlo simulations. More recent data (Jain et al. 2021) have shown the annual decay rates for arid regions to be 0.043 year^{-1} (compared to the current use of 0.02 year^{-1} in WARM), moderate regions to be 0.074 year^{-1} (compared to 0.04 year^{-1}), and wet regions to be 0.09 year^{-1} (compared to 0.06 year^{-1}). Although the 100-year modeling timeframe does mitigate some of this concern, overall, potentially not updating these values may result in underreported estimates for current US landfill gas generation, which has been become a mainstream topic (Duren et al. 2019; Bruggers 2021). The last concern related to landfill biogenic carbon emissions modeling is the high default collection efficiencies (75% for all years). In Anshassi et al. 2022 when following 40 CFR 60 Subpart XXX regulations the average minimum required collection efficiency ranged from ~20% to 65%, depending on the decay rate and concentration of nonmethane organic compounds. The results from the study were for the lifetime total gas efficiency (total gas collected divided by total gas generated), and although this is not directly comparable to the 75% rate, it still suggests the value is higher and when users compare landfilling to alternatives it may underscore the true GHG emissions impacts.

Table 1. Data from Anshassi et al. 2021

Methane Yield (m3/Mg wet)	WARM	MSW-DST	SWOLF	EASETECH
Newspaper	70	63	65	64
Cardboard	185	168	163	158
Office Paper	248	225	240	221
Yard Waste	65	51	45	127
Food Waste	120	103	122	127

References:

Anshassi, M., Townsend, T.G., 2021. Reviewing the underlying assumptions in waste LCA models to identify impacts on waste management decision making. Journal of Cleaner Production 313, 127913.

Anshassi, M., Smallwood, T., Townsend, T.G., 2022. Life cycle GHG emissions of MSW landfilling versus Incineration: Expected outcomes based on US landfill gas collection regulations. Waste Management 142, 44–54.

Bruggers, J., McKenna, P., Green, A., Benincasa, R., 2021. Your Trash Is Emitting Methane In The Landfill. Here's Why It Matters For The Climate. NPR.

Christensen T.H., E. Gentil, A. Boldrin, A.W. Larsen, B.P. Weidema, M. Hauschild (2009). C balance, carbon dioxide emissions and global warming potentials in LCA-modelling of waste management systems. Waste Management & Research 27:707-215.

Duren, R.M., Thorpe, A.K., Foster, K.T., Rafiq, T., Hopkins, F.M., Yadav, V., Bue, B.D., Thompson, D.R., Conley, S., Colombi, N.K., Frankenberg, C., McCubbin, I.B., Eastwood, M.L., Falk, M., Herner, J.D., Croes, B.E., Green, R.O., Miller, C.E., 2019. California's methane super-emitters. Nature 575, 180–184.

Reviewer	Comments
	Jain, P., Wally, J., Townsend, T.G., Krause, M., Tolaymat, T., 2021. Greenhouse gas reporting data improves understanding of regional climate impact on landfill methane production and collection. PLOS ONE 16, e0246334.
Bergman	Yes, ISO 21930 (2017) standard has clear guidelines on how biogenic carbon emissions for wood building products. The wood sector used ISO 21930 (2017) for development of their wood product category rule (PCR) by UL Environment. The standard is undergoing its 5-year review process.
Kuczenski	Mostly. The "text box" about biogenic carbon emissions on page 1-2 (third instance; PDF page 16) is more or less sound except: The 100-year timescale should be discussed- the GWP factors (1 / 25 / 298) reported on page 1-3 (first instance; PDF page 6) are 100-year factors; IPCC and general consensus hold that 100 year is the common standard. This is important because it justifies ignoring biogenic CO_2 that has a cycling time of much less than 100 years. Saying temporal dynamics are "inconsequential" is not supportable- but you can say that they are "not considered" on the basis of the consensus approach. See also Response 2. Care should be taken that the EPA's approach is to consider a 100 year timetable consistently throughout the model. The soil carbon model discussed in Chapter 4 uses a ten year timescale, which weakens its legitimacy. n.b. your text boxes should be labeled as exhibits, just like figures and tables, so that they can be referred to with precision. e.g. page 1-7 and 1-3 both awkwardly say "the text box in section 1.3.3"
Realff	**Global Warming Potentials Box** Background Chapters: You should really update the emission factors for methane to the latest version of the IPCC report 2021, https://www.ercevolution.energy/ipcc-sixth-assessment-report/. This should include the timeframe of the GWP. I think this is GWP_100 but many people are suggesting that we should also report GWP_20 where methane has a much higher GWP. I would recommend presenting both 20 year and 100 year GWP as it could be that landfill methane emissions would have a bigger impact in the short term as a management option. **Box CO_2 Emissions from Biogenic Sources Background Chapters** The approach taken to timing of biogenic emissions is reasonable but not state of the art. We know that forestry carbon emissions have a cycle of uptake and release and that the first time of harvest increases the release of CO_2 in the short term. At this point the timeframe of emissions matters because we can no longer assume that we are managing for 100 year timeframes but for the next 25-50 years which will be critical to avoid potential tipping points in climate phenomena. Thus, state-of-the-art would suggest spreading out the emissions over the growth and harvest cycles of biomass. For example, the approach presented in:

Reviewer	Comments
	https://doi.org/10.1111/j.1530-9290.2012.00507.x , "Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life," is an example of where the specific timing of biomass harvesting and use is accounted for. Similarly, the decay of biomass in landfills with the production of methane being time-weighted by its instantaneous GWP potential rather than lumping to 100-years or even 20 years would be appropriate but beyond the common best practices which still lump the emissions and weight them by an appropriate horizon. Despite the approach not being state of the art I would not recommend a revision of this specific assumption in the WARM model because there are many other places where effort would be better spent.
Theis	The assumptions regarding the way in which carbon emissions associated with biogenic materials in WARM are summarized in Table 1.3.3 of the WARM background document and are said to be consistent with IPCC guidance. The documentation provided emphasizes that in the United States forest wood is replaced at a significantly faster rate that depletion, consistent with sustainable forest management. So, yes WARM's assumptions are consistent with common modeling practices, with two caveats. First, it is not clear that the rate of biogenic wastage (e.g., lawn and golf course clippings, leaves, etc.) attributed to human actions has remained constant over time over the past hundred years or so. To the extent that landfill emissions from "excess" biogenic wastes have been poorly managed, meaning emitting uncontrolled methane, net GHG emissions may be significant. The Monte Carlo approach for landfill emissions defining "best" and "worst" scenarios is a good way to address this issue. Second, note should be taken that WARM focuses *only* on GHG emissions and energy use. Like many analyses with limited scope, other important environmental impacts, such as biodiversity and land use changes, are not directly addressed.

3.2 Are the assumptions made in WARM regarding carbon storage in forests, soils and landfills scientifically sound and in line with common modeling best practices?

Carbon Storage in Landfills

Three reviewers commented on carbon storage in landfills:

- Two of these reviewers indicated that the assumptions related to carbon storage in landfills are reasonable and in line with common modeling practices.
- The third reviewer noted that, while the model does a good job at capturing certain complexities related to chemical reactions in landfills, it may be prudent to broaden data sources in the future to include more recent field studies.[5]

[5] The reviewer provided the following examples of relevant studies: *Sustainability* 2020, 12(15), 6209; https://doi.org/10.3390/su12156209; *Environ Sci Pollut* Res 29, 24623–24638 (2022); https://doi.org/10.1007/s11356-021-17566-4; *Waste Management* (2019), 87:835-859,ISSN 0956-053X; https://doi.org/10.1016/j.wasman.2018.12.047;

Carbon Storage in Soil

Two reviewers commented on carbon storage in soil:

- One reviewer stated that the model is only provisionally sound with respect to carbon storage in soil and noted that the documentation does not convincingly support the position that compost or digestate carbon will persist in the soil for 100 years.

- The second reviewer noted that the Century model seems very robust and that he otherwise had no comments on this topic.

Carbon Storage in Forests

All five reviewers commented on carbon storage in forests:

- One reviewer indicated that the modeling approach in which paper products are associated with a forest carbon offset through recycling is not common in paper recycling life cycle analysis (LCA) studies or in other waste management-based LCA models.[6] The reviewer provided a citation that suggests that carbon stocks of forests are already in equilibrium and the biological system naturally uptakes or releases emissions throughout its life, meaning there is no need to award an additional offset credit.[7]

- This same reviewer noted that further clarification regarding the lack of consensus for inclusion of forest carbon offsets when paper is recycled is needed in the background documentation and, as with the source reduction user input option (e.g., current mix versus 100T%), perhaps a similar option could be implemented in the tool (e.g., with and without forest carbon storage). This reviewer also noted that WARM users who are not well-versed in the assumptions regarding forest carbon storage (specifically, that carbon offsets contribute more than 90% of the total offsets in the model) may misinterpret the benefits associated with paper recycling relative to other waste components.

- Another reviewer noted that most forests will reach an equilibrium regarding their carbon flux, which means they are losing as much carbon as they are gaining as trees start to die. Therefore, there is a practical limit to how much forest carbon sequestration can occur as it relates to source reduction and recycling.

- This same reviewer noted that the documentation states that to create a finished wood product requires twice the amount of virgin roundwood, not 1.1 short tons/short ton finished product. The value of 1.1 would align well with mechanical pulping using virgin wood or producing recycled pulp, not wood products.

- A third reviewer noted that the forest carbon storage assumptions contradict the biogenic carbon convention established in the methodology. The reviewer feels strongly that forest sequestration credits are not appropriate for source reduction or recycling. The operating assumption is that carbon cycling that results from materials grown on a "sustainable basis" should be omitted because it "close(s) the loop in the natural carbon cycle." On this basis, carbon sequestration credits are given for

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Daniel H Cusworth et al. 2020, *Environ. Res. Lett.* 15 05401; Kormi et al., *Waste Management* (2018), 72:313-328, ISSN 0956-053X; https://doi.org/10.1016/j.wasman.2016.11.024.

[6] Anshassi, M., Townsend, T.G., 2021. Reviewing the underlying assumptions in waste LCA models to identify impacts on waste management decision making. Journal of Cleaner Production 313, 127913.

[7] Merrild, H., Damgaard, A., Christensen, T.H., 2008. Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. Resources, Conservation and Recycling 52, 1391–1398.

wood products assumed to remain in use and for bio-based carbon that is modeled to persist in a landfill (e.g., carbon that is pulled out of the natural cycle). Emissions from combustion of bio-based carbon are ignored. Those credits and that omission are possible only because carbon uptake from the natural forest stock under management is also ignored. Thus, carbon uptake should not be counted in the cradle-to-gate lifecycle of the products, and neither should it be credited when that cradle-to-gate activity is assumed to be avoided.

- This reviewer also noted that the declared scope of the WARM tool is waste management strategies for products that have already been produced. For source reduction, EPA suggests that "trees that would otherwise be harvested are left standing in forests," but this contradicts the "sustainable basis" of forest management. It is also contradicted by the literature.

- This same reviewer commented that, in the review document, EPA makes the argument that forest CO_2 content in the U.S. has steadily increased on a historical basis. While this is true, it is not relevant, because modeling this flow is outside the scope of the WARM tool. Changes in the national baseline CO_2 flux, particularly for non-sustainably managed forest, cannot be attributed to any management decisions contemplated by WARM users.

- The third reviewer also stated that the argument that source reduction results in both absolute and marginal increases in carbon emissions is doubly wrong on the "sustainable basis" of the material harvesting. Timber under sustainable management is maintained at a steady state that balances extraction with re-planting. The reduction in demand for paper products (a) does not necessarily result in a reduction in demand for timber, and (b) does not induce a long-term change in sustainable forest management.

- A fourth reviewer noted that the assumption around export values for paper (currently at 40%) is out of date given that China's National Sword policy dramatically reduced the amount of paper exported to China and dramatically increased the amount of recycled pulp exported to China from the U.S.[8,9] This means that U.S. energy use for recycling is increased by the amount of energy required to produce pulp, which includes a substantial amount of energy used for drying.

- The fifth reviewer noted that the effects of cross-border trade (especially with Canada) seem vaguely treated. The U.S. does not harvest enough softwood to meet its needs (for housing, etc.); around 80% of U.S. softwood needs are imported from Canada. The WARM methodology "counts" the carbon storage of forests as the trees grown in the U.S. This is lost after trees have been cut down or exported, but to date, replacing trees far exceeds losses. However, while imported trees yield no carbon storage benefits for the importing country (U.S.), they do represent an alternate source of wood that, according to WARM's methodology, should reduce domestic harvesting. A relatively recent study by Hertwich and Wood may help clarify the problem.[10]

Reviewer	Comments
Anshassi	The assumptions related to carbon storage in landfills were discussed initially in Question 1, to continue some of that discussion here some data on the carbon sequestration potential for

[8] Colin Staub, 2021. "Scrap paper exports jump 21% in first half of year." August 10, 2021. https://resource-recycling.com/recycling/2021/08/10/scrap-paper-exports-jump-21-in-first-half-of-year/

[9] Jared Paben, 2022. "US scrap paper exports sink slightly as plastics drop sharply." June 14, 2022. https://resource-recycling.com/recycling/2022/06/14/us-scrap-paper-exports-sink-slightly-as-plastics-drop-sharply/

[10] Edgar G Hertwich and Richard Wood (2018). *Environ. Res. Lett*. 13 104013.

Reviewer	Comments
	five waste components and several LCA models are compared (Table 2). From Table 2 it is evident that the magnitudes are relative to one another, indicating that the modeling calculation used to derive the WARM factors are within common modeling best practices. Composting and anaerobic digestion are associated with a soil carbon storage, as well as an avoided fertilizer application offset; a practice that is typically accounted for in LCA modeling of biological treatment (Goglio et al. 2015; Stanley et al. 2018).

Table 2. Data from Anshassi et al. 2021 and for landfilling.

Carbon Sequestration Potential (tCOeq./Mg)	WARM	MSW-DST	SWOLF	EASETECH
Newspaper	1.08	1.32	1.32	1.19
Cardboard	0.65	0.83	0.8	0.85
Office Paper	0.11	0.15	0.13	0.57
Yard Waste	0.49	0.45	0.61	0.33
Food Waste	0.08	0.08	0.17	0.17

Regarding the carbon storage in forests, this is modeled when paper products are recycled, in which the waste paper is used in place of virgin paper that must be harvested from trees, and since the trees are not harvested it results in an increased soil carbon storage and therefore a forest carbon offset is credited. This modeling approach, whereby paper products are associated with a forest carbon offset through recycling is not common in paper recycling LCA studies or in other waste management-based LCA models (Anshassi et al. 2021). One paper does discuss that the carbon stocks of forests are already in equilibrium and the biological system naturally uptakes or releases emissions along its life so there is no need to award an additional offset credit (Merrild et al. 2008). When reviewing the Exhibit 2-2 for recycling emissions factors it is apparent that the forest carbon offsets contribute more 90% of the total offsets. WARM users who are not well-versed in the assumptions regarding forest carbon storage (that it is not commonly practiced) may misinterpret the benefits associated with paper recycling relative to other waste components. In addition, in many cases paper products dominate the nationwide waste composition (and on a local state level), which might artificially overestimate the GHG emissions offsets from paper recycling (especially considering paper is 20-25% of the total outbound composition of a materials recovery facility). Further clarification regarding the lack of consensus for inclusion of forest carbon offsets when paper is recycled is needed in the background documentation, and like the source reduction user input option (e.g., current mix vs 100%) perhaps a similar option can be implemented in the tool (e.g., with forest carbon storage vs without forest carbon storage).

References:

Anshassi, M., Townsend, T.G., 2021. Reviewing the underlying assumptions in waste LCA models to identify impacts on waste management decision making. Journal of Cleaner Production 313, 127913.

Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., McConkey, B.G., Campbell, C.A., Nemecek, T., 2015. Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review. Journal of Cleaner Production 104, 23–39.

Reviewer	Comments
	Merrild, H., Damgaard, A., Christensen, T.H., 2008. Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. Resources, Conservation and Recycling 52, 1391–1398. Stanley, P.L., Rowntree, J.E., Beede, D.K., DeLonge, M.S., Hamm, M.W., 2018. Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems. Agricultural Systems 162, 249–258.
Bergman	Given the specific limitations on economic inputs-outputs such as on inflexibility, the following is not considered which is greater demand leads to higher prices and less purchasing and then eventually more supply and visa versus. Another limitation, most forests will reach an equilibrium in regard to their carbon flux which means that they are losing as much as carbon as they are gaining as trees age out and start to die. In a practical sense, there is a practical limit to how much forest carbon sequestration can occur on source reduction and recycling. 4.4.1. To create a finished wood product requires twice the amount of virgin roundwood, not 1.1 short tons/short ton finished product. The value of 1.1 would align well with mechanical pulping using virgin wood or producing recycled pulp, now wood products. This was similar to the issue related to the call-out box on pg. 4-2 that I noted below. I have not used USFS FORCARB II model. FPL is working on updating WoodCarb with the current USFS Northern Research Station (NRS) but FPL/NRS lack personnel and funding to update quickly as we would like.
Kuczenski	**For landfills:** Yes. For soil carbon: provisionally. The magnitude is small and it is probably directionally OK, but the documentation does not well support the position that compost OR digestate carbon will persist in the soil for 100 years. The analysis seems to use a 10-year timescale. **For forest carbon:** No; they contradict the biogenic carbon convention established in the text box in section 1.3.3. After close review and consideration, I feel strongly that forest sequestration credits are not appropriate for source reduction or recycling. The operating assumption is that carbon cycling that results from materials grown on a "sustainable basis" should be omitted because it "close(s) the loop in the natural carbon cycle." On this basis, carbon sequestration credits are given for wood products assumed to remain in use and for bio-based carbon that is modeled to persist in a landfill (e.g. carbon that is pulled out of the natural cycle), and emissions from combustion of bio-based carbon are ignored. Those credits and that omission are possible only because carbon uptake from the natural forest stock under management is also ignored. Thus, carbon uptake should not be counted in the cradle-to-gate lifecycle of the products, and neither should it be credited when that cradle-to-gate activity is assumed to be avoided.

Reviewer	Comments
	The declared scope of the WARM tool is waste management strategies for products that have already been produced (Section 1.3.2.1). For source reduction, EPA makes the suggestion that "trees that would otherwise be harvested are left standing in forests" (sections 1.2.3 and 1.4.3.1) but that is not supported and it contradicts the "sustainable basis" of forest management. It is also contradicted by the literature (see Response 6). The EPA makes the argument that forest CO_2 content in the US has steadily increased on a historical basis. This is true, but it is not relevant, and modeling this flow is outside the scope of the WARM tool. Changes in the national baseline CO_2 flux, particularly for non-sustainably-managed forest, cannot be attributed to any management decisions contemplated by WARM users. The further argument that source reduction results in both absolute and marginal increases, i.e. "increased storage of carbon .. relative to BAU baseline" is doubly wrong, on the "sustainable basis" of the material harvesting. Timber under sustainable management is maintained at a steady state that balances extraction with re-planting. The reduction in demand for paper products (a) does not necessarily result in a reduction in demand for timber and (b) does not induce a long-term change in sustainable forest management. To argue that there is a *marginal* increase in forest carbon uptake requires that (1) source reduction results in direct land use change, i.e. that forest land is removed from sustainable management and returned to wildland permanently and (2) that wild lands uptake carbon with greater efficiency than managed lands. Neither of these claims is approached by the documentation and neither of them is properly in scope. In any case, the marginal changes indicated in exhibit 4-3 are small in magnitude and inconclusive in directionality. There is also a data error in exhibit 4-3: both panels show the same data. A factual error in section 4.1: "In the early stages of growth, trees store carbon rapidly; consequently, as tree growth slows, so does carbon sequestration." https://www.nature.com/articles/nature12914/ "Rate of tree carbon accumulation increases continuously with tree size"
Realff	The assumptions on carbon storage are reasonable but the timing is very out of date as described in section 4.3. The impact of reduction of forest harvesting is not 1:1 on carbon storage because over time the forestry growth declines and so carbon storage amounts decrease, this is captured in the FORCARB II model as described in section 4.3.2. The graphs in this section, Exhibit 4-3, are indexed to 2010 which is at least 10 years out of date and by the description provided maybe 25 years from how they should be indexed. Since in 4.3.2 the statement is made: "The choice of 2020 represents a delay of about 5 to 15 years for the onset of incremental recycling, long enough to reflect the effects of the recycling program, but at a rate lower than the peak effect in 2030."

Reviewer	Comments
	I think that this has no impact on the numbers themselves, as I assume that the model has been re-indexed to 2022 rather than 2010 with regards to the storage but it would be helpful to confirm this. A much more serious issue in the way that WARM is modeling the pulp and paper industry is the assumption around export values that are embedded in Exhibit 4.2. This has an export value of 40% which is very out of date. The US recycled approximately 70 million tons a year and exported about 9 million tons. The national sword program of China has dramatically reduced the amount of paper that is sent their and dramatically increased the amount of recycled pulp that is sent there. https://resource-recycling.com/recycling/2021/08/10/scrap-paper-exports-jump-21-in-first-half-of-year/ "During the first quarter of 2022, U.S. firms exported nearly 122,000 short tons of recycled pulp, up 36% from the same period in 2021. During the first quarter of 2017, before the impacts of National Sword set in, U.S. recycled pulp exports totaled only 18,000 short tons." https://resource-recycling.com/recycling/2022/06/14/us-scrap-paper-exports-sink-slightly-as-plastics-drop-sharply/ The most important discrepancy is the export of pulp rather than the unprocessed paper. This means that the U.S. energy use for the recycling is increased by the amount it takes to produce pulp, which includes drying energy which is substantial. The change in export in e. of Exhibit 4.2 changes column (b) of Exhibit 4.4 because the reduction in timber harvest is sensitive to the total amount exported (the values of column (b) 0.58 and 0.89 come from the analysis in Exhibit 4.2.)
Theis	As the documentation makes clear, reactions within landfills are complex and, at least for microbial degradation (producing methane), take place over many years. I would say that WARM does as good a job as any capturing these complexities. There is considerable reliance on the laboratory studies of Mort Barlaz, an expert by acclamation in landfill science, but even he recognizes that such lab studies are likely to overestimate the rate of degradation in comparison with actual landfill systems. That said, it may be prudent to broaden data sources in the future to include more recent field studies (e.g., *Sustainability* 2020, 12(15), 6209; https://doi.org/10.3390/su12156209*; Environ Sci Pollut* Res 29, 24623–24638 (2022). https://doi.org/10.1007/s11356-021-17566-4, *Waste Management* (2019), 87:835-859,ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2018.12.047; Daniel H Cusworth et al 2020 *Environ. Res. Lett.* 15 05401; Kormi et al., *Waste Management* (2018), 72:313-328, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2016.11.024). I have no comments on the way carbon is stored in soils. The Century model seems very robust. WARM developers understand that forest systems are ecologically and economically complex. The main issue I see is that the effects of cross-border trade (especially with Canada) seem vaguely treated. The US does not harvest enough softwood to meet its needs (for housing,

Reviewer	Comments
	etc.); around 80% of US softwood needs are imported from Canada. This is an allocation problem of the sort that arises often in life cycle assessment studies when international borders are involved. The WARM methodology "counts" the carbon storage of forests as the trees are grown in the US. This is lost after trees have been cut down or exported but to date replacing trees far exceeds losses. However, while imported trees yield no carbon storage benefits for the importing country (US), they do represent an alternate source of wood that, according to WARM's methodology, should reduce domestic harvesting (is this actually the case?). A relatively recent study by Hertwich and Wood may help clarify the problem (Edgar G Hertwich and Richard Wood (2018) *Environ. Res. Lett*. 13 104013).

3.3 Are the assumptions made in WARM regarding utility offsets from combustion scientifically sound and in line with common modeling best practices?

One reviewer indicated that the modeling appears scientifically sound, though referenced concerns described in response to Questions 4 and 5. A second reviewer indicated that the approach is commonly accepted in LCA practice. A third reviewer stated that the methodology for calculating the utility offsets from combustion is scientifically sound, but fraught with difficulties regarding determining the "non-base load power plants" and the actual CO_2 footprint of the displaced generation by combustion; this reviewer recommended that the definition of "non-baseload" be modified to exclude any renewable power generating assets that might have capacity factors in the 20% to 80% range and that the documentation be improved to clarify how often the CO_2e is updated and how the regional variations in power grids are accounted for.

Noting that combustion was not within his area of expertise, a fourth reviewer point out that while textiles, rubber, and leather contribute to the waste-to-energy greenhouse gas (GHG) emissions, these materials aren't listed among the 61 materials included as municipal solid waste (MSW). The reviewer assumes this is because these materials make up a diminishingly small fraction of MSW but have significant energy value for waste-to-energy (WTE) facilities.

The fifth reviewer, who is familiar with wood combustion technology but not WTE technology, suggested using a different fuel value calculator. While Basswood (Tilia americana) is a relatively soft wood, it is a hardwood. Dimensional lumber is from softwoods species like southern pine and Douglas fir. The reviewer suggests using the softwood value in the U.S. Department of Agriculture (USDA) Fuel Value Calculator for dimensional lumber and hardwood for wood flooring (17.2 million BTUs/ton or 20.9 MJ/OD kg, respectively).[11]

Reviewer	Comments
Anshassi	Referring back to Christensen et al. 2009, there are two modeling structures for energy substitution: 1) assumes that biogenic carbon is neutral when combusted, fossil carbon counts towards emissions when combusted, and the utility offsets are only from fossil carbon sources (because the biogenic sources have a neutral impact on energy substitution); and 2) assumes biogenic and fossil carbon sources both count as an emission when combusted and the utility offsets come also from both the biogenic and fossil carbon sources. Currently WARM assumes the biogenic carbon sources are neutral when combusted, the fossil carbon sources do count

[11] Bergman, Richard D.; Bowe, Scott A. 2008. Environmental impact of producing hardwood lumber using life-cycle inventory. Wood and Fiber Science 40(3) (2008): 448-458. https://www.fs.usda.gov/research/treesearch/31113

Reviewer	Comments
	as an emission, and the utility offsets come from both fossil and carbon sources. It is slightly unclear whether this approach is scientifically sound when using Christensen et al. 2009 findings as a reference because of the five criteria evaluated by the authors did not include the approach modeled in WARM. Yet when comparing WARM's approach to other peer-reviewed literature it becomes clear that this approach is commonly accepted in LCA practice (e.g., more than 10 out of 14 studies reported utility offsets originating from both fossil and carbon sources, and many only accounted for emissions from fossil carbon sources during combustion (Anshassi et al. 2021)). References: Anshassi, M., Sackles, H., Townsend, T.G., 2021. A review of LCA assumptions impacting whether landfilling or incineration results in less greenhouse gas emissions. Resources, Conservation and Recycling 174, 105810.
Bergman	I am not familiar with waste-to-energy combustion technology but with wood combustion technology. Basswood (Tilia americana) is a relatively soft wood but it is a hardwood. Dimensional lumber is from softwoods species like southern pine and Douglas fir. Using the Fuel Value Calculator, I would suggest using the softwood value for dimensional lumber and hardwood for wood flooring or simply 17.2 million BTUs/ton or 20.9 MJ/OD kg what was pulled from Bergman and Bowe (2008). Bergman and Bowe (2008) has a new URL, Bergman, Richard D.; Bowe, Scott A. 2008. Environmental impact of producing hardwood lumber using life-cycle inventory. Wood and Fiber Science 40(3) (2008): 448-458. https://www.fs.usda.gov/research/treesearch/31113 Fuel Value Calculator https://www.fpl.fs.usda.gov/documnts/techline/fuel-value-calculator.pdf
Kuczenski	The modeling appears sound, with concerns as noted in Questions 4 and 5.
Realff	The assumption of using the marginal "non-baseload" energy producer on the grid is reasonable but makes the analysis significantly more complex and subject to a high degree of variability based on regional grid markets. To quote the definition of non-baseload 'All power plants with capacity factors below 20% are considered "non-baseload". Plants that run at over 80% capacity are considered "baseload" generation and not considered the "non-baseload"; a share of generation from plants that run between 80% and 20% capacity is included based on a "linear relationship". ' I understand this definition in concept, but I am not sure how it was implemented, or what the final grid carbon intensity was for the WARM model and how that varies by region. There are two particular concerns.

<table>
<tr><th>Reviewer</th><th>Comments</th></tr>
<tr><td></td><td> First, the grid make up has changed significantly over the past decade and it is not clear what grid generation profile WARM uses. This is a concern because much of the modeling and data used in WARM is over a decade old and this would dramatically change the assumed grid marginal intensity.
The biggest issues here are

in some states at some times the marginal generation might be from NG combustion turbines which have a very high CO_2 footprint
almost all renewables will have capacity factors between 20-80% because of the nature of solar and wind generation, but these would not be displaced from the grid because they are non-dispatchable and once built the cheapest sources of electricity. These have very low carbon intensity and their inclusion would distort the CO_2 footprint of the "non-baseload" in the opposite direction. Renewables should always be considered baseload.

Second, the documentation here is quite opaque. Section 3.2 details the Periodic Updates made to WARM data which include the state electricity grid emission factors from eGRID database but also "various aspects of the U.S. average electricity mix" which is quite vague. How often are these periodic updates applied?
Thus, overall, I think the methodology for calculating the utility offsets from combustion is scientifically sound but fraught with difficulties of determining the "non-base load power plants" and the actual CO_2 footprint of the displaced generation by combustion. I think that the definition of "non-baseload" should be modified to exclude any renewable power generating assets that might have capacity factors in the 20-80% range. The documentation should be improved and specifically the "Periodic Updates" should be clarified as to how often the CO_2e is updated and how the regional variations in power grids are accounted for. </td></tr>
<tr><td>Theis</td><td>Combustion is not my area of expertise but reading Chapter 5 of the "Management Practices" document on WTE options, I find few inconsistencies in reasoning or data evaluation. The main thing that is a bit puzzling is the inclusion of contributions of textiles, rubber, and leather to WTE GHG emissions, yet these appear to not be listed among the 61 materials included as MSW (exhibit 1-1 in "Background"). I assume this is because these materials make up a diminishingly small fraction of MSW but have significant energy value for WTE facilities.</td></tr>
</table>

3.4 In general, do the data, assumptions and model components in WARM align with real market practices?

Two reviewers said that while data and assumptions used in the model generally do align with real market practices, they had several concerns.

- One of these reviewers noted that, based on existing recycled market trends, the recycling input ratios may be high for plastic. For example, one study reported 1 kg of waste polyethylene terephthalate (PET) bottles produced 0.68 kg of bottle-grade PET[12], which is lower than what is used in WARM.

- This same reviewer pointed out that the modeling assumptions for metals recovery from municipal solid waste incineration (MSWI) facilities in WARM only account for the steel or ferrous fractions and neglect the nonferrous fractions (e.g., copper, aluminum). Although an estimate for the fraction of nonferrous metals recovered is not easily available in public reports[13], many U.S. MSWI facilities do recover nonferrous metals from the MSWI ash. The impacts of metals recovery, especially aluminum, greatly influences the net GHG emissions and energy use footprints for waste incineration and should be included in WARM.

- The second reviewer suggested that EPA note the changing policy landscape for waste management, particularly at the state level. For example, Extended Producer Responsibility (EPR) laws, plastic bag fees or taxes, container deposit/return laws, right-to-repair requirements, and composting regulations are increasingly implemented at the state level. While early EPA laws focused on specific products such as pharmaceuticals, batteries, paint, and carpet, many states are now considering far more general EPR approaches, among them California, Hawaii, Maryland, Massachusetts, and New York.[14] Such laws are likely to alter waste management pathways as new business models are developed. For example, "Right-to-Repair" and EPR laws may extend material usage in the original product, limiting secondary uses.

A reviewer commented that the answer to this charge question depends on the specific commodity being examined because market conditions for commodities like paper, electronics, and carpet are much different today than in 2010 (or earlier, depending on the data sources used). For example:

- The recycling market for paper/cardboard has changed due to the China National Sword program, which has dramatically cut the export of waste paper/cardboard from the U.S. to China. As a result, the export market has shrunk significantly, which changes model output.

- The assumptions around electronics recycling seem to ignore the recovery of active packaged electronic components from circuit boards through disassembly. These components have significant economic value in reuse but also have significant carbon footprints because of the energy intensity of active silicon chip manufacturing. This scenario is part way between electronics reuse, where the product as a whole is reused, and recycling of circuit boards by thermal treatment; this deserves further attention.

- The carpet and carpet recycling market have evolved significantly since 2010, when the last study of this topic was included in WARM.

Another reviewer indicated that, while WARM is generally consistent and of high quality, it is also subject to tremendous technical and institutional constraints because it is the product of a decades-long public-private collaboration. As a result, it deviates from scientific best practices in a number of important ways, including

[12] Haupt, M., Kägi, T., Hellweg, S., 2018. Life cycle inventories of waste management processes. Data in Brief 19, 1441–1457.
[13] Michaels, T., Krishnan, K., 2018. Energy Recovery Council 2018 Directory of Waste-to-Energy Facilities. Energy Recovery Council.
[14] The National Law Review, Volume XII, Number 160, June 9, 2022.

report modeling inputs with a low degree of precision. The reviewer made several specific recommendations for improvement, as detailed in the reviewer's written comments.

Reviewer	Comments
Anshassi	The data and assumptions used in WARM do align, generally with real market practices in the US. There are some concerns with the recycling and combustion assumptions, and this is described below. As materials are transformed into secondary feedstocks for new product manufacture the extent that the non-virgin material can replace virgin material is influential when modeling recycling. This process can be referred to as the recycling input ratio, which describes how much product can be made from one ton of recycled material (non-virgin material). In WARM this ranges from 0.66 (e.g., office paper) to 0.98 (e.g., glass, steel cans), however most materials are in the 0.9-1 range, which indicates most of the recycled material can be utilized in the manufacture of a new product. Based on existing recycled market trends this value may be high for certain products, namely plastic, for example Haupt et al. 2018 reported 1 kg of waste PET bottles produced 0.68 kg of bottle-grade PET (see SI spreadsheet for PET bottles). While for other products the WARM assumptions match closely (e.g., 1 kg cardboard waste produces 0.96 kg secondary cardboard fibers, 1 kg aluminum waste produces 0.94 kg secondary aluminum (Haupt et al. 2018). The modeling assumptions for metals recovery from municipal solid waste incineration (MSWI) facilities in WARM only account for the steel or ferrous fractions and neglect the nonferrous fractions (e.g., copper, aluminum). Although an estimate for the fraction of nonferrous that are recovered is not easily available in public reports (Michaels and Krishnan 2018), many US MSWI facilities do recover nonferrous metals from the MSWI ash. The impacts of metals recovery, especially aluminum, greatly influences the net GHG emissions and energy use footprints for waste incineration and should be included in WARM. References: Haupt, M., Kägi, T., Hellweg, S., 2018. Life cycle inventories of waste management processes. Data in Brief 19, 1441–1457. Michaels, T., Krishnan, K., 2018. Energy Recovery Council 2018 Directory of Waste-to-Energy Facilities. Energy Recovery Council.
Bergman	For source reduction (e.g., light-weighting), dimensional lumber and wood pallets are two wood products that are bought primarily on their price points of which dimensional lumber from softwood species being a commodity product. In doing so, dimensional lumber requires certain physical properties for building construction safety. For wood pallets, while technology drives source reduction of their raw material, trees to produce a pallet but just with the requested (tight) specifications. The backend of reusing less raw materials makes building a recycled/repaired/remanufactured pallet harder considering the new pallets are less robust.

Reviewer	Comments
Kuczenski	The WARM tool is the product of a decades-long public-private collaboration, comprising incremental revisions on top of a "legacy" core. Although it is generally consistent and of high quality, it is also subject to tremendous technical and institutional constraints. Thus there are a number of important ways that it deviates from scientific best practices. Significant figures are dealt with poorly. The tool's convention is to report numbers in fixed notation on a per-ton or per-metric-ton basis. This results in a great many exhibits with a single significant figure, or even an order of magnitude with zero significant figures (e.g. "0.01"). This is the least-precise statement of value possible. This could be reasonable if the value reported in the table is an approximation of a more precise value used in calculations, but in all cases that I tested the low-precision value generates the exact results being reported. It may be suitable to report results with low precision, given the high uncertainties, but model inputs (especially assumptions) should generally not be reported in this way. Examples: • Background; exhibit 5-1, 0.01 gallons per ton mile • Management; exhibit 3-3, etc., Transportation EFs, throughout • Management; exhibits 3-12 through 3-16. In order to maintain the preference for fixed rather than scientific notation, these could be reported as kg, rather than tons. • Management; exhibit 6-14 (a) (c) and (e) • Others SI units should be used. The EPA's reliance on "short tons", ton-miles etc is understandable given the tool's intended user base, but BTUs should be retired from use. Stop using BTUs. This will undoubtedly be a long and challenging adjustment for the agency. Start now. Exhibit 1-1 shows that many material system models are old, some quite old. Barlaz 1998 as a basis of material degradation in landfills (Management ch 6) is 25 years old and anecdotal. Consideration of a second source would be appropriate. Because of the tremendous importance of this factor for carbon cycling (both for methane /biogas generation and carbon sequestration), some effort should be spent to validate the findings in actual landfills. Background; Exhibit 5-1. 0.01 gallons per ton mile is too low. By my reckoning on USLCI processes for short haul trucks, fuel use ranges from 0.014--0.037 gal/ton-mile, with the lower bound being diesel, combination and the higher bound being gasoline, single unit. A single digit of precision should be a conservative estimate; therefore at least 0.02. For recycling, 1.2.3 the assumption that "the GHG emissions from making an equivalent amount of material from virgin inputs are avoided" is a strong assumption and is almost never appropriate (DOI: 10.1111/jiec.12557). A discussion of this assumption should be provided. Perhaps the tool should report results for recycling at 50% displacement and 100% displacement of primary production.

<table>
<tr><th>Reviewer</th><th>Comments</th></tr>
<tr><td></td><td>Several emission factors are not specified, e.g.
Management; exhibit 3-12
Please report fixed emission factors explicitly wherever they are used.
Background Section 1.3.1. "Goal definition and scoping" The term that is universally used is "goal and scope definition." I suppose this paragraph predates ISO 14044.

Management Section 3.2.1 - methane yield should be reported in mass, and not volume, to be consistent with the other entries. Especially since mass is used later in exhibit 3-5. Volume of a gas requires a specification of temperature and pressure to be meaningful.</td></tr>
<tr><td>Realff</td><td>The answer to this question depends on the specific commodity being examined. I am not an expert on most of the commodities handled in WARM but in reading the documentation there is one general concern which is the age of the data and the assumed practices. In most cases the assumptions date back to the early 2000's with some updates to 2010. For some commodities this is likely to be a reasonable assumption but for others the situation around recycling markets and practices will have changed significantly over the last decade. The macro-picture is that China is no longer accepting as much material for recycling across a broad swath of commodities, and particularly paper and plastic. This changes the export percentages of these commodities which feeds through to the carbon footprint because more material is retained in the U.S. for use.

The three commodities with which I am familiar, paper, electronics and carpet there are some differences in the market conditions today compared to the last time WARM was updated.
Paper – as mentioned in the response to Q2, the recycling market for paper/cardboard has changed due to the China National Sword program which has dramatically cut the export of waste paper/cardboard to China. As a result the export market has shrunk significantly and this does change the results as indicated in Q2.
Electronics – the assumption around electronics recycling seems to ignore the recovery of active packaged electronic components from circuit boards through disassembly. These components have significant economic value in reuse but also have significant carbon footprints because of the energy intensity of active silicon chip manufacturing. This scenario is part way between electronics reuse where the product as a whole is reused and recycling of circuit boards by thermal treatment. This deserves further attention.
Carpet – unfortunately the carpet market and the carpet recycling market has evolved significantly since 2010 when the last study of this topic was included in WARM.

"Carpet is collected curbside and at special recovery events, or individuals can bring it to designated drop-off sites." This is not how most carpet is recycled today. A very large fraction of recycled carpet is recycled because of programs in California. A very large fraction of this carpet is collected at retailers in designated containers that are then picked up by the recycler. There is some additional collection at drop-off sites for individual consumers in the more sparsely populated areas and where recyclers in</td></tr>
</table>

Reviewer	Comments
	general do not operate. I would say that no carpet is collected curbside and none at special recovery events. "Exhibit 3-6: Residential Face Fiber Mix 1995-2000 Plastic Resin." This was true over this time period. The current mix of residential face fiber is VERY different today compared to this period. PET has become over 50% of the residential face fiber market and PP has shrunk along with N66. N66 is now 10% of the market in the residential space and N6 holds roughly where it was before. This dramatically changes the displaced carpet fiber carbon intensity since PET is a much less carbon intensive fiber than N66 and has significantly less associated emissions in the process. "Exhibit 3-13: Secondary Resins Produced from Recycled Carpet Fibers." Unfortunately, this information is very out of date as to what happens to recycled carpet because of changes in the industry. Much less N6 is recycled to fiber because the Evergreen recycling facility closed down. That which is recycled is transported to Europe by Aquafil so the transportation is much longer, but the recycling process is likely much less energy intensive due to the process changes. However, this would mean that from a WARM perspective this should be treated as exported N6 fiber and excluded from the model. The other sectors have grown significantly, particularly the production of PET pellets and the use of PET as a supplement in gasification. There is a lot of information available on the California program because of its mandated nature. Carpet recycling outside of CA is modest today, and if it were to increase it would likely follow a similar path as it has in CA. I would use the report on the CA program as a starting point to update the WARM model. https://carpetrecovery.org/wp-content/uploads/2022/09/2021_CA_AnnualReport_ADAcompliant_FINAL.pdf Table 4.9 on p28 of this report has the information on recycling yield. What should be noticed is that the vast majority of the recycled material is either polymer used in products as a resin or depolymerized, or the calcium carbonate from the backing. The depolymerization is a modest component of the market compared to the use of fiber in carpet underlay or as an engineered resin and depolymerization requires the export of the fiber.
Theis	In general, yes, WARM includes the major pathways and materials for a robust analysis of GHG emissions associated with solid waste management and uses current data (such as emission factors) to generate GHG emissions (however note the need to explore the inclusion of consumer behavior in Q7). Note should be taken of the changing policy landscape for waste management, mostly at the State level. Federal actions on waste management have often been supplemented and in many cases extended through State initiatives. These have taken a variety of forms, including Extended Producer Responsibility (EPR) laws, plastic bag fees or taxes, container deposit/return laws, right-to-repair requirements, and composting regulations. Most of these laws have been enacted to address a particular kind of waste problem; holistic approaches for

Reviewer	Comments
	waste management are still elusive. Nevertheless, there is still considerable activity in the regulatory area that is aimed at "closing the loop" and reducing waste generation. Two policy shifts, in particular, may significantly extend product and material utility: (1) "Right-to-Repair" laws have proliferated rapidly at the State level, driven in part by the desire, in some cases, to open markets for local repair shops and spur competition for large manufacturers, and (2) Extended Producer Responsibility (EPR) laws have also proliferated. EPR legislation places the responsibility for the disposition of products at end-of-life on producers, manufacturers, and retailers. In this sense EPR comes closer than most waste management laws to "circularizing" the economy since all stages of the product life cycle are included. Initially most EPR laws have been limited to specific products such as pharmaceuticals, batteries, paint, and carpet. Yet many states are now considering far more general EPR approaches, among them California, Hawaii, Maryland, Massachusetts, and New York (The National Law Review, Volume XII, Number 160, June 9, 2022). Such laws are likely to alter waste management pathways as new business models are developed, for example "Right-to-Repair" and EPR laws may extend material usage in the original product, limiting secondary uses.

3.5 Please comment on any ways to improve the clarity, transparency, relevance and usability of WARM and its documentation.

A reviewer commented that the WARM documentation is well organized, clear, and provides information for both laymen and highly technical users, but also noted that more transparency is needed concerning why certain assumptions were not incorporated into the WARM model. Specifically: 1) the landfill construction, operation, closure, and post-closure emissions and energy usage are not explicitly stated as modeled even though they have been reported to contribute to global warming[15]; 2) the landfilled lifetime (e.g., 20 to 30 years) is not reported; 3) there is no documentation regarding the type of engine used for the landfill gas-to-energy facility; 4) data are not reported for MSW incinerator facility lifetime, for any emissions from facility construction, or for ancillary chemicals (e.g., activated carbon, lime, ammonia); and, 5) there are no data related to the emissions associated with construction and operation of a materials recovery facility.

This same reviewer also recommended that EPA: 1) add a discussion concerning how WARM can and cannot be used to meet certain LCA standards (per ISO 14040 and 14044); and 2) clarify that although WARM does not provide a full LCA, it can still be used as a tool to create a waste management-focused LCA study that can comply with the ISO framework.

Another reviewer wrote that, overall, the documentation and spreadsheet model are clear and easy to use. The methodology is transparent, except for the way the model handles the offsetting WTE emissions. Specifically, the model allows selection of a different region but does not display the non-baseload CO_2e of the electricity being displaced. This is not documented anywhere as it is subject to periodic updating.

[15] Wang, Y., Levis, J.W., Barlaz, M.A., 2021. Life-Cycle Assessment of a Regulatory Compliant U.S. Municipal Solid Waste Landfill. Environ. Sci. Technol. 55, 13583–13592.

This same reviewer noted that, because the model data are outdated, it is not clear how relevant some of the GHG studies are for operations occurring today. First, many of the Franklin Associates life cycle inventory (LCI) studies were done in the late 1990s. The composition of the U.S. electricity grid energy mix has changed substantially since that time and likely the carbon footprints of source reduction and recycling would be different as a result. Second, the recycling processes themselves have changed for some commodities due to new investments (e.g., carpets, electronics). Finally, the export markets for commodities such as paper and plastics have changed dramatically due to the implementation of the National Sword policy in China; this has changed the destination of exported commodities and also reduced the total amount of material exported.

A third reviewer suggested that EPA consider adding products such as biochar to assess from a waste management perspective. The USDA Forest Service is moving toward using wood material from forest restoration activities to make biochar to be spread back on the forest floor and there is huge potential for carbon storage from the recalcitrant part, with the carbon stored for hundreds of years. The reviewer also noted that, in general, sources or tools (especially for wood/forests) tend to be somewhat dated.

A fourth reviewer noted that the radio buttons for questions 4, 5, 6, 7, 8, and 9 on the data entry tab do not function in LibreOffice and recommended that a drop-down field using data validation be used instead. This reviewer also provided detailed feedback on potential refinements to the WARM documentation, including omit repetitive statements or make them identical when used; correct and improve pagination and chapter numbering to better facilitate document navigation; omit unnecessary methodological details; and edit text for typographical errors and to ensure internal referencing is correct.

The fifth reviewer found the Excel version of WARM relatively straightforward to use and noted that the documentation is extensive. However, the reports WARM generates do not help the user interpret the results. This could be addressed via an extensive, searchable glossary or index to improve transparency and/or by embedding short videos illustrating both inputting and outputting information to/from WARM. This might include case studies that provide interpretation of results. The reviewer noted that he had provided additional comments regarding clarity in response to Question 9.

Reviewer	Comments
Anshassi	WARM documentation is well organized, clear, and provides information for the laymen, as well as informs any highly technical users. However, more transparency describing why certain assumptions were not incorporated into WARM is needed. Specifically: 1) the landfill construction, operation, closure, and post-closure emissions and energy usage are not explicitly stated as modeled even though they have been reported to contribute to global warming (Wang et al. 2021); 2) the landfill lifetime (e.g., 20-30 years) is not reported (is this assumed to be the 56 years of operation from the 2014 monte carlo report?); 3) what type of engine is used for the landfill gas-to-energy facility?; 4) the municipal solid waste incinerator facility lifetime, any emissions from the construction of the facility, and ancillary chemicals (e.g., activated carbon, lime, ammonia) is not reported; and 5) what are the emissions associated with construction and operation of a materials recovery facility (MRF). In addition, some supplementary discussion relating to how WARM can and cannot be used to meet certain LCA standards (per the International Organization for Standardization (ISO) 14040 and 14044) in the "WARM Background and Overview" pg 1-4 would be useful to users. Specifically add clarification that although WARM does not provide a full LCA it can still be used as a tool, to some extent, to create a waste management focused LCA study that can comply with the ISO framework. Essentially, just because WARM is a streamlined LCA does not negate

Reviewer	Comments
	its usefulness as a tool and source of data for a GHG emissions or energy use focused ISO complacent LCA study. References: Wang, Y., Levis, J.W., Barlaz, M.A., 2021. Life-Cycle Assessment of a Regulatory Compliant U.S. Municipal Solid Waste Landfill. Environ. Sci. Technol. 55, 13583–13592.
Bergman	WARM could consider adding additional products such as biochar from their waste management perspective. The USDA Forest Service is moving to utilizing wood material from forest restoration activities to make biochar and likely field spread back on the forest floor (Bergman et al. 2022). There is huge potential for carbon storage from the recalcitrant part with the carbon stored for hundreds of years. In general, sources or tools especially for wood/forests tend to be somewhat dated. I am not able to help out because of my own priorities.
Kuczenski	**On the tool:** The "radio buttons" for questions 4, 5, 6, 7, 8, 9 on the data entry tab do not function in LibreOffice. A drop-down field using data validation (i.e. same as what is used in Question 3) is well standardized and should be used instead. **On the documentation:** Remove repetition, especially when the repeated versions slightly differ. Examples: Management Practices document provides a complete description of anaerobic digestion, composting, landfilling, combustion; yet these impact tables are all repeated in the materials-specific documents. They should only be reported once. This will make the documentation more concise and less prone to self-contradiction. The utility offset mechanism is documented three times in the Management PDF: section 3.2.4, section 5.2.4, and section 6.2.5. In all three cases it is presented differently; section 3.2.4 uses only national grid factors instead of regional ones; the chapter 5 and 6 presentations are totally different (e.g. MT CO_2E/Million BTU versus kg CO_2e/kWh). This should be done once, in a dedicated chapter, not repeated, and then used consistently in all cases where waste-derived energy is used to offset grid emissions (and not re-reported). The pagination is inconvenient and/or incorrect. Pages 1-1 through 1-4 appear THREE times in the Background document. • Consecutive page numbering (e.g. conventional, starting from p.1 through p.87) would improve usability over the current 1-1, 5-1, 7-1 etc. • different volumes should be labeled, e.g. A-G or I-VII or 1-7, so that reference to e.g. "the Landfill chapter" could be made unambiguously.

Reviewer	Comments
	• alternatively, chapters could be numbered sequentially so that there is only one Chapter 1; Management Practices "Source Reduction" would start as Chapter 7 (after Backround Chapter 6 "Production and End of Life Impacts") and so on. Having 7 different "Chapter 1"s is annoying. Small methodological details are presented in peculiar ways, e.g. • Exhibit 1-2 for Newsprint, "For the carbon sequestration portion of the factor, it was assumed that the paper was all mechanical pulp." Why does this belong here? Carbon sequestration is not discussed in any other table entries • 1.4.1.1 Recycling processes "generally require less energy" is generally true but not universally true, and is irrelevant and distracting. Simply say that for recycling, the impacts of recycling are compared against the impacts of primary production. • 4.2.3 starting with "The Oregon DEQ study..." the emission factor of 0.03 MT CO_2e/ton does not follow from the provided citation; in any case, home+garden composting does not appear to be in scope so why is it even mentioned? The editing is sloppy throughout and should be proof-read. • Section 3.2.7 "see section 2.4 in the Composting chapter" but Composting is chapter 4. Did they mean Section 4.4 or section 4.2.4? • Anaerobic Digestion Chapter 3 comes before Composting Chapter 4, but refers to Composting repeatedly- maybe Composting should come first? • Section 4.2.4 refers to Section 4.2.4 • Typo in exhibit 4-5 • Background exhibit 4-3 is wrong • Numerous other editorial/ minor issues
Realff	Overall, the structure of the documentation and the spreadsheet model are clear and the spreadsheet is ease to use. The documentation follows a set path for each recycled commodity and as a result is easy to follow. The main criticisms of the model have been presented in the responses to Q1 to Q4. I will summarize them here. Clarity and transparency – most of the documentation is very clear and the methodology transparent, there is one point where it is not clear. • the way the model handles the offsetting emissions from waste-to-energy is not transparent. The model allows selection of a different region but does not display the non-baseload CO_2e of the electricity being displaced, nor is this documented anywhere as it is subject to periodic updating.

Reviewer	Comments
	Relevance – the data used in the model is often very out of date. It is not clear how relevant some of the GHG studies are for operations today for several reasons. • First, many of the LCI studies completed by Franklin Associates were done in the late 1990's. The composition of the energy mix for the U.S. electricity grid has changed substantially during this time period and likely the carbon footprints of source reduction and recycling would be different as a result. • Second, the recycling processes themselves have changed for some commodities due to new investments. This has been pointed out for carpet and electronics. • Third, the export markets for commodities such as paper and plastics have changed dramatically due to the implementation of the National Sword policy in China. This has changed the destination of exported commodities but also reduced the total amount exported.
Theis	Managing solid waste is complicated, and so is WARM. The documentation is extensive as one would expect. I fiddled around with the Excel version supplied and found it relatively straightforward to use. I input simple scenarios (baseline landfilling vs recycling) for one commodity at a time. I was initially puzzled by some of results that showed an absolute value for recycling that was greater than landfilling. If I am comparing the two results that says to me that recycling either sequestered GHGs or more likely displaced products that would have been manufactured from virgin resources, generating a negative GHG value. Cool! The output spreadsheets were OK, but the reports that were generated do not explain much—for instance how to interpret a negative value. This kind of result might send users into the hundreds of pages of documentation to find answers. One way to address this might be an extensive, and searchable, glossary or index. Not fun to do, but it might improve transparency. Another approach, which we have used in our group for software usability, is to embed short videos illustrating both inputting and outputting information to/from WARM. This might include case studies that include the interpretation of results. Other suggestions for clarity are contained in Q9.

3.6 Please suggest any applicable studies or data sources not currently used in WARM that could be useful.

Reviewers provided over 20 references in response to this question on topics including forest carbon sequestration and accounting, wood products as sources of carbon storage, displaced primary production of aluminum from recycling, recent data on carpet recovery, information on paper exports, carpet and paper recycling, information related to methane emissions from natural gas flares, and developments to use pyrolysis for plastics recycling. Two reviewers noted that additional references were provided in response to other charge questions.

A reviewer noted that one reference he suggested supports the contention that change in forest carbon sequestration are equivalent to changes in land use, and thus out of scope for WARM. Another reviewer suggested that EPA consider carbon storage in wood pallets as another carbon storage source, noting that, like residential buildings, wood pallets make up most (approximately 90%) of their individual markets in the United States and that there currently are 1.8 billion U.S. wood pallets in circulation.

Reviewer	Comments
Anshassi	Please refer to the other questions and the referenced literature.
Bergman	For U.S. wood pallet sector, LCI datasets were developed both for new and reuse/recycling/repair. Given the viewpoint on the decisions made by WARM, I suggest considering another carbon storage source, the carbon storage in wood pallets. Like residential buildings, wood pallets make up most, ~90% of their individual markets in the United States. They are currently 1.8 billion U.S. wood pallets in circulation. 1. Alanya Rosenbaum, Sevda; Bergman, Richard; Gething, Brad; Mousavi Avval, Seyed Hashem. 2022. Life cycle assessment of the wood pallet repair and remanufacturing sector in the United States. Biofuels, Bioproducts and Biorefining. 16(5): 1342-1352. https://doi.org/10.1002/bbb.2379. https://www.fs.usda.gov/research/treesearch/64847 2. Alanya-Rosenbaum, S.; Bergman, R.D.; Gething, B. 2021. Assessing the life-cycle environmental impacts of the wood pallet sector in the United States. Journal of Cleaner Production. 320: 128726. https://doi.org/10.1016/j.jclepro.2021.128726. https://www.fs.usda.gov/research/treesearch/63069 3. Alanya-Rosenbaum, Sevda; Bergman, Richard D. 2020. Cradle-to-grave life-cycle assessment of wooden pallet production in the United States. Res. Pap. FPL-RP-707. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 82 p. https://www.fs.usda.gov/research/treesearch/61866 For engineered wood flooring, 1. Bergman, Richard D.; Bowe, Scott A. 2011. Life cycle inventory of manufacturing prefinished engineered wood flooring in eastern U.S. with comparison to solid strip wood flooring. Wood and fiber science 43(4): 421-441. https://www.fs.usda.gov/research/treesearch/39777 2. Bergman, Richard D.; Bowe, Scott A. 2011. Life-cycle environmental performance of renewable building materials in the context of residential construction : phase II research report : an extension to the 2005 phase I research report. Module N, Life-cycle inventory of manufacturing prefinished engineered wood flooring in the eastern United States. Seattle, WA : Consortium for Research on Renewable Industrial Materials (CORRIM) , 2011: viii, 47 p. https://www.fs.usda.gov/research/treesearch/40833 For biochar pellets, 1. Bergman, Richard; Sahoo, Kamalakanta; Englund, Karl; Mousavi-Avval, Seyed Hashem. 2022. Lifecycle Assessment and Techno-Economic Analysis of Biochar Pellet Production from Forest Residues and Field Application. Energies. 15(4): 1559.

Reviewer	Comments
	https://doi.org/10.3390/en15041559. https://www.fs.usda.gov/research/treesearch/63852 For reclaimed/recovered wood (softwood lumber and wood flooring) from old buildings for reuse 1. Bergman, Richard D.; Falk, Robert H.; Gu, Hongmei; Napier, Thomas R.; Meil, Jamie. 2013. Life-cycle energy and GHG emissions for new and recovered softwood framing lumber and hardwood flooring considering end-of-life scenarios. Res. Pap. FPL-RP-672. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 35 p. https://doi.org/10.2737/FPL-RP-672
Kuczenski	**On Tree growth:** https://www.nature.com/articles/nature12914/ "Rate of tree carbon accumulation increases continuously with tree size" **On displaced primary production by recycling:** -DOI 10.1111/jiec.12557 "Toward Estimating Displaced Primary Production from Recycling: A Case Study of U.S. Aluminum" -DOI 10.1111/jiec.12355 "Common Misconceptions about Recycling" **On Forest Carbon Sequestration:** -10.1111/gcbb.12016 "Approaches for inclusion of forest carbon cycle in life cycle assessment – a review" "To capture the dynamic nature of forest carbon stocks, a reference situation for forest land use has to be defined appropriately, consistent with the goal and scope of the study. On the basis of the review it can be concluded that the reference situation should be natural relaxation in attributional LCA and alternative land use in consequential LCA." This supports the contention that changes in forest carbon sequestration are equivalent to changes in land use, and thus out of scope for WARM. https://doi.org/10.3389/fbuil.2021.729096 "Embodied GHG Emissions of Wooden Buildings—Challenges of Biogenic Carbon Accounting in Current LCA Methods" meta-analysis.. main point is to show that the literature is inconsistent and often wrong - 10.1080/10549811.2013.839386

Reviewer	Comments
	"Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests" Pretty useful article; it does not support the 'source reduction = CO_2 credit' approach "Even harvesting for inefficient products or wood energy that create an initial net CO_2 loss (Figure 7b) can sequester more CO_2 in the combination of products, wood energy, and forest than in the unharvested forest provided the stand regrows long enough" "The greatest CO_2 and FF savings from wood use are by avoiding the excess FF energy used to make steel and concrete structures (avoidance pathway)." "If catastrophic fires do not occur and forest regrowth after harvest is not considered, saving CO_2 by not harvesting the forest growth is slightly more efficient than harvesting just for wood energy—but generally less efficient than harvesting for construction products. This efficiency of CO_2 storage in unharvested forests also assumes none of the wood blows over or otherwise rots in the forest—an unrealistic assumption in most of the world." -10.1007/s11367-013-0597-x "A comparison of the GHG emissions caused by manufacturing tissue paper from virgin pulp or recycled waste paper" Establishing relevance: "Thus, the future of forest lands is directly linked to the production of paper, given that 40–42 % of all wood harvested globally for industrial use is used by the sector" Not until the discussion do they mention this key methodological point: "Here, it is worth mentioning that the biogenic CO_2 emissions are not considered in the analysis. The carbon neutrality of biogenic sources of CO_2 emissions are implemented on the basis that the wood pulp comes from sustainably managed forest. We have also neglected the temporary storage of carbon in the tissue paper, considering the short life span of the tissue paper as compared to other products from wood, such as furniture, buildings, etc. Hence, only the CO_2 emissions which are released from the combustion of fossilised fuel sources were taken into account." They do mention: "Further reduction of emissions results when RWP is used to replace pulped wood from forestland, as the recycling of waste paper reduces the demand on forest wood and then eliminates subsequent energy and material requirements of the paper pulping processes. This could also increase forest carbon sequestration because the woods are left to grow to maturity, although such assumption cannot be guaranteed because it totally ignores the possible use of wood for other activities. " but they do not implement this in their analysis -10.1016/j.resconrec.2012.07.003 "An investigation of the relationship between recycling paper and card and greenhouse gas emissions from land use change" "Furthermore, although some LCAs considering the changes in international trade (e.g. Kärnä et al., 1994, Wang and Hua, 2007), none consider market mechanisms which determine the

Reviewer	Comments
	source of virgin fibre which may be avoided when switching to recycled content, nor the source of virgin fibre which will be switched to when considering a move from recycled fibre." EPA WARM does discuss this in limitations, but not convincingly. "Despite this objective, no published studies have been identified which consider the impact of changes in demand for virgin and recycled fibre in paper making in relation to land use change (LUC). As an internationally traded commodity, the impact of changes in demand for virgin pulp for paper-making is related to international trends in forest cover." This paper cites EPA's problematic approach "Given that demand for timber products is not a driver for afforestation, it may therefore be inappropriate to attribute carbon sequestration credits to products, as was carried out in some studies identified in Section 2.1." "A final hypothesised driver for afforestation is recycling, as espoused on numerous websites (e.g. www.conservatree.com). If recycling paper means that trees are not cut down to provide pulp, then, given that demand is not a driver for continued planting of forests, an increase in recycling rates could lead to an increase in forest area. Through the literature review no evidence has been identified to support this view." "UNECE (2010) identify that "the rapid growth in wood energy demand and woody biomass production has created concern about competition for raw material from existing forest products sectors, primarily the pulp and paper and composite panel sectors". A rise in demand for wood, for any application, with a finite supply available, could lead to indirect LUC. As this is a consequence of the overall level of demand, it would be driven by extraction of wood for any application." 5.3 "As afforestation is not driven by demand for forest products, the credit for increases in carbon should be allocated to the measure which brought about the change, rather than demand for forest products. This is particularly relevant for changes in primary forest cover and carbon." "Carbon Footprint of Cartons in Europe – Carbon Footprint methodology and biogenic carbon sequestration" (2010) https://www.diva-portal.org/smash/get/diva2:1552203/FULLTEXT01.pdf Actually assumes the *opposite* - allocates carbon sequestration from *managed* forests to positive demand for paper products, rather than reduced demand They also make completely bonkers assumptions about EOL
Realff	For carpet recycling the most up to date information is available at: https://carpetrecovery.org/wp-content/uploads/2022/09/2021_CA_AnnualReport_ADAcompliant_FINAL.pdf

Reviewer	Comments
	For paper recycling the following are reasonable references for exports: https://resource-recycling.com/recycling/2021/08/10/scrap-paper-exports-jump-21-in-first-half-of-year/ https://resource-recycling.com/recycling/2022/06/14/us-scrap-paper-exports-sink-slightly-as-plastics-drop-sharply/ For forestry carbon accounting: 10.1111/j.1530-9290.2012.00507.x
Theis	Several references have been cited in answers to other charge questions. But here are a couple of recent articles that may be of interest: "Inefficient and unlit natural gas flares both emit large quantities of methane", SCIENCE 29 Sep 2022, Vol 377, Issue 6614, pp. 1566-1571 DOI: 10.1126/science.abq0385. "All in on plastics pyrolysis", C&EN | CEN.ACS.ORG | OCTOBER 10, 2022, pp 23-27.

3.7 Do the greenhouse gas emission assumptions in WARM align with climate change modeling best practices?

One reviewer stated that the lifecycle GHG accounting perspective used in WARM is acceptable because WARM's goal is for users to evaluate, from a large-scale perspective, the impact of policy decisions and to understand GHG emission throughout a material's lifecycle.

Two reviewers noted that WARM uses IPCC (2007) GWP values and should use values from the most recent (2021) IPCC report instead.

A reviewer suggested that WARM report both GWP_{20} and GWP_{100} numbers rather than just the latter because the timescale of emissions and impact on climate are such that both timescales are now relevant to global warming.

Another reviewer noted that the impact of consumer preferences and behavior on GHG emissions is not considered and may be quite significant. For example, the adoption of cell phones has displaced telephone land lines, cameras, calculators, physical wallets, private cars (in favor of ride shares), and trips to malls and grocery stores in favor of online shopping. The reviewer recommends including behavior economics or a similar tool in the methodology. While WARM currently relies on input-output modeling for economic analysis, which includes social measures such as tax generation and job creation (or loss), there have been significant advances in social LCA approaches that could be incorporated to capture impact of consumer behavior.[16]

[16] Derek D. Reed, Justin C. Strickland, Brett W. Gelino, Steven R. Hursh, David P. Jarmolowicz, Brent A. Kaplan, Michael Amlung (2022)." Applied behavioral economics and public health policies: Historical precedence and translational promise,, *Behavioural Processes,* 198, 104640, https://doi.org/10.1016/j.beproc.2022.104640.

Reviewer	Comments
Anshassi	The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer". The environmental mechanisms used to measure climate change are the GHGs that partially absorb the transformed solar radiation (longwave infrared radiation), instead of releasing it back into space which causes the temperature of Earth's atmosphere to increase. As the concentration of GHGs increase in the atmosphere the temperature increases as well. Another mechanism impacting climate change is the change in Earth's cover which impacts the albedo, an effect whereby the solar radiation is absorbed by the planetary surface and released back into the atmosphere as infrared radiation. The method to estimate or calculate the climate change impacts is by use of global warming potentials (GWP) which integrates for a specific gas its thermal radiation absorption, concentration, and time horizon (e.g., duration the modeling occurs for (20, 100 years)). The typical assumption for time horizon follows 100 years and the normalized units for measurement are in mass of CO_2 equivalents. The IPCC reports cumulated radiative forcing of CO_2 (also referred to as GWP) for a list of GHGs (e.g., CO_2, CH_4, N_2O). WARM takes a lifecycle GHG accounting perspective, which relies on measurements of various GHGs from different data sources and then the application of the GWP to estimate the overall climate change impacts. This approach is acceptable since WARM's goals, in relation to waste management, is for users to evaluate from a large-scale perspective the impact of policy decisions and to understand overall the GHG emissions throughout a materials' lifecycle.
Bergman	WARM uses IPCC (2007) GWP values which are somewhat dated. I would suggest using more recent GWP values from IPCC 2021. IPCC 2021 is the successor of the IPCC 2013 method, which was developed by the Intergovernmental Panel on Climate Change. It contains the Global Warming Potential (GWP) climate change factors of IPCC with a timeframe of 100 years. Note that the GWP 100 factors are recommended as default by UNEP-GLAM (2017), and the GWP20 and GTP100 factors for sensitivity analysis. This method is based on the final government distribution version of the IPCC report "AR6 Climate Change 2021: The Physical Science Basis" GWP100 CO_2=1 GWP100 CH4=29.8 GWP100 N20= 273 GWP100 CF4=7,380 GWP100 C2F6=12,400
Kuczenski	All my thoughts on this are included in the responses to the above questions.
Realff	In my opinion, there are two considerations in which WARM does not align with best practices.

Reviewer	Comments
	• The most recent IPCC report should be used for the GWP factors, particularly for methane. • WARM should report both GWP_{20} and GWP_{100} numbers rather than just the latter. This is because the timescale of emissions and impact on climate are such that both timescales are now relevant to global warming. A further consideration is the accounting for biogenic CO_2 where it could be argued that the best practice is to consider the timing of CO_2 releases from forestry cycles. I think this level of complexity is too much and would not alter choices for management strategies.
Theis	As noted in the documentation, WARM GHG calculations do not follow most other GHG inventory methods in two ways: (1) WARM begins its inventory from the point of waste creation, and (2) consumer behavior (or changes in consumer behavior) are not included in the analysis. Further, upstream extraction and manufacturing GHG emissions are included only when recycling and/or source reduction is part of the material cycle. The rationale behind this is the intention that WARM is meant to be used only for comparative purposes, i.e., one scenario compared with another. And it is assumed that (1) consumer behavior never changes as long as the functionality of the product is essentially the same, and (2) the manufacturing emissions only change when the quantity (source reduction) or mix of input materials (recycled content) changes. These assumptions are clearly stated and explained. For short-term comparisons WARM is a great tool for helping decision-makers, regulators, and manufacturers manage GHG emissions. However, the omission of consumer behavior on GHG emissions may be quite significant. Any product designer will admit that one of the chief drivers in product design is indeed to change consumer acquisition and use behaviors (e.g., *International Journal of Production Economics* 210 (2019) 155–168). One need look no further than the impacts of multifunctional products, for example smart phones (SP). Within a decade or so a significant fraction of users has ditched their telephone land lines, cameras, calculators, physical wallets, private cars (in favor of SP-enabled ride shares), and trips to malls and grocery stores in favor of online shopping. This is not to mention shifts in the social milieu driven by cyber-enabled platforms. We are a consumer-driven economy. Most life cycle approaches have faced similar problems—how to account for consumer preferences and changes, and the impacts of products and services on the quality of their lives. A good approach to this is to include behavioral economics, or something similar, in the LCA methodology. At present WARM relies on input-output modeling for economic analysis, which includes social measures such as tax generation and job creation (or loss). This is fine, but significant advances in social LCA approaches are available: (https://www.lifecycleinitiative.org/library/guidelines-for-social-life-cycle-assessment-of-products-and-organisations-2020/, And behavioral models are being developed: Derek D. Reed, Justin C. Strickland, Brett W. Gelino, Steven R. Hursh, David P. Jarmolowicz, Brent A. Kaplan, Michael Amlung (2022)." Applied behavioral economics and public health

Reviewer	Comments
	policies: Historical precedence and translational promise", *Behavioural Processes,* 198, 104640, https://doi.org/10.1016/j.beproc.2022.104640). Perhaps future versions of WARM can include the impact of consumer choices on GHG emissions.

3.8 Do the management practices modeled in WARM reflect the typical range of management practices used in the United States?

Three reviewers indicated the management practices modeled in WARM reflect the typical ranges of management practices used in the U.S. However, one of these reviewers noted that reuse is not captured as a management practice. Reuse is relevant to certain commodities such as electronics, but otherwise is a relatively small component of the waste management stream.

A fourth reviewer was impressed with the thoroughness with which WARM examines the six management practices currently included and noted that they cover most but not all management practices in place at this time. This reviewer suggested that future additions to WARM might include:

- **Textile management.** WARM does not explicitly include textiles in its material database (although it does include them for WTE facilities). Textile products are recycled at a very low rates but typically end up in landfills. In some cases, the material composition is biogenic (cotton, wool, linen), but others are composed of synthetic fibers.
- **Plastics recycling.** Typical practice involves mechanical shredding followed by various heat treatments; however, significant resources are currently being brought to bear on chemical recycling (where the polymer is unwound) or mechanical/chemical recycling. Implementation of chemical recycling will undoubtedly change emission factors.
- **Effect of trade.** International plastics trade may have impacts on recycling systems.
- **Effects of colorants.** A factor in recycling plastics is the addition of colorants to initial production of plastic containers. While it is possible to separate waste plastics into similarly colored lots, it is often difficult to find a market large enough to justify the extra expense. It is fairly common practice to separate plastics into two lots—clear (or "natural") and mixed colors. The latter fetch lower prices and are usually remanufactured into darker shades (brown to black). Some products are being packaged this way (e.g., motor oil), but more often these end up in various secondary uses such as flower pots, fencing, piping, etc.
- **Advances in plastic separation**. WARM focuses on (high-density polyethylene) HDPE and PET, since these are the most recovered materials, but advances in identifying and recovering other plastics continue to be made.[17]
- **Open burning**. The reviewer does not have recent data on open burning of solid waste, leaves, twigs, or crop residues, but noted that this is not banned in many (mostly rural) jurisdictions.

[17] Antonopoulos et al., (2021) *Waste Management* 126: 694–705.

Reviewer	Comments
Anshassi	The main management practices modeled in WARM are source reduction (and production), recycling, landfilling, combustion, composting, and anaerobic digestion. These do reflect the typical range of management practices in the US, which is evident from nationwide reports (US EPA 2020), and state reports (FDEP 2022; Crowell 2018; CalRecycling 2021). Some waste management practices that are not included in WARM (e.g., pyrolysis, gasification, aerated static pile composting, in-vessel composting, mixed waste processing) are not commonly practiced in the US and for that reason are reasonably not modeled in WARM. References: US EPA, 2020. Advancing sustainable materials management: 2018 fact sheet. Office of Resource Conservation and Recovery. Florida Department of Environmental Protection, 2022. Solid Waste Management in Florida 2021 Annual Report. Crowell, B., 2018. Minnesota Report on SCORE Programs 2016. Minnesota Pollution Control Agency. CalRecycle 2021. State Agency Waste Management Annual Report 2020.
Bergman	One issue detailed below and highlighted in the attached Background document using 'Tracked Changes' was forest C stored would be ~twice the wood carbon stored in HWPs because of processing losses from trees to useable HWPs to be placed in service. These processing losses are called mill residues and can be used internally for onsite energy for drying or sold for use in other engineered wood products, pulp, or energy.
Kuczenski	To the best of my knowledge, yes.
Realff	Yes – the documentation alludes to the idea of including re-use which would be the only omission of some importance for certain commodities, such as electronics, but other than that I think re-use is a relatively small component of the waste management stream. The commodity with which I am most familiar, carpet, is hardly ever reused, less than 1M lbs of carpet were reused in 2021 about 0.1% of the gross collections of carpet in the state of CA. The documentation does spend significant time explaining the source reduction energy and carbon footprint calculations, but source reduction is not a waste management practice. Source reduction has implications in the context of recycling and that is how it is used in the WARM model, but it is quite confusing to see the two columns in the spreadsheet F and G that are identical save for a minus sign.
Theis	WARM identifies six management practices: Source Reduction, Recycling, Composting, Anaerobic Digestion, Combustion, and Landfilling. Specific approaches within these practices are also explored (e.g., source reduction might be achieved through redesign, reuse, repair, expanding useful lifetimes, or avoiding some quantity of materials in initial designs). These practices (except repair) are further analyzed for several product types (e.g., non-durable

Reviewer	Comments
	goods, packaging, glass, metals, paper, plastics, and PLA—61 materials in all). I am impressed with the degree of thoroughness with which each of these practices have been examined. And I believe these options cover the majority of management practices in place at this time in the US, but not all. Future additions to WARM might include: • Textile management. WARM does not explicitly include textiles in its material database as yet (although it does include them for WTE facilities). Textile products are recycled at a very low rates (~2-5%), but typically end up in landfills. In some cases, the material composition is biogenic (cotton, wool, linen), but others are composed of synthetic fibers. It is acknowledged that EPA is considering inclusion of textile fabrics in future versions of WARM. • Plastics recycling. Typical practice involves mechanical shredding followed by various heat treatments, however significant resources are currently being brought to bear on chemical recycling (where the polymer is unwound), or mechanical/chemical recycling (Ragaert et al (2017), Waste Management 69:24-58). Implementation of chemical recycling will undoubtedly change emission factors. • Effect of trade. Also, as noted in Q2, international plastics trading may have impacts on recycling systems. • Effects of colorants. Another factor in recycling plastics is the addition of colorants to initial production of plastic containers. While it is possible to separate waste plastics into similarly colored lots, it is often difficult to find a market large enough to justify the extra expense. It is fairly common practice to separate plastics into two lots—clear (or "natural") and mixed colors. The latter fetch lower prices and are usually remanufactured into darker shades (brown to black). Some products are being packaged this way (e.g., motor oil), but more often these end up in various secondary uses such as flower pots, fencing, piping, etc. (https://plasticsrecycling.org/images/library/2018-postconsumer-bottle-recycling-report.pdf). • Advances in plastic separation. WARM focuses on HDPE and PET, since these are the most recovered materials, but advances in identifying and recovering other plastics continues to be made (Antonopoulos et al, (2021) *Waste Management* 126: 694–705). As noted above, separating plastics by attributes does not necessarily mean there will be economically viable markets. • Open burning. I don't have any recent data on "open burning" of solid waste ("barrel burning"), and the open burning of leaves, twigs, crop residues, etc., but it is not banned in many jurisdictions, mostly rural.

3.9 Does WARM accurately model the typical second use for recycled materials in the United States?

One reviewer stated that, when considering the current second uses for recycled materials, "WARM presents a modeling approach that is generally typical in the U.S." Four reviewers provided substantive suggestions for improvements to modeling for second use of recycled materials.

One of these reviewers noted that the process data may not spatially represent the impact of changes in recycling markets over time. The WARM process data for recycling are from the early 2000s and 2010s, prior to significant changes in global recycling markets and remanufacturing processes, and development of domestic legislation related to material use. The reviewer recommended that the WARM documentation include a discussion on the use of the dated data and whether WARM developers expect any of the noted changes to impact recycling impact factors.

A second reviewer indicated that there is not enough information to provide a definitive answer regarding the model's accuracy. While the framework is logical, the model may have difficulty handling certain complex scenarios, such as: 1) products composed of multiple materials that require disassembly steps and feed into more than one material stream, closed or open, and 2) a "repair" pathway—sometimes this is assumed to refer to local repair shops for cars and electronics, but it also applies to products being remanufactured under extended producer responsibility. This reviewer also noted that Sections 2.1.1 and 2.1.3 were a "tough read" and provided suggestions for improvement.

The other two reviewers provided feedback and recommendations regarding typical second use for recycled materials modeling:

- **Glass**. The first of these reviewers stated that closed loop glass recycling is increasingly rare because of low recovery efficiency in single-stream recycling. While may be reasonable to assume closed-loop recycling, WARM users must be made aware that this is a somewhat exceptional case and should not be used for generic glass recycling.
- **Wood**. This reviewer also suggested that EPA consider modeling scrap wood that is open-loop recycled as mulch.
- **Tires.** Finally, this reviewer provided three suggestions concerning tires. First, tire-derived aggregate should replace aggregate, not sand, even though the impact factor is likely the same. Second, tire-derived fuel is used almost exclusively for process heat generation, not for electricity generation. Therefore tire-derived heat should not be assumed to replace utility electricity, but rather combustion of alternative fuels. And third, EPA should consider modeling tire-derived crumb rubber used as rubber-modified asphalt.
- **Carpet.** The second reviewer stated that WARM's modeling of carpet is inaccurate and provided detailed feedback about various components of carpet and how changes in their use or availability require changes to how second use is modeled.

Reviewer	Comments
Anshassi	In the last several years some recycling markets have dramatically changed in terms of where the material is exported to and how it is remanufactured (e.g., open versus closed loop). Paper and plastic products were subjected to the biggest global changes, for example the historic main outlet was to export to China, India, and other south Asian countries and now local US papermills and plastic remanufactures are beginning to absorb some of the local US supply. Likewise, certain nationwide and local policies encouraging the use of recycled content in product manufacture has also become popular. Since much of the process data for recycling are from the early 2000s and 2010s the impacts of these recycling market changes may not be spatially represented in WARM. A discussion on the use of the dated data and whether WARM developers expect any of the previously mentioned market changes to impact recycling impact factors is needed, perhaps in the WARM Background and Overview document. When considering the current second uses for recycled materials WARM presents a modeling approach that is generally typical in the US. Although each material can be recycled following

Reviewer	Comments
	both an open and closed-loop approach certain materials will primarily be recycled following one approach. Metals and glass will usually follow closed-loop recycling, even though the market for glass has been challenged due to contamination. Plastics, specifically PET and HDPE products will be closed-loop recycled. Although other plastics (e.g., LDPE, LLDPE, PP, PS, PVC) can be closed-loop recycled, especially if they are collected separately or able to be sorted, it is more likely that they would be open-loop recycled since materials recovery facilities (MRF) will bale and sell them as mixed plastics, which can be used to make furniture and textiles. In a similar sense, MRFs will sort newspaper and cardboard from the recyclables stream (to be closed-loop recycled) and any other paper products will likely be sold as mixed paper which will follow an open-loop recycling approach. The electronics, tires, and C&D waste components are commonly open-loop recycled, with the exception of certain materials (e.g., asphalt concrete is milled from the surface and directly used in the manufacture of new mix asphalt concrete; wood flooring is ground and pieced together using adhesives and glues to make new wood flooring).
Bergman	For wood products, reusing flooring and pallets are the best illustrations of the wood sector's abilities. For wood pallets, the sector is getting close to 50% coming from the repair/recycling/remanufacturing stage instead of from new/virgin pallets. The wood pallet PCR describes in detail how to consider reuse while the cradle-to-grave wooden LCA illustrates how to use in practice. Wood pallets are built differently for different end-uses and from many wood species in conjunction have a different reference service life. Reviewing the 'Modeling Reuse in EPA's Waste Reduction Model', in the Limitation section, one thing that is driving reuse of wood products is the pricing particularly in dimensional lumber although the lack of grading rules for recovered dimensional (softwood) lumber is holding the market back. For wood pallets, it is almost better instead of a single pallet would be to consider a large number, say 1,000 old pallets producing 800 repair/recycled/remanufactured, 150 reuse as is pallets, and the rest of wood being used for energy, compost, energy, or landfilled. The pallet papers provide this information in detail.
Kuczenski	**- Glass:** No; closed loop glass recycling is increasingly rare because of low recovery efficiency in single-stream recycling. It may be reasonable to assume closed-loop recycling, but tool users must be made aware that this is a somewhat exceptional case and should not be used for generic glass recycling. **- Metals:** ok **- Paper:** ok **- Plastics:** ok **- Construction materials:** ok **- Electronics:** ok **- Wood:** suggest the agency consider modeling scrap wood being open-loop recycled as mulch

Reviewer	Comments
	- Tires: Tire-derived aggregate (TDA) should replace aggregate, not sand, but the impact factor is likely the same. Tire-derived fuel (TDF) is used almost exclusively for process heat generation, not for electricity generation. Therefore tire-derived heat should NOT be assumed to replace utility electricity, but rather combustion of alternative fuels. EPA should consider modeling tire-derived crumb rubber used as rubber-modified asphalt.
Realff	This varies by commodity – but in the case of carpet the modeling is inaccurate because the market has shifted significantly since the data used in WARM was generated. The recycling data in WARM is based on studies performed in 2008-2009 and reported to WARM model analysists in 2010. At the time the dominant carpet fiber was nylon, both nylon 6 (N6) and nylon 6,6 (N66). The main route of recycling nylon 6 carpet was depolymerization at Evergreen in Augusta GA. This plant subsequently closed. Depolymerization activities are carried out in Eastern Europe by Aquafil but the dominant route for N6 and N66 is to recycle them into products without depolymerization. N66 has almost been completely eliminated from the market for new carpet due to plant closures and exit from the market by one of the major N66 producers. It now represents less than 10% of recycled materials. N6 is still a significant component of the recycle stream and continues to be used, probably 25% of the recycle market. The rise of PET face fiber carpet, from 15 to 50% of the residential market over the last decade has dramatically shifted the markets for secondary materials. A significant fraction of the PET face fiber is incorporated into pad for carpet backing or into a PET pellet that is subsequently gasified and used as a chemical feedstock. PET carpet did not figure strongly in the analysis of 2010, and so the second use of carpet fiber is not accurately modeled. Finally, for carpet there has been a substantial rise in the use of the calcium carbonate (so called PC4) material that is liberated from the carpet during the recycling process. This is now about 25% of the recycled stream from CA, 17Mlbs of 67Mlbs. The PC4 material displaces a variety of fillers in an open loop recycling system and requires significant energy input to recover with a modest improvement over virgin calcium carbonate from an energy and carbon perspective which is strongly dependent on the transportation distances and modes for both the recycled and virgin materials.
Theis	The essential features of WARM's second use modeling are contained in sections 2.1.1. and 2.1.3. Here the differences between "open loop" and "closed loop" recycling are explained and the subsequent modeling of GHG generation is presented. I understand the logic, but it is a tough read. First, "open" and "closed" terminologies have different meanings in other BOKs: thermodynamics, economics, social science, anthropology, history, philosophy, and of course manufacturing (the latter seems to be the meaning implied here). WARM defines these terms so I understand the contextual meaning. I mention this because I assume that WARM has many users with disparate backgrounds for whom the meaning (including me) may not be obvious. Second, these sections would benefit from schematic diagrams and sample calculations, as seem to be presented in other chapters of documentation materials. The question uses the term "accurately" and I don't believe there is enough information to provide a definitive answer. The framework is logical, but I can imagine some scenarios that might complicate things, for example products composed of multiple materials that require

Reviewer	Comments
	disassembly steps and feed into more than one material stream, closed or open. Another is a "repair" pathway (see Q4). Sometimes this is assumed to refer to local repair shops for cars and electronics, but it also applies to products being remanufactured under EPR business models, sometimes by large manufacturers. The Xerox "Lakes" project in the late 1990s and early 2000s comes to mind (https://www.xerox.com/en-us/about/history-timeline).

APPENDIX A

CHARGE TO REVIEWERS

Technical Charge to External Peer Reviewers

Contract No. 68HERH19D0033

Task Order 68HERC22F0138 (ERG Task 66)

September 2022

External Letter Peer Review of EPA's

Waste Reduction Model (WARM) Methodology

BACKGROUND

Extracting, harvesting, processing, transporting, and disposing of materials result in greenhouse gas (GHG) emissions, in part due to the large amounts of energy required for these life-cycle stages. Decisions about how goods (such as food, plastic packaging, and building materials) are produced, transported, used, and disposed of can make a big difference in the amount of the resources used, greenhouse gases emitted, environmental impacts created, and waste produced. GHG emissions and other environmental impacts associated with goods result from the energy, land, and water used to produce, transport, consume, and dispose of them. According to the Global Resources Outlook 2019 report from the United Nations Environment Program's International Resource Panel, up to half the global GHG emissions stem from the extraction and processing of materials, fuels, and food. Reducing, reusing, recycling, and composting are strategies that can lessen the environmental impact of goods.

The U.S. Environmental Protection Agency's (EPA) Waste Reduction Model (WARM), the focus of this peer review, is a tool designed to help managers and policymakers understand and compare the life cycle GHG, energy, and economic implications of materials management options (recycling, source reduction, landfilling, combustion with energy recovery, anaerobic digestion, and composting) for materials commonly found in the waste stream. By comparing a baseline scenario (e.g., landfilling) to an alternate scenario (e.g., recycling), WARM can assess the economic, energy, and GHG implications that would occur throughout the material life cycle.

Currently, WARM includes six different waste management practices including source reduction, recycling, composting, anaerobic digestion, combustion, and landfilling. It calculates emissions, energy units and economic factors across sixty material types commonly found in municipal solid waste and construction and demolition debris.

WARM is periodically updated as new information becomes available and new material types are added. The website provides the model history to better understand the differences among various versions of WARM.

PEER REVIEW MATERIALS

- WARM Tools
  - WARM v16 Excel Tool (protected – does not provide access to hidden sheets where some of the calculations are performed; does not allow modification of formulas)
  - WARM v16 Excel Tool (unlocked – allows access to hidden sheets and modification of formulas)
- User Guide
  - WARM Excel User's Guide
- Documentation Chapters

    - WARM Background Chapters
    - Management Practices Chapters
    - Organic Materials Chapters
    - Construction Materials Chapters
    - Containers, Packaging, and Non-Durable Good Materials Chapters
    - Electronics Chapters
    - Tires Chapters
- Miscellaneous Background Documentation (not the focus of this review; these are being provided to aid reviewers as needed)
    - Modeling Food Donation Benefits in EPA's Waste Reduction Model
    - Modeling Reuse in EPA's Waste Reduction Model
    - WARM Component-Specific Decay Rate Methods
    - Using WARM Emission Factors for Materials and Pathways Not in WARM
    - Modeling Increased Product Lifetime in WARM
    - Life-Cycle GHG Accounting Versus GHG Emission Inventories
    - Landfill Gas Monte Carlo Model Documentation and Results
    - Landfill Carbon Storage in EPA's Waste Reduction Model

CHARGE QUESTIONS

Question 1: Are the assumptions made in WARM regarding biogenic carbon emissions scientifically sound and in line with common modeling best practices?
Response 1:
Question 2: Are the assumptions made in WARM regarding carbon storage in forests, soils and landfills scientifically sound and in line with common modeling best practices?
Response 2:
Question 3: Are the assumptions made in WARM regarding utility offsets from combustion scientifically sound and in line with common modeling best practices?
Response 3:
Question 4: In general, do the data, assumptions and model components in WARM align with real market practices?
Response 4:
Question 5: Please comment on any ways to improve the clarity, transparency, relevance and usability of WARM and its documentation.

Response 5:
Question 6: Please suggest any applicable studies or data sources not currently used in WARM that could be useful.
Response 6:
Question 7: Do the greenhouse gas emission assumptions in WARM align with climate change modeling best practices?
Response 7:
Question 8: Do the management practices modeled in WARM reflect the typical range of management practices used in the United States?
Response 8:
Question 9: Does WARM accurately model the typical second use for recycled materials in the United States?
Response 9:

APPENDIX B

INDIVIDUAL REVIEWER COMMENTS

COMMENTS SUBMITTED BY

Dr. Malak Anshassi
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External Peer Review of EPA's Waste Reduction Model (WARM) Methodology

CHARGE QUESTIONS

Question 1: Are the assumptions made in WARM regarding biogenic carbon emissions scientifically sound and in line with common modeling best practices?

Response 1:

In WARM, biogenic carbon emissions are expressed for paper products, food waste, wood products, yard trimmings, and other organic sources when they are biologically treated (composted, anaerobically digested) and landfilled. The current sources of biogenic carbon yields used for these modeling is from Barlaz (1998), Wang et al. (2011, 2013), and Levis et al. (2013), and when data was unavailable for specific solid waste components a proxy was used. Most of the data is greater than 10 years old which does suggest newer updated sources for measurements of biogenic carbon is needed, especially since the technology available to measure the biogenic carbon content has improved and that the waste stream components have changed (e.g., how has increased recycled content and biodegradable/compostable products effected biogenic carbon content). On the other hand, the improvements to the instrumentation and the changes in the waste stream are likely not going to result in tremendous changes to the existing biogenic carbon contents since the inherent material makeup and manufacturing processes are likely to not have changed greatly.

The practices for balancing carbon vary amongst waste management approaches (see Christensen et al. 2009) and influences the overall greenhouse gas (GHG) emissions factors used in WARM. For example, for landfill modeling it is appropriate to assume that the biogenic CO_2 entering the waste system is stored, and its emissions is a climate positive impact (adverse) and that carbon (CO_2) storage is a neutral impact. However, it is also appropriate to assume that emitting biogenic CO_2 in the short term is neutral and storing CO_2 is beneficial. WARM currently models the later assumption for both landfilling and composting biogenic carbon waste sources. This modeling approach is common amongst lifecycle assessment (LCA) studies of solid waste management and is scientifically sound on the basis that the biogenic carbon emissions modeling approach is consistent throughout WARM; the emissions are modeled in the same manner when waste components are landfilled or biologically treated. When biogenic carbon sources are combusted, they are also assumed to be CO_2 neutral, further matching the consistency of the modeling approach.

As biogenic carbon containing materials degrade, they release methane, one of the primary greenhouse gases (GHG) accounted for in WARM. When comparing the predicted methane potential yields for some waste components in WARM to other commonly used LCA tools, the values are within reasonable ranges (Table 1). One concern for the current WARM methane emissions modeling stems from the dated decay rates used as part of the 2014 Landfill Gas Monte Carlo simulations. More recent data (Jain et al. 2021) have shown the annual decay rates for arid regions to be 0.043 $year^{-1}$ (compared to the current use of 0.02 $year^{-1}$ in WARM), moderate regions to be 0.074 $year^{-1}$ (compared to 0.04 $year^{-1}$), and wet regions to be 0.09 $year^{-1}$ (compared to 0.06 $year^{-1}$). Although the 100-year modeling timeframe does mitigate some of this concern, overall, potentially not updating these values may result in underreported estimates for current US landfill gas generation, which has been become a mainstream topic (Duren et al. 2019; Bruggers 2021). The last concern related to landfill biogenic carbon emissions modeling is the high default collection efficiencies (75% for all years). In Anshassi et al. 2022 when following 40 CFR 60 Subpart XXX regulations the average minimum required collection efficiency ranged from ~20% to 65%, depending on the decay rate and concentration of nonmethane organic compounds. The results from the study were for the lifetime total gas efficiency (total gas collected divided by total gas generated), and although this is not directly comparable to the 75% rate, it still suggests the value is higher and when users compare landfilling to alternatives it may underscore the true GHG emissions impacts.

Table 1. Data from Anshassi et al. 2021

Methane Yield (m3/Mg wet)	WARM	MSW-DST	SWOLF	EASETECH
Newspaper	70	63	65	64
Cardboard	185	168	163	158
Office Paper	248	225	240	221
Yard Waste	65	51	45	127
Food Waste	120	103	122	127

References:

Anshassi, M., Townsend, T.G., 2021. Reviewing the underlying assumptions in waste LCA models to identify impacts on waste management decision making. Journal of Cleaner Production 313, 127913.

Anshassi, M., Smallwood, T., Townsend, T.G., 2022. Life cycle GHG emissions of MSW landfilling versus Incineration: Expected outcomes based on US landfill gas collection regulations. Waste Management 142, 44–54.

Bruggers, J., McKenna, P., Green, A., Benincasa, R., 2021. Your Trash Is Emitting Methane In The Landfill. Here's Why It Matters For The Climate. NPR.

Christensen T.H., E. Gentil, A. Boldrin, A.W. Larsen, B.P. Weidema, M. Hauschild (2009). C balance, carbon dioxide emissions and global warming potentials in LCA-modelling of waste management systems. Waste Management & Research 27:707-215.

Duren, R.M., Thorpe, A.K., Foster, K.T., Rafiq, T., Hopkins, F.M., Yadav, V., Bue, B.D., Thompson, D.R., Conley, S., Colombi, N.K., Frankenberg, C., McCubbin, I.B., Eastwood, M.L., Falk, M., Herner, J.D., Croes, B.E., Green, R.O., Miller, C.E., 2019. California's methane super-emitters. Nature 575, 180–184.

Jain, P., Wally, J., Townsend, T.G., Krause, M., Tolaymat, T., 2021. Greenhouse gas reporting data improves understanding of regional climate impact on landfill methane production and collection. PLOS ONE 16, e0246334.

Question 2: Are the assumptions made in WARM regarding carbon storage in forests, soils and landfills scientifically sound and in line with common modeling best practices?

Response 2:

The assumptions related to carbon storage in landfills were discussed initially in Question 1, to continue some of that discussion here some data on the carbon sequestration potential for five waste components and several LCA models are compared (Table 2). From Table 2 it is evident that the magnitudes are relative to one another, indicating that the modeling calculation used to derive the WARM factors are within common modeling best practices. Composting and anaerobic digestion are associated with a soil carbon storage, as well as an avoided fertilizer application offset; a practice that is typically accounted for in LCA modeling of biological treatment (Goglio et al. 2015; Stanley et al. 2018).

Table 2. Data from Anshassi et al. 2021 and for landfilling.

Carbon Sequestration Potential (tCOeq./Mg)	WARM	MSW-DST	SWOLF	EASETECH
Newspaper	1.08	1.32	1.32	1.19
Cardboard	0.65	0.83	0.8	0.85
Office Paper	0.11	0.15	0.13	0.57
Yard Waste	0.49	0.45	0.61	0.33
Food Waste	0.08	0.08	0.17	0.17

Regarding the carbon storage in forests, this is modeled when paper products are recycled, in which the waste paper is used in place of virgin paper that must be harvested from trees, and since the trees are not harvested it results in an increased soil carbon storage and therefore a forest carbon offset is credited. This modeling approach, whereby paper products are associated with a forest carbon offset through recycling is not common in paper recycling LCA studies or in other waste management-based LCA models (Anshassi et al. 2021). One paper does discuss that the carbon stocks of forests are already in equilibrium and the biological system naturally uptakes or releases emissions along its life so there is no need to award an additional offset credit (Merrild et al. 2008). When reviewing the Exhibit 2-2 for recycling emissions factors it is apparent that the forest carbon offsets contribute more 90% of the total offsets. WARM users who are not well-versed in the assumptions regarding forest carbon storage (that it is not commonly practiced) may misinterpret the benefits associated with paper recycling relative to other waste components. In addition, in many cases paper products dominate the nationwide waste composition (and on a local state level), which might artificially overestimate the GHG emissions offsets from paper recycling (especially considering paper is 20-25% of the total outbound composition of a materials recovery facility). Further clarification regarding the lack of consensus for inclusion of forest carbon offsets when paper is recycled is needed in the background documentation, and like the source reduction user input option (e.g., current mix vs 100%) perhaps a similar option can be implemented in the tool (e.g., with forest carbon storage vs without forest carbon storage).

References:

Anshassi, M., Townsend, T.G., 2021. Reviewing the underlying assumptions in waste LCA models to identify impacts on waste management decision making. Journal of Cleaner Production 313, 127913.

Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., McConkey, B.G., Campbell, C.A., Nemecek, T., 2015. Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review. Journal of Cleaner Production 104, 23–39.

Merrild, H., Damgaard, A., Christensen, T.H., 2008. Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. Resources, Conservation and Recycling 52, 1391–1398.

Stanley, P.L., Rowntree, J.E., Beede, D.K., DeLonge, M.S., Hamm, M.W., 2018. Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems. Agricultural Systems 162, 249–258.

Question 3: Are the assumptions made in WARM regarding utility offsets from combustion scientifically sound and in line with common modeling best practices?

Response 3:

Referring back to Christensen et al. 2009, there are two modeling structures for energy substitution: 1) assumes that biogenic carbon is neutral when combusted, fossil carbon counts towards emissions when combusted, and the utility offsets are only from fossil carbon sources (because the biogenic sources have a neutral impact on energy substitution); and 2) assumes biogenic and fossil carbon sources both count as an emission when combusted and the utility offsets come also from both the biogenic and fossil carbon sources. Currently WARM assumes the biogenic carbon sources are neutral when combusted, the fossil carbon sources do count as an emission, and the utility offsets come from both fossil and carbon sources. It is slightly unclear whether this approach is scientifically sound when using Christensen et al. 2009 findings as a reference because of the five criteria evaluated by the authors did not include the approach modeled in WARM. Yet when comparing WARM's approach to other peer-reviewed literature it becomes clear that this approach is commonly accepted in LCA practice (e.g., more than 10 out of 14 studies reported utility offsets originating from both fossil and carbon sources, and many only accounted for emissions from fossil carbon sources during combustion (Anshassi et al. 2021)).

References:

Anshassi, M., Sackles, H., Townsend, T.G., 2021. A review of LCA assumptions impacting whether landfilling or incineration results in less greenhouse gas emissions. Resources, Conservation and Recycling 174, 105810.

Question 4: In general, do the data, assumptions and model components in WARM align with real market practices?

Response 4:

The data and assumptions used in WARM do align, generally with real market practices in the US. There are some concerns with the recycling and combustion assumptions, and this is described below.

As materials are transformed into secondary feedstocks for new product manufacture the extent that the non-virgin material can replace virgin material is influential when modeling recycling. This process can be referred to as the recycling input ratio, which describes how much product can be made from one ton of recycled material (non-virgin material). In WARM this ranges from 0.66 (e.g., office paper) to 0.98 (e.g., glass, steel cans), however most materials are in the 0.9-1 range, which indicates most of the recycled material can be utilized in the manufacture of a new product. Based on existing recycled market trends this value may be high for certain products, namely plastic, for example Haupt et al. 2018 reported 1 kg of waste PET bottles produced 0.68 kg of bottle-grade PET (see SI spreadsheet for PET bottles). While for other products the WARM assumptions match closely (e.g., 1 kg cardboard waste produces 0.96 kg secondary cardboard fibers, 1 kg aluminum waste produces 0.94 kg secondary aluminum (Haupt et al. 2018).

The modeling assumptions for metals recovery from municipal solid waste incineration (MSWI) facilities in WARM only account for the steel or ferrous fractions and neglect the nonferrous fractions (e.g., copper, aluminum). Although an estimate for the fraction of nonferrous that are recovered is not easily available in public reports (Michaels and Krishnan 2018), many US MSWI facilities do recover nonferrous metals from the MSWI ash. The impacts of metals recovery, especially aluminum, greatly influences the net GHG emissions and energy use footprints for waste incineration and should be included in WARM.

References:

Haupt, M., Kägi, T., Hellweg, S., 2018. Life cycle inventories of waste management processes. Data in Brief 19, 1441–1457.

Michaels, T., Krishnan, K., 2018. Energy Recovery Council 2018 Directory of Waste-to-Energy Facilities. Energy Recovery Council.

Question 5: Please comment on any ways to improve the clarity, transparency, relevance and usability of WARM and its documentation.

Response 5:

WARM documentation is well organized, clear, and provides information for the laymen, as well as informs any highly technical users. However, more transparency describing why certain assumptions were not incorporated into WARM is needed. Specifically: 1) the landfill construction, operation, closure, and post-closure emissions and energy usage are not explicitly stated as modeled even though they have been reported to contribute to global warming (Wang et al. 2021); 2) the landfill lifetime (e.g., 20-30 years) is not reported (is this assumed to be the 56 years of operation from the 2014 monte carlo report?); 3) what type of engine is used for the landfill gas-to-energy facility?; 4) the municipal solid waste incinerator facility lifetime, any emissions from the construction of the facility, and ancillary chemicals (e.g., activated carbon, lime, ammonia) is not reported; and 5) what are the emissions associated with construction and operation of a materials recovery facility (MRF).

In addition, some supplementary discussion relating to how WARM can and cannot be used to meet certain LCA standards (per the International Organization for Standardization (ISO) 14040 and 14044) in the "WARM Background and Overview" pg 1-4 would be useful to users. Specifically add clarification that although WARM does not provide a full LCA it can still be used as a tool, to some extent, to create a waste management focused LCA study that can comply with the ISO framework. Essentially, just because WARM is a streamlined LCA does not negate its usefulness as a tool and source of data for a GHG emissions or energy use focused ISO complacent LCA study.

References:

Wang, Y., Levis, J.W., Barlaz, M.A., 2021. Life-Cycle Assessment of a Regulatory Compliant U.S. Municipal Solid Waste Landfill. Environ. Sci. Technol. 55, 13583–13592.

Question 6: Please suggest any applicable studies or data sources not currently used in WARM that could be useful.
Response 6: Please refer to the other questions and the referenced literature.
Question 7: Do the greenhouse gas emission assumptions in WARM align with climate change modeling best practices?
Response 7: The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer". The environmental mechanisms used to measure climate change are the GHGs that partially absorb the transformed solar radiation (longwave infrared radiation), instead of releasing it back into space which causes the temperature of Earth's atmosphere to increase. As the concentration of GHGs increase in the atmosphere the temperature increases as well. Another mechanism impacting climate change is the change in Earth's cover which impacts the albedo, an effect whereby the solar radiation is absorbed by the planetary surface and released back into the atmosphere as infrared radiation. The method to estimate or calculate the climate change impacts is by use of global warming potentials (GWP) which integrates for a specific gas its thermal radiation absorption, concentration, and time horizon (e.g., duration the modeling occurs for (20, 100 years)). The typical assumption for time horizon follows 100 years and the normalized units for measurement are in mass of CO_2 equivalents. The IPCC reports cumulated radiative forcing of CO_2 (also referred to as GWP) for a list of GHGs (e.g., CO_2, CH_4, N_2O). WARM takes a lifecycle GHG accounting perspective, which relies on measurements of various GHGs from different data sources and then the application of the GWP to estimate the overall climate change impacts. This approach is acceptable since WARM's goals, in relation to waste management, is for users to evaluate from a large-scale perspective the impact of policy decisions and to understand overall the GHG emissions throughout a materials' lifecycle.
Question 8: Do the management practices modeled in WARM reflect the typical range of management practices used in the United States?
Response 8: The main management practices modeled in WARM are source reduction (and production), recycling, landfilling, combustion, composting, and anaerobic digestion. These do reflect the typical range of management practices in the US, which is evident from nationwide reports (US EPA 2020), and state reports (FDEP 2022; Crowell 2018; CalRecycling 2021). Some waste management practices that are not included in WARM (e.g., pyrolysis, gasification, aerated static pile composting, in-vessel composting, mixed waste processing) are not commonly practiced in the US and for that reason are reasonably not modeled in WARM. References: US EPA, 2020. Advancing sustainable materials management: 2018 fact sheet. Office of Resource Conservation and Recovery.

Florida Department of Environmental Protection, 2022. Solid Waste Management in Florida 2021 Annual Report.

Crowell, B., 2018. Minnesota Report on SCORE Programs 2016. Minnesota Pollution Control Agency.

CalRecycle 2021. State Agency Waste Management Annual Report 2020.

Question 9: Does WARM accurately model the typical second use for recycled materials in the United States?

Response 9:

In the last several years some recycling markets have dramatically changed in terms of where the material is exported to and how it is remanufactured (e.g., open versus closed loop). Paper and plastic products were subjected to the biggest global changes, for example the historic main outlet was to export to China, India, and other south Asian countries and now local US papermills and plastic remanufactures are beginning to absorb some of the local US supply. Likewise, certain nationwide and local policies encouraging the use of recycled content in product manufacture has also become popular. Since much of the process data for recycling are from the early 2000s and 2010s the impacts of these recycling market changes may not be spatially represented in WARM. A discussion on the use of the dated data and whether WARM developers expect any of the previously mentioned market changes to impact recycling impact factors is needed, perhaps in the WARM Background and Overview document.

When considering the current second uses for recycled materials WARM presents a modeling approach that is generally typical in the US. Although each material can be recycled following both an open and closed-loop approach certain materials will primarily be recycled following one approach. Metals and glass will usually follow closed-loop recycling, even though the market for glass has been challenged due to contamination. Plastics, specifically PET and HDPE products will be closed-loop recycled. Although other plastics (e.g., LDPE, LLDPE, PP, PS, PVC) can be closed-loop recycled, especially if they are collected separately or able to be sorted, it is more likely that they would be open-loop recycled since materials recovery facilities (MRF) will bale and sell them as mixed plastics, which can be used to make furniture and textiles. In a similar sense, MRFs will sort newspaper and cardboard from the recyclables stream (to be closed-loop recycled) and any other paper products will likely be sold as mixed paper which will follow an open-loop recycling approach. The electronics, tires, and C&D waste components are commonly open-loop recycled, with the exception of certain materials (e.g., asphalt concrete is milled from the surface and directly used in the manufacture of new mix asphalt concrete; wood flooring is ground and pieced together using adhesives and glues to make new wood flooring).

COMMENTS SUBMITTED BY

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External Peer Review of EPA's Waste Reduction Model (WARM) Methodology

CHARGE QUESTIONS

Question 1: Are the assumptions made in WARM regarding biogenic carbon emissions scientifically sound and in line with common modeling best practices?

Response 1:

Yes, ISO 21930 (2017) standard has clear guidelines on how biogenic carbon emissions for wood building products. The wood sector used ISO 21930 (2017) for development of their wood product product category rule (PCR) by UL Environment. The standard is undergoing its 5-year review process.

Question 2: Are the assumptions made in WARM regarding carbon storage in forests, soils and landfills scientifically sound and in line with common modeling best practices?

Response 2:

Given the specific limitations on economic inputs-outputs such as on inflexibility, the following is not considered which is greater demand leads to higher prices and less purchasing and then eventually more supply and visa versus.

Another limitation, most forests will reach an equilibrium in regard to their carbon flux which means that they are losing as much as carbon as they are gaining as trees age out and start to die. In a practical sense, there is a practical limit to how much forest carbon sequestration can occur on source reduction and recycling.

4.4.1. To create a finished wood product requires twice the amount of virgin roundwood, not 1.1 short tons/short ton finished product. The value of 1.1 would align well with mechanical pulping using virgin wood or producing recycled pulp, now wood products. This was similar to the issue related to the call-out box on pg. 4-2 that I noted below.

I have not used USFS FORCARB II model. FPL is working on updating WoodCarb with the current USFS Northern Research Station (NRS) but FPL/NRS lack personnel and funding to update quickly as we would like.

Question 3: Are the assumptions made in WARM regarding utility offsets from combustion scientifically sound and in line with common modeling best practices?

Response 3:

I am not familiar with waste-to-energy combustion technology but with wood combustion technology.

Basswood (Tilia americana) is a relatively soft wood but it is a hardwood. Dimensional lumber is from softwoods species like southern pine and Douglas fir. Using the Fuel Value Calculator, I would suggest using the softwood value for dimensional lumber and hardwood for wood flooring or simply 17.2 million BTUs/ton or 20.9 MJ/OD kg what was pulled from Bergman and Bowe (2008). Bergman and Bowe (2008) has a new URL, Bergman, Richard D.; Bowe, Scott A. 2008. Environmental impact of producing hardwood lumber using life-cycle inventory. Wood and Fiber Science 40(3) (2008): 448-458. https://www.fs.usda.gov/research/treesearch/31113

Fuel Value Calculator

https://www.fpl.fs.usda.gov/documnts/techline/fuel-value-calculator.pdf

Question 4: In general, do the data, assumptions and model components in WARM align with real market practices?

Response 4:

For source reduction (e.g., light-weighting), dimensional lumber and wood pallets are two wood products that are bought primarily on their price points of which dimensional lumber from softwood species being a commodity product. In doing so, dimensional lumber requires certain physical properties for building construction safety.

For wood pallets, while technology drives source reduction of their raw material, trees to produce a pallet but just with the requested (tight) specifications. The backend of reusing less raw materials makes building a recycled/repaired/remanufactured pallet harder considering the new pallets are less robust.

Question 5: Please comment on any ways to improve the clarity, transparency, relevance and usability of WARM and its documentation.

Response 5:

WARM could consider adding additional products such as biochar from their waste management perspective. The USDA Forest Service is moving to utilizing wood material from forest restoration activities to make biochar and likely field spread back on the forest floor (Bergman et al. 2022). There is huge potential for carbon storage from the recalcitrant part with the carbon stored for hundreds of years.

In general, sources or tools especially for wood/forests tend to be somewhat dated. I am not able to help out because of my own priorities.

Question 6: Please suggest any applicable studies or data sources not currently used in WARM that could be useful.

Response 6:

For U.S. wood pallet sector, LCI datasets were developed both for new and reuse/recycling/repair. Given the viewpoint on the decisions made by WARM, I suggest considering another carbon storage source, the carbon storage in wood pallets. Like residential buildings, wood pallets make up most, ~90% of their individual markets in the United States. They are currently 1.8 billion U.S. wood pallets in circulation.

- Alanya Rosenbaum, Sevda; Bergman, Richard; Gething, Brad; Mousavi Avval, Seyed Hashem. 2022. Life cycle assessment of the wood pallet repair and remanufacturing sector in the United States. Biofuels, Bioproducts and Biorefining. 16(5): 1342-1352. https://doi.org/10.1002/bbb.2379. https://www.fs.usda.gov/research/treesearch/64847

- Alanya-Rosenbaum, S.; Bergman, R.D.; Gething, B. 2021. Assessing the life-cycle environmental impacts of the wood pallet sector in the United States. Journal of Cleaner Production. 320: 128726. https://doi.org/10.1016/j.jclepro.2021.128726. https://www.fs.usda.gov/research/treesearch/63069
- Alanya-Rosenbaum, Sevda; Bergman, Richard D. 2020. Cradle-to-grave life-cycle assessment of wooden pallet production in the United States. Res. Pap. FPL-RP-707. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 82 p. https://www.fs.usda.gov/research/treesearch/61866

For engineered wood flooring,

- Bergman, Richard D.; Bowe, Scott A. 2011. Life cycle inventory of manufacturing prefinished engineered wood flooring in eastern U.S. with comparison to solid strip wood flooring. Wood and fiber science 43(4): 421-441. https://www.fs.usda.gov/research/treesearch/39777
- Bergman, Richard D.; Bowe, Scott A. 2011. Life-cycle environmental performance of renewable building materials in the context of residential construction : phase II research report : an extension to the 2005 phase I research report. Module N, Life-cycle inventory of manufacturing prefinished engineered wood flooring in the eastern United States. Seattle, WA : Consortium for Research on Renewable Industrial Materials (CORRIM) , 2011: viii, 47 p. https://www.fs.usda.gov/research/treesearch/40833

For biochar pellets,

- Bergman, Richard; Sahoo, Kamalakanta; Englund, Karl; Mousavi-Avval, Seyed Hashem. 2022. Lifecycle Assessment and Techno-Economic Analysis of Biochar Pellet Production from Forest Residues and Field Application. Energies. 15(4): 1559. https://doi.org/10.3390/en15041559. https://www.fs.usda.gov/research/treesearch/63852

For reclaimed/recovered wood (softwood lumber and wood flooring) from old buildings for reuse

- Bergman, Richard D.; Falk, Robert H.; Gu, Hongmei; Napier, Thomas R.; Meil, Jamie. 2013. Life-cycle energy and GHG emissions for new and recovered softwood framing lumber and hardwood flooring considering end-of-life scenarios. Res. Pap. FPL-RP-672. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 35 p. https://doi.org/10.2737/FPL-RP-672

Question 7: Do the greenhouse gas emission assumptions in WARM align with climate change modeling best practices?

Response 7:

WARM uses IPCC (2007) GWP values which are somewhat dated. I would suggest using more recent GWP values from IPCC 2021. IPCC 2021 is the successor of the IPCC 2013 method, which was developed by the Intergovernmental Panel on Climate Change. It contains the Global Warming Potential (GWP) climate change factors of IPCC with a timeframe of 100 years. Note that the GWP 100 factors are recommended as default by UNEP-GLAM (2017), and the GWP20 and GTP100 factors for sensitivity analysis.

This method is based on the final government distribution version of the IPCC report "AR6 Climate Change 2021: The Physical Science Basis" GWP100 CO_2=1 GWP100 CH4=29.8 GWP100 N20= 273 GWP100 CF4=7,380 GWP100 C2F6=12,400
Question 8: Do the management practices modeled in WARM reflect the typical range of management practices used in the United States?
Response 8: One issue detailed below and highlighted in the attached Background document using 'Tracked Changes' was forest C stored would be ~twice the wood carbon stored in HWPs because of processing losses from trees to useable HWPs to be placed in service. These processing losses are called mill residues and can be used internally for onsite energy for drying or sold for use in other engineered wood products, pulp, or energy.
Question 9: Does WARM accurately model the typical second use for recycled materials in the United States?
Response 9: For wood products, reusing flooring and pallets are the best illustrations of the wood sector's abilities. For wood pallets, the sector is getting close to 50% coming from the repair/recycling/remanufacturing stage instead of from new/virgin pallets. The wood pallet PCR describes in detail how to consider reuse while the cradle-to-grave wooden LCA illustrates how to use in practice. Wood pallets are built differently for different end-uses and from many wood species in conjunction have a different reference service life. Reviewing the 'Modeling Reuse in EPA's Waste Reduction Model', in the Limitation section, one thing that is driving reuse of wood products is the pricing particularly in dimensional lumber although the lack of grading rules for recovered dimensional (softwood) lumber is holding the market back. For wood pallets, it is almost better instead of a single pallet would be to consider a large number, say 1,000 old pallets producing 800 repair/recycled/remanufactured, 150 reuse as is pallets, and the rest of wood being used for energy, compost, energy, or landfilled. The pallet papers provide this information in detail.

COMMENTS SUBMITTED BY

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External Peer Review of EPA's Waste Reduction Model (WARM) Methodology

CHARGE QUESTIONS

Question 1: Are the assumptions made in WARM regarding biogenic carbon emissions scientifically sound and in line with common modeling best practices?

Response 1:

Mostly. The "text box" about biogenic carbon emissions on page 1-2 (third instance; PDF page 16) is more or less sound except: The 100-year timescale should be discussed- the GWP factors (1 / 25 / 298) reported on page 1-3 (first instance; PDF page 6) are 100-year factors; IPCC and general consensus hold that 100 year is the common standard. This is important because it justifies ignoring biogenic CO_2 that has a cycling time of much less than 100 years. Saying temporal dynamics are "inconsequential" is not supportable- but you can say that they are "not considered" on the basis of the consensus approach.

See also Response 2.

Care should be taken that the EPA's approach is to consider a 100 year timetable consistently throughout the model. The soil carbon model discussed in Chapter 4 uses a ten year timescale, which weakens its legitimacy.

n.b. your text boxes should be labeled as exhibits, just like figures and tables, so that they can be referred to with precision. e.g. page 1-7 and 1-3 both awkwardly say "the text box in section 1.3.3"

Question 2: Are the assumptions made in WARM regarding carbon storage in forests, soils and landfills scientifically sound and in line with common modeling best practices?

Response 2:

For landfills: yes. For soil carbon: provisionally. The magnitude is small and it is probably directionally OK, but the documentation does not well support the position that compost OR digestate carbon will persist in the soil for 100 years. The analysis seems to use a 10-year timescale.

For forest carbon: No; they contradict the biogenic carbon convention established in the text box in section 1.3.3. After close review and consideration, I feel strongly that forest sequestration credits are not appropriate for source reduction or recycling.

The operating assumption is that carbon cycling that results from materials grown on a "sustainable basis" should be omitted because it "close(s) the loop in the natural carbon cycle." On this basis, carbon sequestration credits are given for wood products assumed to remain in use and for bio-based carbon that is modeled to persist in a landfill (e.g. carbon that is pulled out of the natural cycle), and emissions from combustion of bio-based carbon are ignored. Those credits and that omission are possible only because carbon uptake from the natural forest stock under management is also ignored.

Thus, carbon uptake should not be counted in the cradle-to-gate lifecycle of the products, and neither should it be credited when that cradle-to-gate activity is assumed to be avoided.

The declared scope of the WARM tool is waste management strategies for products that have already been produced (Section 1.3.2.1). For source reduction, EPA makes the suggestion that "trees that would otherwise be harvested are left standing in forests" (sections 1.2.3 and 1.4.3.1) but that is not supported and it contradicts the "sustainable basis" of forest management. It is also contradicted by the literature (see Response 6).

The EPA makes the argument that forest CO_2 content in the US has steadily increased on a historical basis. This is true, but it is not relevant, and modeling this flow is outside the scope of the WARM tool. Changes in the national baseline CO_2 flux, particularly for non-sustainably-managed forest, cannot be attributed to any management decisions contemplated by WARM users.

The further argument that source reduction results in both absolute and marginal increases, i.e. "increased storage of carbon .. relative to BAU baseline" is doubly wrong, on the "sustainable basis" of the material harvesting. Timber under sustainable management is maintained at a steady state that balances extraction with re-planting. The reduction in demand for paper products (a) does not necessarily result in a reduction in demand for timber and (b) does not induce a long-term change in sustainable forest management.

To argue that there is a *marginal* increase in forest carbon uptake requires that (1) source reduction results in direct land use change, i.e. that forest land is removed from sustainable management and returned to wildland permanently and (2) that wild lands uptake carbon with greater efficiency than managed lands. Neither of these claims is approached by the documentation and neither of them is properly in scope.

In any case, the marginal changes indicated in exhibit 4-3 are small in magnitude and inconclusive in directionality.

There is also a data error in exhibit 4-3: both panels show the same data.

A factual error in section 4.1: "In the early stages of growth, trees store carbon rapidly; consequently, as tree growth slows, so does carbon sequestration."

https://www.nature.com/articles/nature12914/

"Rate of tree carbon accumulation increases continuously with tree size"

Question 3: Are the assumptions made in WARM regarding utility offsets from combustion scientifically sound and in line with common modeling best practices?

Response 3:

The modeling appears sound, with concerns as noted in Questions 4 and 5.

Question 4: In general, do the data, assumptions and model components in WARM align with real market practices?

Response 4:

The WARM tool is the product of a decades-long public-private collaboration, comprising incremental revisions on top of a "legacy" core. Although it is generally consistent and of high quality, it is also subject to tremendous technical and institutional constraints. Thus there are a number of important ways that it deviates from scientific best practices.

Significant figures are dealt with poorly. The tool's convention is to report numbers in fixed notation on a per-ton or per-metric-ton basis. This results in a great many exhibits with a single significant figure, or even an order of magnitude with zero significant figures (e.g. "0.01"). This is the least-precise statement of value possible. This could be reasonable if the value reported in the table is an approximation of a more precise value used in calculations, but in all cases that I tested the low-precision value generates the exact results being reported.

It may be suitable to report results with low precision, given the high uncertainties, but model inputs (especially assumptions) should generally not be reported in this way. Examples:

- Background; exhibit 5-1, 0.01 gallons per ton mile
- Management; exhibit 3-3, etc., Transportation EFs, throughout
- Management; exhibits 3-12 through 3-16. In order to maintain the preference for fixed rather than scientific notation, these could be reported as kg, rather than tons.
- Management; exhibit 6-14 (a) (c) and (e)
- Others

SI units should be used. The EPA's reliance on "short tons", ton-miles etc is understandable given the tool's intended user base, but BTUs should be retired from use. Stop using BTUs. This will undoubtedly be a long and challenging adjustment for the agency. Start now.

Exhibit 1-1 shows that many material system models are old, some quite old.

Barlaz 1998 as a basis of material degradation in landfills (Management ch 6) is 25 years old and anecdotal. Consideration of a second source would be appropriate. Because of the tremendous importance of this factor for carbon cycling (both for methane /biogas generation and carbon sequestration), some effort should be spent to validate the findings in actual landfills.

Background; Exhibit 5-1. 0.01 gallons per ton mile is too low. By my reckoning on USLCI processes for short haul trucks, fuel use ranges from 0.014--0.037 gal/ton-mile, with the lower bound being diesel, combination and the higher bound being gasoline, single unit. A single digit of precision should be a conservative estimate; therefore at least 0.02.

For recycling, 1.2.3 the assumption that "the GHG emissions from making an equivalent amount of material from virgin inputs are avoided" is a strong assumption and is almost never appropriate (DOI: 10.1111/jiec.12557). A discussion of this assumption should be provided. Perhaps the tool should report results for recycling at 50% displacement and 100% displacement of primary production.

Several emission factors are not specified, e.g.

-Management; exhibit 3-12

-Please report fixed emission factors explicitly wherever they are used.

Background Section 1.3.1. "Goal definition and scoping" The term that is universally used is "goal and scope definition." I suppose this paragraph predates ISO 14044.

Management Section 3.2.1 - methane yield should be reported in mass, and not volume, to be consistent with the other entries. Especially since mass is used later in exhibit 3-5. Volume of a gas requires a specification of temperature and pressure to be meaningful.

Question 5: Please comment on any ways to improve the clarity, transparency, relevance and

usability of WARM and its documentation.
Response 5: **On the tool:** The "radio buttons" for questions 4, 5, 6, 7, 8, 9 on the data entry tab do not function in LibreOffice. A drop-down field using data validation (i.e. same as what is used in Question 3) is well standardized and should be used instead. **On the documentation:** Remove repetition, especially when the repeated versions slightly differ. Examples: Management Practices document provides a complete description of anaerobic digestion, composting, landfilling, combustion; yet these impact tables are all repeated in the materials-specific documents. They should only be reported once. This will make the documentation more concise and less prone to self-contradiction. The utility offset mechanism is documented three times in the Management PDF: section 3.2.4, section 5.2.4, and section 6.2.5. In all three cases it is presented differently; section 3.2.4 uses only national grid factors instead of regional ones; the chapter 5 and 6 presentations are totally different (e.g. MT CO_2E/Million BTU versus kg CO_2e/kWh). This should be done once, in a dedicated chapter, not repeated, and then used consistently in all cases where waste-derived energy is used to offset grid emissions (and not re-reported). The pagination is inconvenient and/or incorrect. • Pages 1-1 through 1-4 appear THREE times in the Background document. • Consecutive page numbering (e.g. conventional, starting from p.1 through p.87) would improve usability over the current 1-1, 5-1, 7-1 etc. • Different volumes should be labeled, e.g. A-G or I-VII or 1-7, so that reference to e.g. "the Landfill chapter" could be made unambiguously. • Alternatively, chapters could be numbered sequentially so that there is only one Chapter 1; Management Practices "Source Reduction" would start as Chapter 7 (after Backround Chapter 6 "Production and End of Life Impacts") and so on. Having 7 different "Chapter 1"s is annoying. Small methodological details are presented in peculiar ways, e.g. • Exhibit 1-2 for Newsprint, "For the carbon sequestration portion of the factor, it was assumed that the paper was all mechanical pulp." Why does this belong here? Carbon sequestration is not discussed in any other table entries • Recycling processes "generally require less energy" is generally true but not universally true, and is irrelevant and distracting. Simply say that for recycling, the impacts of recycling are compared against the impacts of primary production.

- 4.2.3 starting with "The Oregon DEQ study..." the emission factor of 0.03 MT CO_2e/ton does not follow from the provided citation; in any case, home+garden composting does not appear to be in scope so why is it even mentioned?

The editing is sloppy throughout and should be proof-read.

- Section 3.2.7 "see section 2.4 in the Composting chapter" but Composting is chapter 4. Did they mean Section 4.4 or section 4.2.4?
- Anaerobic Digestion Chapter 3 comes before Composting Chapter 4, but refers to Composting repeatedly- maybe Composting should come first?
- Section 4.2.4 refers to Section 4.2.4
- Typo in exhibit 4-5
- Background exhibit 4-3 is wrong
- Numerous other editorial/ minor issues

Question 6: Please suggest any applicable studies or data sources not currently used in WARM that could be useful.

Response 6:

On Tree growth:

https://www.nature.com/articles/nature12914/

"Rate of tree carbon accumulation increases continuously with tree size"

On displaced primary production by recycling:

-DOI 10.1111/jiec.12557

"Toward Estimating Displaced Primary Production from Recycling: A Case Study of U.S. Aluminum"

-DOI 10.1111/jiec.12355

"Common Misconceptions about Recycling"

On Forest Carbon Sequestration:

-10.1111/gcbb.12016

"Approaches for inclusion of forest carbon cycle in life cycle assessment – a review"

"To capture the dynamic nature of forest carbon stocks, a reference situation for forest land use has to be defined appropriately, consistent with the goal and scope of the study. On the basis of the review it can be concluded that the reference situation should be natural relaxation in attributional LCA and alternative land use in consequential LCA."

This supports the contention that changes in forest carbon sequestration are equivalent to changes in land use, and thus out of scope for WARM.

https://doi.org/10.3389/fbuil.2021.729096

"Embodied GHG Emissions of Wooden Buildings—Challenges of Biogenic Carbon Accounting in Current LCA Methods"

meta-analysis.. main point is to show that the literature is inconsistent and often wrong

- 10.1080/10549811.2013.839386

"Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests"

pretty useful article; it does not support the 'source reduction = CO_2 credit' approach

"Even harvesting for inefficient products or wood energy that create an initial net CO_2 loss (Figure 7b) can sequester more CO_2 in the combination of products, wood energy, and forest than in the unharvested forest provided the stand regrows long enough"

"The greatest CO_2 and FF savings from wood use are by avoiding the excess FF energy used to make steel and concrete structures (avoidance pathway)."

"If catastrophic fires do not occur and forest regrowth after harvest is not considered, saving CO_2 by not harvesting the forest growth is slightly more efficient than harvesting just for wood energy—but generally less efficient than harvesting for construction products. This efficiency of CO_2 storage in unharvested forests also assumes none of the wood blows over or otherwise rots in the forest—an unrealistic assumption in most of the world."

-10.1007/s11367-013-0597-x

"A comparison of the GHG emissions caused by manufacturing tissue paper from virgin pulp or recycled waste paper"

establishing relevance: "Thus, the future of forest lands is directly linked to the production of paper, given that 40–42 % of all wood harvested globally for industrial use is used by the sector"

not until the discussion do they mention this key methodological point:

"Here, it is worth mentioning that the biogenic CO_2 emissions are not considered in the analysis. The carbon neutrality of biogenic sources of CO_2 emissions are implemented on the basis that the wood pulp comes from sustainably managed forest. We have also neglected the temporary storage of carbon in the tissue paper, considering the short life span of the tissue paper as compared to other products from wood, such as furniture, buildings, etc. Hence, only the CO_2 emissions which are released from the combustion of fossilised fuel sources were taken into account."

They do mention: "Further reduction of emissions results when RWP is used to replace pulped wood from forestland, as the recycling of waste paper reduces the demand on forest wood and then eliminates subsequent energy and material requirements of the paper pulping processes. This could also increase forest carbon sequestration because the woods are left to grow to maturity, although such assumption cannot be guaranteed because it totally ignores the possible use of wood for other activities. " but they do not implement this in their analysis

-10.1016/j.resconrec.2012.07.003

"An investigation of the relationship between recycling paper and card and greenhouse gas emissions from land use change"

"Furthermore, although some LCAs considering the changes in international trade (e.g. Kärnä et al., 1994, Wang and Hua, 2007), none consider market mechanisms which determine the source of virgin fibre which may be avoided when switching to recycled content, nor the source of virgin fibre which will be switched to when considering a move from recycled fibre."

EPA WARM does discuss this in limitations, but not convincingly.

"Despite this objective, no published studies have been identified which consider the impact of changes in demand for virgin and recycled fibre in paper making in relation to land use change (LUC). As an internationally traded commodity, the impact of changes in demand for virgin pulp for paper-making is related to international trends in forest cover."

This paper cites EPA's problematic approach

"Given that demand for timber products is not a driver for afforestation, it may therefore be inappropriate to attribute carbon sequestration credits to products, as was carried out in some studies identified in Section 2.1."

"A final hypothesised driver for afforestation is recycling, as espoused on numerous websites (e.g. www.conservatree.com). If recycling paper means that trees are not cut down to provide pulp, then, given that demand is not a driver for continued planting of forests, an increase in recycling rates could lead to an increase in forest area. Through the literature review no evidence has been identified to support this view."

"UNECE (2010) identify that "the rapid growth in wood energy demand and woody biomass production has created concern about competition for raw material from existing forest products sectors, primarily the pulp and paper and composite panel sectors". A rise in demand for wood, for any application, with a finite supply available, could lead to indirect LUC. As this is a consequence of the overall level of demand, it would be driven by extraction of wood for any application."

5.3 "As afforestation is not driven by demand for forest products, the credit for increases in carbon should be allocated to the measure which brought about the change, rather than demand for forest products. This is particularly relevant for changes in primary forest cover and carbon."

"Carbon Footprint of Cartons in Europe – Carbon Footprint methodology and biogenic carbon sequestration" (2010)

https://www.diva-portal.org/smash/get/diva2:1552203/FULLTEXT01.pdf

Actually assumes the *opposite* - allocates carbon sequestration from *managed* forests to positive demand for paper products, rather than reduced demand

They also make completely bonkers assumptions about EOL

Question 7: Do the greenhouse gas emission assumptions in WARM align with climate change modeling best practices?
Response 7: All my thoughts on this are included in the responses to the above questions.
Question 8: Do the management practices modeled in WARM reflect the typical range of management practices used in the United States?
Response 8: To the best of my knowledge, yes.
Question 9: Does WARM accurately model the typical second use for recycled materials in the United States?
Response 9: - **Glass:** No; closed loop glass recycling is increasingly rare because of low recovery efficiency in single-stream recycling. It may be reasonable to assume closed-loop recycling, but tool users must be made aware that this is a somewhat exceptional case and should not be used for generic glass recycling. - **Metals:** ok - **Paper:** ok - **Plastics:** ok - **Construction materials:** ok - **Electronics:** ok - **Wood:** suggest the agency consider modeling scrap wood being open-loop recycled as mulch - **Tires:** Tire-derived aggregate (TDA) should replace aggregate, not sand, but the impact factor is likely the same. Tire-derived fuel (TDF) is used almost exclusively for process heat generation, not for electricity generation. Therefore tire-derived heat should NOT be assumed to replace utility electricity, but rather combustion of alternative fuels. EPA should consider modeling tire-derived crumb rubber used as rubber-modified asphalt.

COMMENTS SUBMITTED BY

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External Peer Review of EPA's Waste Reduction Model (WARM) Methodology

CHARGE QUESTIONS

Question 1: Are the assumptions made in WARM regarding biogenic carbon emissions scientifically sound and in line with common modeling best practices?

Response 1:

Global Warming Potentials Box

Background Chapters: You should really update the emission factors for methane to the latest version of the IPCC report 2021, https://www.ercevolution.energy/ipcc-sixth-assessment-report/.

This should include the timeframe of the GWP. I think this is GWP_100 but many people are suggesting that we should also report GWP_20 where methane has a much higher GWP. I would recommend presenting both 20 year and 100 year GWP as it could be that landfill methane emissions would have a bigger impact in the short term as a management option.

Box CO_2 Emissions from Biogenic Sources Background Chapters

The approach taken to timing of biogenic emissions is reasonable but not state of the art. We know that forestry carbon emissions have a cycle of uptake and release and that the first time of harvest increases the release of CO_2 in the short term. At this point the timeframe of emissions matters because we can no longer assume that we are managing for 100 year timeframes but for the next 25-50 years which will be critical to avoid potential tipping points in climate phenomena. Thus, state-of-the-art would suggest spreading out the emissions over the growth and harvest cycles of biomass. For example, the approach presented in:

https://doi.org/10.1111/j.1530-9290.2012.00507.x , "Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life," is an example of where the specific timing of biomass harvesting and use is accounted for.

Similarly, the decay of biomass in landfills with the production of methane being time-weighted by its instantaneous GWP potential rather than lumping to 100-years or even 20 years would be appropriate but beyond the common best practices which still lump the emissions and weight them by an appropriate horizon. Despite the approach not being state of the art I would not recommend a revision of this specific assumption in the WARM model because there are many other places where effort would be better spent.

Question 2: Are the assumptions made in WARM regarding carbon storage in forests, soils and landfills scientifically sound and in line with common modeling best practices?

Response 2:

The assumptions on carbon storage are reasonable but the timing is very out of date as described in section 4.3. The impact of reduction of forest harvesting is not 1:1 on carbon storage because over time the forestry growth declines and so carbon storage amounts decrease, this is captured in the FORCARB II model as described in section 4.3.2. The graphs in this section, Exhibit 4-3, are indexed to 2010 which is at least 10 years out of date and by the description provided maybe 25 years from how they should be indexed. Since in 4.3.2 the statement is made: "The choice of 2020 represents a delay of about 5 to 15 years for the onset of incremental recycling, long enough to reflect the effects of the recycling program, but at a rate lower than the peak effect in 2030."

I think that this has no impact on the numbers themselves, as I assume that the model has been re-indexed to 2022 rather than 2010 with regards to the storage but it would be helpful to confirm this.

A much more serious issue in the way that WARM is modeling the pulp and paper industry is the assumption around export values that are embedded in Exhibit 4.2. This has an export value of 40% which is very out of date.

The US recycled approximately 70 million tons a year and exported about 9 million tons. The national sword program of China has dramatically reduced the amount of paper that is sent their and dramatically increased the amount of recycled pulp that is sent there.

https://resource-recycling.com/recycling/2021/08/10/scrap-paper-exports-jump-21-in-first-half-of-year/

"During the first quarter of 2022, U.S. firms exported nearly 122,000 short tons of recycled pulp, up 36% from the same period in 2021. During the first quarter of 2017, before the impacts of National Sword set in, U.S. recycled pulp exports totaled only 18,000 short tons."

https://resource-recycling.com/recycling/2022/06/14/us-scrap-paper-exports-sink-slightly-as-plastics-drop-sharply/

The most important discrepancy is the export of pulp rather than the unprocessed paper. This means that the U.S. energy use for the recycling is increased by the amount it takes to produce pulp, which includes drying energy which is substantial.

The change in export in e. of Exhibit 4.2 changes column (b) of Exhibit 4.4 because the reduction in timber harvest is sensitive to the total amount exported (the values of column (b) 0.58 and 0.89 come from the analysis in Exhibit 4.2.)

Question 3: Are the assumptions made in WARM regarding utility offsets from combustion scientifically sound and in line with common modeling best practices?

Response 3:

The assumption of using the marginal "non-baseload" energy producer on the grid is reasonable but makes the analysis significantly more complex and subject to a high degree of variability based on regional grid markets. To quote the definition of non-baseload

'All power plants with capacity factors below 20% are considered "non-baseload". Plants that run at over 80% capacity are considered "baseload" generation and not considered the "non-baseload"; a share of generation from plants that run between 80% and 20% capacity is included based on a "linear relationship". '

I understand this definition in concept, but I am not sure how it was implemented, or what the final grid carbon intensity was for the WARM model and how that varies by region. There are two particular concerns.

First, the grid make up has changed significantly over the past decade and it is not clear what grid generation profile WARM uses. This is a concern because much of the modeling and data used in WARM is over a decade old and this would dramatically change the assumed grid marginal intensity.

The biggest issues here are

- in some states at some times the marginal generation might be from NG combustion turbines which have a very high CO_2 footprint
- almost all renewables will have capacity factors between 20-80% because of the nature of solar and wind generation, but these would not be displaced from the grid because they are non-dispatchable and once built the cheapest sources of electricity. These have very low carbon intensity and their inclusion would distort the CO_2 footprint of the "non-baseload" in the opposite direction. Renewables should always be considered baseload.

Second, the documentation here is quite opaque. Section 3.2 details the Periodic Updates made to WARM data which include the state electricity grid emission factors from eGRID database but also "various aspects of the U.S. average electricity mix" which is quite vague. How often are these periodic updates applied?

Thus, overall, I think the methodology for calculating the utility offsets from combustion is scientifically sound but fraught with difficulties of determining the "non-base load power plants" and the actual CO_2 footprint of the displaced generation by combustion. I think that the definition of "non-baseload" should be modified to exclude any renewable power generating assets that might have capacity factors in the 20-80% range. The documentation should be improved and specifically the "Periodic Updates" should be clarified as to how often the CO_2e is updated and how the regional variations in power grids are accounted for.

Question 4: In general, do the data, assumptions and model components in WARM align with real market practices?

Response 4:

The answer to this question depends on the specific commodity being examined. I am not an expert on most of the commodities handled in WARM but in reading the documentation there is one general concern which is the age of the data and the assumed practices. In most cases the assumptions date back to the early 2000's with some updates to 2010. For some commodities this is likely to be a reasonable assumption but for others the situation around recycling markets and practices will have changed significantly over the last decade. The macro-picture is that China is no longer accepting as much material for recycling across a broad swath of commodities, and particularly paper and plastic. This changes the export percentages of these commodities which feeds through to the carbon footprint because more material is retained in the U.S. for use.

The three commodities with which I am familiar, paper, electronics and carpet there are some differences in the market conditions today compared to the last time WARM was updated.

- Paper – as mentioned in the response to Q2, the recycling market for paper/cardboard has changed due to the China National Sword program which has dramatically cut the export of waste paper/cardboard to China. As a result the export market has shrunk significantly and this does change the results as indicated in Q2.

- Electronics – the assumption around electronics recycling seems to ignore the recovery of active packaged electronic components from circuit boards through disassembly. These components have significant economic value in reuse but also have significant carbon footprints because of the energy intensity of active silicon chip manufacturing. This scenario is part way between electronics reuse where the product as a whole is reused and recycling of circuit boards by thermal treatment. This deserves further attention.

- Carpet – unfortunately the carpet market and the carpet recycling market has evolved significantly since 2010 when the last study of this topic was included in WARM.

  "Carpet is collected curbside and at special recovery events, or individuals can bring it to designated drop-off sites." This is not how most carpet is recycled today. A very large fraction of recycled carpet is recycled because of programs in California. A very large fraction of this carpet is collected at retailers in designated containers that are then picked up by the recycler. There is some additional collection at drop-off sites for individual consumers in the more sparsely populated areas and where recyclers in general do not operate. I would say that no carpet is collected curbside and none at special recovery events.

  "Exhibit 3-6: Residential Face Fiber Mix 1995-2000 Plastic Resin." This was true over this time period. The current mix of residential face fiber is VERY different today compared to this period. PET has become over 50% of the residential face fiber market and PP has shrunk along with N66. N66 is now 10% of the market in the residential space and N6 holds roughly where it was before. This dramatically changes the displaced carpet fiber carbon intensity since PET is a much less carbon intensive fiber than N66 and has significantly less associated emissions in the process.

  "Exhibit 3-13: Secondary Resins Produced from Recycled Carpet Fibers." Unfortunately, this information is very out of date as to what happens to recycled carpet because of changes in the industry. Much less N6 is recycled to fiber because the Evergreen recycling facility closed down. That which is recycled is transported to Europe by Aquafil so the transportation is much longer, but the recycling process is likely much less energy intensive due to the process changes. However, this would mean that from a WARM perspective this should be treated as exported N6 fiber and excluded from the model. The other sectors have grown significantly, particularly the production of PET pellets and the use of PET as a supplement in gasification.

  There is a lot of information available on the California program because of its mandated nature. Carpet recycling outside of CA is modest today, and if it were to increase it would likely follow a similar path as it has in CA. I would use the report on the CA program as a starting point to update the WARM model. https://carpetrecovery.org/wp-content/uploads/2022/09/2021_CA_AnnualReport_ADAcompliant_FINAL.pdf

  Table 4.9 on p28 of this report has the information on recycling yield. What should be noticed is that the vast majority of the recycled material is either polymer used in products as a resin or depolymerized, or the calcium carbonate from the backing. The depolymerization is a modest component of the market compared to the use of fiber in carpet underlay or as an engineered resin and depolymerization requires the export of the fiber.

Question 5: Please comment on any ways to improve the clarity, transparency, relevance and usability of WARM and its documentation.

Response 5:

Overall, the structure of the documentation and the spreadsheet model are clear and the spreadsheet is ease to use. The documentation follows a set path for each recycled commodity and as a result is easy to follow. The main criticisms of the model have been presented in the responses to Q1 to Q4. I will summarize them here.

Clarity and transparency – most of the documentation is very clear and the methodology transparent, there is one point where it is not clear.

- the way the model handles the offsetting emissions from waste-to-energy is not transparent. The model allows selection of a different region but does not display the non-baseload CO_2e of the electricity being displaced, nor is this documented anywhere as it is subject to periodic updating.

Relevance – the data used in the model is often very out of date. It is not clear how relevant some of the GHG studies are for operations today for several reasons.

- First, many of the LCI studies completed by Franklin Associates were done in the late 1990's. The composition of the energy mix for the U.S. electricity grid has changed substantially during this time period and likely the carbon footprints of source reduction and recycling would be different as a result.
- Second, the recycling processes themselves have changed for some commodities due to new investments. This has been pointed out for carpet and electronics.
- Third, the export markets for commodities such as paper and plastics have changed dramatically due to the implementation of the National Sword policy in China. This has changed the destination of exported commodities but also reduced the total amount exported.

Question 6: Please suggest any applicable studies or data sources not currently used in WARM that could be useful.

Response 6:

For carpet recycling the most up to date information is available at:

https://carpetrecovery.org/wp-content/uploads/2022/09/2021_CA_AnnualReport_ADAcompliant_FINAL.pdf

For paper recycling the following are reasonable references for exports:

https://resource-recycling.com/recycling/2021/08/10/scrap-paper-exports-jump-21-in-first-half-of-year/

https://resource-recycling.com/recycling/2022/06/14/us-scrap-paper-exports-sink-slightly-as-plastics-drop-sharply/

For forestry carbon accounting:

10.1111/j.1530-9290.2012.00507.x

Question 7: Do the greenhouse gas emission assumptions in WARM align with climate change modeling best practices?

Response 7:

In my opinion, there are two considerations in which WARM does not align with best practices.

- The most recent IPCC report should be used for the GWP factors, particularly for methane.
- WARM should report both GWP_{20} and GWP_{100} numbers rather than just the latter. This is because the timescale of emissions and impact on climate are such that both timescales are now relevant to global warming.

A further consideration is the accounting for biogenic CO_2 where it could be argued that the best practice is to consider the timing of CO_2 releases from forestry cycles. I think this level of complexity is too much and would not alter choices for management strategies.

Question 8: Do the management practices modeled in WARM reflect the typical range of management practices used in the United States?

Response 8:

Yes – the documentation alludes to the idea of including re-use which would be the only omission of some importance for certain commodities, such as electronics, but other than that I think re-use is a relatively small component of the waste management stream.

The commodity with which I am most familiar, carpet, is hardly ever reused, less than 1M lbs of carpet were reused in 2021 about 0.1% of the gross collections of carpet in the state of CA.

The documentation does spend significant time explaining the source reduction energy and carbon footprint calculations, but source reduction is not a waste management practice. Source reduction has implications in the context of recycling and that is how it is used in the WARM model, but it is quite confusing to see the two columns in the spreadsheet F and G that are identical save for a minus sign.

Question 9: Does WARM accurately model the typical second use for recycled materials in the United States?

Response 9:

This varies by commodity – but in the case of carpet the modeling is inaccurate because the market has shifted significantly since the data used in WARM was generated. The recycling data in WARM is based on studies performed in 2008-2009 and reported to WARM model analysists in 2010. At the time the dominant carpet fiber was nylon, both nylon 6 (N6) and nylon 6,6 (N66). The main route of recycling nylon 6 carpet was depolymerization at Evergreen in Augusta GA. This plant subsequently closed. Depolymerization activities are carried out in Eastern Europe by Aquafil but the dominant route for N6 and N66 is to recycle them into products without depolymerization. N66 has almost been completely eliminated from the market for new carpet due to plant closures and exit from the market by one of the major N66 producers. It now represents less than 10% of recycled materials. N6 is still a significant component of the recycle stream and continues to be used, probably 25% of the recycle market.

The rise of PET face fiber carpet, from 15 to 50% of the residential market over the last decade has dramatically shifted the markets for secondary materials. A significant fraction of the PET face fiber is incorporated into pad for carpet backing or into a PET pellet that is subsequently gasified and used as a chemical feedstock. PET carpet did not figure strongly in the analysis of 2010, and so the second use of carpet fiber is not accurately modeled. Finally, for carpet there has been a substantial rise in the use of the calcium carbonate (so called PC4) material that is liberated from the carpet during the recycling process. This is now about 25% of the recycled stream from CA, 17Mlbs of 67Mlbs. The PC4 material displaces a variety of fillers in an open loop recycling system and requires significant energy input to recover with a modest improvement over virgin calcium carbonate from an energy and carbon perspective which is strongly dependent on the transportation distances and modes for both the recycled and virgin materials.

COMMENTS SUBMITTED BY

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External Peer Review of EPA's Waste Reduction Model (WARM) Methodology

CHARGE QUESTIONS

Question 1: Are the assumptions made in WARM regarding biogenic carbon emissions scientifically sound and in line with common modeling best practices?

Response 1:

The assumptions regarding the way in which carbon emissions associated with biogenic materials in WARM are summarized in Table 1.3.3 of the WARM background document and are said to be consistent with IPCC guidance. The documentation provided emphasizes that in the United States forest wood is replaced at a significantly faster rate that depletion, consistent with sustainable forest management. So, yes WARM's assumptions are consistent with common modeling practices, with two caveats.

First, it is not clear that the rate of biogenic wastage (e.g., lawn and golf course clippings, leaves, etc.) attributed to human actions has remained constant over time over the past hundred years or so. To the extent that landfill emissions from "excess" biogenic wastes have been poorly managed, meaning emitting uncontrolled methane, net GHG emissions may be significant. The Monte Carlo approach for landfill emissions defining "best" and "worst" scenarios is a good way to address this issue.

Second, note should be taken that WARM focuses *only* on GHG emissions and energy use. Like many analyses with limited scope, other important environmental impacts, such as biodiversity and land use changes, are not directly addressed.

Question 2: Are the assumptions made in WARM regarding carbon storage in forests, soils and landfills scientifically sound and in line with common modeling best practices?

Response 2:

As the documentation makes clear, reactions within landfills are complex and, at least for microbial degradation (producing methane), take place over many years. I would say that WARM does as good a job as any capturing these complexities. There is considerable reliance on the laboratory studies of Mort Barlaz, an expert by acclamation in landfill science, but even he recognizes that such lab studies are likely to overestimate the rate of degradation in comparison with actual landfill systems. That said, it may be prudent to broaden data sources in the future to include more recent field studies (e.g., *Sustainability* 2020, 12(15), 6209; https://doi.org/10.3390/su12156209*; Environ Sci Pollut* Res 29, 24623–24638 (2022). https://doi.org/10.1007/s11356-021-17566-4, *Waste Management* (2019), 87:835-859,ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2018.12.047; Daniel H Cusworth et al 2020 *Environ. Res. Lett.* 15 05401; Kormi et al., *Waste Management* (2018), 72:313-328, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2016.11.024).

I have no comments on the way carbon is stored in soils. The Century model seems very robust.

WARM developers understand that forest systems are ecologically and economically complex. The main issue I see is that the effects of cross-border trade (especially with Canada) seem vaguely treated. The US does not harvest enough softwood to meet its needs (for housing, etc.); around 80% of US softwood needs are imported from Canada. This is an allocation problem of the sort that arises often in life cycle assessment studies when international borders are involved. The WARM methodology "counts" the carbon storage of forests as the trees are grown in the US. This is lost after trees have been cut down or exported but to date replacing trees far exceeds losses. However, while imported trees yield no carbon storage benefits for the importing country (US), they do represent an alternate source of wood that, according to WARM's methodology, should reduce domestic harvesting (is this actually the case?). A relatively recent study by Hertwich and Wood may help clarify the problem (Edgar G Hertwich and Richard Wood (2018) *Environ. Res. Lett*. 13 104013).

Question 3: Are the assumptions made in WARM regarding utility offsets from combustion scientifically sound and in line with common modeling best practices?

Response 3:

Combustion is not my area of expertise but reading Chapter 5 of the "Management Practices" document on WTE options, I find few inconsistencies in reasoning or data evaluation. The main thing that is a bit puzzling is the inclusion of contributions of textiles, rubber, and leather to WTE GHG emissions, yet these appear to *not* be listed among the 61 materials included as MSW (exhibit 1-1 in "Background"). I assume this is because these materials make up a diminishingly small fraction of MSW but have significant energy value for WTE facilities.

Question 4: In general, do the data, assumptions and model components in WARM align with real market practices?

Response 4:

In general, yes, WARM includes the major pathways and materials for a robust analysis of GHG emissions associated with solid waste management and uses current data (such as emission factors) to generate GHG emissions (however note the need to explore the inclusion of consumer behavior in Q7).

Note should be taken of the changing policy landscape for waste management, mostly at the State level. Federal actions on waste management have often been supplemented and in many cases extended through State initiatives. These have taken a variety of forms, including Extended Producer Responsibility (EPR) laws, plastic bag fees or taxes, container deposit/return laws, right-to-repair requirements, and composting regulations. Most of these laws have been enacted to address a particular kind of waste problem; holistic approaches for waste management are still elusive. Nevertheless, there is still considerable activity in the regulatory area that is aimed at "closing the loop" and reducing waste generation.

Two policy shifts, in particular, may significantly extend product and material utility: (1) "Right-to-Repair" laws have proliferated rapidly at the State level, driven in part by the desire, in some cases, to open markets for local repair shops and spur competition for large manufacturers, and (2) Extended Producer Responsibility (EPR) laws have also proliferated. EPR legislation places the responsibility for the disposition of products at end-of-life on producers, manufacturers, and retailers. In this sense EPR comes closer than most waste management laws to "circularizing" the economy since all stages of the product life cycle are included. Initially most EPR laws have been limited to specific products such as pharmaceuticals, batteries, paint, and carpet. Yet many states are now considering far more general EPR approaches, among them California, Hawaii, Maryland, Massachusetts, and New York (The National Law Review, Volume XII, Number 160, June 9, 2022).

Such laws are likely to alter waste management pathways as new business models are developed, for example "Right-to-Repair" and EPR laws may extend material usage in the original product, limiting secondary uses.

Question 5: Please comment on any ways to improve the clarity, transparency, relevance and usability of WARM and its documentation.

Response 5:

Managing solid waste is complicated, and so is WARM. The documentation is extensive as one would expect. I fiddled around with the Excel version supplied and found it relatively straightforward to use. I input simple scenarios (baseline landfilling vs recycling) for one commodity at a time. I was initially puzzled by some of results that showed an absolute value for recycling that was greater than landfilling. If I am comparing the two results that says to me that recycling either sequestered GHGs or more likely displaced products that would have been manufactured from virgin resources, generating a negative GHG value. Cool!

The output spreadsheets were OK, but the reports that were generated do not explain much—for instance how to interpret a negative value. This kind of result might send users into the hundreds of pages of documentation to find answers. One way to address this might be an extensive, and searchable, glossary or index. Not fun to do, but it might improve transparency.

Another approach, which we have used in our group for software usability, is to embed short videos illustrating both inputting and outputting information to/from WARM. This might include case studies that include the interpretation of results.

Other suggestions for clarity are contained in Q9.

Question 6: Please suggest any applicable studies or data sources not currently used in WARM that could be useful.

Response 6:

Several references have been cited in answers to other charge questions. But here are a couple of recent articles that may be of interest:

"Inefficient and unlit natural gas flares both emit large quantities of methane", SCIENCE 29 Sep 2022, Vol 377, Issue 6614, pp. 1566-1571 DOI: 10.1126/science.abq0385.

"All in on plastics pyrolysis", C&EN | CEN.ACS.ORG | OCTOBER 10, 2022, pp 23-27.

Question 7: Do the greenhouse gas emission assumptions in WARM align with climate change modeling best practices?

Response 7:

As noted in the documentation, WARM GHG calculations do not follow most other GHG inventory methods in two ways: (1) WARM begins its inventory from the point of waste creation, and (2) consumer behavior (or changes in consumer behavior) are not included in the analysis. Further, upstream extraction and manufacturing GHG emissions are included only when recycling and/or source reduction is part of the material cycle. The rationale behind this is the intention that WARM is meant to be used only for comparative purposes, i.e., one scenario compared with another. And it is assumed that (1) consumer behavior never changes as long as the functionality of the product is essentially the same, and (2) the manufacturing emissions only change when the quantity (source reduction) or mix of input materials (recycled content) changes. These assumptions are clearly stated and explained. For short-term comparisons WARM is a great tool for helping decision-makers, regulators, and manufacturers manage GHG emissions.

However, the omission of consumer behavior on GHG emissions may be quite significant.

Any product designer will admit that one of the chief drivers in product design is indeed to change consumer acquisition and use behaviors (e.g., *International Journal of Production Economics* 210 (2019) 155–168). One need look no further than the impacts of multifunctional products, for example smart phones (SP). Within a decade or so a significant fraction of users has ditched their telephone land lines, cameras, calculators, physical wallets, private cars (in favor of SP-enabled ride shares), and trips to malls and grocery stores in favor of online shopping. This is not to mention shifts in the social milieu driven by cyber-enabled platforms. We are a consumer-driven economy.

Most life cycle approaches have faced similar problems—how to account for consumer preferences and changes, and the impacts of products and services on the quality of their lives. A good approach to this is to include behavioral economics, or something similar, in the LCA methodology. At present WARM relies on input-output modeling for economic analysis, which includes social measures such as tax generation and job creation (or loss). This is fine, but significant advances in social LCA approaches are available: (https://www.lifecycleinitiative.org/library/guidelines-for-social-life-cycle-assessment-of-products-and-organisations-2020/,

And behavioral models are being developed:

Derek D. Reed, Justin C. Strickland, Brett W. Gelino, Steven R. Hursh, David P. Jarmolowicz, Brent A. Kaplan, Michael Amlung (2022)." Applied behavioral economics and public health policies: Historical precedence and translational promise", *Behavioural Processes,* 198, 104640, https://doi.org/10.1016/j.beproc.2022.104640).

Perhaps future versions of WARM can include the impact of consumer choices on GHG emissions.

Question 8: Do the management practices modeled in WARM reflect the typical range of management practices used in the United States?

Response 8:

WARM identifies six management practices: Source Reduction, Recycling, Composting, Anaerobic Digestion, Combustion, and Landfilling. Specific approaches within these practices are also explored (e.g., source reduction might be achieved through redesign, reuse, repair, expanding useful lifetimes, or avoiding some quantity of materials in initial designs). These practices (except repair) are further analyzed for several product types (e.g., non-durable goods, packaging, glass, metals, paper, plastics, and PLA—61 materials in all). I am impressed with the degree of thoroughness with which each of these practices have been examined. And I believe these options cover the majority of management practices in place at this time in the US, but not all. Future additions to WARM might include:

- Textile management. WARM does not explicitly include textiles in its material database as yet (although it does include them for WTE facilities). Textile products are recycled at a very low rates (~2-5%), but typically end up in landfills. In some cases, the material composition is biogenic (cotton, wool, linen), but others are composed of synthetic fibers. It is acknowledged that EPA is considering inclusion of textile fabrics in future versions of WARM.

- Plastics recycling. Typical practice involves mechanical shredding followed by various heat treatments, however significant resources are currently being brought to bear on chemical recycling (where the polymer is unwound), or mechanical/chemical recycling (Ragaert et al (2017), Waste Management 69:24-58). Implementation of chemical recycling will undoubtedly change emission factors.
- Effect of trade. Also, as noted in Q2, international plastics trading may have impacts on recycling systems.
- Effects of colorants. Another factor in recycling plastics is the addition of colorants to initial production of plastic containers. While it is possible to separate waste plastics into similarly colored lots, it is often difficult to find a market large enough to justify the extra expense. It is fairly common practice to separate plastics into two lots—clear (or "natural") and mixed colors. The latter fetch lower prices and are usually remanufactured into darker shades (brown to black). Some products are being packaged this way (e.g., motor oil), but more often these end up in various secondary uses such as flower pots, fencing, piping, etc. (https://plasticsrecycling.org/images/library/2018-postconsumer-bottle-recycling-report.pdf).
- Advances in plastic separation. WARM focuses on HDPE and PET, since these are the most recovered materials, but advances in identifying and recovering other plastics continues to be made (Antonopoulos et al, (2021) *Waste Management* 126: 694–705). As noted above, separating plastics by attributes does not necessarily mean there will be economically viable markets.
- Open burning. I don't have any recent data on "open burning" of solid waste ("barrel burning"), and the open burning of leaves, twigs, crop residues, etc., but it is not banned in many jurisdictions, mostly rural.

Question 9: Does WARM accurately model the typical second use for recycled materials in the United States?

Response 9:

The essential features of WARM's second use modeling are contained in sections 2.1.1. and 2.1.3. Here the differences between "open loop" and "closed loop" recycling are explained and the subsequent modeling of GHG generation is presented. I understand the logic, but it is a tough read. First, "open" and "closed" terminologies have different meanings in other BOKs: thermodynamics, economics, social science, anthropology, history, philosophy, and of course manufacturing (the latter seems to be the meaning implied here). WARM defines these terms so I understand the contextual meaning. I mention this because I assume that WARM has many users with disparate backgrounds for whom the meaning (including me) may not be obvious. Second, these sections would benefit from schematic diagrams and sample calculations, as seem to be presented in other chapters of documentation materials.

The question uses the term "accurately" and I don't believe there is enough information to provide a definitive answer. The framework is logical, but I can imagine some scenarios that might complicate things, for example products composed of multiple materials that require disassembly steps and feed into more than one material stream, closed or open. Another is a "repair" pathway (see Q4).

Sometimes this is assumed to refer to local repair shops for cars and electronics, but it also applies to products being remanufactured under EPR business models, sometimes by large manufacturers. The Xerox "Lakes" project in the late 1990s and early 2000s comes to mind (https://www.xerox.com/en-us/about/history-timeline).