Genesis, Methodology & Sources for MEBCalc

Over the past 25 years Sound Resource Management Group, Inc. (SRMG) developed the Measuring Environmental Benefits Calculator (MEBCalc) life cycle assessment tool for waste discards management. SRMG personnel and numerous other researchers conducted the research and analysis used for the information and data embodied in the calculator. This document explains MEBCalc's genesis and methodology, and summarizes its sources.

Genesis

Handling and disposal of municipal solid waste (MSW) and construction and demolition (C&D) discards causes external environmental costs and benefits. Environmental externalities include impacts on human health and the environment from pollutant emissions that are not "counted" in the prices and costs associated with handling and disposal of MSW and C&D discards. Many climate-changing, human toxic or carcinogenic, and ecosystem toxic pollutant emissions are not regulated and can be released to air, water or ground at no cost to the emitting facility. Others are regulated, but emissions below regulatory limits can be released to the environment at no cost. This means that the costs of unregulated and fugitive pollutant emissions are not charged to owners or managers of facilities that handle or dispose of discards.

For example, using recycled materials instead of virgin raw material resources to manufacture paper, aluminum cans or tin cans creates measurable environmental benefits. Many of these benefits are from reduced energy use in the production process. Lower energy use typically reduces pollutant emissions. Yet virgin-content product manufacturers with their higher energy uses do not have to pay for their higher pollutant releases. Hence, recycling and recyclers often do not benefit economically and competitively from recycling's lower pollution footprint.

The same story holds for benefits of diverting organic material discards from landfill, combustion, or conversion facilities that directly or indirectly convert biogenic materials into heat and power. Some of the carbon in landfilled organics is biodegraded into methane, a powerful greenhouse gas (GHG), carbon dioxide, and trace amounts of other GHGs. Depending on the efficiency of landfill gas capture systems, some or all of these GHGs may escape into the atmosphere and increase climate change impacts.

Combustion turns virtually all the carbon in organics into carbon dioxide which is released to the atmosphere and contributes to climate change. Recyclers obtain no financial or competitive advantage versus disposers because landfills, combustion and conversion facilities don't pay anything for their GHG emissions to the atmosphere.

Research on Public Health and Environmental Costs of Pollutant Emissions

The MEBCalc model both quantifies and monetizes the benefits of waste reduction, recycling and composting from reducing pollutant emissions. This is possible due to substantial strides in measuring pollutant emissions, impacts of pollution on human health and other environmental receptors, and costs of damages to those receptors from pollution. Progress has come from, *inter alia*:

1. Regulatory impact analyses (RIAs) mandated by federal law and executive order.
2. Research on potential impacts of climate change.
3. Analyses of the impacts and costs of pollution and other environmental dis-amenities (for example, noise and odor) on the health of humans, other-than-human species, and ecosystems.
4. Life cycle analysis of pollution and energy embodied in materials and products, as well as emitted during resource extraction, refining, and manufacturing of those materials and products.
5. Economic analysis on the value of additional years of life and the costs of increased morbidity.

Publicly Available Data on Pollutant Emissions

Data now exist for pollutant releases and pollution profiles from resource extraction and refining, as well as for material and product manufacturing, product use, and end-of-useful-life management of product and packaging discards. Some of these data are maintained in publicly available data bases, including:

1. U.S Environmental Protection Agency's (EPA's) National Emissions Inventory (NEI).
2. EPA's Greenhouse Gas Inventory (GHGI).
3. EPA's Toxics Release Inventory (TRI).
4. EPA's Compilation of Air Pollutant Emissions Factors (AP-42) for more than 200 industrial air pollution source categories (where a category is a specific industry sector or group of similar emitting sources).
5. Data gathered, codified and maintained by state environmental protection agencies.
6. Data gathered and maintained by state and local clean air and clean water management, control and permitting agencies.

Connecting Pollutant Emission Quantities to Human Health and Environmental Impacts

A very important development in connecting pollutant emissions quantities to environmental impacts came from the United Nations Intergovernmental Panel on Climate Change (IPCC). IPCC developed, or at least helped popularize, an index that defines in one number the amount of climate forcing emissions released into Earth's atmosphere each year. The Climate forcing strengths of GHG pollutants are codified in global warming potentials (GWPs) for each atmospheric pollutant that contributes to trapping of incoming solar heat energy. GWPs are updated each time that IPCC produces a new Assessment Report.

Examples from the IPCC 2014 Fifth Assessment Report (AR5) of GWPs important for MSW management range from 1 for carbon dioxide (CO_2) to 28 for methane (CH_4) and 265 for nitrous oxide (N_2O). AR5 GWPs top out at 23,500 for sulfur hexafluoride (SF_6), used in aluminum casting as a refining and degassing agent. These examples of GWPs represent each GHG's climate forcing average effect over the 100 years following their release.

GWPs for many GHGs over a shorter time frame are different, except for CO_2 which always has a GWP of 1. Twenty-year GWPS are also reported in the IPCC assessment reports. For example, for the 20 years following release methane's average GWP is 84. The difference between average GWPs for methane over 100 years versus 20 years is mostly because once in the atmosphere methane begins oxidizing to carbon dioxide and water vapor. Methane's lifetime in the atmosphere is over after about 12 years. Carbon dioxide emissions and their climate changing impacts, by contrast, persist in the atmosphere for many years beyond 100.

GWPs express the global warming potential of any greenhouse gas (GHG) relative to the global warming potential of carbon dioxide. Using GWP weights, then, one can sum up the relative global warming potential of a profile of greenhouse gas releases from an activity or pollution source. This sum is termed carbon dioxide equivalents and is denoted by eCO_2 or CO_2E. It facilitates comparison of an activity's total GWP to any other activity's total GWP, provided one has a GHG emissions profile for both. For example, GWP weight summations allow comparison of the climate impact potential among alternative methods for producing the same product or material, or carrying out the same waste management system activity such as disposal via burying versus burning MSW discards.

Given this carbon dioxide equivalents indexing methodology for GHG emissions, there was still a need for comparative impact potential and summary assessment indicators for human health and environmental impacts besides climate change. In this case the enabling tool came from EPA in the form of TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts). As of TRACI version 2.1, this tool provides characterization factors for the public health and environmental impacts of 3,944 chemicals and other substances. There are characterization factors for each of these 3,944 pollutants for each of 9 environmental impacts – climate change; human health impairments from particulates, toxics or carcinogens;

waterways eutrophication; atmospheric acidification; ecosystems toxicity; ozone depletion and ground level smog formation.

Many chemicals and substances have TRACI characterization factors of zero for some impacts. For example, for climate change only 91 of the 3,944 TRACI chemicals and substances have GWP characterization factors greater than zero.

For climate change the characterization factors are IPCC GWPs which can be summed to carbon dioxide equivalents. For the other eight impact categories TRACI's characterization factors also are based on consensus among researchers and scientists on the relative effects of each pollutant in comparison to other pollutants that have the same environmental impact. One particular pollutant serves as the environmental impact indicator for each of the other eight categories of public health and environmental impacts, just as carbon dioxide equivalents serve as the climate impact potential indicator for GHG emissions.

The upshot here is that, given a pollution emissions profile for the life cycle of a product, material, MSW activity or other pollution emitter of interest, TRACI 2.1 provides impact potentials for 9 different human health and environmental impacts. TRACI's comprehensive characterization factors make possible comparison of recycled- versus virgin-content environmental impacts for an MSW material. This comparison is used in calculating the environmental benefits of diverting MSW discards from garbage and its associated virgin-content production life cycle, to recycling and its associated recycled-content production life cycle. Comparison of resource extraction along with product and packaging manufacturing impacts (aka "upstream" impacts) for virgin-content versus recycled-content products and packaging materials is one of the important analyses provided in MEBCalc.

Methodologies for Calculating Life Cycle Emissions Profiles

Life cycle emissions profiles for the upstream impacts of some MSW and C&D materials are available from life cycle supply chain analysis. Supply chain analysis is conducted by inquiries of virgin- and recycled-content manufacturers regarding their product, wastes and pollutant emissions outputs, along with their associated inputs of materials, energy and chemicals. This is followed by acquiring the same information from suppliers of these input materials, energy and chemicals; information from suppliers of suppliers; and so on. Such data gathering and refining requires many judgements about which inputs require follow-up with suppliers of those inputs, and how far up the supply chain to proceed with the investigation. This method of gathering life cycle inventory (LCI) data for life cycle assessment (LCA) is called a process LCI.

Figure 1 graphicly illustrates the activities and resources that need to be taken into account in a process LCI for a waste management system.[1] The upstream portion of a discard's life cycle is illustrated in the top half of Figure 1. As implied by the numerous inputs and outputs depicted on Figure 1, process LCIs for the upstream life cycle are data and information intensive, time consuming and quite costly.

For upstream life cycle impacts of materials and products that have not been investigated by process LCIs, there are economic input-output life cycle assessments (EIO-LCAs) available from several sources -- for example, Carnegie Mellon University Green Design Institute provides EIO-LCA models at www.eiolca.net. That website states:

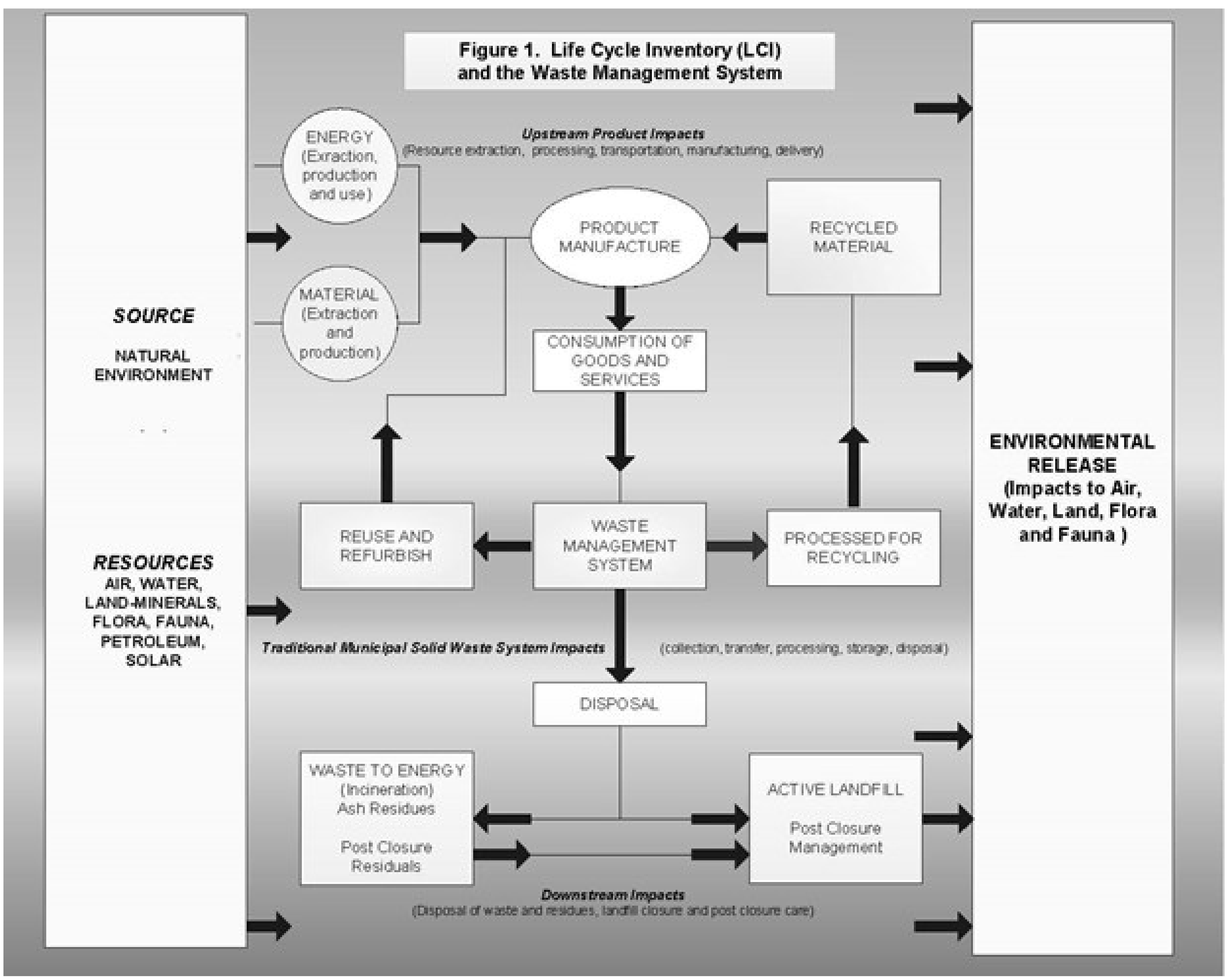
> "The Economic Input-Output Life Cycle Assessment (EIO-LCA) method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy. The EIO-LCA method was theorized and developed by economist Wassily Leontief in the 1970s based on his earlier input-output work from the 1930s for which he received the Nobel Prize in Economics. Researchers at the Green Design Institute (GDI) of Carnegie Mellon University operationalized Leontief's method in the mid-

[1] Source, Morris, j., Bagby, J., Economic Analysis of New Waste Prevention and Recycling Programs, Appendix D, page D-6 in *City of Seattle Solid Waste Management Plan (2011 revision)*, approved by Washington State Department of Ecology in 2013. Appendix D also discusses some of the same information detailed in this document.

1990s, once sufficient computing power was widely available to perform the large-scale matrix manipulations required in real-time."

The interested reader can review these models and their methodological underpinnings at sites such as the one maintained by Carnegie Mellon.[2] One of the advantages of EIO-LCAs is that they are much less time consuming and costly than process LCIs. They build on work conducted every five years by the U.S. Department of Commerce Bureau of Economic Analysis (BEA) to develop and update economic input-output models of the U.S. economy. BEA EIO models are connected to pollution emissions profiles using available sources such as those listed previously in the section *Publicly Available Data on Pollutant Emissions.* The result is an EIO-LCA model. This type LCA model is sometimes useful for depicting the upstream LCI portion of a material or product discard managed in a waste management system.

One shortcoming of life cycle inventory data produced by the EIO-LCA methodology is that emissions data are aggregated by industry. BEA EIO models typically encompass fewer than 500 industries. This means that many industries are broad and not well suited to estimating upstream emissions profiles and environmental impacts for less aggregated industries. For example, EIO-LCA paper/paperboard and aluminum manufacturing industry data do not separate out pollution emissions data for virgin-content from recycled-content cardboard box manufacturing or virgin-content from recycled-content aluminum can manufacturing.



[2] Also, see Hendrickson, C.T., Lave, L.B., Matthews, H.S. (2006), *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach.* Resources for the Future, Washington, DC.

Activities encompassed in a waste management system are depicted in the lower half of Figure 1. They include collection of recyclables, compostables, and garbage; transfer and hauling of those collected discards; processing of collected discards streams; and management of discards at points of final disposition. The latter include recycled-content product and packaging manufacturers, compost producers and disposal facilities. LCIs for all of these waste management system activities are available through resources such as those listed in the next section.

MEBCalc Methodology and Sources

The MEBCalc tool estimates environmental impacts from diversion of discards to waste prevention, recycling, and composting, and to use as an industrial fuel in the case of wood wastes, used oil and certain other discards. The tool bases its life cycle impacts, both upstream and waste handling system activities, on TRACI's characterization factors and life cycle inventory and activity data from well-recognized and well-regarded sources, such as:

1. EPA's Waste Reduction Model (WARM).
2. The EPA-funded MSW Decision Support Tool's *Life-Cycle Data Sets for Material Production of Aluminum, Glass, Paper, Plastic and Steel in North America*, available from Research Triangle Institute.
3. The Environmental Paper Network's Paper Calculator.
4. The Sustainable Packaging Coalition's Comparative Packaging Assessment tool (COMPASS, now available through Trayak at https://trayak.com/company).
5. California Air Resources Board's *Method for Estimating Greenhouse Gas Emissions Reductions from Recycling*.
6. Oregon Department of Environmental Quality's *Life Cycle Inventory of Packaging Options for Shipment of Retail Mail-Order Soft Goods, Final Peer-Reviewed Report*.
7. Carnegie Mellon University Green Design Institute's EIO-LCA models (available at www.eiolca.net)
8. California Department of Resources Recovery and Recycling (CalRecycle) study on used oil recycling – R. Geyer *et al*, *Life Cycle Assessment of Used Oil Management in California*.
9. Franklin Associates, A Division of Eastern Research Group (ERG), (2018), *Life Cycle Impacts for Postconsumer Recycled Resins: PET, HDPE, and PP.* Prepared for The Association of Plastic Recyclers (APR).
10. Numerous peer-reviewed journal articles -- such as, for wood wastes, Morris, J., (2017), Recycle, bury or burn wood waste biomass? LCA answer depends on carbon accounting, emissions controls, displaced fuels, & impact costs, *Journal of Industrial Ecology*, 21 (4) 844-856; for organic wastes, Brown, S., and Beecher, N., (2020), Carbon accounting for compost use in urban areas, *Compost Science*, forthcoming in print; and Morris, J., (2010), Bury or burn North America MSW: LCAs provide answers for climate impacts & carbon neutral power potential, *Environmental Science & Technology,* 44 (20) 7944-7949.

Monetizing the Nine Life Cycle Impacts

The final step for MEBCalc is to monetize each public health and environmental impact. Monetization uses estimated damage costs for the nine impacts. There are numerous challenges in estimating these damage costs for pollution externalities.

Pollutants That Cause Multiple Environmental Impacts

One challenge is that a pollutant may have more than one environmental impact. For example, sulfur dioxide (SO_2) emissions to the atmosphere can cause human respiratory impacts when SO_2 reacts with other compounds in the atmosphere to form small particles. Inhaling these particulates causes respiratory illnesses. SO_2 also is a precursor (i.e., chemical forerunner) to acid rain because it combines with water, oxygen and other chemicals in the atmosphere to form sulfuric acid. Sulfuric acid then deposits on buildings, cars, and trees, as well as in waterways, causing harm to plant and animal life and to buildings, among other impacts. Human health respiratory impacts from SO_2 emissions and acid rain impacts from SO_2 emissions each have different damage costs.

<u>Environmental Impacts Must be Mutually Exclusive</u>

Another challenge is converting emissions of numerous pollutants into a manageable number of mutually exclusive environmental impacts. Mutually exclusive impact categories mitigate the double counting problems that could occur with pollutants such as sulfur dioxide that can cause more than one type of environmental impact.

EPA's TRACI model is a life cycle impact assessment tool with mutually exclusive impact categories. As mentioned previously in this document, TRACI provides indexing weights known as characterization factors for each pollutant that is a potential cause of each environmental impact. These characterization factors allow emissions of disparate pollutants that cause each impact to be aggregated/summed into an equivalent quantity of emissions for a single reference pollutant that also causes the given impact.[3] This greatly simplifies modeling, reporting, and analysis of pollution impacts. It makes environmental impact data far more accessible to policy makers. Otherwise policy makers would have to contend with impact data on hundreds of pollutants.

The IPCC's aggregation technique for climate changing pollutant emissions also was discussed briefly earlier in this document. Releases of various greenhouse gases (GHGs) -- carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and others -- cause global warming which leads to climate change. In its periodic climate change assessments, the IPCC thoroughly reviews available scientific data to determine the strength of each GHG pollutant relative to carbon dioxide in causing global warming. Based on the global warming potential (GWP) for each GHG pollutant, the emissions of all GHGs associated with an activity or product can be aggregated into the single reference substance eCO_2. IPCC GWPs from the AR6 report are used in the TRACI model for aggregating the climate changing potential of an GHGs emissions profile for an activity or product.

Another example illustrates how the TRACI model avoids double counting. Substances that are scored by TRACI 2.1 as having human respiratory impacts greater than zero include filterable and condensable particulate matter, SO_2, nitrogen oxides (NO_x), and total suspended particulates. These substances all have zero characterization factor scores for human health carcinogenic and toxicity impacts. What might seem like a possibility for double counting is thus avoided using TRACI methodology for keeping impacts mutually exclusive.

MEBCalc uses TRACI characterization factors for the nine public health and environmental impacts codified in the TRACI model. The nine mutually exclusive impacts and the estimated 2018 damage cost per ton (2000 pounds) for each impact's reference substance are:

- Climate change – the potential increase in greenhouse effects due to anthropogenic emissions. CO_2 from burning fossil fuels is the most common source of GHGs. Methane from anaerobic decomposition of organic material is a large source of methane. The reference substance for climate change potential is carbon dioxide and the pollutants that have climate impacts are

[3] Jane C. Bare, *Developing a Consistent Decision-Making Framework by Using the U.S. EPA's TRACI,* U.S. Environmental Protection Agency, Cincinnati, OH, 2002; Jane C. Bare, Gregory A. Norris, David W. Pennington and Thomas McKone, TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. *Journal of Industrial Ecology* 2003, 6(3-4): 49-78; and Jane C. Bare, TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental Impacts 2.0. *Clean Technologies and Environmental Policy*, 2011, 13(5) 687-696, provide expositions on the original and more recent versions of the TRACI model.

characterized and converted by the TRACI model into carbon dioxide equivalents, eCO_2. Cost of eCO_2 emissions = $195 per ton.[4]

- Human respiratory disease and death from particulates – potential human health impacts from anthropogenic releases of coarse particles known to aggravate respiratory conditions such as asthma, releases of fine particles that can lead to more serious respiratory symptoms and disease, and releases of particulate precursors such as nitrogen oxides and sulfur oxides. The reference substance for human respiratory disease potential is particulate matter no larger than 2.5 microns, $PM_{2.5}$. Pollutants that have respiratory health impacts are converted into reference pollutant equivalences, $ePM_{2.5}$. Cost of $ePM_{2.5}$ emissions = $557,269 per ton.
- Human disease and death from toxics -- potential human health impacts (other than respiratory and carcinogenic effects) from releases of chemicals that are toxic to humans. There are many chemical and heavy metal pollutants that are toxic to humans, including 2,4-D, benzene, DDT, formaldehyde, permethrin, toluene, chromium, copper, lead, mercury, silver, and zinc. The reference substance for human toxicity potential used in MEBCalc is toluene and pollutants that have human toxicity impacts are characterized and converted by the TRACI model into toluene equivalents, eT. Cost of eT emissions = $315 per ton.
- Human disease and death from carcinogens -- potential human health impacts from releases of chemicals that are carcinogenic to humans. There also are many chemical and heavy metal pollutants that are carcinogenic to humans, including 2,4-D, benzene, DDT, formaldehyde, kepone, permethrin, chromium, and lead. The reference substance for human carcinogenic potential is benzene and the pollutants that have human carcinogenic impacts are aggregated into benzene equivalents, eB. Cost of eB emissions = $2,254 per ton.
- Eutrophication -- potential environmental impacts from addition of mineral nutrients to the soil or water resulting from emissions of eutrophying pollutants to air, soil or water. The addition to soil or water of mineral nutrients, such as nitrogen and phosphorous, can yield generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. In water, nutrient additions tend to increase algae growth, which can lead to reductions in oxygen and death of fish and other species. The reference substance for waterways eutrophication potential is nitrogen and pollutants that have waterways eutrophying impacts are characterized by nitrogen equivalents, eN. Cost of eN emissions = $22,918 per ton.
- Acidification -- potential environmental impacts from anthropogenic releases of acidifying compounds, principally from fossil fuel and biomass combustion, which affect trees, soil, buildings, animals and humans. The main pollutants involved in acidification are sulfur, nitrogen and hydrogen compounds – e.g., sulfur oxides, sulfuric acid, nitrogen oxides, hydrochloric acid, and ammonia. The reference substance for acidification potential is sulfur dioxide and the pollutants that have acidifying impacts are characterized by sulfur dioxide equivalents, eSO_2. Cost of eSO_2 emissions = $337 per ton.
- Ecosystems toxicity -- the relative potential for chemicals released into the environment to harm terrestrial and aquatic ecosystems, including wildlife. There are many chemical and heavy metal pollutants that are toxic to ecosystems, including 2,4-D, benzene, DDT, ethyl benzene, formaldehyde, kepone, permethrin, toluene, chromium, copper, lead, silver, and zinc. The reference substance for ecotoxicity potential used in MEBCalc is 2,4-D and pollutants that have

[4] Estimated environmental economic costs –also known as environmental economic values (EEVs) – for climate change and the other eight environmental impacts that MEBCalc assesses are based on *Economic Damage Costs for Nine Human Health and Environmental Impacts,* prepared by Dr. Jeffrey Morris from SRMG for the Oregon Department of Environmental Quality and Oregon Metro, July 2020. All nine EEVs are expressed in U.S. 2020$.

toxicity impacts to ecosystems are characterized by 2,4-D equivalents, e2,4-D. Cost of e2,4-D emissions = $3,841 per ton.

- Ozone depletion – the relative potential for chemical compounds released into the atmosphere to cause degradation of the Earth's ozone layer. The reference substance for ozone depletion potential (ODP) is trichlorofluoromethane, CFC-11, where CFC is the acronym for chlorofluorocarbon. CFC-11 is sometimes called R-11, and is also called carbon tetrachloride. Cost of eCFC-11 emissions = $52,220 per ton.
- Ground level smog formation – the relative potential for chemical compounds released into the atmosphere to react with sunlight, heat and fine particles to form ozone (O_3). For example, nitrogen oxides (NO_x) and volatile organic compounds (VOCs) released during fuel combustion are some of the chemical compounds that contribute to ground level smog formation. The reference substance for smog formation is ozone itself. Cost of eO_3 emissions = $224 per ton.

Uncertainties in Estimating Damage Costs

In addition to the challenges from multiple environmental impacts for a single pollutant and ensuring that environmental impact categories are mutually exclusive, estimating damage costs, and the uncertainties thereof, provides a third challenge. Available estimates for damage costs sometimes vary widely. The cost of climate impacts for CO_2 emissions provides a good example of the uncertainties that arise in estimating damage costs.

The low-end cost that might be used for CO_2 as the reference substance for climate change is its trading price for voluntary greenhouse gas emission reductions. Operating much as the markets in sulfur dioxide emissions allowances do, except without the Clean Air Act mandated emissions caps, markets are sometimes available for trading voluntary greenhouse gas emissions reduction pledges. Over some years prices on voluntary markets have ranged widely, bottoming out near zero and averaging around $5 per short ton.[5]

Carbon dioxide trading values on the European Union Emissions Trading System for emissions permits based on mandatory caps are higher, ranging around $20 per short ton, but fluctuating down to nearly zero and up to $35.[6] Fluctuations in the EU's carbon prices have been due to a variety of factors specific to the EU's carbon cap and trade system. In addition, the financial chaos of 2007-08 and the following recession contributed to that market's instabilities. When demand for goods and services falls, mandatory caps may no longer provide binding constraints that require firms to buy carbon credits in order to meet their emissions caps.[7] Hence demand to purchase emissions credits from carbon markets falls.

Prices on both voluntary and mandatory markets for GHG emissions tend to be lower than prices derived from direct attempts to estimate the costs of climate change. This may reflect the social and political difficulties of imposing costs on today's economic activity that are based on potential future scenarios that are not well understood or universally accepted.

One example of a well-respected, relatively recent study is the review of the economic costs of climate change conducted by Nicholas Stern (former Chief Economist at the World Bank). That review determined that a reasonable estimate for the cost of then current greenhouse gas emissions was $85 per metric ton of eCO_2. This

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[5] Richard G. Newell, William A. Pizer, Daniel Raimi, Carbon Markets 15 Years after Kyoto: Lessons Learned, New Challenges. *Journal of Economic Perspectives*, 2013, 27(1), 123-146.

[6] Ibid.

[7] EPA's annual auction of sulfur dioxide emissions allowances under its acid rain program illustrates the price volatility that can be induced in a cap and trade system as a result of economic cycles. The spot market auction clearing price was in a steady upward trajectory from $126 in 2000 to $860 in 2006. The financial crisis of 2007-08 reversed that trend with the 2007 and 2008 clearing prices falling to $433 and $380, respectively. The following Great Recession coincided with a steepening decline to $62 and $36 in 2009 and 2010, respectively. Reflecting the displacement of coal-fired power by other energy sources for generating electricity, clearing prices in the 2011-2019 auctions were, in chronological order, $2, $1 and $0.17, $0.35, $0.11, $0.06, $0.04, $0.06, and $0.04.

estimate was based on the risk of catastrophic environmental impacts in the future if substantial reductions in greenhouse gas emissions were not implemented at that time in the mid-2000s.[8]

A 2011 working paper from the U.S. offices of the Stockholm Environment Institute provided a very high estimate near $1,000 per metric ton of carbon dioxide equivalents.[9] At the other end of this spectrum for research-based climate costs of carbon emissions is a study that estimated GHG emissions costs to be $8 per metric ton, which is lower than trading prices for emissions permits under mandatory cap and trade.[10]

Revised Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

Note: CO_2 costs are emissions-year specific.

In 2013 the Interagency Working Group on the Social Cost of carbon (IWGSCC) issued revised estimates for the social cost of carbon emissions. The table above shows these estimates as a function of the social discount rate and the year in which an additional metric ton of CO_2 is emitted.[11,12] Because climate impact costs are projected to ramp up as time passes and the amount of CO_2 in the atmosphere increases, the discounted value of future impacts from a current year's emissions rises as years go by and those future events come ever closer. Also, a lower discount rate results in higher discounted present values for those future costs.[13]

<u>Local versus Global Damage Costs</u>

A fourth issue that one encounters when developing economic cost estimates for environmental impacts is that some impacts are more global and others more local. CO_2 emissions have global impacts, whereas emissions of other pollutants, say chromium or cadmium or lead, likely have effects that are more severe close to the

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[8] Nicholas Stern, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge, England and New York, NY, 2007.

[9] Frank Ackerman and Elizabeth A. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. Stockholm Environment Institute – U.S. Center working paper, Somerville, MA, 2011.

[10] Nicholas Z. Muller, Robert Mendelsohn, William Nordhaus, Environmental Accounting for Pollution in the United States Economy. *American Economic Review*, 2011, 101 (August), 1649-1675.

[11] Interagency Working Group on Social Cost of Carbon, U.S. Government (with participation by Council of Economic Advisers, Council on Environmental Quality, Dept. of Agriculture, Dept. of Commerce, Dept. of Energy, Dept. of Transportation, EPA, National Economic Council, OMB, Office of Science and Technology Policy, and Dept. of Treasury), Technical Support Document – Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis – Under Executive Order 12866, May 2013.

[12] Avg in the table refers to the average future damage costs estimated by three different integrated climate impact assessment models for an increase in one metric ton of CO_2 emissions in the year indicated by the table rows. 95th refers to the damage cost for the three models at the 95% probability level, meaning that one would expect based on the models that estimated costs have only a 5% chance of being higher than this level for emissions in the year indicated by table rows.

[13] There is much debate among economists as to what the social discount rate should be, with some suggesting that the discount rate in future years should follow the declining exponential function tending toward zero for more distant years. See, for example, Paul R. Portney and John P. Weyant (eds.), *Discounting and Intergenerational Equity*, Resources for the Future, Washington, DC, 1999.

place where they are emitted, or more severe given the type of media to which they are emitted. TRACI 2.1 begins to deal with this issue by providing separate cancer, non-cancer and ecotoxicity characterization factors for emissions to urban versus non-urban air, emissions to fresh versus saltwater, and emissions to agricultural land versus non-agricultural land. Such distinctions are very useful if one knows the point source of emissions. They also may provide an indication of the effect that uncertainty about location of emissions can have on environmental damage cost estimates.

Damage Costs Change Over Time

A fifth challenge, and the final one discussed herein, is illustrated by the IWGSCC's table on CO_2 damage costs for climate change. Damage costs may change over time for a variety of reasons. For CO_2 emissions damage costs rise over time because any year's carbon dioxide emissions persist in the atmosphere for many years. Hence, potential damages from climate change increase over time as CO_2 emissions from past years accumulate and the future damages they will cause come closer in time.

Damage costs for other environmental impacts may also change over time. Damage costs for acidification that are based on the spot allowance clearing price at each year's EPA auction of sulfur dioxide emission allowances under the Clean Air Act's Acid Rain Program have fluctuated widely over time. Recently the annual clearing price has dropped dramatically, in part because closure of coal-fired power plants has reduced the demand for sulfur dioxide emission allowances.

In addition, the 2007-8 financial crisis, resultant economic contraction, and very slow economic recovery also reduced energy demand. This meant that the caps under EPA's Acid Rain Program no longer served to constrain sulfur dioxide emissions by energy producers such as coal-fired power plants. Lower energy demand means that energy producers are less likely to bump up against their SO_2 emissions limits, and have less need to buy additional emissions permits at the annual auctions.

As another example of changing cost estimates, human health damage costs for respiratory diseases caused by particulate emissions increase over time. Increased economic activity and population growth put more human receptors in emission pathways for the increases in particulates emitted into the atmosphere that are generated by economic growth.