DRAFT APPENDIX 3:
METHODS AND MEANS OF QUANTIFYING COSTS RELATED TO GREENHOUSE GAS EMISSIONS

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Introduction

This Appendix 3 to the *Guidance for Greenhouse Gas Impact Assessments under the Montana Environmental Policy Act* (Guidance Document) provides a review of methods for quantifying the economic costs and impacts of greenhouse gas (GHG) emissions, with the specific purpose of documenting existing research and examining these methods and means to a greater extent and providing more technical detail than the main body of the Guidance Document.

This Appendix 3 is focused on methods for estimating the costs from GHG emissions. Alternative impact assessment approaches are discussed in the Guidance Document's Appendix 2. Secondary Impacts from GHG Emissions. A detail discussion of the Social Cost of Greenhouse Gases (SC-GHG) as a method of quantifying the costs related to GHGs is provided along with the limitations and appropriateness for use in the Montana Environmental Policy Act (MEPA) process. Other methods of quantifying costs related to GHGs are also discussed including marginal abatement costs and a framework for evaluating damages and their limitations and appropriateness.

Social Cost of Greenhouse Gases

GHGs are gases that trap heat in the atmosphere; the primary gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which, in CO_2-equivalent (CO_2e) terms,[1] collectively comprised 96.9 percent of U.S. GHG emissions[2] and 98.8 percent of Montana GHG emissions[3] in 2022. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change ([IPCC] 2021) describes the anthropogenic influence on global warming as "unequivocal": "The likely range of human-induced warming in global-mean surface air temperature in 2010–2019 relative to 1850–1900 is 0.8°C–1.3°C, encompassing the observed warming of 0.9°C–1.2°C, while the change attributable to natural forcings is only −0.1°C to +0.1°C" (Eyring et al. 2021). This temperature increase, driven by GHG emissions, leads to a host of additional effects associated with climate change, including changes in precipitation patterns, sea level rise, and the shifting of geographic ranges of terrestrial species toward the poles or to higher elevations. See Appendix 2: Secondary Impacts from Greenhouse Gas Emissions for more details.

[1] To facilitate comparisons between different GHGs, emissions are often reported in CO_2e terms. To do this, emissions are multiplied by the gas's global warming potential (GWP), which measures how much energy 1 ton of that gas will absorb over a given period (typically chosen to be 100 years), relative to 1 ton of CO_2. The GWP thus accounts for (i) the heat-trapping ability and (ii) the lifetime of the gas, relative to CO_2 (the GWP of which is 1).
[2] https://www.epa.gov/ghgemissions/overview-greenhouse-gases.
[3] U.S. Environmental Protection Agency (EPA) State Inventory Tool (SIT), using input files provided by Montana Department of Environmental Quality (DEQ).

The SC-GHG is a monetary estimate of the net economic damages associated with the emission of 1 metric ton of a GHG in a given year. Since the three primary GHGs mentioned above have different warming impacts on the Earth, as well as different lifetimes in the atmosphere, each will have its own SC-GHG value.

Summary of the Approach and Application for Social Cost of GHGs

Here, we briefly summarize the approach and application of SC-GHG; more details on the approach are given in the "Modular Approach for Estimating SC-GHG" section.

Approach

As previously mentioned, the SC-GHG is an estimate of net economic damages associated with the emission of 1 metric ton of a GHG in a given year. Calculating these marginal damages thus requires two modeling runs: a reference case and a case with an additional emissions pulse (e.g., an extra metric ton of emissions of a GHG in a specific year). These two modeling runs will generate slightly different projections of future annual global climate damages (out to a given year, often taken to be 2300 due to the long atmospheric lifetime of CO_2). These annual time series of damages are summed (after discounting), and the difference between the two quantities is the SC-GHG value for the year in which the additional pulse was emitted. Increased damages from additional units of GHG emissions thus result in a positive SC-GHG value (i.e., a net cost).

Each modeling run (regardless of the exact model used, described further below) generally involves the following five steps:

1. Emissions: Using a chosen socioeconomic scenario, under which assumptions about population, global and technological development, and environmental policy preferences are made, projections of annual GHG emissions are formed.

2. Concentrations: Given annual emissions time series, annual GHG atmospheric concentrations can be calculated that account for removal mechanisms for each gas (e.g., uptake of CO_2 by the Earth's system and breaking down of N_2O by ultraviolet radiation).

3. Climate: Heightened GHG concentrations (i.e., above their preindustrial values) lead to positive radiative forcing: increased trapped radiation (i.e., the greenhouse effect) by the atmosphere that warms the Earth's surface.

4. Damages: As previously mentioned, this warming leads to additional climate effects (e.g., changes in precipitation patterns and sea levels). Damage functions relate these

changes in climatic variables to monetary impacts on society. Such impacts can include, but are not limited to, changes in agricultural productivity, property damage from storms, energy expenditures (e.g., increased cooling needs), mortality rates, and ecosystem services. Models generally have damage functions that take as input temperature and sea level rise changes, while those that incorporate other climatic quantities, such as precipitation, are rarer.

5. Discounting: Once annual damages are calculated, they are discounted to their present value in the year that the emissions pulse was released (in the second of the two modeling runs, described above).

Application

SC-GHG (particularly that for CO_2) has been applied at the federal, state, and local levels, as well as internationally for both regulatory and nonregulatory uses (Rose and Bistline 2016). The social cost of carbon (SCC, the SC-GHG for CO_2) has been used by the EPA and Department of Transportation (DOT) to quantify benefits of the Corporate Average Fuel Economy standards.[4] In February 2023, Minnesota became the first U.S. state to adopt the EPA's updated SC-GHG values when it amended its utilities law to require the state's Public Utilities Commission to use these values for resource planning. Austin, Texas uses federal SCC numbers in its Value of Solar program, which values avoided carbon emissions when crediting customers for their solar generation.[5]

The Presidential Executive Order (EO) 14154[6] disbanded the US Interagency Working Group on Social Cost of Carbon (IWG) and declared SC-GHG estimates "based, in whole or in part, on the IWG's work or guidance" no longer "representative of governmental policy." A recent report[7] from the Department of Energy's Climate Working Group noted various sources of uncertainty (some of which are detailed in the "Limitations and Appropriateness of Using SC-GHG to Quantify Costs from GHGs under MEPA" section) associated with the SC-GHG calculation, including the discount rate, the equilibrium climate sensitivity, and damage function coefficients.

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[4] EPA–U.S. National Highway Traffic Safety Administration (NHTSA). EPA, 40 Code of Federal Regulations (CFR) Parts 85, 86, and 600, DOT NHTSA, 49 CFR Parts 531, 533, 536, 537 and 538, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule. Federal Register, Vol. 75, No. 88, May 7, 2010, 25324–25728.
[5] https://services.austintexas.gov/edims/document.cfm?id=395573.
[6] https://www.whitehouse.gov/presidential-actions/2025/01/unleashing-american-energy/
[7] Climate Working Group (2025) A Critical Review of Impacts of Greenhouse Gas Emissions on the U.S. Climate. Washington DC: Department of Energy, July 23, 2025.

Summary of Various Models for Calculating SC-GHG

This section expands upon the methodology of calculating SC-GHG by describing two different specific approaches: (i) a modular approach, in which there are separate modules for each general step (i.e., socioeconomics and emissions, climate, damages, and discounting); and (ii) integrated assessment models, which are singular models containing each of the four steps.

Modular Approach for Estimating SC-GHG

Following the recommendations made by the National Academies of Science, Engineering, and Medicine (National Academies), the EPA's SC-GHG updated estimates employ a modular approach. For each of the four components (socioeconomics and emissions, climate, damage, and discounting), the methodology draws on the latest scientific research for that component.

1. Socioeconomic and emissions module

   In this module, a socioeconomic pathway is selected that lays out annual projections of population, GDP, and GHG emissions for the duration of the modeling run.[8] These pathways make assumptions about technological development and emissions mitigation policies, either deterministically (i.e., in a given scenario, these activities and their effect on emissions follow a certain defined path in time) or probabilistically (where these activities have likelihoods assigned through a combination of statistical techniques and expert judgment). All else equal, a higher population and income will result in increased emissions and climate damages. A slowly growing economy may have reduced emissions but also decrease countries' ambitions to meet emission reduction pledges, as well as technological capability (EPA 2022). Conversely, a world with high economic growth could see higher emissions in the short to medium term but then be able to more quickly decarbonize given greater technological development.

   Potential options for socioeconomic pathways include the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways used by the IPCC in its Fifth and Sixth Assessment reports (IPCC 2013, 2021). Thus, while they are prominently employed in global climate modeling simulations, they suffer from two primary drawbacks when it comes to SC-GHG calculations. The first is that they are deterministic, that is, they are intended as plausible storylines but were developed without probabilities attached. Their usage would preclude resulting SC-GHG estimates from capturing the relationship between climate risk and socioeconomic uncertainty. The second is that they only go to 2100, requiring extrapolation out to 2300.

[8] As previously mentioned, these simulations often go out to the year 2300 to capture the majority of discounted climate damages.

EPA (2022) instead makes use of the Resources for the Future Socioeconomic and Emissions Projections (RFF-SPs) for its recently updated SC-GHG calculations. These projections are probabilistic and account for the likelihood of future emissions mitigation policies and technological developments. In addition to extending to 2300, the RFF-SPs' chief advantage is its formal characterization of uncertainty in economic growth and population over time. Figure 1 shows a comparison between RFF-SP and SSP projections of net annual global emissions of CO_2 from 1900-2300 (taken from EPA 2022). The RFF-SP mean and median projections align most closely with the SSP2 scenario (often described as a "middle of the road" trajectory in which social, economic, and technological trends do not shift markedly from historical patterns), with emissions peaking around or before 2050 and decreasing out to 2300.

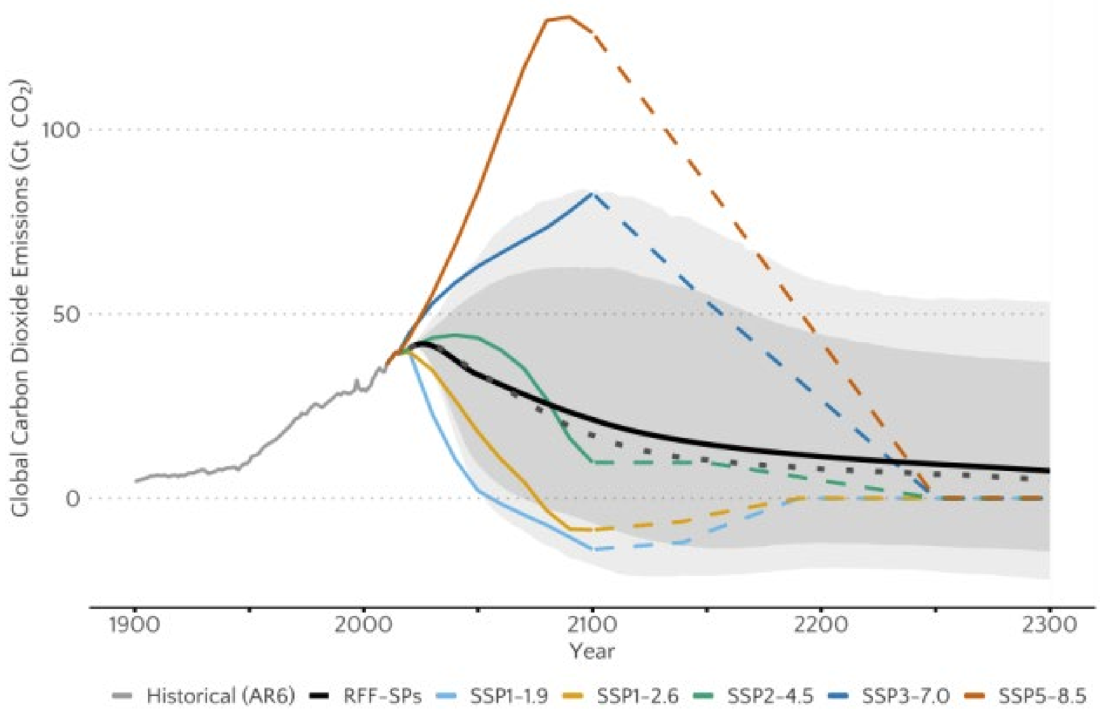

Figure 1. RFF-SP projections based on RFF-SPs (Rennert et al. 2022).

Black lines represent the mean (solid) and median (dotted) CO2 emissions projections along with 5th to 95th (dark shade) and 1st to 99th (light shade) percentile ranges. SSP data through 2100 are from the International Institute for Applied Systems Analysis SSP Database (Riahi et al. 2017). SSPs beyond 2100 (dashed lines) are based on the commonly used extensions provided by the Reduced Complexity Model Intercomparison Project (Nicholls et al. 2020). Reprinted from EPA 2022 Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances.

2. Climate module

In this module, the emissions projections from the previous step are translated into atmospheric concentrations, then to radiative forcing, and then to global mean surface temperature. From here, other climatic variables (most commonly sea level rise) can be generated, if needed for the damage module.

In SC-GHG calculations, reduced-complexity (RC) models are used in place of standard global climate models to translate emissions time series into temperature responses due to the latter's high computational cost. In addition to being easier (i) to use and (ii) to conduct a large number of modeling runs if desired, an advantageous feature of RC models for this application is their lack of interannual variability, which is otherwise an inherent feature of the Earth's climate system. This allows one to estimate or quantify the impact of a relatively small GHG emission pulse, which would otherwise be difficult, if not impossible, to track amidst the year-to-year variability in a standard climate model.

The RC model used by EPA (2022) is the Finite amplitude Impulse Response (FaIR) climate model, which is open source and has been calibrated to findings (e.g., climate sensitivity: the equilibrium change in surface temperature following a doubling of atmospheric CO_2 concentrations from preindustrial levels) from the IPCC's Sixth Assessment Report (AR6). FaIR emulates the behavior of AR6 climate models in representing the lifetime of GHGs once emitted, accounting for (i) the cycling of CO_2 between atmospheric, terrestrial, and oceanic reservoirs; and (ii) the destruction of CH_4 and N_2O via atmospheric reactions.

Other RC models include the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) and the Hector model. MAGICC (which is discussed in more detail in Appendix 2: Secondary Impacts from Greenhouse Gas Emissions) has also been calibrated to AR6 findings. The Hector model has some additional representations of the climate system, including ocean acidification, permafrost, and land carbon cycles, but it has not been calibrated to AR6 findings.

3. Damage module

In this module, damage functions translate changes in temperature (and potentially other climate variables) into monetized estimates of net economic impacts. These impacts include both market and non-market pathways: examples of the former include agricultural impacts, labor productivity, and energy expenditures; and examples of the latter include changes in mortality and ecosystem services. Ecosystem services are the various benefits that society derives from ecosystems, both tangible (e.g., food and timber) and intangible (e.g., erosion control and aesthetic appreciation of nature). Damage functions can generally take a bottom-up approach (in which damages are estimated for separate spatial regions or sectors, then aggregated) or a top-down approach (in which damages, as a fraction of GDP, are estimated directly from the global mean surface temperature increase).

EPA (2022) employs three damage functions, and for their final estimate, average the SC-GHG values calculated from each. The first function is based on the Data-driven Spatial Climate Impact Model (DSCIM)[9], which is a subnational-scale, sectoral damage function that considers five impact categories: health (heat- and cold-related mortality); energy (expenditures for electricity and other direct fuel consumption); labor productivity (labor disutility costs[10] due to increased temperatures); agriculture (production impacts for maize, rice, wheat, soybeans, sorghum and cassava); and coastal regions (sea level rise impacts including inundation, migration, mortality, and physical capital loss). The second function is based on the Greenhouse Gas Impact Value Estimator (GIVE); it is also a sectoral damage function but at the country scale. GIVE evaluates four impact categories (health, energy, agriculture, and coastal regions) in a similar manner as DSCIM but using different empirical bases and methodologies. The third function is a meta-analysis-based global damage function estimation based on Howard and Sterner (2017). Meta-analysis refers to the practice of combining results from multiple studies and, in this case, into a single damage function. The Howard and Sterner (2017) formulation is a quadratic relationship between global mean surface temperature increase and damage as a fraction of GDP.

4. Discounting module

   In this final step, the annual time series of damages generated by the previous module is discounted to its present value in the year when the additional emissions pulse was released. Fundamentally, the discount rate reflects how much weight is placed on future impacts or damages as opposed to present-day impacts. Future costs (and benefits) are generally considered less valuable than equivalent ones in the present day; the discount rate quantifies this. Generally two main approaches are used to assign this value: descriptive and prescriptive. The descriptive method employs market rates of return, with proponents arguing that this is the expected growth that would be forgone if the marginal damages were avoided (i.e., by withholding the extra GHG emissions), and "no justification exists for choosing [a social welfare function] different from what decisionmakers actually use" (Arrow et al. 1995). The prescriptive method specifies a

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[9] The damage functions within the Framework for Evaluating Damages and Impacts (FrEDI) make use of several of the sectoral analyses of the Climate Impact Lab, which developed DSCIM. FrEDI's damage functions translate temperature changes and sea level rise into climate-related impacts in the contiguous U.S. in more than 20 sectors (EPA 2024).

[10] Labor disutility costs refer to negative aspects (i.e., dissatisfaction) associated with working, as opposed to positive utility derived from leisure.

discount rate that "formalizes the normative judgments that the decision-maker wants to incorporate into the policy evaluation" (EPA 2022). In other words, it is a way of specifying a priority for how future damages/benefits *should* be valued.

Previously, the IWG (2010) released SC-GHG estimates employing the descriptive approach and three different constant discount rates. The middle rate of 3 percent was roughly consistent with the average rate of return for long-term Treasury notes (at the time). In their recent updates, EPA (2022), following recommendations from the National Academies (2017), switched to Ramsey discounting, which follows this formula:

$$r_t = \rho + \eta g_t,$$

where r_t is the discount rate in year t, ρ is the pure rate of time preference (the rate at which future utility is discounted due to a preference for utility sooner rather than later), η is the elasticity of marginal utility with respect to consumption (the rate at which marginal utility of consumption falls as consumption grows), and g_t is the consumption growth rate in year t. A primary advantage of Ramsey discounting is that the discount rate is correlated with the consumption growth rate.

The Ramsey approach can be either descriptive or prescriptive. Arguments have been made for the pure rate of time preference ρ to be zero; these arguments state that climate damages/benefits should not be considered any less important to future generations than to those living today. EPA (2022) has maintained its descriptive approach, again following the National Academies (2017) recommendation that the Ramsey parameters ρ and η be calibrated based on observed interest rate data.

Integrated Assessment Models for Estimating SC-GHG

Compared to the modular approach described above and adopted by the EPA (2022) in its latest update, integrated assessment models (IAMs) follow the same general steps in calculating SC-GHG but are singular model frameworks. While the individual "modules" within IAMs are generally less up to date compared to the state-of-the-art research that would be highlighted in the modular approach, there is an improved chance of internal consistency, particularly regarding assumptions made across modules.

IWG (2010) previously employed three peer-reviewed IAMs: Dynamic Integrated Climate and Economy (DICE), Policy Analysis of the Greenhouse Gas Effect (PAGE), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND). While equilibrium climate sensitivity was harmonized across the three models, all other model aspects (e.g., representation of the carbon cycle, which affects the timing of the temperature response and, therefore, damages; damage functions) were designed by each individual model developer.

DICE is a relatively simple globally aggregated model (i.e., emissions are provided and damages calculated at the global level). It does not model any GHGs other than CO_2; rather, it specifies GHG radiative forcing exogenously. PAGE has a similar treatment of GHGs (though it also models the effect of aerosol emissions), but it is disaggregated into eight world regions as opposed to DICE's simple global treatment. Additionally, PAGE has a much larger emphasis on uncertainty, using Monte Carlo simulations to capture uncertainty in 31 variables, including climate sensitivity and carbon cycle dynamics. Lastly, the FUND model has the most detailed treatment of GHGs, with exogenous emissions inputs for CH_4, N_2O, and SF_6, as well as aerosols. FUND is also the most regionally and sectorally disaggregated of the three models, with 16 world regions and 14 damage categories.

Rose et al. (2014) compared outputs from the three IAMs and found significant differences. One is that for the same pulse of 1 billion metric tons of carbon in 2020, the temperature response by 2040 is approximately twice as large in DICE as it is in FUND, a difference attributed to the models' disparate treatment of the carbon cycle. An even larger difference is in the models' estimate of expected climate damages: under the same temperature change, the DICE and PAGE models yielded approximately four times as many damages as did FUND under a high emissions scenario. In general, FUND projects lower climate damages: it predicts net benefits (from increased agricultural productivity and reduced heating costs) at low levels of warming.

Limitations and Appropriateness of Using SC-GHG to Quantify Costs from GHGs under MEPA

Several limitations and large uncertainties arise from SC-GHG calculations. The first is that outputs (namely damages) from these models tend to be spatially coarse. As mentioned, the DICE IAM and the meta-analysis damage function described in the modular approach have global outputs. The 8 and 16 regions in the PAGE and FUND IAMs generally cover very large countries and continents, while the GIVE damage function is more spatially resolved in yielding outputs at the country level. The DSCIM has the highest spatial resolution in its damage module, with outputs at the subnational level, although this comes at a high computation cost. Rather than running 10,000 Monte Carlo simulations with the probabilistic RFF-SP socioeconomic projections, EPA (2022) employed an emulator methodology that approximated the direct modeling approach used with the other two modular damage functions.

Second, as mentioned in the context of three IAMs presented, differences in climate and damage modules can result in highly varying damage estimates. Many physical climate impacts and their economic impacts are not explicitly accounted for (e.g., changes in extreme temperatures are often more impactful than changes in mean temperatures, yet only the latter is generally represented in damage functions). The damage functions that do exist in the literature are often based on limited historical data and may not reflect new climate regimes not previously observed. Additionally, SC-GHG models often do not include large-scale Earth system feedback effects (e.g., "tipping points" such as permafrost thaw and slowdown of the Atlantic Meridional Overturning Circulation). The PAGE IAM is somewhat of an exception to this, with its emphasis on uncertainty: it includes catastrophic thresholds and sharp discontinuities in its damage structure (Nordhaus 2014). However, the other limitations discussed here still apply.

Third, the discount rate[11] has significant implications for the estimated SC-GHG, particularly for long-lived GHGs such as CO_2 and N_2O, which have typical atmospheric lifetimes exceeding 100 years (as opposed to CH_4, which typically lasts in the atmosphere for approximately 10 years). Table 1 shows the SC-GHG estimates from IWG (2021), and Table 2 provides the estimates from EPA (2022) with the rows corresponding to emission years and the columns corresponding to the three primary GHGs but also different discount rates. As mentioned previously, the former employs constant discount rates while the latter employs Ramsey discount rates. For EPA's updated estimates, the Ramsey discount rates (which vary over time), were calibrated to yield near-term (over the first 10 years) rates of 1.5 percent, 2.0 percent, and 2.5 percent. Differences in the 2.5 percent-rate values (which can be larger than 50 percent) can be attributed to both the different types of rates (i.e., constant vs. Ramsey), as well as the different approaches: IWG's estimates were based on the DICE, FUND, and PAGE IAMs. For an emission year of 2020, the EPA's updated social cost for N_2O varies by a factor of approximately 2.5, while for CO_2 it varies by nearly a factor of 3. The variation in costs resulting from the chosen discount rate introduces significant uncertainty in SC-GHG estimates.

Table 1. Estimates of the SC-GHG from the IWG in 2021.

	SC-CO_2 (2020 dollars per metric ton of CO_2)			SC-CH_4 (2020 dollars per metric ton of CH_4)			SC-N_2O (2020 dollars per metric ton of N_2O)		
Emission Year	Constant rate			Constant rate			Constant rate		
	5.0%	3.0%	2.5%	5.0%	3.0%	2.5%	5.0%	3.0%	2.5%
2020	14	51	76	670	1,500	2,000	5,800	18,000	27,000
2025	17	56	83	800	1,700	2,200	6,800	21,000	30,000
2030	19	62	89	940	2,000	2,500	7,800	23,000	33,000
2035	22	67	96	1,100	2,200	2,800	9,000	25,000	36,000
2040	25	73	103	1,300	2,500	3,100	10,000	28,000	39,000
2045	28	79	110	1,500	2,800	3,500	12,000	30,000	42,000
2050	32	85	116	1,700	3,100	3,800	13,000	33,000	45,000

Source: IWG 2021. Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide. Interim Estimates under Executive Order 13990.

[11] Discount rates are the annual percentage rates used in economic analysis to calculate the present value of future costs and benefits. In SC-GHG calculations, discount rates determine how much weight is given to climate damages occurring decades in the future compared to immediate costs.

Table 2. Estimates of the SC-GHG from the EPA in 2022.

	SC-CO_2 (2020 dollars per metric ton of CO_2)			SC-CH_4 (2020 dollars per metric ton of CH_4)			SC-N_2O (2020 dollars per metric ton of N_2O)		
Emission Year	Near-term rate			Near-term rate			Near-term rate		
	2.5%	2.0%	1.5%	2.5%	2.0%	1.5%	2.5%	2.0%	1.5%
2020	120	190	340	1,300	1,600	2,300	35,000	54,000	87,000
2030	140	230	380	1,900	2,400	3,200	45,000	66,000	100,000
2040	170	270	430	2,700	3,300	4,200	55,000	79,000	120,000
2050	200	310	480	3,500	4,200	5,300	66,000	93,000	140,000
2060	230	350	530	4,300	5,100	6,300	76,000	110,000	150,000
2070	260	380	570	5,000	5,900	7,200	85,000	120,000	170,000
2080	280	410	600	5,800	6,800	8,200	95,000	130,000	180,000

Source: EPA 2022. Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances.

In addition, *Belk v. Mont. Dep't of Envtl. Quality* (2022 MT 38, DA 21-0117) clarified that MEPA does not require quantitative economic analysis as it "require[s] assessments of impacts on human populations—including health, agriculture, tax bases, and culture—but they *do not require quantitative economic forecasts*" (emphasis added).

In summary, SC-GHG as a measure to quantify the cost of GHG emissions has several limitations and uncertainties and is not required under MEPA.

Other Methods of Quantifying Costs Related to Greenhouse Gases

Marginal Abatement Cost

An alternative method of quantifying the value of avoided CO_2 emissions is the marginal abatement cost (MAC) approach, or target-consistent approach. MAC provides monetary estimates for GHG emissions based on the marginal abatement cost for achieving a given emissions reduction target (i.e., the cost of abating the last metric ton of carbon dioxide needed to meet a particular emissions target at least cost to society).

It should be noted that the SC-GHG and MAC approaches are fundamentally different. While both can be expressed in units of $/ton of GHG, EPA (2022) states that MAC is "not an alternative way of valuing damages from GHG emissions in benefit-cost analysis." In fact, unlike the SC-GHG, which is defined as the marginal damage from emitting an additional metric ton of GHG, the MAC approach does not calculate damages (i.e., societal impacts) at all. Rather, once an emissions reduction target has been externally set, it is simply the cost of removing the last, most expensive metric ton of GHG emission needed to meet that goal.

MAC values are generally derived from marginal abatement cost curves, such as those shown on Figure 2. These cost curves can be generated in a bottom-up manner (left side of Figure 2) in which experts evaluate individual abatement options (e.g., increasing efficiency of residential appliances, afforestation, and installing solar photovoltaic arrays). These options are then ranked from least expensive (oftentimes with a negative marginal abatement cost, in which case the technology or action pays for itself) to most expensive. Each block represents one GHG emission reduction solution, with the width depicting the amount of emissions that can be abated with that solution, and the height denoting the cost per ton of GHG.

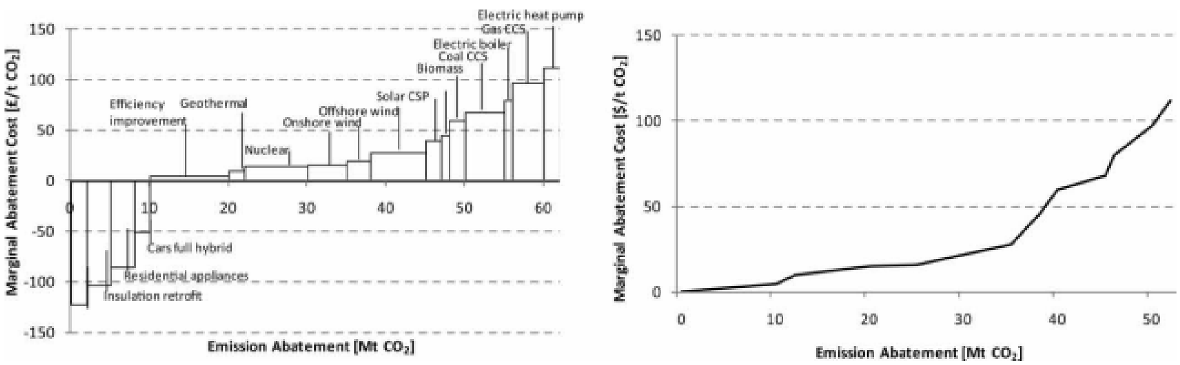

Figure 2. Stylized Depictions of MAC Curves Drawn from Expert-Based Approach (left) and Models (right). Reprinted from Resources for the Future (RFF) and New York State Energy Research and Development Authority (NYSERDA) 2020. Estimating the Value of Carbon: Two Approaches.

MAC curves can also be generated in a top-down manner (right side of Figure 2) using economic or energy models. These models set a carbon price (in $/ton) and evaluate the degree to which emissions reductions would take place. While MAC curves generated this way do not explicitly reveal what technologies or options would result in the abatement, they can potentially include interactions between economic sectors, which would not be accounted for in individual expert-based studies (RFF and NYSERDA 2020).

The final MAC value then (in $/ton) would be the marginal abatement cost (i.e., the y-axis value in either type of curve) corresponding to the emission abatement (the x-axis value) that equals the emissions target. Using the curves in Figure 2 as an example, if, for example, the target was 50 Mt CO_2, the MAC value using the bottom-up approach would be approximately $60/ton of CO_2, while using the top-down approach would be approximately $100/ton of CO_2.

The MAC approach avoids some of the uncertainties associated with SC-GHG. Namely, it does not require a representation of the climate system or a mapping from temperature impacts on economic damages. Rather, the burden is shifted externally in determining the relevant emissions reduction target (thus, the MAC approach can also be applied locally more easily than the SC-GHG method). Uncertainties around the MAC methodology instead revolve around the determination of abatement costs and how these change over time. Estimated abatement costs are also often underestimated, neglecting system costs and the costs of policy implementation (RFF and NYSERDA 2020).

The marginal abatement cost does not measure damages associated with GHG emissions (and the value of avoiding those emissions) and, therefore, it is generally not relevant for evaluating the costs of GHG emissions from a proposed action under MEPA.

Framework for Evaluating Damages and Impacts (FrEDI)

Another alternative method of quantifying costs related to GHG emissions is the Framework for Evaluating Damages and Impacts (FrEDI; EPA 2024). More specifically, FrEDI contains damage functions that translate either U.S. or global temperature change, as well as sea level rise, into climate-related impacts in the contiguous U.S. in more than 20 sectors. FrEDI makes use of several of the sectoral analyses of the Climate Impact Lab, which developed DSCIM, one of the sets of damage functions used by EPA (2022). However, FrEDI does not provide quantification of the costs due to GHG emissions.

Summary

In summary, various approaches are used to calculate SC-GHG, but all follow essentially the same methodology: conduct a reference modeling run (generally to the year 2300), calculate damages from climate impacts such as temperature increases and sea level rise, then conduct a second modeling run with an additional pulse (e.g., 1 billion tons) of GHG in a given year. Taking the difference in damages between the two modeling runs, discounting each year's difference to the year of the emission pulse, and taking the sum of these discounted values results in an estimate of SC-GHG for a given GHG. Two approaches for estimating SC-GHG include (i) integrated assessment models, which potentially allow for greater consistency between the different steps involved in calculating SC-GHG; and (ii) a modular approach. The latter methodology was adopted by the EPA in 2022 for its updated SC-GHG estimates.

The SC-GHG calculation is prone to several important uncertainties that may limit its usage. For example, the choice of discount rate has significant effects on the resulting SC-GHG value. Challenges related to the quantification (and non-inclusion) of physical climate impacts (such as changes in temperature extremes and precipitation) and the associated damage pathways also lead to large uncertainties. SC-GHG values are currently provided at global and regional levels, making it a challenge to apply at the state or project level, a pertinent issue for Montana agencies. Furthermore, *Belk v. Mont. Dep't of Envtl. Quality* (2022 MT 38, DA 21-0117) clarified that MEPA does not require quantitative economic analysis.

A related, but fundamentally different calculation, the marginal abatement cost, does not calculate climate damages (and therefore the benefits of avoiding GHG emissions). The EPA's FrEDI approach quantifies cumulative damages for a given amount of global or U.S. temperature increase or sea level rise but does not provide quantification of the costs due to GHG emissions.

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