APPENDIX 2:
SECONDARY IMPACTS FROM GREENHOUSE GAS EMISSIONS

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Purpose and Introduction

This Appendix 2 to the *Guidance for Greenhouse Gas Impact Assessments under the Montana Environmental Policy Act* (Guidance Document) reviews existing research on secondary impacts from greenhouse gas (GHG) emissions and provides Montana-specific context and guidance for evaluating these impacts in Montana Environmental Policy Act (MEPA) analyses.

Per MEPA, secondary impacts are defined in Administrative Rules of Montana 17.4.603(18) as "a further impact to the human environment that may be stimulated or induced by or otherwise result from a direct impact of the action." These are impacts that occur at a different location or later time than the proposed action that triggers the effect. In the context of GHG emissions, secondary impacts refer to the effects on Montana's environment (§ 75-1-201(1)(b)(iv), Montana Code Annotated [MCA]) that result from climate changes caused by a project's GHG emissions. State law explicitly excludes upstream, downstream, and other indirect actions that occur independently or are caused in part or exclusively by the proposed action per § 75-1-220(10)(b)(i), MCA.

Secondary impacts of GHG emissions from a proposed action on Montana's environment could include changes to temperature, precipitation, extreme weather patterns, and other climate-related factors as the emissions from a project (the direct impact) contribute to global GHG concentrations. Once a project emits a GHG, these emissions accumulate with other global emissions in the atmosphere and contribute to alterations in climate patterns at global, regional, and local scales. These altered climate patterns could then trigger further environmental and health effects, such as ecosystem disruptions and human health impacts (e.g., heat-related illnesses).

Discussion of the Linkage between GHG Emissions and Climate Change

Climate is the long-term weather pattern (typically over a period of 30 years or longer) of a region, and climate change is an identifiable (i.e., statistically significant) and persistent change in long-term climate (Intergovernmental Panel on Climate Change [IPCC] 2021). Variables such as temperature, precipitation, relative humidity, and sea level are often used to identify climate change trends.

In brief, climate change is governed by the relationship between incoming and outgoing heat in the Earth's atmosphere (Denning 2017). The Earth receives radiation from the sun, primarily as heat and visible light (heat in). Approximately 30 percent of this radiation is reflected into space by the atmosphere (e.g., clouds and atmospheric particles) or by the Earth's surface (e.g., ice and snow), and 70 percent is absorbed by the atmosphere and the Earth's surface. The Earth then re-emits this absorbed energy as infrared radiation (heat out).

The greenhouse effect is the trapping of heat by GHGs, a specific set of gases that, due to their chemical structure, absorb infrared radiation emitted by the Earth and re-radiate it in all directions, including back to the Earth's surface. The primary GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor, and fluorinated gases. While the greenhouse effect occurs naturally and is essential for keeping Earth's temperatures habitable, the intensity of this effect increases with the concentration of GHGs in the atmosphere. Higher concentrations of GHGs trap more heat, leading to enhanced warming and higher global surface temperatures.

GHGs tend to be long-lived in the atmosphere, and average lifetimes vary per gas. CO_2 is cycled through the carbon cycle and can remain in the atmosphere from hundreds to thousands of years. CH_4 and N_2O have average atmospheric lifetimes of 11.8 years and 109 years, respectively, while some fluorinated gases have a wide range of atmospheric lifetimes, from a few weeks to thousands of years (IPCC 2021; U.S. Environmental Protection Agency (EPA) 2025a).

Radiative forcing is the net change in the energy balance of the Earth's system due to an added disturbance, such as an increase in GHG emissions, measured in watts per square meter (W/m^2). Prior to the industrial era, incoming radiation and outgoing radiation were relatively balanced, with stable Earth surface temperatures. GHGs accumulate in the atmosphere as the rate of GHG emissions by sources, such as burning fossil fuels, deforestation, and agriculture, exceeds the rate of natural processes that remove them (sinks). This creates a positive radiative forcing that disrupts the energy balance, causing surface temperatures to rise until a new energy balance is achieved. The IPCC estimates in its 2021 Sixth Assessment Report (AR6) that anthropogenic activities since pre-industrial times have created a radiative forcing of approximately 2.72 W/m^2, meaning the atmosphere is trapping an additional 2.72 watts per square meter compared to natural conditions (IPCC 2021). One way to measure radiative forcing over a specific time horizon for specific gases is called global warming potential (GWP). This metric represents the combined effects of the differing atmospheric lifetimes of gases such as CH_4 and N_2O and their radiative forcing relative to CO_2. Table 1 shows the 100-year and 20-year time horizon GWPs[1] from IPCC AR6 (IPCC 2021).

[1] 100-year and 20-year GWPs are used to compare the climate impact of different GHGs over 100 years and 20 years. 100-year GWPs measure the cumulative heat-trapping effect of a gas relative to CO_2 over a 100-year period and tend to average the impact of gases, giving less weight to potent but short-lived GHGs such as CH_4. 20-year GWPs prioritize short-lived GHGs (e.g., CH_4), making their climate impact appear greater in the short term.

Table 1. 100-year and 20-year global warming potentials for carbon dioxide, methane, and nitrous oxide.

Time Horizon	CO_2	CH_4	N_2O
100-Year	1	27.0 (non-fossil) 29.8 (fossil)	273
20-Year	1	79.7 (non-fossil) 82.5 (fossil)	273

Source: IPCC 2021.

Note: IPCC provides different GWP estimates for CH_4 depending on whether the source originates from fossil carbon or biogenic sources. Methane emitted from fossil fuel sources has a higher warming potential because it represents a net addition of carbon to the atmosphere, while biogenic methane is part of the existing carbon cycle. For example, agencies should use the non-fossil GWP for methane emissions from biogenic sources (e.g., methane from livestock enteric fermentation, landfills and waste decomposition, or biomass combustion). Agencies should use the fossil GWP for methane emissions from non-biogenic sources (e.g., methane leaks from oil and gas extraction and transport, coal mining methane emissions, or industrial processes involving fossil carbon methane emissions).

The geologic record demonstrates that the Earth's climate has gone through major variations throughout its existence. Milankovitch cycles are natural changes in Earth's orbit and tilt that happen over tens to hundreds of thousands of years (NASA 2020). These cycles slowly change how much sunlight different parts of our planet receive and can trigger ice ages (glacial periods) and warmer "interglacial" periods (NASA 2020). Icehouse and greenhouse (sometimes referred to as "hothouse") periods are much longer phases in Earth's overall climate, lasting for millions of years (Lear et al. 2020). An icehouse Earth has ice sheets at the poles and regular ice ages, while a greenhouse Earth is much warmer with little to no ice anywhere (Lear et al. 2020). The main difference between these two climate states in Earth's history is the timescale and cause of each. Milankovitch cycles cause shorter-term (tens of thousands to hundreds of thousands of years) swings between ice ages and warm periods by changing the way Earth receives solar radiation. Icehouse and greenhouse periods are the planet's long-term climate states (millions to hundreds of millions of years), determined mostly by GHG levels and global geological changes such as volcanic eruptions, ocean currents, changes in land cover, and changes in ocean chemistry (Lear et al. 2020). While Earth's climate has varied naturally over geological time, the current rate and pattern of change is unprecedented and directly linked to human activities.

Because GHGs are the primary drivers of anthropogenic climate change, emissions of GHGs are used as an indicator of potential climate change impacts. Climate change can be attributed to both natural and anthropogenic causes but has been largely driven by the significant increase in global GHG emissions from anthropogenic fossil fuel combustion since pre-industrial times. According to the IPCC (2021): "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over centuries to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentration of greenhouse gases have increased." The IPCC AR6 reports that human activity led to atmospheric warming of 1.07 ± 0.23°C from 1850 to 2019 (IPCC 2021).

As GHG emissions increase, the global temperature of Earth's surface increases, and climate is affected by this change in heat, causing additional secondary effects throughout the climate system. These changes in climate can manifest in myriad ways, including increased frequency and intensity of heat waves and wildfires, global glacier retreat and mass loss, lengthened growing seasons, and shifts in the geographic range of terrestrial species poleward or to higher elevations (IPCC 2021).

The IPCC developed Representative Concentration Pathway (RCP) scenarios for its Fifth Assessment Report to project future climate possibilities attributed to future GHG concentrations. The four RCPs are described in Table 2 and are named by their approximate radiative forcing in 2100 relative to the year 1750 (e.g., RCP2.6 indicates a radiative forcing of 2.6 W/m^2 in 2100). These RCPs represent a range of climate policy scenarios, from mitigation (RCP2.6) to stabilization (RCPs 4.5 and 6.0), to high GHG emissions (RCP8.5). Various models form the basis for these RCPs, including integrated assessment models, simple climate models, atmospheric chemistry, and global carbon cycle models (IPCC 2013). RCPs represent climate forcing trajectory outcomes.

Building on the RCP framework, IPCC's AR6 used Shared Socioeconomic Pathways (SSP) to reflect global trends in human activity, economic development, technology, and resulting changes in both GHG and aerosol concentrations, described in Table 2. SSPs model the possible socioeconomic pathways that, when combined with the RCP forcing levels, create integrated scenarios from SSP1-2.6, representative of a sustainable future with strong climate policy, through SSP5-8.5, which is representative of fossil fuel development and high GHG emissions. Each SSP describes a different societal pathway that can lead to or avoid specific climate outcomes.

Table 2. Shared socioeconomic pathway scenarios.

SSP	Description	Projected Surface Temperature Change for 2021-2040 (°C)	Projected Surface Temperature Change for 2041-2060 (°C)	Projected Surface Temperature Change for 2081-2100 (°C)
SSP1-1.9	This scenario (Sustainability) reflects widespread global climate change mitigation policies, clean energy technologies, and natural environment conservancy. It is a very low GHG emissions scenario with net zero CO_2 emissions in about 2050.	1.5	1.6	1.4
SSP1-2.6	This is also a Sustainability scenario but reflects the international climate policy goal of limiting global warming below 3.6°F (2.0°C) in 2100.	1.5	1.7	1.8
SSP2-4.5	This Middle of the Road scenario assumes moderate global climate mitigation and adaptation and slow progress in climate protection measures. It is a medium GHG concentration pathway with global temperatures increasing by 4.9±1.3°F (2.7±0.7°C) in 2100 compared to pre-industrial levels.	1.5	2.0	2.7
SSP3-7.0	This Regional Rivalry scenario models high challenges to mitigation and adaptation. Nationalism drives policy, and regional and local issues take precedence over global issues. Global temperatures increase by 6.5±1.6°F (3.6±0.9°C) in 2100 compared to pre-industrial levels.	1.5	2.1	3.6
SSP5-8.5	This Fossil-fueled Development scenario assumes high challenges to mitigation and low challenges to adaptation and is characterized by steadily increasing GHG emissions. It represents the upper boundary of the range of scenarios. Global temperatures increase by 7.9±2.2°F (4.4±1.2°C) in 2100 compared to pre-industrial levels.	1.6	2.4	4.4

Note: Temperature differences are relative to the average global surface temperature of the period 1850–1900. SSP = Shared Socioeconomic Pathway. Sources: IPCC 2021; EPA 2025.

The climate science described above provides context for understanding how individual project emissions contribute to global climate change. Climate change results from the cumulative effect of GHG emissions from all sources worldwide. Each source contributes to atmospheric concentrations, radiative forcing, and ultimately temperature increases. The emissions from individual MEPA projects therefore contribute incrementally to cumulative global GHG emissions and, consequently, to cumulative climate impacts, as discussed in detail in the Guidance Document's Appendix 4. Cumulative Impacts from GHG Emissions.

Overview of Methods for Attributing Climate Impacts on GHG Emissions

Scientific Basis for Attribution Challenges

Due to the inherent cumulative and global nature of climate change, it is difficult to link one source of GHG emissions to a specific environmental impact. CO_2 and other GHGs become well mixed in the atmosphere within a year due to atmospheric circulation, meaning that GHG emissions from one region are incorporated worldwide within that timeframe (National Oceanic and Atmospheric Administration [NOAA] 2025; EPA 2025b; EPA 2025c). This global mixing blurs regional signals, making it very difficult to trace atmospheric concentrations back to specific emissions sources. This is the reason GHGs cause widespread global climate effects regardless of where they are emitted.

While the relationship between cumulative CO_2 emissions and global mean temperature rise is approximately linear over the observed period (NOAA 2025), the climate and environmental effects of this increase in global surface temperature are nonlinear due to complex feedback loops, interactions, and thresholds in the Earth's natural systems (e.g., geosphere, biosphere, hydrosphere, and atmosphere). These nonlinearities further complicate attribution efforts because even small increases in GHG concentrations and resulting temperature increases can cause disproportionately large or sudden environmental changes, making it extremely difficult to predict the specific environmental consequences of emissions from any individual project.

Given the complex and long-term nature of climate change, quantifying specific secondary climate impacts from individual projects is challenging (as discussed below); therefore, GHG emissions from a project serve as a practical proxy for assessing the project's potential contribution to secondary climate impacts.

Earth System Complexities

<u>Feedback Loops</u>

Many feedback loops are at play within the Earth's natural systems that either dampen warming temperatures through negative feedback loops or amplify warming temperatures through positive feedback loops. Examples of positive feedback loops are the ice-albedo feedback, permafrost-carbon feedback, and water vapor feedback.

The ice-albedo feedback refers to the reduction in the Earth's surface reflectivity (albedo) that occurs when ice melts, as ice has a higher albedo than surfaces such as ocean water, land, or vegetation. This reduction in reflectivity allows the Earth's surface to absorb more radiation than it reflects, thereby leading to further warming, and further melting of ice.

The permafrost-carbon feedback occurs when rising temperatures thaw permafrost (permanently frozen ground) in the high latitudes, exposing previously frozen organic matter. Microbial decomposition of this material releases large amounts of CO_2 and CH_4 into the atmosphere, further warming the atmosphere and accelerating permafrost thaw.

The water vapor feedback loop occurs when global air temperature increases, and the concentration of water vapor in the atmosphere increases since warmer air holds more moisture. The water vapor then absorbs infrared radiation emitted by the Earth and traps it, further warming the atmosphere and increasing its capacity to hold water vapor (National Aeronautics and Space Administration [NASA] 2022).

Examples of negative feedback loops are the photosynthesis feedback and the low cloud feedback loop. Photosynthesis feedback occurs when higher atmospheric CO_2 levels initially stimulate plant growth through the CO_2 fertilization effect, thereby removing CO_2 from the atmosphere and partially offsetting CO_2 concentrations. However, CO_2 fertilization is expected to weaken over time due to nutrient limitations, temperature stress, and other constraining factors (IPCC 2021). Low-lying clouds (cumulus and stratus clouds) can reflect larger amounts of sunlight back into space, effectively reducing the amount of radiation absorbed by the Earth's surface. In contrast, high clouds (cirrus clouds) can have the opposite effect and create a positive feedback loop wherein they allow sunlight to pass through but trap outgoing radiation from Earth's surface, enhancing the greenhouse effect. Cloud dynamics are frequently highlighted as a challenge in climate modeling due to these complex interactions.

These interconnected feedback loops create cascading effects that make it extremely difficult to attribute specific environmental changes to individual emission sources.

<u>Climate Tipping Points</u>

Critical thresholds, often referred to as tipping points, add another level of complexity to environmental responses to climate change. These tipping points are critical limits in Earth's systems that, once crossed, lead to abrupt and sometimes irreversible changes. Armstrong McKay et al. (2022) identified key climate tipping points, including the Greenland ice sheet, West Antarctic ice sheet, Boreal Permafrost Collapse, and Atlantic Meridional Overturning Circulation (AMOC). The unpredictable timing and rapid nature of these threshold responses further complicate efforts to link individual emission sources to specific environmental outcomes.

An increase in both the net surface melt and calving of the Greenland ice sheet have led to major shrinking of the ice sheet, and early warning signs of a tipping point have been noted in west Greenland (Armstrong McKay et al. 2022). Armstrong McKay et al. (2022) note that this threshold for the Greenland ice sheet is approximately 1.5°C (0.8 to 3°C range) and will be exacerbated by a self-perpetuating feedback process: as the ice sheet melts and loses height, it descends into warmer air and melts more quickly.

The West Antarctic ice sheet is also susceptible to collapse. Large portions of the ice sheet, namely Thwaites Glacier, rest on bedrock that is below sea level. Over the past 30 years, the ice shelf of Thwaites Glacier has retreated, subsequently causing the flow of the glacier to increase. Thwaites Glacier's grounding line (the point where the glacier transitions from resting on bedrock to floating on water) has been retreating inland as warmer ocean water flows underneath the ice shelf and has retreated 14 kilometers (km) inland since the late 1990s (Davis et al. 2023). Ice that used to be on land becomes ice that floats (and eventually melts) in the ocean, raising sea levels. The downhill slope of the bedrock means that as the grounding line moves back, it exposes even larger portions of ice to ocean water, thereby accelerating the flow of the glacier into the ocean. The West Antarctic ice sheet collapse is also likely to occur at approximately 1.5°C (1 to 3°C range; Armstrong McKay et al. 2022; Hoegh-Guldberg et al. 2018).

The AMOC is a major ocean current system that redistributes heat globally and helps regulate climate patterns. Global warming inhibits convection in the deep ocean, slowing down the AMOC, which some reconstructions suggest has weakened by approximately 15 percent over the last 50 years (Armstrong McKay et al. 2022). The IPCC has low confidence in historical AMOC trends but assesses the likelihood of AMOC collapse before 2100 as "unlikely" (medium confidence; IPCC 2021). AMOC collapse would impact global temperature and precipitation patterns, making it a critical global tipping element with multiple associated uncertainties.

In summary, due to the complexity and nonlinearity of Earth's systems resulting from feedback loops and tipping points, current scientific methods cannot reliably attribute specific environmental changes that occur in any one location (e.g., Montana) to individual project GHG emissions. While projects contribute incrementally to cumulative global emissions that drive climate change toward these thresholds, the specific environmental consequences and timing of any single project's contribution cannot be meaningfully isolated or quantified.

Attribution Methodologies

Simple proportional attribution approaches assume that each emission source contributes to climate impacts in direct proportion to its share of total global emissions. The problem with this approach is that it assumes climate impacts are uniformly distributed globally, treats emissions timing as irrelevant, and does not account for complex feedback loops and tipping points.

Emissions timing is relevant when considering climate impacts because the climate system responds differently to emissions based on when they are emitted due to changes in carbon cycle efficiency and cumulative atmospheric buildup of GHGs. This means early emissions contribute more to current warming while recent emissions drive future impacts, making simple proportional calculations scientifically inaccurate for attributing climate impacts.

More sophisticated tools can provide better approximations of emissions contributions to global climate change impacts at larger scales. One such tool is the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC). This model is widely used because it is peer reviewed, publicly available, computationally efficient, can quickly run emissions scenarios, and approximates results from complex climate models. MAGICC can be used to calculate the change (delta or Δ) in projected global surface temperature by running the model with a baseline scenario (global emissions), then running the model with the specified emissions subtracted from the baseline scenario, and comparing the change in projected temperature outputs:

> ΔTemperature = ΔTemperature (baseline global emissions) - ΔTemperature (baseline global emissions minus specified emissions).

MAGICC provides a more scientifically robust approach than simple proportional methods because it incorporates climate system dynamics and can account for timing of emissions and basic feedback mechanisms. While the attribution challenges discussed above make it extremely difficult to link specific emission sources to measurable environmental outcomes, MAGICC represents one of the few publicly available, peer-reviewed tools that can provide quantitative estimates of emissions contributions to global temperature change. Despite its limitations—particularly for smaller emission quantities—MAGICC offers a scientifically grounded approach to contextualizing emissions at sectoral and state scales. The following analysis demonstrates both the utility and limitations of this approach for Montana's MEPA review process.

Attachment A. MAGICC Walkthrough, which accompanies this appendix, provides step-by-step guidance for using MAGICC to estimate climate contributions for sectoral and aggregated emissions analyses.

MAGICC

<u>Background</u>

MAGICC is a peer-reviewed reduced-complexity climate model developed by the collaborative efforts of various climate scientists (Meinshausen et al. 2011). It was created to integrate various climate system interactions, including the carbon cycle, climate feedback loops, and radiative forcing to simulate the effects of changing GHG emissions on atmospheric composition, radiative forcing, and global mean temperature change (MAGICC 2015). MAGICC is particularly advantageous because it emulates the complex and computationally intensive climate models efficiently. MAGICC simplifies climate modeling by combining three main components: an ocean layer, an atmosphere layer, and a carbon cycle model. MAGICC also simplifies the energy balance process by accounting for the extra energy in the Earth's system (e.g., from increased GHG emissions) as either heat stored in the ocean or radiated energy back to space, depending on temperature change and feedback effects. MAGICC derives simple equations from key physical and biological processes, thereby simplifying where necessary while retaining the core mechanisms of the Earth's systems. Using physical processes rather than solely statistical relationships gives MAGICC a major advantage, making it reliable when modeling new scenarios that differ from the original data it was trained on. The MAGICC platform provides comprehensive documentation and ready-to-use baseline emission scenarios that can be easily customized for specific user requirements. MAGICC is publicly available online at https://live.magicc.org/, and the associated baseline emissions files can be downloaded as editable .csv files.

MAGICC has been used extensively by the IPCC in the Third, Fourth, Fifth, and Sixth Climate Assessment Reports to produce projections of various GHG scenarios, as well as in the IPCC Special Report on Global Warming of 1.5°C, which reported on the impacts of global warming of 1.5°C above pre-industrial levels and related global GHG emission pathways (IPCC 2018).

In U.S. regulatory applications, MAGICC was also used by the National Highway Traffic Safety Administration (NHTSA) and EPA in the regulatory impact analysis for the Final Rule for Model Year 2012 - 2016 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards (EPA 2010). NHTSA and EPA used MAGICC to assess the change in the atmospheric CO_2 concentrations, global mean surface temperature, and sea level rise over time due to the emissions scenario specified in the rule (EPA 2010). The output from the rule's emissions scenario was subtracted from the reference (no policy or baseline) emissions case scenario to calculate the reductions in atmospheric CO_2 concentration, temperature, and sea level rise specifically attributable to the rule (EPA 2010). As a more recent example, NHTSA and EPA used MAGICC in the Final Environmental Impact Statement for the Model Year 2027-2031 Corporate Average Fuel Economy Standards and Model Year 2030-2035 Heavy-Duty Pickup Truck and Van Fuel Efficiency Standards, with the Department of Energy as a cooperating agency (NHTSA 2024). In this analysis, MAGICC was applied to estimate impacts of different regulatory alternatives using the Shared Socioeconomic Pathway scenarios as a reference baseline (SSP1-2.6, SSP2-4.5, and SSP3-7.0).

Additionally, the U.S. Bureau of Land Management (BLM) used MAGICC in the 2023 BLM Specialist Report (BLM 2024) using a "delta approach." The "delta approach" involves running

MAGICC twice: once with the baseline SSP scenario emissions and once with the same scenario emissions minus the specified emissions, then subtracting the change in temperature results to isolate those emissions' contribution to warming. This method approximates the climate impact by comparing "world with project" versus "world without project" scenarios. MAGICC model inputs were set up by assuming that projected federal fossil fuel GHG emissions were included in SSP scenarios since emissions are inherently cumulative. BLM then subtracted the projected federal fossil fuel-related GHG emissions from the baseline SSP scenario emissions levels. The results from the MAGICC model runs from the modified scenarios were subtracted from the unmodified baseline scenario results to calculate the federal contribution to the various parameters (e.g., change in surface temperature).

MAGICC and other simplified climate models have also been used to evaluate country- and sector-level emissions similar in scale to Montana's. For example, a recent analysis evaluated temperature increases from Ireland's country-level emissions using MAGICC and other simplified models with results broken down by sector (Wheatley 2024).

To contextualize emissions contributions to climate change for MEPA analyses in Montana, one can use the same "delta approach" with MAGICC's outputs. This requires the user to run a baseline SSP emissions scenario (such as SSP1-2.6, SSP3-7.0, or SSP5-8.5) once, download the output results from the baseline run, then edit the baseline SSP emissions scenario to subtract the specified CO_2, CH_4, and N_2O emissions from the baseline conditions, and run that scenario through MAGICC. The results from the modified scenarios can be subtracted from the baseline scenario results to calculate the overall contribution of the specified emissions to the modeled parameters from the modified scenario run. The user is modeling climate conditions with and without the specified GHG contributions to help contextualize the magnitude of the impact of the emissions on future global climate. The model outputs include variables such as atmospheric concentrations of CO_2, CH_4, and N_2O; effective radiative forcing; heat content of the ocean; and surface temperature from the year 1995 to 2100. Near-term impacts can be assessed for the years 2030-2050, whereas more pronounced temperature shifts can be seen in the long-term impacts (2050-2100).

This method provides useful context for understanding emissions contributions to climate change because it provides computationally efficient analysis of multiple emission scenarios, can be easily accessed online with no special modeling tools or software required, the baseline scenario files are freely available and can be easily modified, and different SSP pathways can be modeled. Additionally, the emissions files have separate inputs for different GHGs so it can be tailored for gas-specific emissions. The model also provides the option to run the scenarios probabilistically, enabling the user to run MAGICC 100 times to retain the range of outcomes that come with probabilistic ensembles while keeping the runtime fast. As opposed to simple attribution methods, this method uses established climate physics relationships and accounts for carbon cycle dynamics, including climate system inertia and lags that are represented in the model results. MAGICC is a reduced-complexity model, meaning that it does not account for interannual variability and, therefore, is useful in assessing changes in emissions, atmospheric concentrations, or radiative forcings that would be otherwise lost due to yearly variabilities of Earth's systems in more complex models (Sarofim et al. 2021).

MAGICC has some key assumptions, uncertainties, and limitations, including:

- MAGICC is a powerful tool for understanding climate behavior, but it presents mathematical approximations of an incredibly complex physical system.
- MAGICC estimates contributions to global mean temperature change but cannot attribute specific or local environmental impacts (e.g., changes in precipitation patterns, wildfire frequency, or ecosystem shifts) to those temperature changes due to the nonlinear system responses, feedback loops, and regional variability discussed above.
- While MAGICC can estimate temperature contributions from emissions at various scales, individual project emissions produce temperature changes too small to provide meaningful context for individual MEPA assessment, making the tool more useful for sectoral or large (e.g., statewide or regional) aggregated emissions analyses. However, the MEPA assessment for a project may report the sector's contribution to global temperature change as a quantitative representation of the upper bound of climate impacts from individual projects in that sector

<u>MAGICC Results for the State Total Emissions and Emissions from Large Sectors</u>

Table 3 provides the modeled mid-century (2050) and end-century (2100) changes in global average surface temperature for Montana's statewide emissions and large emission sectors, specifically (i) Energy; (ii) Land Use, Land-Use Change, and Forestry (LULUCF); and (iii) Agriculture. These sectors are from the EPA's annual GHG emissions inventory and SIT tool following the reporting guidelines of the United Nations Framework Convention on Climate Change. The EPA SIT tool also provides emissions for the "Waste" and "Industrial Processes"; these sectors were not included in the MAGICC analysis as they are less than 2 million metric tons CO_2e.

The emissions levels used in MAGICC are shown in Table 3 and reflect the mean emissions of each sector from the EPA SIT estimate of Montana's emissions from 2020, 2021, and 2022. These emission levels were modeled in MAGICC using the "probabilistic" MAGICC setup as opposed to the "single run" default MAGICC setup because climate models have inherent uncertainties in parameters (such as climate sensitivity). The 100-run ensemble captures this range rather than giving a single possible outcome. The delta method was applied to emission scenarios for two scenarios – SSP1-2.6, representing a sustainability pathway that limits global warming below 3.6°F (2.0°C) by 2100, and SSP5-8.5, representing a fossil fuel development future with steadily increasing GHG concentrations. These examples demonstrate how MAGICC can be applied to contextualize Montana's overall and sectoral contributions to global temperature change.

These sectoral results provide useful context for understanding the scale of potential impacts of a project in Montana: any individual project within a given sector would result in temperature contributions smaller than the sector's total contribution shown here. Thus, the MEPA assessment for a project may report the sector's contribution to global temperature change as a quantitative representation of the upper bound of climate impacts from individual projects in that sector. While individual project temperature contributions are extremely small, all GHG emissions contribute incrementally to atmospheric GHG concentrations and radiative forcing, driving global surface temperature increases and climate change impacts. In Montana, this increase in surface temperatures would contribute to the cumulative climate impacts discussed in the Guidance Document's Appendix 1. Cumulative Impacts from GHG Emissions.

Table 3. Change in average global surface temperature (ΔT) for Montana statewide emissions and emissions from large sectors as determined by MAGICC via the delta method.

Sector	Sector Description[1]	Annual Emissions[2] (million metric tons CO_2e/yr)	SSP1-2.6 ΔT by 2050 (°C)	SSP5-8.5 ΔT by 2050 (°C)	SSP1-2.6 ΔT by 2100 (°C)	SSP5-8.5 ΔT by 2100 (°C)
Land Use, Land-Use Change, and Forestry	Emissions and removal of CO_2, and emissions of CH_4 and N_2O from land use, land-use change, and forestry	7.34	8.00E-05	7.00E-05	1.00E-04	8.50E-05
Agriculture	Emissions from agricultural activities except fuel combustion, which are addressed under Energy	10.84	1.25E-04	1.05E-04	1.45E-04	1.25E-04
Energy	Emissions from stationary and mobile energy activities including fossil fuel combustion and fugitive fuel emissions, and non-energy use of fossil fuels	30.47	3.50E-04	2.90E-04	4.00E-04	3.40E-04
Statewide Emissions Scenario	Total statewide emissions from the sectors above as well as "Industrial Processes and Product Use" and "Waste"	50.74	5.9E-04	4.9E-04	6.7E-04	5.7E-04

[1] Sector definitions are from the EPA annual GHG emissions inventory (https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks) and SIT tool (https://www.epa.gov/statelocalenergy/state-inventory-and-projection-tool) following the reporting guidelines of the United Nations Framework Convention on Climate Change (https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2).

[2] Average annual emissions in Montana for each respective sector from 2020-2022 as estimated by DEQ using the EPA State Greenhouse Gas Inventory Tool.

Where additional context on sectoral or aggregated emissions contributions would be useful, MAGICC analysis can be performed following the methodology demonstrated above. A step-by-step guide is provided in Attachment A. MAGICC Walkthrough, which accompanies this appendix.

Summary

All sources of GHG emissions contribute to climate change and the resulting impacts on Montana's environment. IPCC (2023) states that global warming will continue to increase over the next couple of decades due to these increased cumulative GHG emissions, regardless of scenario or pathways, causing increased climate hazards in every region of the world and thereby increasing the risk to humans and ecosystems. This means that any human health or ecosystem changes in Montana are due to the past, present, and future GHG emissions from Montana combined with the global GHG emissions from the past, present, and future. The observed increases in well-mixed GHG concentrations in the atmosphere since about 1750 are caused by GHG emissions from human activities over the same period (IPCC 2023); and, due to the physical characteristics of these gases, cause an increase in the greenhouse effect and increase radiative forcing, thereby increasing global surface temperatures.

Attributing specific secondary impacts from individual GHG emission sources and projects is extremely difficult given the cumulative and global natural of climate change. Because GHGs are well mixed in the atmosphere and climate change occurs because of the cumulative global accumulation of GHGs, combined with non-linear system responses, feedback loops, and tipping points, attributing specific changes in climate variables to specific emission sources is not currently scientifically feasible.

Although it is challenging to estimate the specific impacts of project level GHG emissions on Montana's environment, the MAGICC model provides a peer-reviewed scientific tool that agencies can use to approximate the contribution of a relatively large amount of GHG emissions to global temperature change. Unlike simple proportional attribution methods, MAGICC is a reduced-complexity model that incorporates the physical basis for Earth's system interactions while remaining computationally efficient. This model has been used extensively by IPCC, federal agencies, and others to evaluate climate impacts from different emission scenarios. While MAGICC results represent global approximations rather than precise local predictions, they provide a quantitative approach to contextualize the contribution of GHGs to climate change in MEPA analysis and provide an upper bound for global temperature change due to projects, although it cannot provide a rigorous attribution of climate impacts from individual projects due to the global and cumulative nature of climate change. However, this analysis provides useful context for understanding the scale of Montana's overall contribution to global climate change.

The emissions from individual GHG-generating projects in Montana and elsewhere contribute incrementally to cumulative global GHG concentrations and radiative forcing, driving climate impacts worldwide, including in Montana, as detailed in the Guidance Document's Appendix 4. Cumulative Impacts from GHG Emissions.

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Attachments

Attachment A. MAGICC Walkthrough

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ATTACHMENT A TO APPENDIX 2: SECONDARY IMPACTS FROM GREENHOUSE GAS EMISSIONS

MAGICC WALKTHROUGH

January 2026

Contracted by:

Montana Department of Environmental Quality

Prepared by:

Ramboll

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Introduction

This Attachment A provides a step-by-step walkthrough of the MAGICC model, described in detail in Appendix 2: Secondary Impacts from Greenhouse Gas Emissions.

Walkthrough

To use MAGICC, the user must create an account at https://live.magicc.org/. Once an account is created, the user will be directed to the Scenarios page, as shown in Figure 1.

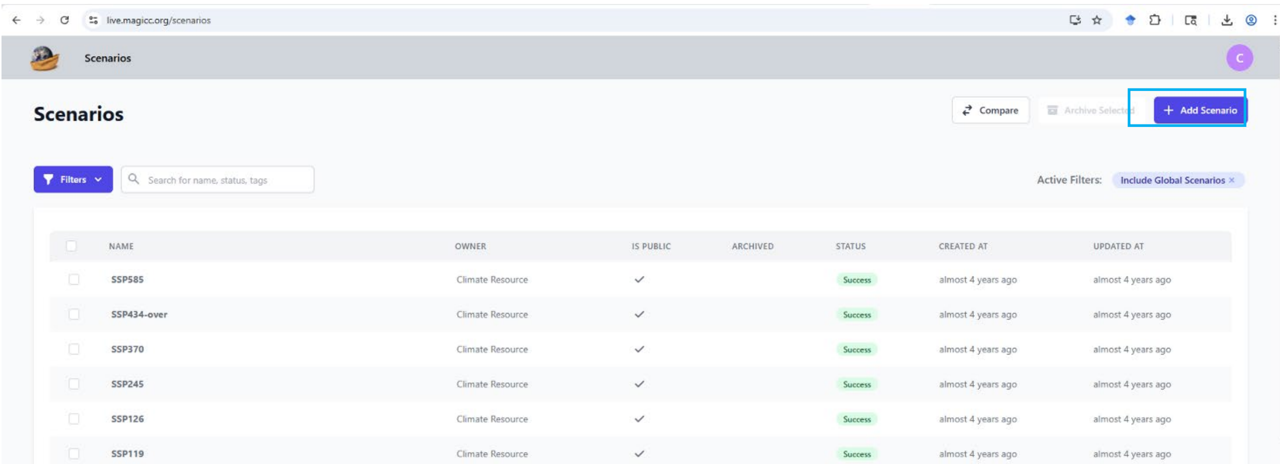

Figure 1. MAGICC's "Scenario" homepage.

The user will then click the upper-right hand box "Add Scenario," which will open a new "Create new scenario" page displayed in Figure 2.

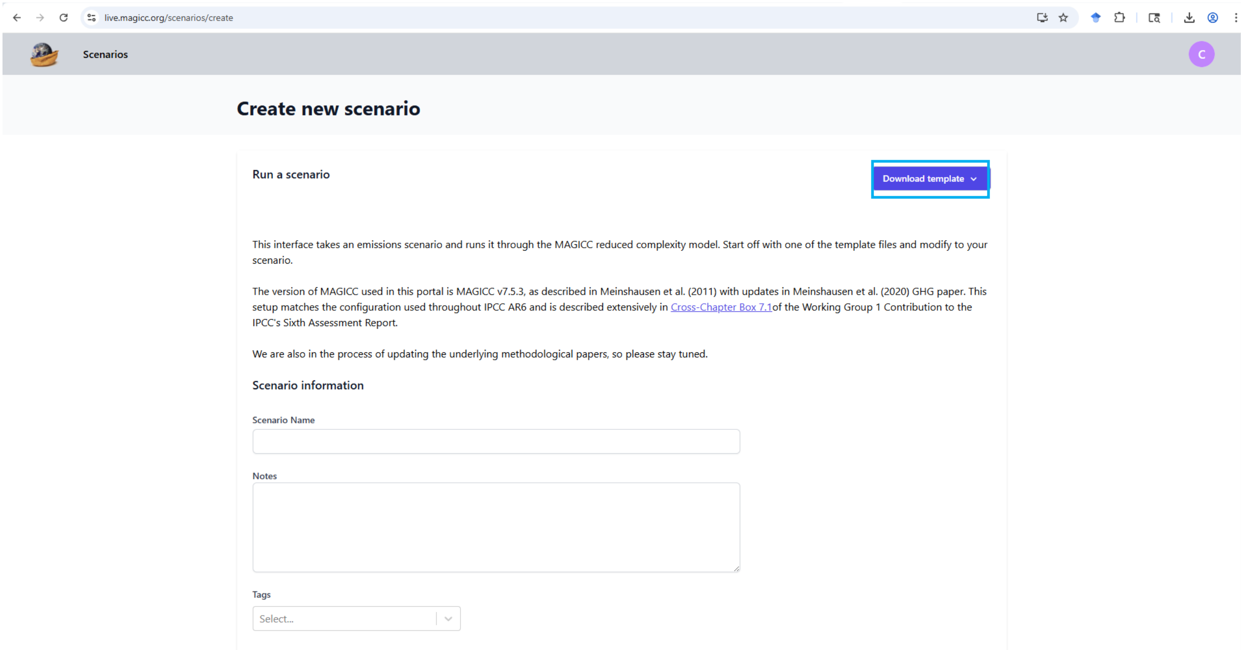

Figure 2. MAGICC's "Create new scenario" webpage.

Within the "Create new scenario" page, the user can click "Download Template" to enable a drop-down menu and choose which emissions scenario .csv file to download. MAGICC provides baseline scenario templates for SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, and SSP5-8.5. These templates contain the baseline emissions for the specific SSP scenario for the year 2015 and every decade from 2020 through 2100. Save a copy of the template file to edit. To edit the copied file, the user needs to subtract their emissions from the appropriate variable column from the appropriate year. For instance, if the specified emissions are related to fossil fuels and are scheduled for the years 2030 through 2060, the user should subtract the CO_2e emissions from the "Emissions|CO2|MAGICC Fossil and Industrial" row for the years 2030, 2040, 2050, and 2060. The correct category (row) for emissions adjustments should be determined based on the emission source type. Note that the units for each variable as some are listed in million metric tons (e.g., Mt CO_2 / yr), and other variables are listed in kilotonnes per year (e.g., kt N_2O / yr).

Once the emissions are subtracted from the baseline emissions, save the .csv file with a unique descriptive name. The user can then complete the "Create new scenario" page by entering the Scenario Name of the modified emissions file, adding any notes and tags, and the uploading the modified emissions file. The last step is to choose how to run the MAGICC model. For the most representative results, it is recommended to use the "IPCC AR6 WG1 (Probabilistic)" MAGICC setup option as shown in Figure 3. This will allow the model to run 100 times to provide a better estimate of the outputs of the modified emissions. Click "Run Scenario."

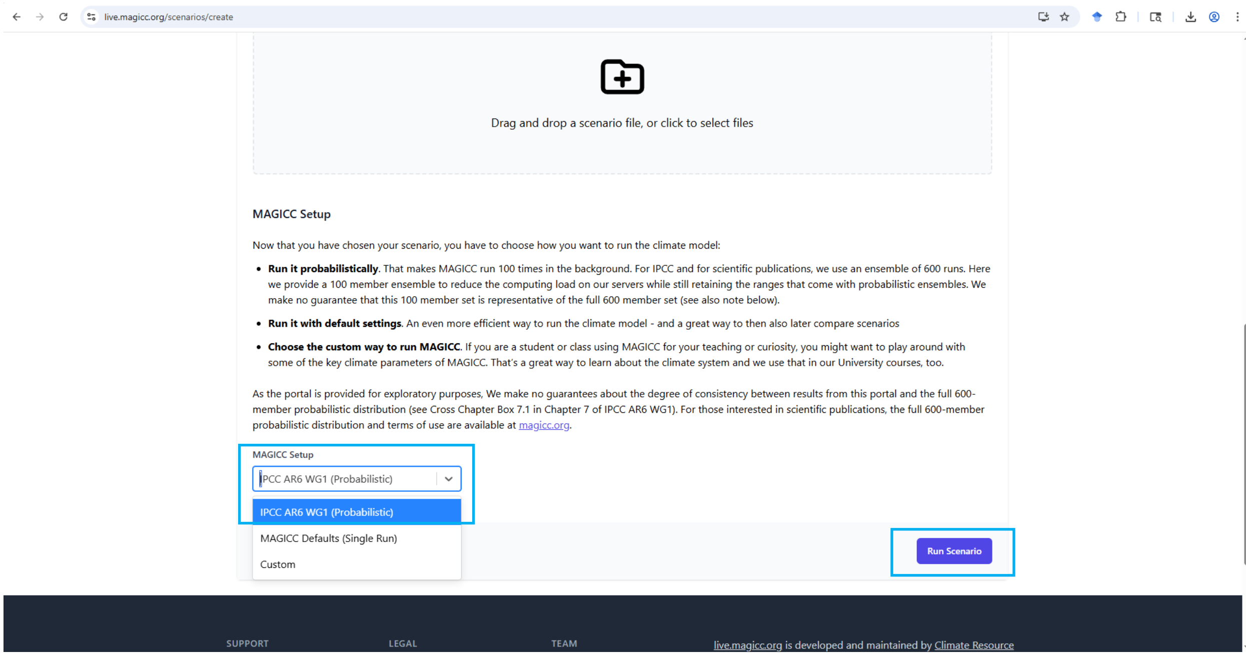

Figure 3. MAGICC's "Create new scenario" webpage showing the different MAGICC setup options.

After running the modified emissions scenario, a page will appear that displays a graph of the change in surface temperature of the scenario and has a "Download Output" button below that graph. Click "Download Output" to get the results of your model run in .csv format. Scrolling down on the results page, the user can explore various statistics associated with the model run.

Additionally, the user will need to navigate back to the list of scenarios by clicking "Scenarios" in the upper lefthand corner. From there, upload the unedited baseline emissions file that was originally downloaded to run the baseline emissions scenario (e.g., SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, and SSP5-8.5) and run that scenario with the same "IPCC AR6 WG1 (Probabilistic)" MAGICC setup option to get the baseline results. Once this SSP scenario results page for the baseline run is loaded, click "Download Output" as was done previously to get the MAGICC model results for that baseline SSP scenario.

Now that the two files of MAGICC results are downloaded (the baseline SSP emissions results and the modified emissions results), the delta approach can be applied.

For the variable in question, subtract the modified emissions result from the baseline emissions result. For example, if you were interested in the surface temperature change in 2050, find the row that lists the variable as "Surface Temperature" and the column that lists the year "2050" to navigate to the appropriate cell in the baseline SSP emissions file. This cell represents the estimated change in surface temperature in 2050 (note that this is in °K, but because we are accounting for change in temperature, this is equivalent to change in °C) from pre-industrial temperatures given the baseline SSP emissions file. Next, do the same for the modified emissions file. You will then subtract the value in the modified emissions results file from the value in the baseline SSP emissions results file to get the temperature change. Results should be interpreted as approximations rather than precise predictions.

While MAGICC can estimate temperature contributions from emissions at various scales, individual project emissions produce too small of temperature changes to provide meaningful context for environmental impact assessment, making the tool more useful for sectoral or large aggregated emissions analyses.