Consumed Emissions Estimates Technical Documentation

March 2025

Highlights of Technical Documentation

- CarbonFlow™ is an emission tracking method that treats the emissions created during power generation as a feature of the generated power and traces that power through the network to allocate it to loads.
- MISO's data provides generation, load and power flow on the transmission grid. Data inputs cover the MISO footprint and some areas beyond MISO, which are used to estimate emissions imported into MISO from surrounding areas.
- Market sensitive data is protected by ensuring that all near-real-time published estimates aggregate across at least four assets or market participants. More granular estimates are lagged and temporally aggregated to align with publication timelines for existing public data.

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TABLE OF CONTENTS

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Overview

CarbonFlow™ is an emissions tracking method implemented by Singularity Energy[1] based on state-of-the-art, peer-reviewed academic research on power flow tracing of emissions.[2] CarbonFlow™ treats the emissions created during power generation as a feature of the generated power and traces that power through the network to allocate it to loads. CarbonFlow™ considers both the spatial distribution of generation assets and the direction and magnitude of power flows on lines across the physical network. The resulting consumed emission rates estimate the emissions of power consumed by customers at specific locations on MISO's electrical grid at a more granular spatial resolution than previously available. See the "CarbonFlow™ in context" call-out box for discussion of how CarbonFlow™ data fits into the landscape of emissions accounting.

CarbonFlow™ uses a power flow tracing methodology. Active power flows are first calculated on each component of MISO's transmission grid using operational data from MISO. Emissions are then estimated for all generation on the grid using historical, plant-specific heat rate curves calculated from Singularity's Open Grid Emissions (OGE) dataset. Finally, those emissions estimates are attached to the power flowing across each system component and tracked across the grid from source to load. Load emissions estimates can then be aggregated up to various levels, including but not limited to: Local Balancing Authorities, states, and MISO subregions.

Conceptually, the consumed emission rates of CarbonFlow™ are similar to existing consumed emission rate data, which is available from multiple data providers on the Balancing Authority level using data from the Energy Information Administration's (EIA) Hourly Electric Grid Monitor. Consumed emissions estimates aim to allow electricity consumers to perform more accurate location-based emissions accounting by revealing the full picture of emissions associated with electricity consumption, considering both emissions from regional power generation and power imports and exports.

Existing sources of consumed emissions estimates provide data points at the level of balancing authorities (such as MISO) at an hourly resolution. Over the past decade, the standard for emissions estimates has moved from annual to hourly due to the increasing acknowledgement of the importance of dynamic emission rates.[3] This data release offers emission rates on much finer spatial scales for the first time.

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[1] Shi, Wenbo, Xin Chen and Na Li. 2023. Apparatus and method for optimizing carbon emissions in a power grid,US Patent 18/102,408, filed January 27, 2023, and issued July 12, 2023.

[2] Kang, C., et al . "Carbon emission flow from generation to demand: A network-based model.". IEEE Transactions on Smart Grid, 2015. Chen, Xin, Hungpo Chao, Wenbo Shi, and Na Li. "Towards carbon-free electricity: A comprehensive flow-based framework for power grid carbon accounting and decarbonization." arXiv preprint arXiv:2308.03268 (2023).

[3] For example, Miller et al. found that using hourly emission rates significantly changed estimated emissions from loads across US BAs: https://iopscience.iop.org/article/10.1088/1748-9326/ac6147/meta

THE LANDSCAPE OF EMISSIONS ESTIMATES: CARBONFLOW™ IN CONTEXT

Emissions analysis of electricity consumption in electrical grids[4]

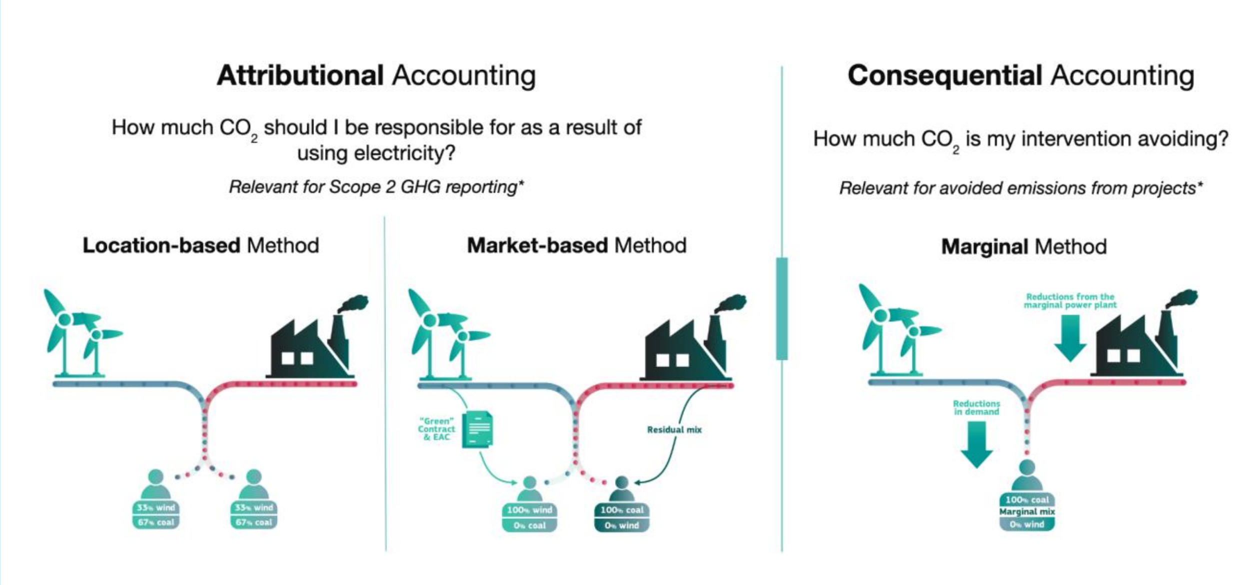

Figure 1: Illustration of Greenhouse Gas Accounting Methods

Greenhouse gas (GHG) accounting provides a useful overview of the different frameworks to allocate or attribute emissions estimates from generation to load, as summarized above (Figure 1). Although we introduce these frameworks using accounting terminology, these categories of GHG analysis are also actively used in research and policy applications.

For attributional accounting, all emissions generated on the grid must be allocated to energy consumed on the grid, either by loads or in transmission losses. There are two main approaches, both outlined in the WRI GHG Accounting Protocol: location-based and market-based.

In a location-based approach, emissions estimates are assigned based on a user's location on the grid. In the example shown above, both consumers A and B get the same mix of 33% of wind and 67% of coal. The location-based method is intuitive and can provide researchers and policymakers with important insights about the fuel mix and emissions of the grid. Existing location-based methods in the U.S. provide data at the balancing-authority level, but CarbonFlow™ provides much more granular data.

For accounting applications, a key limitation of the location-based approach is that consumers have limited ability to actively reduce their emissions since they have little control over the fuel mix at their substation. This led to the development of the market-based method, in which consumers can acquire environmental attributes from specific sources of generation through certificates to make emissions claims. In the example above, consumer A claims the wind attributes to be 100% wind, leaving consumer B to be 100% coal. The market-based method is independent of the physical aspects of the power system and assigns emissions based on contractual agreements. CarbonFlow™ is not a market-based tool and does not consider the market contracts of MISO's market participants.

[4] NOTE: Important analysis of emission estimates has additional use cases: at power plants, including environmental regulation, analysis of health impacts, and equity research.

Separately from attributional accounting, there is a third framework known as consequential accounting. This framework addresses how emissions would be impacted by an intervention or change. Unlike the location-based and market-based methods, consequential accounting is not intended for attributing emissions estimates but rather for evaluating interventions and projects to assess their influence on systemwide emissions. CarbonFlow™ is not a consequential data product.

MISO Implementation of CarbonFlow™

This section describes how the CarbonFlow™ methodology has been implemented for MISO, including descriptions of the data inputs, emissions and power flow calculations, and spatial aggregations of the data. An overview of this data pipeline is illustrated in Figure 2.

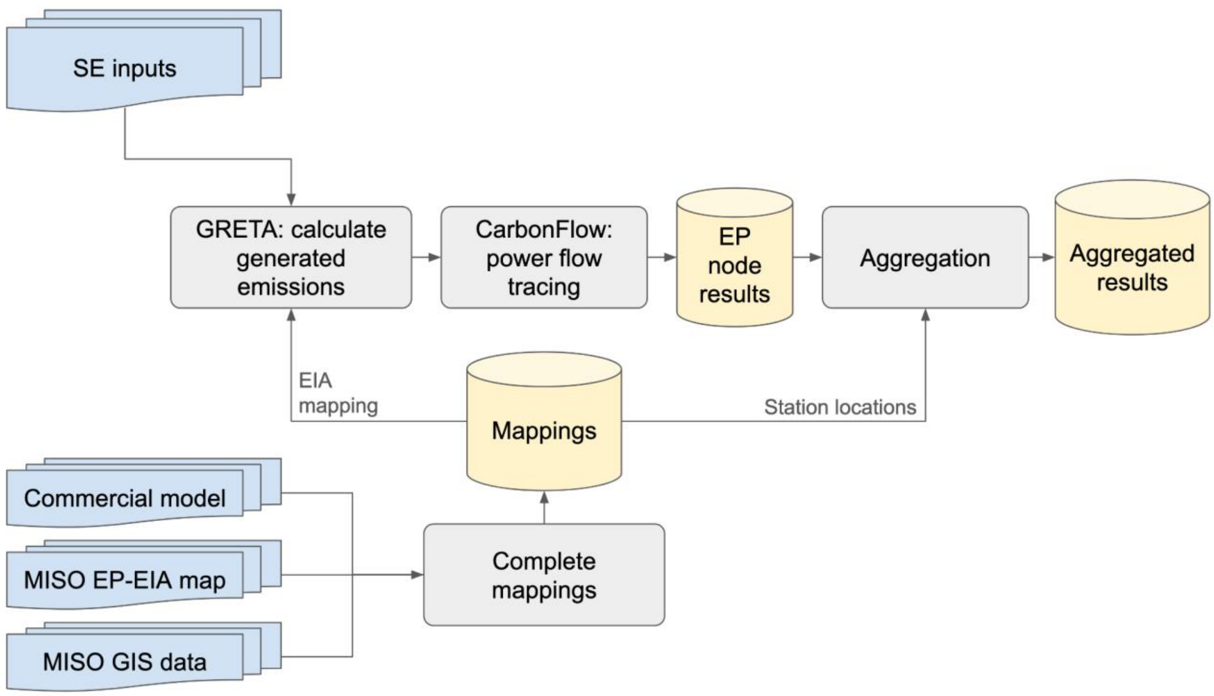

Figure 2: System diagram showing connections between MISO inputs (blue file icons), computational steps (gray rectangles), and main Singularity-produced data (yellow cylinder icons). Each computational step is elaborated in a section of this documentation.

DATA INPUTS

The CarbonFlow™ data pipeline uses three main types of inputs:

- **Near-real-time operational data**: MISO's data provides generation, load, and power flow on the transmission grid. The spatial coverage for input data matches that of MISO's network model and includes most of the Eastern Interconnection, except for Florida and New England. Data for areas beyond MISO are collected from neighboring grid operators and are used to determine imports into the MISO footprint, but this data is potentially of lower fidelity than MISO's data.
- **Mapping Tables**: These tables are used to map EP node-level data from MISO's network model to EIA databases and physical locations. These tables cover all EP nodes in the network model and are updated on a quarterly basis.
- **Public EPA and EIA data**: Singularity uses data on generator-specific generation, emissions, and facility attributes reported to the EPA and EIA to calculate emissions, facilitate mapping, and validate data. All emissions data comes from Singularity's publicly available Open Grid Emissions dataset, which itself accesses the EPA and EIA data through databases maintained by the Public Utility Data Liberation (PUDL) project.

Near-Real Time Operational Data: MISO's State Estimator (SE)

The data used for CarbonFlow™ comes from MISO's State Estimator.

State estimation is used by transmission system operators, including MISO, to gain visibility to their system in real time. It uses measured SCADA data from within the operator's footprint and data shared by neighbors to estimate the current state (active and reactive power, generation, load and losses) of each component in the network model.

The State Estimator uses measured data where available, which it interpolates and adjusts to create a complete picture of power injections, withdrawals, and flows on the grid. The state estimation process interpolates between the measured data to produce a single consistent picture of the system state, which is necessary for CarbonFlow™. An inconsistent picture of the system (for example, where two measured numbers indicate negative losses on a line) would result in inconsistencies between generated and consumed emissions estimates. This process solves for the system state within a small tolerance relative to the total power on the system.

Despite being estimates, state estimation results are generally very high-quality and capture the granular system behavior enough to be used for critical real-time operational decision making by MISO. Using operational data as the data source for consumed emissions estimates ensures that input data will be high quality and consistently available, since the data is vital across MISO operations.

MISO exports a snapshot of State Estimator results for CarbonFlow™ every five minutes, at the close of each market interval.

Mapping Tables

The consumed emissions pipeline relies on multiple mapping tables, which are updated on a quarterly basis to align with the quarterly Commercial Model update process. Completed mappings are produced by collecting and aligning multiple input mappings from MISO and performing additional manual mappings where there are gaps.

The State Estimator describes power flows in the system for each Elemental Pricing (EP) node. EP nodes are the most granular modeling unit in MISO's Network Model. To assign emissions to each generator, generator EP nodes must be mapped to EIA plant and generator IDs so that external emissions databases can be used. Additionally, to aggregate EP node data spatially, each EP node must be mapped to a physical location.

Quarterly Model Update Process

MISO's Commercial Model is updated quarterly (March, June, September, and December). Typically, several dozen new generator EP nodes are added in each model update, usually reflecting generators that will come online in following months. Each Commercial Model is released in the week before it takes effect (e.g., the September commercial model is released in the last week of August). In the week after the Commercial Model is released, Singularity uses the manual matching process above to match as many new nodes as possible to fuel types or generators. Typically, about half of the new nodes can be matched, with the other half labeled as "unknown" generation until more data is available, often from other internal MISO data regarding these nodes.

Mapping Generator EP nodes to EIA IDs

To estimate emissions from the generation of each generator in MISO's network model, the specific identity (i.e. EIA plant identification code and generator ID) is used where available (83% of generation in the MISO network model footprint; see "Coverage of MISO's Map" section below). Where an EIA ID cannot be identified, or the generator does not report data to EIA, the fuel type (e.g. wind, nuclear, or solar) of each generator is used. An "unknown" fuel type is assigned for generators where neither the specific identity nor fuel type is known.

Generator-specific matches for emitting power plants produce the highest quality emissions estimates, since heat rates and emission factors of different generators of the same fuel type can vary widely. In plants where generators use different fuel types, using a generator-level mapping ensures that the emission rates of each fuel type are correctly accounted for.

COVERAGE OF MISO'S MAP

MISO maintains a partial mapping of 4,859 generator EP nodes to their EIA ID and/or fuel type, which covers 71% of EP nodes within MISO's network model. Although 71% of the EP nodes are mapped using MISO's map, the percentage of generation from these EP nodes is 83% of the total generation in a sample period.[5] Considering only generators within the MISO footprint (MISO's network model includes both the MISO footprint and neighboring regions), the MISO map coverage is even higher, accounting for 99% of in-MISO generation. In rare cases (50 total EP nodes), MISO's generator-level mapping matches an EIA Plant ID but not a generator ID. In these cases, the plant-level mapping is used.

Singularity manually mapped an additional 1900+ generator EP nodes, seen in MISO's Commercial Model updates between June 2023 and September 2024 (see "Manual matching of EP nodes not in MISO's map" section below), for a total of 6807 mapped EP nodes, covering all generator EP Nodes in MISO's current network model.

MANUAL MATCHING OF EP NODES NOT IN MISO'S MAP

To map the generator EP nodes not included in MISO's map, Singularity first determined possible EIA mappings for each generator using a combination of the generator's location and the name assigned to the generator in MISO's network model. The best match is manually identified by comparing metadata from information each generator reports to the EIA for each possible match (including operational dates, capacities, names, and locations) to the MISO network model. Where no EIA plant was a good match for an EP node, the plant was assigned a fuel type.

For certain carbon-free resources (most often wind, solar, and batteries), it is not possible to identify a specific EIA plant ID, but the name of the resource in the network model includes abbreviations that indicate likely fuel types (see Table 1 below). In these cases, a fuel type is assigned. For carbon-free resources, matching a specific plant ID is not important for emissions estimation since the emission rate for all these plants is zero.

[5] In two weeks of data, 2024/7/16-2024/7/30

Station name or resource ID prefix or suffix	Fuel type assignment
DER	unknown
DDR	unknown
BESS	storage
SP	solar
WF	wind
WIND	wind
HYD	hydro

Table 1: Fuel type assignments. Assignments are based upon network model EP node names.

In a small number of cases, an "unknown" fuel type/identity is assigned to a generator:

- For any generator EP nodes where it is not possible to confidently determine an identity or fuel type
- For any load assets with negative load (generation), which likely represent behind-the-meter generation sources
- For any system components that are classified as generators in the network model but are not actual active power generators (e.g., static Var compensators, synchronous condensers)
- For retired generators. Some nodes in the Network Model map to plants that have been retired, in some cases for over a decade, and physically demolished. These most often occur far from MISO's borders and may reflect cases where parts of the network model have not been updated. In these cases, the State Estimator may assign generation to those retired plants. 110 EP nodes mapped to plants retired before 2022 are labeled as "unknown".

Mapping stations to locations

MISO provides geographical information system (GIS) data to map certain EP node stations to geographic coordinates. This covers approximately half of the station names found in the network model. Coordinates are assigned to remaining stations using relationships between stations.

Assigning coordinates based on model mappings

Sometimes, a station with unknown coordinates may be associated with another station with known coordinates in another mapping table. For example, for each EP node, the commercial model posting lists two bus names from the Network Model system, associated with the PSS/E EMS or IDC export, respectively. If the coordinates associated with one bus name are known, mappings between bus names are used to assign coordinates to associated bus names and the EP node station names. Singularity creates a mapping of all associations between each pair of names from the following sources:

- Commercial Model Posting excel file: EP node station, EMS bus name, IDC bus name
- Commercial Model Posting PSSE .raw file: bus name, station name
- SE model exports: station name and bus name sampled from three timestamps in the past three months

Assigning coordinates based on EIA mappings
In the case that the coordinates of a station are unknown but a generating EP node with a known EIA plant ID is located at that station, the coordinates reported to the EIA for that plant are used as the coordinates of the station.

Interpolating coordinates from adjacent stations
For any remaining missing coordinates, Singularity interpolates the location based on the node's location relative to other nearby known nodes, using the network model included with the commercial model posting and the network model from a recent SE model export. If a station/bus is located between other buses with known coordinates, the coordinates of all surrounding buses are averaged to estimate the location for the unknown bus. If a station is adjacent to a single other station with known coordinates, it is assigned the same coordinates as the single adjacent location. Interpolation is repeated until all stations are assigned coordinates. This interpolation represents a best-available guess for the location of these stations, although this may result in imprecise spatial aggregations, especially at high spatial resolutions, such as the county level.

Approach	Number (percent) of stations mapped
MISO-provided mapping table	30,045 (41.8%)
MISO-provided mapping table of associated station	34,579 (48.1%)
EIA plant mapping of station	214 (0.3%)
EIA plant mapping of associated station	264 (0.4%)
Interpolated from adjacent buses	6,744 (9.4%)
Total	71,864 (100%)

Table 3. Summary of methods used to interpolate station coordinates from adjacent stations, as of the June 2024 Commercial Model posting.

CALCULATING GENERATED EMISSIONS

Gross to net generation conversion

In MISO's network model, most generation is represented as net generation. Net generation is the energy injected into the bulk transmission system after station self-consumption is netted out. In general, net generation is used as the basis for consumption-based emissions calculations. Conceptually, net generation more realistically represents the generation that serves end users, because the power (and the emissions associated with the power) consumed by station loads is never sent out to the bulk power system for transmission and delivery. However, certain generators in the network model are represented using a gross generation convention, where the gross output is represented as a generator node and the station load is represented as a load node.

Station loads (sometimes referred to as house loads, station use, parasitic loads, and auxiliary loads) can be auxiliary equipment used to generate electricity (pumps, compressors, feed systems), emissions control equipment, and loads from the plant building or other adjacent administrative buildings (lighting, air conditioning, SCADA systems).

During network preprocessing, any loads that are located at the same bus as a generator are treated as auxiliary/parasitic loads and are used to adjust the generation of the generation units at that bus. The sum of all auxiliary load at each bus is allocated proportionally to each generator at that bus such that the output of each generator is reduced by the same percentage. Any loads that are located at the same station, but not at the same bus as a generator are not included in this conversion.

Heat Rate Curve-Based Emissions Estimates using GRETA

Before tracing fuel mix and emissions to specific load nodes, the fuel type and emissions rate must be assigned at the point of generation. To do this, Singularity uses its emissions calculation engine, called GRETA (Generator REal-Time emissions Assignment). For each interval, GRETA assigns a time-specific fuel type and emission rate to each generator based on the generator's modeled heat rate curve. These heat rate curves are modeled using public data that each generator reports to the EPA and/or EIA. Public data is the best source of consistent, high-quality data across the MISO network model footprint because all large fossil generators report emissions and generation data.

The use of GRETA, rather than static average emissions factors, enables a greater level of accuracy because:

- Certain generators cofire multiple fuels or switch fuels throughout the year. GRETA estimates a time-specific fuel type based on past generator behavior.
- The efficiency (heat rate) of generators vary based on their output level (i.e., a generator operating at full capacity may be more efficient than when it is operating at 50% capacity). GRETA uses heat rate curves to assign output-specific emission rates to generators.
- The heat rate of a generator can also vary by season based on ambient temperatures and seasonal requirements to operate pollution controls. GRETA includes season-specific heat rate models for each generator.
- Generators generally are less efficient during start-up and can also burn different fuel during startup. GRETA attempts to detect startup events and assign startup-specific fuel types and heat rate curves to the data.

Where the EIA ID of a generator is known but there is insufficient data to calculate a heat rate curve for a plant (for example, for a new plant with less than a year of publicly available data), a fuel-specific average heat rate curve is used.

Full documentation for this Singularity methodology can be found in the GRETA documentation, available under separate cover.

Assigning fuel categories to generation

All generation is labeled with a fuel category before power flow tracing. Fuel category assignment, like emissions assignment, can be variable over time, and uses a combination of GRETA models and static fuel category assignments where an EIA mapping is unavailable.

Fuel mix is reported in the following categories (listed alphabetically):

- Biomass

- Coal
- Hydro (not including pumped hydro)
- Natural gas
- Nuclear
- Other
- Petroleum
- Solar
- Storage (including pumped hydro)
- Unknown
- Waste
- Wind

Each category groups multiple energy sources, which are assigned at the plant or generator level according to EIA data. In each interval, a fuel type is assigned based on sub-plant level attributes (if sub-plant level mapping is available). If only plant-level mapping is available, the fuel type is assigned based on the primary attribute of the entire plant. The fuel type is assigned as follows:

- If the (sub)plant is a single fuel (sub)plant, the "primary fuel" identified in the Open Grid Emissions Dataset is assigned. This is based on the fuel type reported in EIA-860 and actual fuels consumed as reported to EIA-923 (see the methodology here).
- If the generator fuel switches or co-fires multiple fuels at once, the fuel type is assigned based on a regression model trained on historical fuel consumption data that the generator reports to EIA-923. This model identifies the probability of a certain fuel type being consumed at the plant in a given month. The model then assigns the fuel type with the greatest probability of consumption in that month.

Energy sources are assigned to fuel categories as follows:

Description	CarbonFlow™ Fuel Category
Agricultural Byproducts	biomass
Anthracite Coal	coal
Blast Furnace Gas	natural gas
Bituminous Coal	coal
Black Liquor	biomass
Distillate Fuel Oil/Diesel	petroleum
Geothermal	geothermal
Jet Fuel	petroleum
Kerosene	petroleum
Landfill Gas	biomass
Lignite Coal	coal
Municipal Solid Waste (biogenic)	waste
Municipal Solid Waste (non-biogenic)	waste

Municipal Solid Waste	waste
Energy Storage	storage
Natural Gas	natural gas
Nuclear	nuclear
Other Biomass Gas	biomass
Other Biomass Liquids	biomass
Other Biomass Solids	biomass
Other Gas	natural gas
Other	other
Petroleum Coke	petroleum
Propane Gas	petroleum
Process Gas	natural gas
Purchased Steam	other
Refined Coal	coal
Residual Fuel Oil	petroleum
Coal-Derived Syngas	coal
Petroleum Coke-Derived Syngas	petroleum
Sludge Waste	biomass
Subbituminous Coal	coal
Solar	solar
Tire-Derived Fuels	waste
Hydroelectric / Pumped Storage	storage
Waste/Other Coal	coal
Wood Waste Liquids	biomass
Wood/Wood Waste Solids	biomass
Waste Heat	other
Wind	wind
Waste/Other Oil	petroleum

Table 2: Fuel category assignments to resource types. Assignments are made to all resources.

Emission Rates for Carbon-free Resources

Generators with carbon-free fuel types (hydro, nuclear, wind, solar, and storage) are always assigned zero emissions. In some cases, a plant that produces primarily carbon-free energy may have a fossil backup generator. Emissions will be assigned for these backup generators only in cases where the backup generator is separately mapped in MISO's network model and can be assigned a separate fuel type or EIA generator ID from the main carbon-free plant.

Fleet-specific Backfill Emission Rates

Backfill emission rates for carbon-emitting fuel types are the average of all plants of that fuel type in the same MISO LBA (or BA for areas external to MISO). For example, if there is a natural gas EP node in Alliant East (ALTE) that has not been mapped to a specific EIA ID, its power is assigned the average emission rate of all natural gas plants mapped to an EP node in ALTE.

Emission rate data for backfill rates comes from Singularity's Open Grid Emissions (OGE) project. OGE is updated each fall with approximately a two-year lag; the most recent year of data is used. For example, 2024 consumed emissions estimates will use 2022 OGE data until 2023 OGE data is released in November; 2025 consumed emissions estimates will use 2023 OGE data until 2024 data is released, likely in November.

Because generators in Canada do not report data to the EIA, GRETA cannot be used to assign emissions to these generators. Instead, fleet-specific emission rates are assigned to Canadian generators based on data reported to Statistics Canada for each Canadian balancing area.

Emission Rates for "unknown" Fuel Types

EP nodes with "unknown" fuel types are assigned the average emission rate of *all emitting plants* in the same MISO LBA (or BA for areas external to MISO). This calculation is the same as that described above for fleet-specific backfill emission rates but averages all plants in a region instead of just those of a specific fuel type.

Energy Storage

Currently, CarbonFlow™ does not trace emissions through energy storage assets, although this functionality will be added in the future. Emissions from storage discharge are assigned an emission rate of as 0, and emissions from storage charging are considered part of consumed emissions. This means that emissions and fuel types do not "pass through" a battery to the end user of stored power later, but instead are assumed to be consumed at the battery at the time of charging. The stored power, when it is eventually discharged and used by other loads in the system, has a fuel category "storage" with an emission rate of 0.

CO_2 Equivalent Values

All emissions estimates are reported in CO_2 equivalent (CO_2e).

The combustion of fuel for power generation results in emission of various greenhouse gases (GHGs) including Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O). Each of these GHGs contributes to global warming differently, as described by its Global Warming Potential (GWP). These GWPs can be used to calculate a CO2-equivalent (CO_2e) value. The Intergovernmental Panel on Climate Change (IPCC) regularly updates these values over time in published Assessment Reports (AR). Emissions occurring in 2021 and later use the AR6 values, so CO_2e estimates are currently calculated in OGE using AR6 IPCC weights.

POWER FLOW TRACING

Power flow tracing (sometimes called load flow) is a common tool in power system analysis; it has been used in academic literature dating back to the 1990s when it was developed to analyze transmission costs associated with specific loads in newly deregulated electricity markets. CarbonFlow™ applies a matrix formulation of power flow tracing to track generator emissions estimates from power sources to power consumption (losses and loads).

Active power is traced for consumed emissions estimates because active power generation is responsible for most emissions.

Underlying Principles

Power flow tracing is based on the idea that certain features of power generation should be allocated to the consumers of that power. CarbonFlow™ allocates emissions from power generation to the loads that consume that power. Although this does not reflect a physical reality, in that the emissions are not physically transported along with the power to end users, it does reflect a widely shared assumption across emissions accounting that emissions from power generation can and should be allocated to users of that power.

Emissions are generated on the grid at emitting power plants. Loads on the grid consume power from those plants, and emissions can be allocated from generators to loads for analysis, emissions accounting, or policy evaluation. There are two categories of approaches to emissions allocation: market-based analysis considers energy and attribute contracts, while location-based analysis considers grid emissions to which a load is physically connected. CarbonFlow™ is a location-based tool, specifying at high granularity what emissions were used to generate the power serving each load.

Power flow tracing relies on several intuitive assumptions about how emissions relate to power flows on the system, which allows us to make these allocations:

1. **Power flowing into a bus is evenly mixed** before flowing out of the bus. For example, if a wind generator and a coal generator are attached to the system at the same bus, the power flowing out of that bus will be a mix of wind and coal power.
2. **Total emissions are preserved**. The total emissions of power flowing into a bus equals the total emissions of power flowing out of the bus.
3. For components that transfer power, such as lines and transformers, **the emission rate of power flowing into a system component is the same as that of the power flowing out of the system component**. In a system with losses, the *total* emissions flowing into a line will equal the total emissions flowing out of the line *plus* the emissions lost in line losses.

These assumptions allow Singularity to use active power flows to allocate all emissions estimates from generation to energy consumption by end users or losses.

Simple Example of Tracing Emissions Via Power Flows

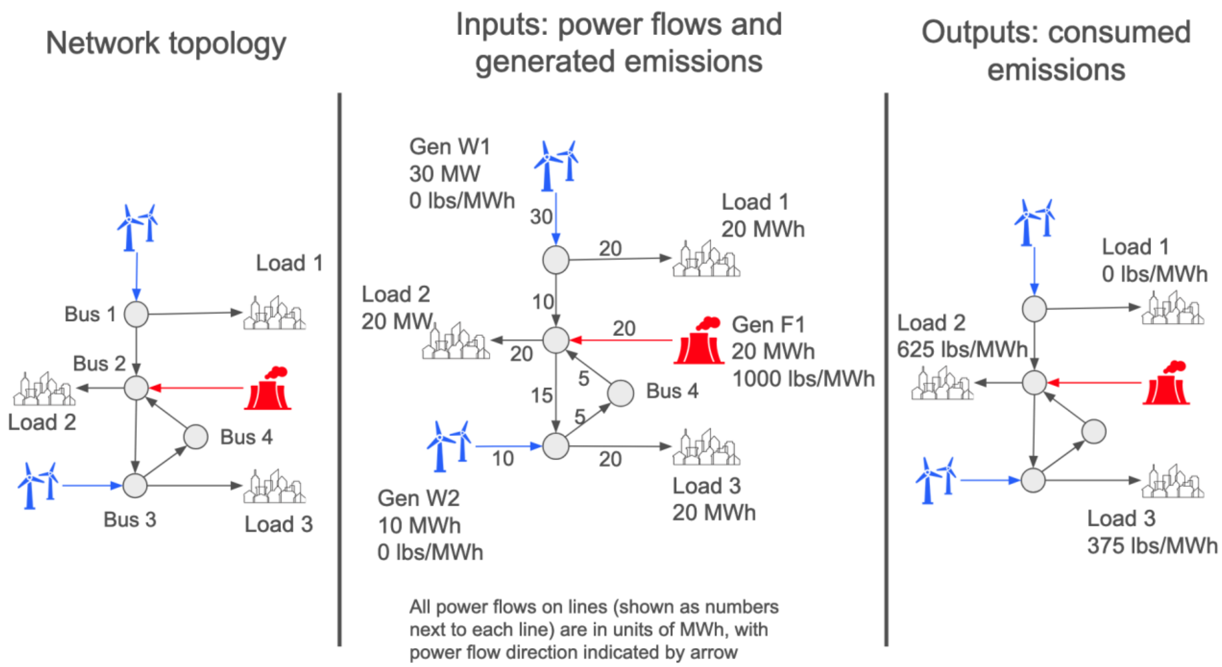

Figure 3: Small example system, labeled with component names (left), power flows, and generated emission rates at an example hour (center) and consumed emission rates calculated using power flow tracing (right). In this example, transmission losses are ignored for simplicity.

Power flow tracing is demonstrated here on a simple network to build intuition about the process. The network is shown above, with three equally sized loads (each consumes 20 MWh in this timestamp) and three generators. There is one large wind generator W1 which generates 30 MWh, one fossil generator F1 which generates 20 MWh, and one smaller wind generator W2 which generates 10 MWh.

This network has one loop. Loops are common in transmission networks (although not in distribution networks) because they increase reliability.

For purposes of simplicity in this example, the network is simplified in a few ways:

- One hour-long interval is shown, with all power given in units of MWh. In the MISO implementation, CarbonFlow™ runs on five-minute interval data.
- The example network has only lines, buses, loads, and generators; real networks may also have transformers, DC lines, and other resources.
- The network has no losses. This does not change the calculation; rather, it simplifies the understanding of the results.

From looking at the network, it is possible to intuit some characteristics of the consumed emissions estimates of each load. Starting at the top of the network, the only power delivered to Bus 1 is from a wind generator. Since Load 1 receives power from Bus 1, it will consume only wind power and will have a consumed emission rate of 0 lbs/MWh. Bus 2 is a more complicated case: it receives wind power from Bus 1, but also fossil power from a generator as well as a mix of power from Bus 4. Load 3 will receive more wind power than Load 2, since Load 3 is closer to the wind power injected at Bus 3 and Load 2 is closer to the fossil power injected at Bus 2. To calculate the exact emission rates at Load 2 and Load 3, a system of equations is needed to describe the power flows through the system.

To describe the system, the assumptions introduced at the top of this section are used:

- Emissions from all power delivered to a bus are evenly mixed.
- Emissions entering a bus equal emissions leaving a bus.
- The emission rate of power entering a line is the same as the emission rate of power leaving the line.
    - In a network with losses, this means that the losses have the same emission rate as delivered power.

These rules let us write an equation describing the emission rate of the power at each bus:

- Let b_1, b_2, b_3, and b_4 represent the emission rate of power at each bus in lbs CO_2/MWh
    - At Bus 1, there is 30 MWh of power flowing out of the bus with emission rate b_1 and 30 MWh flowing into at the bus with an emission rate of 0:
        - (30 MWh)*(b_1 lbs/MWh) = (30 MWh)*(0 lbs/MWh)
    - At Bus 2, there is 35 MWh of power flowing out of the bus with emission rate b_2, 10 MWh flowing into the bus with an emission rate of b_1, and 5 MWh flowing into the bus with emission rate b_4. There's also 20 MWh flowing in from generator F1 with an emission rate of 1000 lbs/MWh. Dropping units and putting bus flows on the left and generator flows on the right, this is:
        - -10*b1 + 35*b2 - 5*b4 = 20*1000
- The same balance for buses 3 and 4 is as follows:
        - -15*b2 + 25*b3 = 10 * 0
        - -5*b3 + 5*b4 = 0

This gives us the following four equations with four unknowns:

$$30 \cdot b_1 = 0$$
$$-10 \cdot b_1 + 35 \cdot b_2 - 5 \cdot b_4 = 20{,}000$$
$$-15 \cdot b_2 + 25 \cdot b_3 = 0$$
$$-5 \cdot b_3 + 5 \cdot b_4 = 0$$

Solving these gives:

b_1 = 0 lbs/MWh
b_2 = 625 lbs/MWh
b_3 = 375 lbs/MWh
b_4 = 375 lbs/MWh

With these emission rates in hand, it is possible to analyze the total emissions generated and consumed in the system. As expected, Load 1 has zero emissions because it consumes only wind, Load 2 has the highest emissions because it is closest to the fossil generator, and Load 3 has intermediate emissions. The total generated emissions is (20MWh)*(1000 lbs CO_2/MWh) = 20,000 lbs. The total consumed emissions is also 20,000 lbs:

20 MWh * b_1 = 0 lbs at load 1
20 MWh * b_2 = 12500 lbs at load 2
20 MWh * b_3 = 7500 lbs at load 3

Note that if this system had losses, the emissions of lost power would also need to be considered to balance total generated and consumed emissions.

To solve larger, more complex systems, the same approach can be formulated using matrix notation and solved using standard linear algebra techniques.

Mathematical Formulation

This formulation closely follows that of Kang et al. (2015), with some notation changes for clarity.[6]

Assume a network with K generators and N buses. Matrices are defined to describe generation, generated emissions, and power flows through each network bus, as follows:

E_G is the emissions intensity of each generator, where each element E_{Gi} is the intensity (CO2/MWh) from generator *i*.

P_G is an NxK matrix describing generation. It is defined element-wise as follows:

- For k in K generators and j in N buses, if k is connected to j and active power output is p, then $P_{Gjk} = p$
- Else, $P_{Gjk} = 0$

P_B is an NxN matrix describing power flows out of each bus. It is defined element-wise as follows:

- $P_{Bij} = p,\ P_{Bji} = 0$ if *p*, the active power outflow from i to j is non-zero
- Else, $P_{Bij} = P_{Bji} = 0$

Now P_N can be calculated using an NxN diagonal matrix describing the total power flowing into each bus, which is the column-wise sum of P_B plus the row-wise sum of P_G for each bus in N. In matrix notation, this is:

$$P_N = diag\left(\mathbf{1} \cdot \begin{pmatrix} P_B \\ P_G^T \end{pmatrix}\right)$$

Since the total emissions flowing into each bus must equal the total emissions flowing out of each bus, an equation can be written describing how nodal emission rates E_N (a row vector of length N) relate to the power flows into each bus (P_N), the power flow out of each bus (P_B), and the power and emission rate from each generator (P_G and E_G):

$$P_N E_N = P_G E_G + P_B^T E_N$$

Rearranging this gives the familiar linear algebra formulation of Ax=b:

$$(P_N - P_B^T) E_N = P_G E_G$$

which can be solved for E_N, the emission rate at each bus.

[6] Kang, C., et al . "Carbon emission flow from generation to demand: A network-based model.". IEEE Transactions on Smart Grid, 2015.

MISO Implementation of Power Flow Tracing

The formulation described above can be directly applied to data from MISO's State Estimator, which describes the topology of the system by listing the bus(es) connected to each component and the power flow into and out of each bus.

Because MISO's system is very large, a sparse representation of the matrix $P_N - P_B^T$ and sparse matrix inversion is used to solve for E_N.

HOURLY AGGREGATION OF OUTPUTS

Raw CarbonFlow™ outputs consist of five-minute, EP node-level estimates. These results are more granular than what most data users need, can be difficult to use, and can reveal confidential information. Estimates are aggregated to hourly, spatially averaged estimates for end users. In general, 12 five-minute intervals are aggregated for each hourly estimate, and anywhere from three to thousands of nodes are aggregated for each spatial aggregation. In the rare case when input data for an interval is missing, the remaining intervals are weighted evenly when aggregating to hourly estimates, regardless of the timestamps associated with each interval.

For an hour with intervals $t_1 \ldots t_n$(where n=12 for most hours since input estimates are at five-minute intervals) and nodes $i_1 \ldots i_M$in region R, hourly, regional rates are calculated as follows.

Input State Estimator data provides load in MW $l_{i,t}$ for each load in the network. Total load at a node i in MWh over the hour is calculated as the sum of the MW of load at i multiplied by the interval length in hours, where all intervals are given equal weight in the hour. Note that if an interval is missing, the remaining intervals are given equal weight; for example, if the 2:35 interval is missing, the remaining 11 intervals at 2:00, 2:05, etc. through 2:55 will each be assigned a length of 1/11 hours, or approximately 5.45 minutes. Mathematically, the total load at node i for an hour with n intervals is:

$$\overline{\mathbf{l}_i} = \sum_{t=1}^{n} \frac{l_{i,t}}{n}$$

For each interval t and load node i, CarbonFlow™ provides a vector of consumed rates $\mathbf{r}_{i,t} \in \mathbb{R}^N$ for each node i where N is the number of quantities of interest (CO_{2e}, non-CFE CO_{2e}, and each fuel category). Total consumed emission quantities over the hour are calculated by multiplying rate by load in MWh within each interval to calculate a total within each interval, then summing those totals over the intervals in an hour. As with load, each interval in the hour is weighted equally. The output of this calculation is a vector of consumed totals:

$$\overline{\mathbf{r}_i} = \sum_{t=1}^{n} \frac{\mathbf{r} \cdot l_{i,t}}{n}$$

SPATIAL AGGREGATION OF OUTPUTS

The hourly consumed emission quantities for each node can be aggregated to a rate for any given region R by summing the consumed totals over all load nodes in R and dividing by the total load over all loads in region R, as follows:

$$\mathbf{r}_R = \frac{\sum_{i=0}^{M} \bar{\mathbf{r}}_i}{\sum_{i=0}^{M} \bar{\mathbf{l}}_i}$$

EP node-level data can be aggregated to lower spatial granularities either based on its physical geographic location or based on its relationship to MISO-specific regions based on the Commercial model.

Geospatial Aggregations

CarbonFlow™ results are aggregated to two different geospatial resolutions based on the location of each EP node:

Aggregation	CP Node Classification for Aggregation
County	Each EP node is assigned to exactly one county based on the latitude and longitude of its station (see below for more on how stations are assigned latitude/longitude coordinates). The Census Bureau's 2018 county boundary shapefile in its maximum resolution(500k) is used to identify the county of each station.
State	Each EP node is assigned to exactly one state based on its county assignment.

Table 4: Description of CP node classifications for EP nodal aggregation.

Assigning Latitude and Longitude Coordinates to Stations

For spatial aggregations (counties and states), Singularity uses Geographical Information System (GIS) information about the MISO network to identify the location of the station belonging to each EP node. See the input data section for more details on how these station locations are assigned.

County Estimates

County-level data is calculated for counties located at least partially in the MISO footprint for which complete network model coverage is available. In some cases, counties may also contain data located in Tier 1 LBAs. Given the spatial granularity of MISO's network model, it is possible that some counties have no transmission node, meaning that those counties will have no data available. The list of included counties may change over time based on changes in station location mapping or MISO's network model. A full list of counties included within MISO's footprint is available upon request.

Caveats and limitations of county-level data: Counties were chosen as a way to represent the nodal carbon flow results without revealing sensitive data about node locations and also because counties are more recognizable by users than transmission nodes. However, MISO's view of the electrical grid stops at the transmission level. This means that MISO's data does not represent how power reaches end consumers through the distribution grid. This could affect the accuracy of county-level results in various ways:

- If the transmission substation serving a distribution network is located in one county, but the distribution network is located primarily in another county
- If end users in a county are served by a mix of distribution networks originating in and out of the county
- If there is no transmission substation in a county, no data will be available.

In larger metropolitan areas, aggregating the data from several counties could help address some of these limitations. Additionally, public resources like Open Infrastructure Map may in some cases provide insight into local distribution networks in a county.

State-Level Estimates

Emission rate estimates include 10 states which are entirely within the MISO footprint and its directly interconnected neighbors (tier 1 LBAs). Because MISO's operational boundaries do not follow state boundaries, most states in the MISO footprint contain at least a small amount of non-MISO load or generation. MISO's network model includes most of the eastern interconnect, although data quality deteriorates with distance from the MISO footprint. In general, MISO has high quality data on directly interconnected or "Tier 1" LBAs. Data quality may be lower in states with a higher fraction of non-MISO load.

MISO States	Complete network model coverage	% of retail electric sales in MISO*	% of load within MISO**	% of load in Tier 1 LBAs**
Wisconsin	Yes	100%	100%	0%
Minnesota	Yes	99%	99%	1%
Michigan	Yes	96%	96%	4%
Louisiana	Yes	93%	93%	7%
Iowa	Yes	93%	90%	10%
Arkansas	Yes	73%	77%	23%
Indiana	Yes	79%	76%	24%
North Dakota	Yes	46%	47%	53%
Mississippi	Yes	44%	45%	55%
Illinois	Yes	34%	35%	65%

Table 6: States within MISO and its directly interconnected neighbors, ranked by percentage of load within MISO and load in Tier 1 LBAs for assessing emission rate estimation.

**May 2023 External Affairs state-level report, retail electric sales in the MISO footprint from EIA861*

***Tier 1 LBAs are those directly interconnected with the MISO footprint. Load percentages based on one week of SE data from 10/1/2023-10/7/2023*

Commercial Aggregations

Commercial aggregations reflect regions based on commercial relationships in MISO's models, such as ownership or administrative regions. Generally, these relationships are mapped based on the local balancing area (LBA) that each EP node is mapped to in the commercial model. Further aggregations are then defined by the relationship of each LBA to LRZs, Subregions, or the MISO footprint.

All LBA aggregations are based on the "control area" mapped in MISO's commercial model. Control areas represent pseudo-ties, which may be different from the LBA territory in which the generator is located. These pseudo ties may exist due to joint ownership relationships or other contractual relationships between generators and LBAs. For example, for a resource that is physically in LBA 1 but pseudo-tied to LBA 2, the control area is LBA 2, so the resource will be aggregated to LBA 2 in CarbonFlow™ results. See MISO BPM 010 for details on the modeling of pseudo-tied EP nodes.

Aggregation	CP Node Classification for Aggregation
LBA (Local Balancing Area)	Each MISO EP node is assigned to exactly one LBA based on the Control Area assigned in the commercial model
LRZ (Local Resource Zone)	Each MISO EP node is assigned to exactly one LRZ based on its LBA and the LBA -> LRZ mapping
Subregion	Each MISO EP node is assigned to exactly one subregion based on its LRZ and the LRZ -> Subregion mapping
Footprint	Each EP node is identified as being in MISO if it belongs to a MISO LBA

The mappings between LBAs, LRZs, and MISO regions for all LBAs in MISO are as follows:

LBA	LRZ	Subregion	In MISO
DPC	1	North	Yes
GRE	1	North	Yes
MDU	1	North	Yes
MP	1	North	Yes
NSP	1	North	Yes
OTP	1	North	Yes
SMP	1	North	Yes
ALTE	2	Central	Yes
MGE	2	Central	Yes
MIUP	2	Central	Yes
UPPC	2	Central	Yes
WEC	2	Central	Yes
WPS	2	Central	Yes
ALTW	3	North	Yes
MEC	3	North	Yes

MPW	3	North	Yes
AMIL	4	Central	Yes
CWLP	4	Central	Yes
GLH	4	Central	Yes
SIPC	4	Central	Yes
AMMO	5	Central	Yes
CWLD	5	Central	Yes
BREC	6	Central	Yes
CIN	6	Central	Yes
HE	6	Central	Yes
HMPL	6	Central	Yes
IPL	6	Central	Yes
NIPS	6	Central	Yes
SIGE	6	Central	Yes
CONS	7	Central	Yes
DECO	7	Central	Yes
EAI	8	South	Yes
CLEC	9	South	Yes
EES	9	South	Yes
LAFA	9	South	Yes
LAGN	9	South	Yes
LEPA	9	South	Yes
EMBA	10	South	Yes
SME	10	South	Yes

Table 5: Mappings for LBAs, LRZs, and MISO regions within MISO.

Data Outputs

Four types of CarbonFlow™ outputs are provided for each spatial aggregation level (subject to any confidentiality limitations):

- **Consumed emission rate**: The consumed emission rate represents the carbon intensity (lb CO_2e / MWh) of electricity consumed at all load nodes in each spatial aggregation, based on flow tracing. It is calculated as the total consumed emissions divided by the total consumed MWh (load).
- **Consumed non-CFE (residual) emission rate**: While all CarbonFlow™ data is "location-based" data, non-CFE emission rates can be used as a reasonable proxy for residual mix emission rates (used for market-based accounting) when these are not available directly.[7] The non-CFE emission rate reflects the average consumed emission rate from all non-Carbon-Free (i.e., CO_2-emitting) generation sources consumed by a load. This is calculated as the sum of all consumed emissions divided by the sum of consumed load from non-CFE sources. Because the emission rate of CFE resources is 0 and the fraction of CFE resources plus the fraction of non-CFE resources must sum to one, non-CFE emission rate estimates are related to the overall emission rate estimate by the following equation: Non-CFE emission rate estimate = (Overall emission rate estimate) / (Fraction of power that is non-CFE). Non-CFE include natural gas, coal, oil, biomass, and waste to energy.
- **Consumed fuel mix percentage**: This represents the percentage of consumed load that is traced from the generation of each fuel type and represents the "power content" of consumed electricity.
- **Consumed emission total**: This value represents the total emissions mass (lb CO_2) to be allocated to loads in a given region based on power flow tracing.

A summary of the aggregations, temporal resolutions, and data release lags for each of these data outputs is described in the following table:

Aggregation	Coverage	Estimate type	Temporal resolution	Release lag	Confidentiality notes
County	All counties located entirely within MISO or partially in MISO as long as the remainder of the county is in Tier 1 interconnected LBAs	Emission rate	Hourly	Quarterly plus 1 month *	In some cases, it can be used to infer plant-level generation, which is confidential until the release of EPA CEMS data **
		Non-CFE (residual) emission rate	Hourly	Quarterly plus 1 month *	
		Fuel mix percentage	Hourly	Quarterly plus 1 month *	
		Emission totals	Not released	Not released	Can be used to infer county-level load totals, which are not otherwise public

[7] See "Guidance for Calculating Residual Mixes," by the Center for Resource Solutions (CRS), 2024.

State	All states located entirely within MISO or partially in MISO as long as the remainder of the state is in Tier 1 interconnected LBAs	Emission rate	Hourly	NRT	
		Non-CFE (residual) emission rate	Hourly	NRT	
		Fuel mix percentage	Hourly	NRT	
		Emission totals	Hourly	NRT	
LBA	All MISO LBAs	Emission rate	Hourly	NRT	
		Non-CFE (residual) emission rate	Hourly	NRT	
		Fuel mix percentage	Hourly	NRT	
		Emission totals	Pending final review **	Pending final review **	See footnote**
LRZ	All MISO LRZs	Emission rate	Hourly	NRT	
		Non-CFE (residual) emission rate	Hourly	NRT	
		Fuel mix percentage	Hourly	NRT	
		Emission totals	Pending final review **	Pending final review **	Because some LRZs contain fewer than four LBAs, they are not sufficiently aggregated to protect potentially sensitive LBA data **
Subregion	All MISO Subregions	Emission rate	Hourly	NRT	
		Non-CFE (residual) emission rate	Hourly	NRT	
		Fuel mix percentage	Hourly	NRT	
		Emission totals	Hourly	NRT	

Footprint	MISO footprint	Emission rate	Hourly	NRT	
		Non-CFE (residual) emission rate	Hourly	NRT	
		Fuel mix percentage	Hourly	NRT	
		Emission totals	Hourly	NRT	

Table 7: List of consumed emission estimate data points to be released, with spatial aggregations, temporal resolution, and report timing. NRT indicates near real-time data, released within two hours of the start time.

** See details in the public data release timing section*

*** The confidentiality status of LBA-level load data, published at a higher resolution and/or shorter lag time than what the LBAs report to EIA-861, is currently under internal MISO review. This review will determine the temporal resolution and lag time of the data that MISO can publish.*

PUBLIC DATA RELEASE TIMING

The earliest time that any hourly consumed emissions estimates are posted is 20 minutes after each hour. MISO exports a snapshot of State Estimator results for CarbonFlow™ every five minutes, at the close of each market interval. These files are received 5-10 minutes after the time represented by the State Estimator snapshot. The CarbonFlow™ pipeline, including processing and validation steps, takes approximately five minutes. After all snapshots have been received and processed for a given hour, a further processing step aggregates the five-minute snapshots to hourly totals, which takes up to an additional five minutes.

Certain data outputs are further lagged due to market sensitivity or data confidentiality concerns. These data lags are described in the following section on confidentiality.

ENSURING CONFIDENTIALITY OF SENSITIVE DATA

Some consumed emissions estimates at the most granular levels can be used to reveal information that is market-sensitive (i.e., could be used to manipulate wholesale energy markets) or confidential (i.e., pertaining to specific MISO market participants). Confidential and sensitive data can sometimes be published if it is sufficiently aggregated, or if its release is lagged until the data is published by external sources or is otherwise no longer sensitive. Generally, confidential data is sufficiently spatially aggregated if it contains data from four or more market participants or assets.

The following sections describe several types of sensitive data and how this data is protected.

Generally, granular load and generation data are considered confidential unless otherwise published. Although no CarbonFlow™ data outputs explicitly include load or generation data, information about load or generation can sometimes be inferred. For example, publishing both emissions totals (lb CO_2) and emission rates (lb CO_2 / MWh) enables the calculation of load through simple division of these two numbers.

Nodal Load Data

CarbonFlow™ results are calculated for every load bus in the MISO network model but are only released at aggregations over many nodes within the MISO footprint. Counties can sometime contain only a single node, so county-level emissions totals are not published.

Nodal Generation Data

CarbonFlow™ consumed emissions estimates represent the carbon intensity of electricity consumed by loads within a given aggregation (e.g., county or LBA). This is in contrast to generated emissions estimates, which represent the carbon intensity of electricity generated by a generator. The load-based carbon intensity is based on a mix of the carbon intensities of all generators that are "upstream" of the loads in the transmission network, based on power flows. In most cases, this will be a mix of dozens of individual generators, making it impossible for precise information about any specific generator (for example, the exact generation level of a generator) to be reverse engineered.

However, a load node located close to a large plant can sometimes be served entirely by generators at that plant. In these cases, the emission rate (for fossil generators) or fuel mix fraction (for all generator types) at that load node may be highly correlated with plant generation. Plant generation can be a single EP node (for single-generator plants) or multiple EP nodes, but in either case, it is sensitive data that should not be available in near real-time.

For aggregation levels other than counties, where many loads across a large spatial area are aggregated together, there is no risk of backing out this nodal generation information. However, some counties aggregate only three or more nodes closely clustered in space, which may all be dominated by a single plant's generation. In these cases, emissions rates are highly correlated with a generator's operating level.

To preserve confidentiality of plant-level generation, county-level data is lagged until hourly, generator-level data is published in other public datasets.

All emitting generators of at least 25 MW capacity are required to submit hourly generation and emissions to the EPA on a quarterly basis, at which point MISO considers this data to no longer be confidential or sensitive. This hourly data is published once per quarter, one month after the end of the quarter. Thus, county-level data is published on the same schedule: May 1 for Jan - March estimates, Aug 1 1 for March - June estimates, November 1 for July - September estimates, and Feb 1 for October - December estimates.

Power Flow Data

CarbonFlow™ analysis uses as inputs the topology of MISO's network and the time-varying status of components within the network, which are sensitive data. Data about power flows across specific transmission lines is not published.

LBA Load Data

Across the U.S., LBA-level load data is widely published (including at high temporal resolutions in near real time), so it is not believed that this data is inherently sensitive or confidential. All utilities (LBAs) are required to report their annual total load to EIA each year (EIA form 861). In addition, EIA selects a representative sample of investor-owned utilities from the submitters to report monthly load data throughout the year (EIA form 861M) on a two-month lag. MISO consulted with additional member LBAs via the stakeholder forum Balancing Authority Committee and aligned upon releasing LBA data on a two-month lag. Additionally, several other ISOs in the U.S. publish hourly-resolution, utility-level data in near real time through EIA Form 930 (the Hourly Electric Grid Monitor). While all states and subregions in MISO contain four or more LBAs, certain LRZs contain fewer than four LBAs. Thus, the lag for LBA-level data will also apply to the release of LRZ-level data.

Future Enhancements

While the CarbonFlow™ data has undergone substantial review and validation, the data inputs represent a highly complex system, and errors are possible. CarbonFlow™ outputs are consistent with existing data, based on results of benchmarking with other data sources.

Additionally, several methodological enhancements are planned to continue improving data quality and the value of emissions estimates outputs over time, as outlined below:

Storage flow tracing: Currently, CarbonFlow™ assigns an emission rate of 0 to storage discharge. However, just as power can be traced across space, power can also be traced through time when it is stored by energy storage resources. In the future, storage flow tracing will be implemented to assign emissions to storage discharge based on the emissions of the electricity used to charge the energy storage.

Mapping improvements: Mapping refinements of network model nodes to EIA generators and geographic locations will continue, including improvements of "unknown" fuel types in the network model.

Calculating hourly data when missing intervals: In hours when one or more five-minute intervals are missing data, hourly totals are calculated by equally weighting the data from each five-minute interval. However, this approach assumes that the missing data will reflect the average of all known intervals in an hour. However, it is more likely that the missing data will be better reflected by a linear interpolation between known values on either side of the missing interval.

County-level data for counties without transmission nodes: Certain counties do not have transmission nodes modeled in the network model. This does not mean that no power is served in this county, but perhaps that load in a county is served by a transmission node in a neighboring county. Attempting to identify these relationships at the sub-transmission level could help improve data coverage.

Glossary

Active power: Power in an electrical system that does work. Measured in Watts (or kW, MW, and GW for larger quantities). This is the type of power that is assigned emissions and traced to loads in CarbonFlow™.

Apparent power: Power in an electrical system is calculated by multiplying root mean square voltage by root mean square current. This includes both active and reactive power, where reactive power is the power associated with the alternation of current direction in an AC system. Only the active power component of apparent power is assigned emissions and traced to loads in CarbonFlow™.

AR: Assessment Report (from the IPCC). Each successive version of the report has a corresponding number.

Balancing Authority: An organization responsible for reliably operating a portion of the transmission grid. MISO is a Balancing Authority.

Bus (network component): A connection point between components (e.g., lines, transformers, loads, and generators) in an electrical system. A system contains many buses.

CarbonFlow™: Technology for calculating spatially granular (nodal), temporally granular (hourly) data regarding the fuel mix and emissions estimates associated with electricity consumed by loads, based on the power flows of the transmission network.

Census Bureau Boundary Files: Shape files produced by the Census defining counties and states. Used here to assign substations to counties based on latitude and longitude data.

CFE: Carbon Free Energy. Energy generated by a resource that emits no direct GHG emissions from fuel combustion. This includes hydro, geothermal, nuclear, solar, and wind.

Consumed Energy / Electricity: Refers to electricity consumed by demand within the network.

Commercial Model (also MISO Commercial Model or CM): Model describing MISO's market system.

CH_4: Methane

CO_2: Carbon dioxide

CP Node: Commercial pricing node. A MISO-market construct representing a market participant.

EIA: Energy Information Administration. This agency collects, analyzes, and disseminates energy information to inform policy making, efficient markets, and public understanding of energy and its interaction with the economy and the environment.

EIA Hourly Electric Grid Monitor (also EIA-930): Energy Information Administration website where users can download and visualize data describing the near-real-time behavior of the electrical grid, including generation mix and power transfers. Data is provided at the Balancing Authority level at an hourly granularity.

EMS: Energy Management System: A system of computer-aided tools used by operators of electric utility grids to monitor, control, and optimize the performance of the generation or transmission system.

Emission transfers: Emissions estimates associated with power transferred across a boundary; for example, emissions estimates associated with power transferred from PJM to MISO across the seams connecting MISO and PJM.

Energy Attribute Certificate (EAC): Certificate describing legal ownership of attributes of power (often renewable generation). Often used to meet market-based clean energy procurement goals or state-mandated RPS standards.

EPA: Environmental Protection Agency. This agency develops and enforces regulations, gives grants, studies environmental issues, and publishes information for the purpose of protecting human health and the environment.

EP Node: Elemental pricing node. Represents the fundamental unit of analysis in the network model.

Fuel mix: Fuel categories used to create the power generated in a region (for a *generated* fuel mix) or serving a region or load (for a *consumed* fuel mix). Can be represented either as total MWh of each fuel category, in which case it sums to total generation or load, or as fractions, in which case it sums to 1.

Generator (network component): A resource that serves energy to the electricity grid; for example, a solar farm or a turbine at a combined cycle natural gas plant.

GHG: Green House Gas(es). Gases in the earth's atmosphere that trap heat.

GIS data: Geographic Information Services data. In this project, the most important GIS data is coordinates (latitude and longitude) for transmission substations.

GWP: Global Warming Potential. Measure of how much infrared thermal radiation a greenhouse gas added to the atmosphere would absorb over a given time frame, as a multiple of the radiation that would be absorbed by the same mass of added carbon dioxide. GWP is 1 for CO_2.

Gross generation (see also net generation): Power generation at a generator or plant before accounting for any loads at the plant (sometimes called house loads, station loads, or parasitic loads).

Heat rate curve (HRC): Curve describing how the heat rate of a generator (power output per unit of fuel consumption) changes with generation level.

House load (also called auxiliary load, station load): Load located at a generator or power plant. House loads generally consume power produced by the plant, decreasing the power delivered to the transmission grid. During startup, shutdown, or other times of very low generation, house loads can consume more than the gross generation of the generator/plant, so power is drawn from the grid during those times.

Interchange Distribution Calculator (IDC): Tool used to compute the distribution of energy interchange between sources and loads in power systems.

IPCC: Intergovernmental Panel on Climate Change. This group is the United Nations' body for assessing science related to climate change.

Kubernetes cluster: Distributed computing infrastructure.

LBA: Local Balancing Authority. Small (sub-state, sub-region) areas used within MISO for operating sections of the MISO grid.

lbCO2/MWh: Increment of emission rate measurement.

Load (network component): An EP node that typically consumes power. In some cases (e.g., behind-the-meter generation), a load-type node can inject power into the grid.

Location-based consumed emissions: Emissions-accounting methodology that uses the location of a load to determine the mix of resources and emissions used to generate the power that served the load. It is one of two attributional emissions accounting approaches along with market-based emissions.

Manitoba Northern Collection System (MHEB): Canadian utility interconnected with MISO at the northern US border, which is dominated by hydro generation. MHEB usually exports power into MISO.

Matrix: A way to formulate linear problems for convenient manipulation and solving.

Market-based consumed emissions: Emissions-accounting methodology that uses the power and REC (Renewable Energy Certificate) contracts of a load to determine the emissions for which the load is responsible. It considers contracts instead of grid physics. It is one of two attributional emissions-accounting approaches along with location-based emissions.

N_2O: Nitrous oxide

Net generation (see also: Gross generation): Power generation at a generator or plant after removing power consumed by any loads at the plant (which are sometimes called house loads, station loads, or parasitic loads).

Network model (or MISO Network model): Power system model of MISO and surrounding territories, maintained by MISO and used for many applications, including as an input to state estimation. See MISO Modeling BPM for more details.

non-CFE: non-Carbon Free Energy. Energy generated by a resource that emits GHG emissions from fuel combustion. This includes biomass/gas, natural gas, coal, petroleum, and waste-to-energy.

Open Grid Emissions (OGE): Singularity Energy's Open Grid Emissions is a peer-reviewed, open-source initiative that seeks to fill a critical need for high-quality, easily accessible, hourly grid emissions estimates for GHG accounting, policymaking, energy attribute certificate markets, and academic research.

Power Flow Tracing: Methodology used to assign attributes of power generation to the loads which consume that power.

PSS/E: GE tool used for power system modeling and simulation.

PyPSA: Python tool for power system modeling and analysis.

Residual mix emission rate. Represents the emissions and generation that remain after certificates, contracts, and supplier-specific factors have been claimed and removed from the calculation. This term is sometimes confused with the "standard delivery mix" which is the mix that a standard ratepayer in a utility territory receives. In contrast, the residual mix is an accounting tool that is used to assign emissions to unspecified imports/transactions, or to null power. The residual mix may also be used by end consumers reporting their scope 2 market-based emissions inventory if a utility-specific emission factor (generally the standard delivery mix) is not available.

Supervisory Control and Data Acquisition (SCADA): Real-time data measurement tool used by utilities and grid operators to monitor grid status. Data from SCADA systems feeds into the State Estimator.

State Estimator (SE): Calculation that takes measured data on some power system components and finds a consistent system state across all system components.

Station (network component): In MISO's network model, a transmission system substation. The most granular available latitudinal/longitudinal data is available at the station level.

Tier 1 LBAs: Largest utilities / grid operators directly interconnected with MISO's system.

Transformer (network component): Power system feature that changes power voltage, e.g., between a high voltage, long-distance line and a lower voltage line that feeds into the distribution system.