CLIMATE TRACE

Marginal Build Emissions Rates (MBERs) for electricity

The Climate TRACE coalition has developed and maintains free global hourly Build Margin data, also known as MBERs, that are compliant with the Greenhouse Gas Protocol's Project Protocol electricity sector guidance, Guidelines for Grid-Connected Electricity Projects ("GHGP Guidelines").

This document contains the data and documentation. All data are free and provided without license restrictions. The methodology is open and can be reproduced by anyone, as detailed below.

What is a MBER?

MBER data are one form of marginal emissions data that measure the causal effect of an electricity sector action on emissions. They are expressed in kilograms of emissions reduced (or induced) per megawatt-hour of net electricity demand reduced (or induced) at a particular place and time. The action may therefore be anything that affects the quantity, time, or place of net electricity demand--whether that is consuming, conserving, generating, storing, load shaping, or transmitting electricity.

Specifically, MBERs estimate the change in emissions from how an action affects how much of which type of new power plants get *built*. When combined with MOER data, which estimate the change in emissions from how an action affects how existing power plants *operate,* the two can jointly produce an estimate of the total consequential effect of an action, aka the long-run marginal emissions rate. For more details, see the GHGP Guidelines or this related white paper from the ZEROgrid initiative.

Data download

Climate TRACE currently provides MBERs from Jan 1, 2020 onwards for a total of 271 power grid regions worldwide.

Hourly MBERs

For 189 grid regions that comprise 98% of global electricity demand, data are provided at the hourly level.

Annual MBERs

For the first release, a number of smaller grid regions totaling 2% of global electricity demand are currently provided at the annual level only.

The annual data is in 1 csv file and the hourly data is in 1 csv file per balancing authority. The balancing authority in the US is prefixed with "USA-" and the non-US are just the country's 3 letter code. All MBERs are based on the 20% threshold. Pumped hydro and battery storage are not considered as generation sources so do not count in MBERS.

Grid region information

Following the GHGP Guidelines, data are aggregated to the balancing authority level unless there are specific reasons to define a grid region differently. Note that most countries have exactly one balancing authority, while some have more--most notably the United States which has dozens. Finally, grid regions in the data downloads are represented by their 3-7 letter abbreviations, which can be mapped to descriptive names using this file.

Model validation

Model validation can be found here.

Future work

Climate TRACE will continue to expand, maintain, and improve MBER data going forward. The next improvement scheduled is to expand the availability of hourly MBERs to all grids worldwide

Marginal Build Emissions Rates (MBERs) methodology overview

The first globally harmonized MBERs dataset was developed by the UNFCCC using a methodology that follows the GHGP Guidelines. (That UNFCCC dataset is available here.) This dataset extends the same methodology to higher spatial and temporal granularity.

The core idea of the algorithm is to use the weighted average emissions rate of the last 20% of power plants that a power grid actually did build as an observable proxy for what type of power plants a grid is most likely build next in response to any increases in net demand.

Specifically that algorithm is to:

1. Assemble a dataset of all power plants in a selected grid for a given operating period (hourly or annual). This dataset must include unit start year, capacity, generation or capacity factor, and CO_2 emissions or emissions factor.
2. For each cohort of units with the same operation and start year in the grid and time period: sum the generation and CO_2 emissions.
3. Ordering units from newest to oldest start year, determine the minimum number of consecutive of years that represents at least 20% of the total grid generation and during which at least 5 units began operating.
4. For these years, sum the generation and the emissions and calculate the MBER as the emissions divided by generation.

For greater detail of this process, see the two examples below, which demonstrate the full calculation of both annual and hourly MBERs for the CISO grid in the USA.

Key data sources for each model input:

- The unit inventory of all power plants is created by combining data from Global Energy Monitor's Global Integrated Power Tracker with the US Energy Information Administration's (EIA) Preliminary Monthly Electric Generator Inventory.
- Annual estimates of country demand and fuel specific annual capacity and generation by fuel type were derived from the EIA's International Electricity dataset and EMBER's Yearly Electricity Data. Additional plant specific annual generation for the US was sourced from EIA's EIA-923.
- Data to disaggregate the annual generation to hourly globally was predicted with internal demand and fuel specific generation models that use the above estimates combined with European Centre for Medium-Range Weather Forecasts' ERA5 weather datasets as inputs. Power grid specific hourly generation by fuel type from EIA's Hourly Electric Grid Monitor were used where available for US grids hourly disaggregation.
- The unit specific carbon intensity was predicted with the Climate TRACE Power sector's carbon intensity model.

The balancing authority country 3 letter alpha codes are taken from Climate TRACE and are based on ISO 3166. In the US, the balancing authority codes are a "USA-" prefix followed by

the code described in the EIA Hourly Electric Grid Monitor's List of Balancing Authorities
Note: Calculations currently exclude energy storage and pumped hydro.

Example calculations

Example 1. Annual MBERs for CISO balancing authority

Following the steps above, one can calculate the annual MBER value for the CISO BA, in the United States, which covers most of California:

1. Assemble a dataset of the operating units of power plants in a selected grid for a given operating period (hourly or annual).

operating_year int64	ba_code varchar	start_year int64	plant_id int64	generator_id varchar	energy_source_simplified varchar	capacity_mw double	ci double	cf double	mwh double
2023	CISO	1985	56036	GEN1	rest	2.2	964.5	0.145	2797.9
2023	CISO	1986	10091	GEN1	rest	9.9	964.5	0.145	12590.7
2023	CISO	2014	58308	4	solar	1.0	0.0	0.208	1820.2
2023	CISO	2023	67179	19038	solar	2.4	0.0	0.208	4368.4
2023	CISO	2017	62689	HFARM	solar	2.2	0.0	0.208	4004.4
2023	CISO	1986	7450	1	gas	27.4	449.4	0.307	73708.3
2023	CISO	1964	315	5	gas	495.0	513.6	0.307	1331591.3
2023	CISO	1975	286	U11	rest	110.0	0.0	0.145	139896.2
2023	CISO	1931	287	H2	hydro	26.7	0.0	0.46	107624.4
2023	CISO	1989	10206	GEN2	gas	5.2	449.4	0.307	13988.4
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2023	CISO	2017	62703	EQ13A	gas	1.8	449.4	0.307	4842.2
2023	CISO	2017	60981	WS526	solar	20.0	0.0	0.208	36403.7
2023	CISO	2014	58757	UH2	solar	1.5	0.0	0.208	2730.3
2023	CISO	1990	10446	GEN1	solar	92.0	0.0	0.208	167457.0
2023	CISO	2002	55807	HPP1	gas	49.0	449.4	0.307	131814.1
2023	CISO	2013	58148	KS	solar	20.0	0.0	0.208	36403.7
2023	CISO	2012	58169	KHS	solar	0.3	0.0	0.208	546.1
2023	CISO	2013	58430	CSE3	solar	34.2	0.0	0.208	62250.3
2023	CISO	2015	57245	S026A	solar	0.5	0.0	0.208	910.1
2023	CISO	2015	57225	S011B	solar	0.5	0.0	0.208	910.1

2255 rows (20 shown)

Table 2. For subsequent calculations, one needs the following for each unit in the grid: operation start year (start_year in table above), capacity (capacity_mw), capacity factor (cf), and carbon intensity (ci), from which one can calculate the unit generation (mwh) and unit co2 emissions (co2).

2. For each cohort of units with the same operation and start year in the grid and time period: count the units and sum the generation and CO_2 emissions.

operating_year int64	ba_code varchar	start_year int64	cnt int64	mw double	mwh double	co2 double
2023	CISO	2023	47	2595.9	4803384.5	5247964.8
2023	CISO	2022	62	2285.8	4260207.2	96944589.4
2023	CISO	2021	82	1694.6	3377445.0	21425835.1
2023	CISO	2020	67	3350.4	7436573.3	1386065810.8
2023	CISO	2019	57	1243.6	2412767.6	106923270.6
2023	CISO	2018	82	1768.1	3963218.6	900979402.0
2023	CISO	2017	91	977.0	1991402.9	77668892.5
2023	CISO	2016	127	3377.4	6563702.0	640638147.3
2023	CISO	2015	152	1656.9	3242577.9	58886492.5
2023	CISO	2014	168	2898.6	5510490.7	155266045.6
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
2023	CISO	1910	4	12.8	51595.2	0.0
2023	CISO	1909	1	2.0	8061.8	0.0
2023	CISO	1908	3	10.5	42324.2	0.0
2023	CISO	1907	7	30.0	120926.3	0.0
2023	CISO	1906	1	2.0	8061.8	0.0
2023	CISO	1905	2	2.0	8061.8	0.0
2023	CISO	1904	2	2.0	8061.8	0.0
2023	CISO	1903	1	1.0	4030.9	0.0
2023	CISO	1902	1	1.0	4030.9	0.0
2023	CISO	1899	4	3.2	12898.8	0.0
103 rows (20 shown)						7 columns

Table 3. For each start year, cumulative count (cnt), cumulative sum of generation (mw) and cumulative sum of co2 emissions (co2) are calculated.

3. Ordering units from newest to oldest start year, determine the minimum number of consecutive of years that represents at least 20% of the total grid generation and during which at least 5 units began operating.

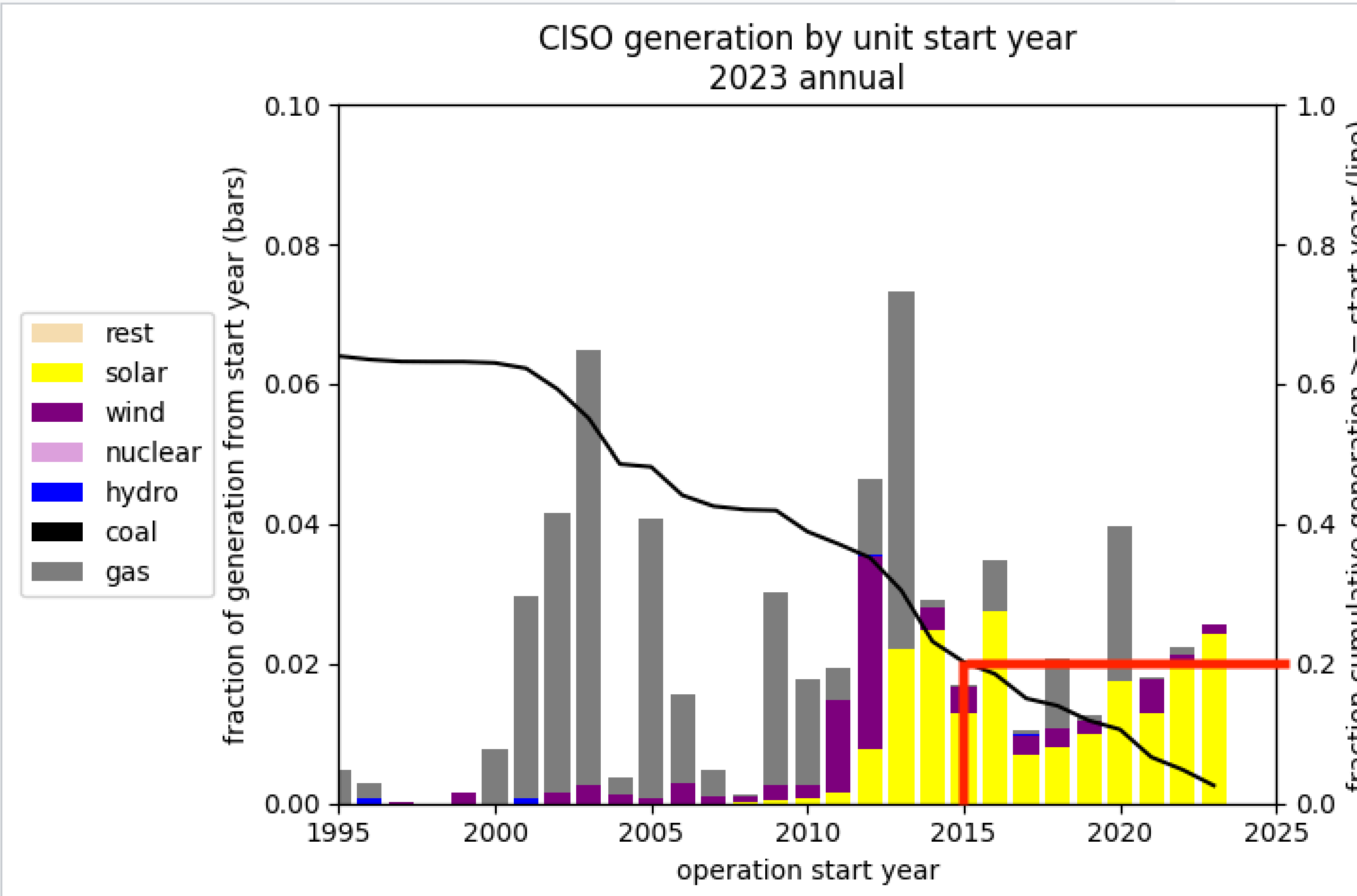

Figure 1. Overall CISO grid generation, by unit type and year. The bars represent the fraction of power generation relative to the entire CISO grid for units that began operation during that year (left y-axis), colored based on the fuel type. The black line represents the cumulative fraction of grid generation represented by units that began for each year beginning with the most recent year (right y-axis). Finally, the red horizontal line represents the point in which 20% of cumulative grid generation was reached moving backward in time from the present, which corresponds roughly to 2015. Therefore, the MBERs would be calculated using units that began during the years 2015 to present.

For this particular example, the MBER is 86.6 kg CO_2 / MWh (see below for full calculation). Expanding this time series backward for the same grid, we observe the transition of from non-renewables toward renewables in recent years:

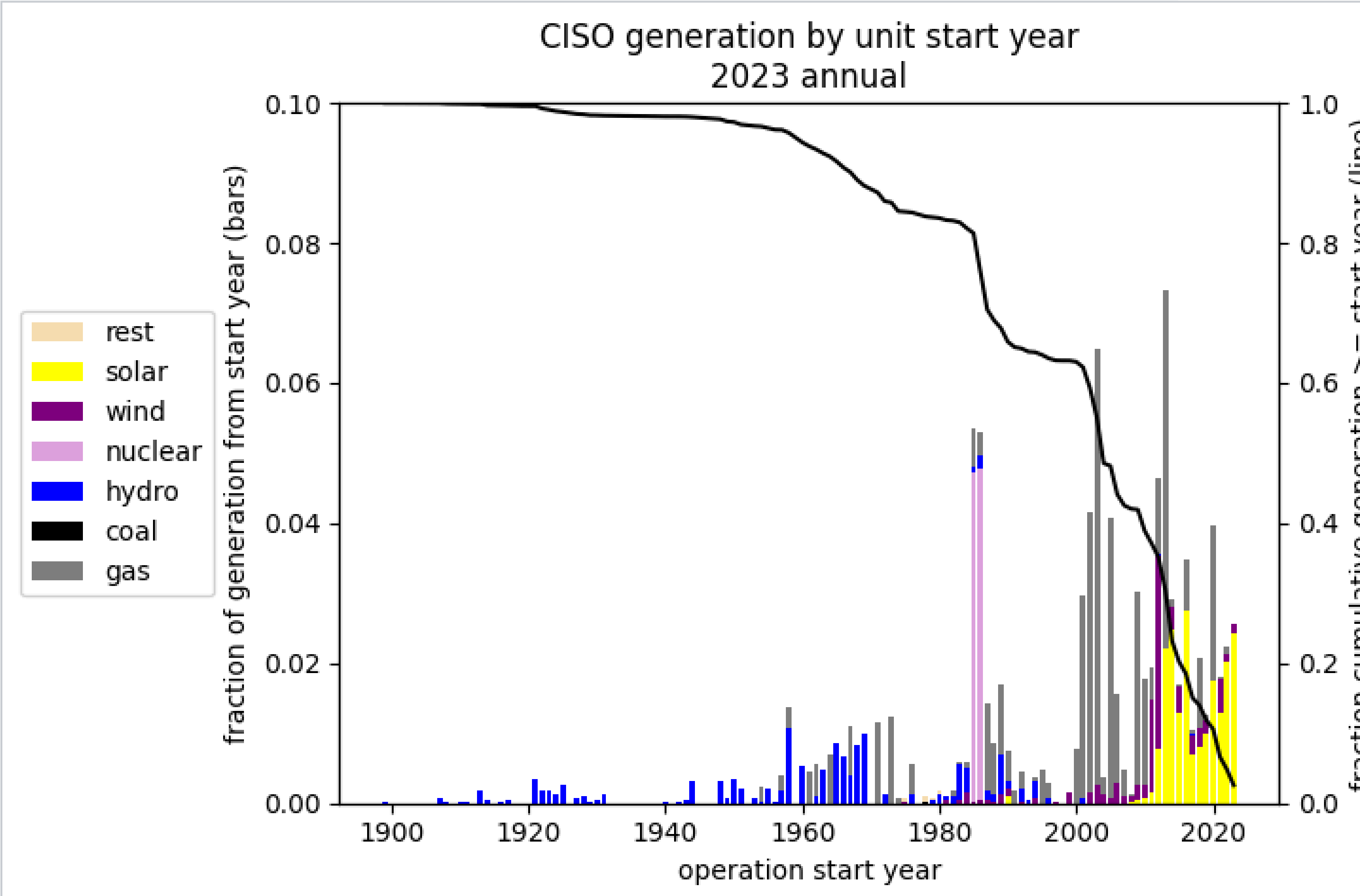

Figure 2. As Figure 1, with expanded time series to demonstrate the grid evolution.

We can also demonstrate this calculation in tabular form:

operating_year int64	ba_code varchar	start_year int64	cnt int64	mw double	mwh double	co2 double	cum_qty int128	cum_mw double	cum_mwh double	cum_co2 double	cum_mwh_frac double	gte_10 boolean	gt b
2023	CISO	2023	47	2595.9	4803384.5	5247964.8	47	2595.9	4803384.5	5247964.8	0.0256	false	fa
2023	CISO	2022	62	2285.8	4260207.2	96944589.4	109	4881.7	9063591.7	102192554.2	0.0482	false	fa
2023	CISO	2021	82	1694.6	3377445.0	21425835.1	191	6576.3	12441036.8	123618389.3	0.0662	false	fa
2023	CISO	2020	67	3350.4	7436573.3	1386065810.8	258	9926.7	19877610.0	1509684200.2	0.1058	true	fa
2023	CISO	2019	57	1243.6	2412767.6	106923270.6	315	11170.3	22290377.7	1616607470.8	0.1187	true	fa
2023	CISO	2018	82	1768.1	3963218.6	900979402.0	397	12938.4	26253596.3	2517586872.8	0.1398	true	fa
2023	CISO	2017	91	977.0	1991402.9	77668892.5	488	13915.4	28244999.2	2595255765.3	0.1504	true	fa
2023	CISO	2016	127	3377.4	6563702.0	640638147.3	615	17292.8	34808701.2	3235893912.5	0.1853	true	fa
2023	CISO	2015	152	1656.9	3242577.9	58886492.5	767	18949.7	38051279.1	3294780405.0	0.2026	true	t
2023	CISO	2014	168	2898.6	5510490.7	155266045.6	935	21848.3	43561769.8	3450046450.6	0.2319	true	t
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2023	CISO	1910	4	12.8	51595.2	0.0	2233	71035.3	187644266.9	35505429825.8	0.9988	true	t
2023	CISO	1909	1	2.0	8061.8	0.0	2234	71037.3	187652328.7	35505429825.8	0.9989	true	t
2023	CISO	1908	3	10.5	42324.2	0.0	2237	71047.8	187694652.9	35505429825.8	0.9991	true	t
2023	CISO	1907	7	30.0	120926.3	0.0	2244	71077.8	187815579.2	35505429825.8	0.9998	true	t
2023	CISO	1906	1	2.0	8061.8	0.0	2245	71079.8	187823640.9	35505429825.8	0.9998	true	t
2023	CISO	1905	2	2.0	8061.8	0.0	2247	71081.8	187831702.7	35505429825.8	0.9998	true	t
2023	CISO	1904	2	2.0	8061.8	0.0	2249	71083.8	187839764.4	35505429825.8	0.9999	true	t
2023	CISO	1903	1	1.0	4030.9	0.0	2250	71084.8	187843795.3	35505429825.8	0.9999	true	t
2023	CISO	1902	1	1.0	4030.9	0.0	2251	71085.8	187847826.2	35505429825.8	0.9999	true	t
2023	CISO	1899	4	3.2	12898.8	0.0	2255	71089.0	187860725.0	35505429825.8	1.0	true	t

103 rows (20 shown)

Table 4. In alignment with the previous two figures, the cutoff (red line) displays the operation start year for which the cumulative generation (cum_mwh_frac) reaches >20%, and includes at least five units.

4. For these years, sum the generation and the emissions and calculate the MBER as the emissions divided by generation.

operating_year int64	ba_code varchar	start_year int64	cum_qty int128	cum_mw double	cum_mwh double	cum_co2 double	cum_mwh_frac double	mber_k do
2023	CISO	2015	767	18949.7	38051279.1	3294780405.0	0.2026	

Table 5. Calculations of the annual CISO grid MBER (mber_kg_per_mwh) using the cumulative generation (cum_mwh) and emissions (cum_co2).

Example 2. Hourly MBERs for CISO balancing authority

A weakness of annual MBERs is that they cannot measure structural change related to timing. This limits their utility in analyses of the effects of load shifting, load shaping, and hourly matching. Thus, Climate TRACE developed what we believe to be the first dataset applying the default GHGP Guidelines for MBERs to the hourly level. An example of this is highlighted below for the CISO comparing MBERs for a typical daytime and nighttime hour.

Daytime CISO MBERs:

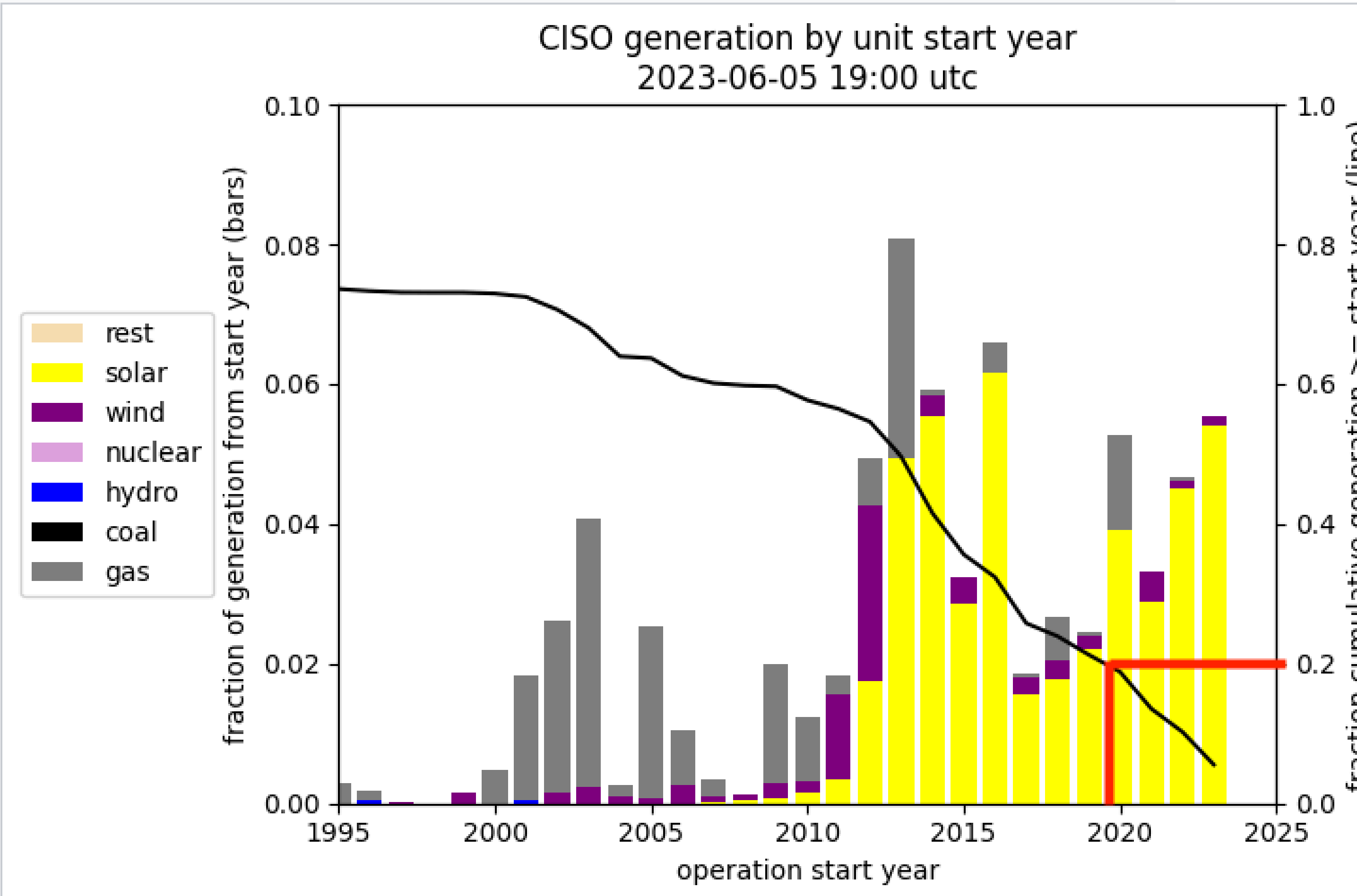

Figure 3. As Figure 1, but specifically for the daytime hour of 19:00UTC (11:00 local time).

CISO has seen such large deployment of solar in the last few years that during a typical daytime hour, the last 20% of generation built is almost entirely solar. The red box captures the last 20% of generation. The model is effectively estimating that any significant increase in daytime net demand in California in 2025 would likely largely cause more solar build. Following the steps above using only the hour of 19:00UTC, this leads to a MBER of 25.0 kg CO_2 / MWh.

However, California is well known for the infamous "duck curve" reflecting the fact that the grid's increasing dependence on solar is leading to different power conditions at different times of day. So, here we contrast the hourly MBER for a typical nighttime hour in CISO:

Nighttime MBERs:

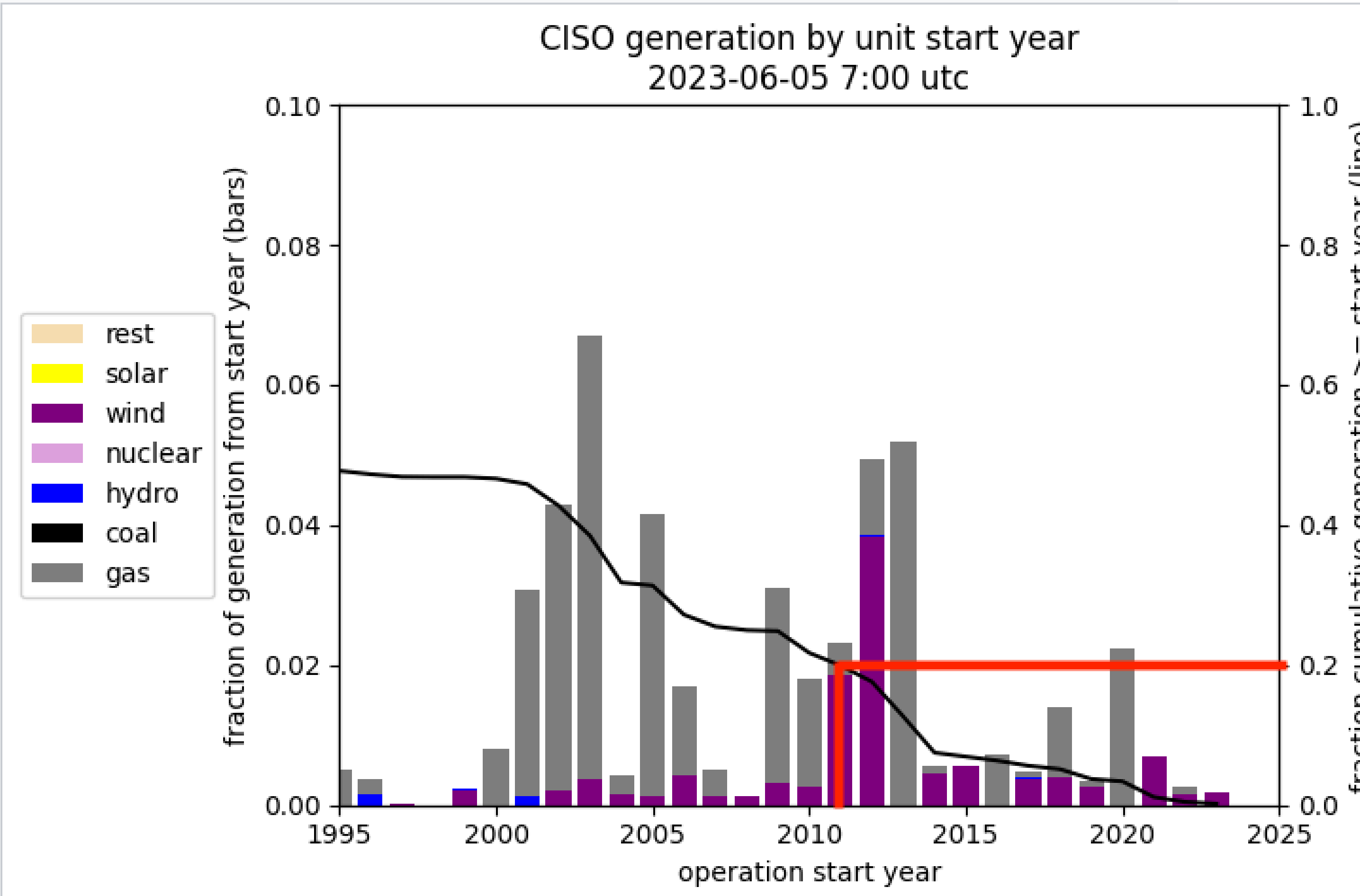

Figure 5. As Figure 3, but during the nighttime hour of 7:00UTC (23:00 local time).

In contrast to the daytime (Figures 3 & 4), the generation during the nighttime comes in large part from natural gas-powered units, many of which date back as far as 2010. While some carbon-free energy is available at night, largely from wind, the end result is a higher MBER than in the daytime. Specifically, a MBER of 228 kg CO_2 / MWh is calculated.

Conclusions

As demonstrated above, there is significant diurnal variability in the MBER for the CISO grid, with roughly an order of magnitude difference in the MBER at nighttime compared to daytime. These results stress the importance of considering the causal effect of timing of electricity load, generation, and storage on inducing structural change in power grids.

Because of rapid growth in solar in many grids worldwide, many grids similarly exhibit lower hourly MBERs during daytime than nighttime hours. However, in some power grids other temporal profiles exist; for example, in grids like SPP where wind build has outpaced solar build, when low MBERs occur is driven by patterns in wind speed rather than sun.

Current known model limitations and future plans

1. For grids totalling 2% of global electricity demand, MBERs are not yet hourly. Future work will expand this.
2. Biomass is currently treating as 0 emissions to measure life cycle, not direct emissions. Future versions will examine whether or not this is appropriate and update accordingly.
3. The GHGP Guidelines indicate one should aggregate in most cases to the area where the local authority has dispatch control (often known as the balancing authority). While for most countries there is one national grid operator, there are some countries with multiple grid operators active (i.e. CHN, USA, CAN, IND, RUS, and possibly VNM and BRA). For this version we were able to model USA balancing authorities. Future work will also separate out national MBERs for these other countries.
4. The GHGP Guidelines also indicated that for grids with very high imports or exports as a share of native generation, it may be appropriate to combine two or more balancing authorities. This is not currently implemented in the first MBER version. Future versions will explore this and implement as appropriate. In the meantime, a limited number of BAs with exceptionally high net imports or net exports have been excluded. This includes: PRY, LAO, USA-GRID, USA-SEC, USA-WWA, USA-SPA, USA-YAD, USA-GRIF, USA-CHPD, USA-AVRN, USA-GWA, USA-SEPA, USA-BPAT, USA-HGMA, and USA-DEAA.
5. The following BAs have significantly different fossil fuel capacities according to different sources, and have been excluded pending further analysis: AFG, CAF, ESH, GLP, GUF, IMN, KHM, LBN, MDA, MTQ, NGA, PSE, REU, SGN, SLE, URY.
6. There are a group of very small countries, e.g. the Vatican, where there is not sufficient data on annual demand or generation to make MBER estimates. These are: AIA, ALA, AND, ATA, ATF, BES, BLM, BVT, CCK, CUW, CXR, ESH, FSM, GGY, GLP, GUF, HMD, IMN, IOT, JEY, LIE, MAF, MCO, MHL, MNP, MTQ, MYT, NFK, PCN, PLW, REU, SCG, SGS, SJM, SMR, SXM, TKL, TUV, UMI, VAT, and WLF

Contact

The annual and hourly MBERs data are created and maintained by the Climate TRACE coalition of nonprofits, universities, and tech companies. The largest contributors to the coalition's electricity sector work are WattTime, Transition Zero, Global Energy Monitor, Pixel Scientia Labs, Planet Labs, and Georgetown University. For questions or more information about MBER data, contact `coalition@climatetrace.org` or visit our contact page here.