An open-source model of the Western Climate Initiative cap-and-trade program with supply-demand scenarios through 2030: Supplemental Information

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# Supplement to Section 1 (Introduction)

## “Covered emissions” and “non-covered emissions”

For both California and Québec, emissions subject to the cap-and-trade program with associated compliance obligations (“covered emissions”) (CARB, 2019a; Québec, 2019) are a subset of the economy-wide total emissions counted in each jurisdiction’s greenhouse gas inventory (CARB, 2019b; MELCC, 2018). Covered emissions are only for the gases CO2, CH4, and N2O, and only from specified activities.

Therefore, emissions of other greenhouse gases—“non-covered emissions,” including various high-GWP (global warming potential) gases such as HFCs—may be included in the jurisdiction’s inventories, but are not counted as covered emissions with associated compliance obligations. Non-covered emissions include emissions from sectors that are generally excluded from the cap-and-trade program, as well as some emissions from sectors that are generally subject to the cap-and-trade program. We address each in turn.

First, while most emissions of the gases CO2, CH4, and N2O are counted as covered emissions, emissions of these gases from certain activities are not counted as covered emissions. For example, most activities in the agricultural sector are excluded (e.g., CH4 from livestock).

Second, some emissions of the gases CO2, CH4, and N2O within so-called “covered sectors” (e.g., emissions from the industrial sector) are not counted as covered emissions. For example, under California’s Mandatory Greenhouse Gas Reporting Regulation (CARB, 2019a), various emissions of CH4 from oil and gas operations that are considered leakage are calculated; however in California’s cap-and-trade regulations (Cal. Code Regs., 2019), some of these leakage emissions are not regulated by the cap-and-trade program, and thus are not counted as covered emissions (see § 95852.2, “Emissions without a Compliance Obligation”).

Also, under California’s regulations, there are thresholds for the quantity of emissions of particular types per facility required for those emissions to be counted as covered emissions (and therefore to incur a compliance obligation). For example, under § 95101(e) for “Petroleum and Natural Gas Systems,” facilities are “required to report under this article when their stationary combustion emissions (including flaring) and process emissions equal or exceed 10,000 metric tons of CO₂e, or their stationary combustion, process, fugitive, and vented emissions equal or exceed 25,000 metric tons of CO₂e.”

Thus, the emissions that are counted as covered emissions within each jurisdiction depend on a complex set of rules that depend on the types of greenhouse gases emitted, the types of emitting activities, and the quantity of emissions per facility.

We calculate non-covered emissions as the total emissions that are counted in each jurisdiction’s greenhouse gas inventory for economy-wide emissions, minus covered emissions (that is, minus those emissions with associated compliance obligations).

## Figure 1 data sources

Data sources for Figure 1 are listed below, for: (a) Historical data for covered emissions and the supply of compliance instruments entering private accounts in the WCI program, and (b) Annual banking metrics, with the number of excess allowances and offsets held in private accounts (Private Bank) and the number of unsold allowances temporarily retained in government accounts (Government Holding Accounts). Details on the calculations are published elsewhere (Cullenward et al., 2019).

**Cap levels:**

* California, 2013-2030: Cal. Code Regs., 2019. tit. 17, § 95841(a).
* Québec, 2013-2020: Quebec Environment Quality Act (chapter Q-2), r. 15.2, <http://legisquebec.gouv.qc.ca/en/ShowDoc/cr/Q-2,%20r.%2015.2>
* Québec, 2021-2030: Quebec Environment Quality Act (chapter Q-2), r. 15.3, <http://legisquebec.gouv.qc.ca/en/ShowDoc/cr/Q-2,%20r.%2015.3>

**Covered emissions:**

* California: Mandatory Greenhouse Gas Reporting (MRR), available at <https://ww2.arb.ca.gov/mrr-data>.
* Québec: Verified and declared greenhouse gas (GHG) emissions of the establishments covered by the Regulation respecting a cap-and-trade (C&T) system for GHG emission allowances, available at <http://environnement.gouv.qc.ca/changements/carbone/documentation-en.htm>.

**Compliance obligations (incurred and satisfied):**

* California: annual Compliance Reports, available at <https://arb.ca.gov/cc/capandtrade/capandtrade.htm>.
* Québec: “Report on the 2013-2014 Compliance Period of the Québec Cap-and-Trade System” and “Report on the 2015-2017 Compliance Period of the Québec Cap-and-Trade System,” available at <http://environnement.gouv.qc.ca/changements/carbone/documentation-en.htm>.

**Supplies from free allocations:**

* California: Cap-and-Trade Program Allowance Allocation annual reports, available at <https://www.arb.ca.gov/cc/capandtrade/allowanceallocation/publicallocation.htm>.
* Québec: MELCC, “Quantité d’unités d’émission versées en allocation gratuite,” published Jan 14, 2019 at <http://environnement.gouv.qc.ca/changements/carbone/documentation-en.htm>. Earlier reports published for individual allocation years were saved from the MELCC website, and are available in the WCI-RULES repository (Inman, 2019).

**Supplies from auction sales:**

* California-only auctions and joint auctions: Quarterly Auction Summary Results Report, available at <https://www.arb.ca.gov/cc/capandtrade/auction/auction_notices_and_reports.htm>.
* Québec-only auctions: Auction of Québec Greenhouse Gas Emission Units: Summary Results, available at <http://environnement.gouv.qc.ca/changements/carbone/ventes-encheres/avis-resultats-en.htm>.

**Supplies from offset issuance:**

* Compliance Instrument Report (CARB, 2019c), available at <https://arb.ca.gov/cc/capandtrade/complianceinstrumentreport.xlsx>.

# Supplement to Section 2 (Methods)

## Global Warming Potentials (GWPs) used in regulations

Each WCI compliance instrument represents 1 tCO2e, with equivalence for the non-CO2 covered gases (CH4 and N2O) using 100-year global warming potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC). As established by California’s Mandatory Reporting Regulations (CARB, 2019a), California’s covered emissions up to 2020 use the 1995 IPCC Second Assessment Report GWPs (21 for CH4, and 310 for N2O), and California’s covered emissions from 2021 onward will use the 2007 IPCC Fourth Assessment Report GWPs (25 for CH4, and 298 for N2O). For Québec, covered emissions in all years are based on the 1995 IPCC Second Assessment Report GWPs (Québec, 2019).

## Voluntary Renewable Electricity (VRE) Program

California also has a Voluntary Renewable Electricity (VRE) Program. Approximately 7 M allowances from budget years 2013-2020 were set aside for the VRE program in a dedicated account; allowances that are transferred into the VRE account are permanently removed from circulation in the cap-and-trade program. No further removals of cap-and-trade allowances for the VRE Program are scheduled for future program years.

## WCI-RULES model framework and validation

Full documentation and code for the WCI-RULES model are available in the WCI-RULES repository hosted by the Open Science Framework (Inman, 2019), as well as on Near Zero’s Github page, <https://github.com/nearzero/WCI-cap-and-trade>. All results in this paper are from WCI-RULES version 1.1.

WCI-RULES is written in Python code, using only open-source libraries, principally:

* Pandas ([https://pandas.pydata.org](https://pandas.pydata.org/)), for handling and analyzing large data sets.
* Jupyter Notebook ([https://jupyter.org](https://jupyter.org/)), for organizing code and creating the user interface.
* Bokeh ([https://bokeh.pydata.org](https://bokeh.pydata.org/)), for creating interactive web graphics.

The model’s full name, WCI Regulations and Uncertainties for Lowering Emissions across Scenarios, refers to the detailed representation of the rules in regulations for the WCI system, and the uncertainties that can be explored through user-specified scenarios.

A full list of the libraries used, with particular version numbers, is in the WCI-RULES repository (Inman, 2019), in the file <environment.yml>.

## WCI-RULES historical data inputs

The model uses historical data on allocations, auctions, offset issuance, and transfers into and out of reserves to simulate all instrument transfers listed in public reports. Input data is drawn from a variety of publications issued by regulators in participating jurisdictions (Table S-1; full data sources in model documentation).

## Effects of Ontario’s linkage and de-linkage

The model also represents the effect of Ontario’s brief linkage with WCI in 2018, which led to a net flow of 13.2 M allowances to entities based in California and/or Québec, beyond the number of allowances issued by these two jurisdictions alone. Despite incomplete public reporting data, the net flow can be attributed to particular vintages of allowances (Mastrandrea et al., 2018). Attributing the net flow to particular vintages affects the calculation of banking metrics as used in this paper, since the metrics for a given year count allowances with vintages of that year and earlier.

In 2019, regulators retired allowances to compensate for the net flow of allowances from Ontario. The Compliance Instrument Report (CIR) (CARB, 2019c) for Q2 2019 stated: “On June 27, 2019, California retired an equal amount of vintages 2021 through 2030 for a total of 11,340,792 allowances. Québec retired 1,846,175 vintage 2017 allowances from the Auction Account on July 10, 2019.” (Note that Québec’s retirements occurred after July 5, 2019, the date at which a snapshot of the state of the market was taken for the CIR, so those retirements are not reflected in the Q2 2019 CIR.) WCI-RULES retires allowances from government holding accounts following regulators’ description above.

## Built-in projections

WCI-RULES relies on several built-in projections that cannot be modified through the model interface (although they could be modified in the model code). These built-in projections do not affect the total quantity of allowances that are in circulation. Thus, these projections have only a minor effect on other aspects of the performance of the program.

The quantities of allowances that California freely allocates to electrical distribution utilities and natural gas suppliers are pre-determined by regulations. California’s remaining allocations vary from year to year; they are primarily industrial allocations, which are determined based on equations in the regulations that adjust the levels based on industrial product output or energy consumption. Similarly, Québec’s allocations are based on equations established in regulations, and the quantities allocated vary from year to year.

For California’s variable allocations that are not pre-established by regulation (primarily, industrial allocations), WCI-RULES uses a forecast that CARB published as part of 2018 rulemaking to implement A.B. 398 (CARB, 2018a). In CARB’s forecast, variable allocations scale down in line with the state’s declining caps. We are not aware of a similar forecast from Québec regulators, so we adopted a projection that Québec’s allocations would similarly scale down in line with the province’s declining caps.

WCI-RULES also makes projections for quantities of allocations to utilities that are consigned to auction. In California’s program, electrical distribution utilities that are Investor Owned Utilities (IOUs) must consign 100% of their allocation to auction, making those allowances available for sale to other parties. Electricity utilities that are Publicly Owned Utilities (POUs) do not have to consign any of their allocation to auction, but may opt to consign some or all of their allocation. Natural gas utilities, whether IOUs or POUs, are required to consign a fraction of their allocation to auction; that fraction is established by regulation and rises from 25% in 2015 to 100% by 2030. California’s natural gas distribution utilities may opt to consign more than the required percentage to auction; however, to date, they have not consigned any significant quantities. WCI-RULES makes a projection for the quantities that California electricity POUs, projecting that the optional consignment percentage will be equal to the historical average for that category; for natural gas utilities, the projection is that optional consignment will be zero.

## Model validation: Comparison to CIR

The CIR aggregates totals across the participating jurisdictions, distinguishing instruments in various types of accounts (e.g., government holding accounts, private accounts, and retirement accounts), and also by allowance vintage or other type (APCR or Early Action non-vintaged allowance). While this data is detailed, changes in each account in a given quarter can reflect a number of market processes, including allocation distributions, auction sales, and surrenders for compliance.

While WCI-RULES represents all major flows of compliance instruments in the program, other one-time movements of instruments can occur that are not fully documented in public data and cannot be predicted by program rules. Examples include penalties for the late surrender of compliance obligations; transfers of allowances in private accounts back to the auction pool upon closure of an entity’s program account; and voluntary retirements of allowances, in which market participants choose to retire allowances without a corresponding compliance obligation being cancelled. Such movements could be responsible for observed differences between WCI-RULES and historical data.

WCI-RULES combines its results in a grouping similar to that of the CIRs, and the model results closely replicate the historical CIRs. Detailed comparisons of WCI-RULES results with the CIR data are in Table S-2 (for private accounts) and Table S-3 (for government holding accounts).

For Table S-2, values in Private Accounts are the sum of all holdings in Entity Accounts (labelled in the CIR as “General,” “Compliance,” and “Limited Use Holding Account (CA)”). Differences are CIR values minus WCI-RULES values; percentage differences are the difference divided by the CIR values. The mean absolute difference is calculated for only allowances of vintages ≤ 2018, the latest vintage that has come completely into normal circulation.

For Table S-3, values in Government Holding Accounts are for jurisdictions’ Allocation Holding Accounts and Auction Holding Accounts (labelled in the CIR as “Auction + Issuance + Allocation”). APCR allowances are those allowances assigned to the Allowance Price Containment Reserves per regulation; they do not include California state-owned allowances that, when unsold for > 24 months, transfer to the APCR. In Q2 2019, there were 52.4 M California allowances in government holding accounts which were designated for the APCR but had not yet been transferred to the APCR account as of the Q2 2019 CIR. Differences are CIR values minus WCI-RULES values; percentage differences are the differences divided by the CIR values. The mean absolute difference is calculated for only allowances of vintages ≤ 2018, the latest vintage that has come completely into normal circulation.

Relative to historical data in the Q2 2019 CIR (the latest CIR available as of this writing), the model has an excess of 2.70 M instruments in private accounts; a deficit of 1.77 M instruments in government holding accounts; and a deficit of 0.30 M instruments in retirement accounts. For Q2 2019, for vintages that have fully come into normal circulation (that is, vintages ≤ 2018), the maximum absolute difference between the historical CIR and the model results for any particular set of allowances is 0.82 M, which was for vintage 2019 allowances held in private accounts; that is a percentage difference of 0.3% for this set of allowances, of which there were 238 M in private accounts according to the CIR.

Across all quarterly comparisons of the model results with the CIRs, discrepancies for each set of allowances (e.g., vintage 2018 allowances in private accounts) are generally within 1% of the historical values; the exceptions are for sets of allowances in the CIRs with relatively small total quantities (< 10 M). Across all vintages of allowances that have fully come into circulation (that is, vintages ≤2018), allowances in private accounts and government holding accounts had absolute mean differences of 0.31 M and 0.18 M, respectively.

## Model validation: Comparison of banking metrics

WCI-RULES’s values for banking metrics (Private Bank, Government Holding Accounts, and Reserve Accounts) closely match values previously published based on the CIRs (Cullenward et al., 2019), as shown in Table S-4. For both Cullenward et al., 2019, and WCI-RULES, compliance obligations are based on compliance reports issued by each jurisdiction (see Section 1.2 above). Both sources adjust compliance obligations to account for permanently unfulfilled obligations— primarily due to the bankruptcy of La Paloma Generating Company, LLC, and a known late surrender from Mexico’s Comisión Federal de Electricidad. In WCI-RULES, the Annual Private Bank is calculated according to the method in Cullenward et al., 2019, but as applied to the model results rather than calculated directly from CIR data. For covered emissions (and hence compliance obligations) in 2018, Cullenward et al., 2019 used a projection that the rate of change from 2017 to 2018 would be the same as from 2016 to 2017 (-0.4%). WCI-RULES instead uses user-specified projections for covered emissions; this paper reports values for the PATHWAYS Scenario, in which covered emissions after 2017 decrease 2% per year.

For the PATHWAYS Scenario, the Private Bank calculated in WCI-RULES for 2018 is 7.1 M higher than in the CIR-based method. This is primarily due to the emissions projection for 2018 being 6.1 M higher than the central estimate used in the CIR-based method. After adjusting for that difference in the 2018 emissions projection, the Private Bank for 2018 in WCI-RULES is only 1.2 M lower than the CIR-based method (a difference of 0.5%). The largest difference in the Private Bank in earlier years is for 2015, a difference of 1.8 M (or 1.7%). Thus, the Annual Private Bank (after adjustment) matches projections of covered emissions in WCI-RULES with the assumption used in Cullenward et al., 2019 (see Table S-4). Government Holding Accounts show corresponding differences of similar size, but opposite sign.

# Supplement to Section 3 (Results)

## Calculation of unused offset credits

There were at least 21 M unused offset credits in the Private Bank at the end of Compliance Period 2, immediately following the Nov. 1, 2018, compliance event (Cullenward et al., 2019). These banked offsets, plus future offset credit sales projected (using the model’s default assumption that issuance would be 75% of the maximum that could be surrendered given the emissions projection), would not lead to excess offsets. That is, this quantity of offsets is less than the maximum that could be surrendered for compliance for emissions incurred through 2030.

## PATHWAYS Scenario: 2017 Scoping Plan emissions projections

CARB’s 2017 Scoping Plan was based on the PATHWAYS model, which projects emissions by sector (CARB, 2017a, 2017b). Using PATHWAYS results, CARB has designated “covered sectors” (Transportation, Electric Power, Industrial, and Residential and Commercial) as distinct from other non-covered sectors (Agriculture, which includes forestry; High GWP, for high global warming potential gases; and Recycling and Wastes) (CARB, 2018b).

However, this split between covered *sectors* versus non-covered *sectors* does not correspond exactly to the split between covered *emissions* versus non-covered *emissions*. Some emissions in “covered sectors” are not covered (that is, are not regulated by the cap-and-trade program); conversely, some emissions in “non-covered sectors” are covered (that is, are regulated by the cap-and-trade program) (see Section 1.1 above).

In both California’s official data and as used in the PATHWAYS modelling for the 2017 Scoping Plan, “covered sector” emissions are about 10% higher than historical covered emissions (Inman et al., 2018). Nonetheless, we considered the rate of change in “covered sector” emissions to be a reasonable proxy for CARB’s expectation for the rate of change of covered emissions (that is, the emissions actually regulated by the cap-and-trade program), due to existing and expected direct policies, but without any effects from the cap-and-trade program. In the PATHWAYS modelling, for the Updated Scoping Plan case over the period 2015-2030, “covered sector” emissions decreased 2.0% on average; similarly, total economy-wide emissions decreased 2.1% on average. Therefore, the PATHWAYS Scenario assumes that covered emissions decrease 2% per year.

# Supplement to Section 4 (Discussion)

## Reductions in covered emissions vs. non-covered emissions

Achieving California’s and Québec’s respective economy-wide emission limits will require reductions in both covered and non-covered emissions. In scenarios in which covered emissions alone are above the statutory limit for economy-wide emissions, the only way of keeping economy-wide emissions below the statutory limit is for non-covered emissions to become net negative (e.g., through carbon sequestration in forestry and/or agriculture sectors) and for these negative emissions to be included in the state’s inventory (which they currently are not).

Table S-5 shows the reductions in non-covered emissions required to keep economy-wide emissions in 2030 below the statutory limits across the range of scenarios addressed in our paper. These data are a summary of the data underlying Figure 4 in the main text.

From 2015 onward, California and Québec’s programs both adopted “broad-scope” covered emissions for assigning compliance obligations, which included transportation fuel emissions in addition to those emissions covered under the program previously. However, regulators in both jurisdictions reported broad-scope covered emissions for years prior to when broad-scope emissions were used for assigning compliance obligations; for California, broad-scope covered emissions reporting began for California in 2011, and for Québec in 2012.

We calculated non-covered emissions as total economy-wide emissions minus broad-scope covered emissions. These data indicate the rate of change over time in this category of emissions, for comparison with the changes required in each scenario for total economy-wide emissions to remain below statutory limits in 2030. The data and calculations are in the WCI-RULES repository (Inman, 2019), in the WCI-RULES data input file, <WCI-RULES\_data\_input\_file.xlsx>, in the sheet “non-covered emissions.”

## Allowance prices and reserve sales projections

WCI-RULES’s projection for reserve sales is only approximate; actual reserve sales could start earlier or later, depending on market conditions and the timing of compliance events.

California’s post-2020 reserve account includes two reserve tiers with prices that reach by 2030 ~$62 and ~$80, respectively, which is below California’s price ceiling of ~$98 (all in 2019 USD). In contrast, Québec’s post-2020 reserves will be sold at a single price level, which by 2030 will be roughly equal to California’s second tier (~$80 in 2019 USD).

Therefore, in scenarios that result in a shortfall in non-reserve instrument supplies by 2030, it is likely that market prices would rise to at least the level of California’s first reserve tier some years before 2030.

**Table S-1:** WCI-RULES data inputs

|  |  |  |
| --- | --- | --- |
| **Report type** | **Frequency** | **Data used in WCI-RULES** |
| Auction notices | Annual | Quantities of allowances consigned by utilities |
| Allocation reports | Annual | Quantities freely allocated to emitters, including true-up allocations due to revisions in earlier years’ allocations |
| Compliance reports | Annual | Instruments surrendered (for allowances, separated by vintage or other type) |
| Auction results | Quarterly | Quantities available and sold, separated by vintage and jurisdiction |
| Compliance Instrument Reports | Quarterly | Offsets issued; net flow from Ontario |

**Table S-2.** Allowances in private accounts in WCI-RULES results compared with the Compliance Instrument Report (CIR), for Q2 2019. All units, except for percentage differences, are million metric tons of carbon dioxide-equivalent (MMtCO2e).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Vintage** | **CIR** | **WCI-RULES** | **Difference** | **% Difference** |
| **2013** | 1.33 | 1.41 | -0.08 | -6.4% |
| **2014** | 4.56 | 4.99 | -0.43 | -9.3% |
| **2015** | 10.54 | 10.96 | -0.42 | -4.0% |
| **2016** | 57.12 | 57.57 | -0.45 | -0.8% |
| **2017** | 121.87 | 122.21 | -0.34 | -0.3% |
| **2018** | 388.60 | 388.74 | -0.14 | 0.0% |
| **2019** | 238.04 | 238.87 | -0.82 | -0.3% |
| **2020** | 24.78 | 24.78 | 0.00 | 0.0% |
| **2021** | 33.26 | 33.26 | 0.00 | 0.0% |
| **2022** | 15.02 | 15.02 | 0.00 | 0.0% |
| **2023** | 0.00 | 0.00 | 0.00 | 0.0% |
| **2024** | 0.00 | 0.00 | 0.00 | 0.0% |
| **2025** | 0.00 | 0.00 | 0.00 | 0.0% |
| **2026** | 0.00 | 0.00 | 0.00 | 0.0% |
| **2027** | 0.00 | 0.00 | 0.00 | 0.0% |
| **2028** | 0.00 | 0.00 | 0.00 | 0.0% |
| **2029** | 0.00 | 0.00 | 0.00 | 0.0% |
| **2030** | 0.00 | 0.00 | 0.00 | 0.0% |
| **Early Action Allowances** | 0.02 | 0.02 | 0.00 | 0.0% |
| **APCR Allowances** | 0.04 | 0.04 | 0.00 | 0.0% |
| **Total** | 895.18 | 897.88 | -2.70 | -0.3% |
| **Average absolute difference (vintages ≤ 2018)** |  |  | 0.31 |  |

**Table S-3.** Allowances in Government Holding Accounts in WCI-RULES results compared with the Compliance Instrument Report (CIR), for Q2 2019. All units, except for percentage differences, are metric tons of carbon dioxide-equivalent (MMtCO2e).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Vintage** | **CIR** | **WCI-RULES** | **Difference** | **% Difference** |
| **2013** | 0.08 | 0.00 | 0.08 | 100.0% |
| **2014** | 0.42 | 0.00 | 0.42 | 100.0% |
| **2015** | 0.21 | 0.00 | 0.21 | 100.0% |
| **2016** | 3.66 | 3.45 | 0.20 | 5.5% |
| **2017** | 7.14 | 7.15 | 0.00 | 0.0% |
| **2018** | 4.62 | 4.48 | 0.14 | 3.1% |
| **2019** | 113.37 | 112.65 | 0.72 | 0.6% |
| **2020** | 338.61 | 338.61 | 0.00 | 0.0% |
| **2021** | 332.34 | 332.34 | 0.00 | 0.0% |
| **2022** | 330.14 | 330.14 | 0.00 | 0.0% |
| **2023** | 335.54 | 335.54 | 0.00 | 0.0% |
| **2024** | 322.05 | 322.05 | 0.00 | 0.0% |
| **2025** | 308.76 | 308.76 | 0.00 | 0.0% |
| **2026** | 295.28 | 295.28 | 0.00 | 0.0% |
| **2027** | 281.89 | 281.89 | 0.00 | 0.0% |
| **2028** | 268.61 | 268.61 | 0.00 | 0.0% |
| **2029** | 255.12 | 255.12 | 0.00 | 0.0% |
| **2030** | 241.77 | 241.74 | 0.00 | 0.0% |
| **Early Action Allowances** | 0.00 | 0.00 | 0.00 | 0.0% |
| **APCR Allowances** | 52.40 | 52.40 | 0.00 | 0.0% |
| **Total** | 3,492.01 | 3,490.24 | 1.77 | 0.0% |
| **Average absolute difference (vintages ≤ 2018)** |  |  | 0.18 |  |

**Table S-4.** Annual Private Bank in WCI-RULES PATHWAYS Scenario compared with Cullenward et al., 2019. All differences are calculated as Cullenward et al., 2019 minus WCI-RULES; percentage differences are calculated as the difference divided by Cullenward et al., 2019. All units, except for percentage differences, are metric tons of carbon dioxide-equivalent (MMtCO2e).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Series** | **Source** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** |
| **Compliance obligations** | Cullenward et al. 2019 | 163.4 | 164.4 | 397.9 | 382.4 | 377.2 | 379.2 |
| WCI-RULES | 163.4 | 164.4 | 397.9 | 382.4 | 377.2 | 373.2 |
| Difference | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 6.1 |
| **Annual Private Bank** | Cullenward et al. 2019 | 11.9 | 43.1 | 106.6 | 68.3 | 106.5 | 227.9 |
| WCI-RULES | 12.4 | 44.2 | 108.4 | 69.0 | 107.0 | 235.1 |
| Difference | -0.5 | -1.1 | -1.8 | -0.7 | -0.5 | -7.1 |
| **Annual Private Bank, Harmonized** | Difference | -0.5 | -1.1 | -1.8 | -0.7 | -0.5 | -1.2 |
| % Difference | -4.0% | -2.7% | -1.7% | -1.0% | -0.5% | -0.5% |

**Table S-5.** Required reductions in non-covered emissions. Given a scenario for the rate of decrease of covered emissions in each jurisdiction, we calculate the maximum that non-covered emissions could be, such that economy-wide emissions would be equal to the statutory limit set for 2030 for each jurisdiction. Starting from the latest historical data for non-covered emissions (for California, 2017; for Québec, 2016), we also calculate the minimum annual rate of change for non-covered emissions that would be required to reduce emissions to the 2030 level indicated, assuming that the change occurs linearly (with a constant rate of change in MMtCO2e per year). In the Business-as-Usual Scenario, for both jurisdictions, covered emissions alone exceed the respective 2030 limits for economy-wide emissions. Therefore, economy-wide emissions would exceed the limit unless non-covered emissions were to become net negative. For comparison, the average rate of change from 2012 through 2016 across economy-wide emissions from California and Québec together was -5.9 MMtCO2e per year, even though economy-wide emissions were approximately four times larger than non-covered emissions.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Covered emissions scenario**  **(annual rate of change)** | | **Non-covered emissions, latest historical data**  **(MMtCO2e)** | **Maximum non-covered emissions in 2030**  **(MMtCO2e)** | **Minimum rate of change required**  **(MMtCO2e per year)** |
| California | 2030 Cap Achieved Scenario (-3.5%) | 104 | 57 | -3.6 |
| PATHWAYS Scenario (-2%) | 104 | 12 | -7.0 |
| Business-as-Usual Scenario (-0.5%) | 104 | -42 | -11.2 |
| Québec | 2030 Cap Achieved Scenario (-3.5%) | 19 | 16 | -0.3 |
| PATHWAYS Scenario (-2%) | 19 | 8 | -0.9 |
| Business-as-Usual Scenario (-0.5%) | 19 | -2 | -1.6 |

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