Facility-Level Industry Representation for Decarbonization Modeling

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Contents

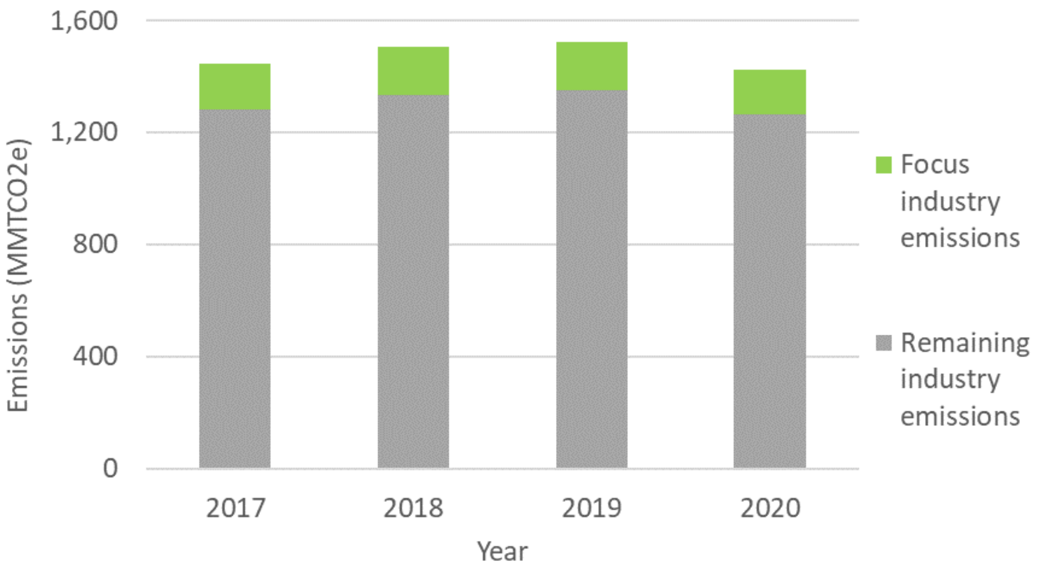
Approach: Overview

- The largest facilities of energy-intensive materials processing industries represent less than 5% of U.S. manufacturing facilities, but contribute nearly 25% of U.S. industrial greenhouse gas (GHG) emissions (McMillan et al. 2016).
- Therefore, characterizing even a subset of these facilities will capture a significant portion of industrial GHG emissions.
  - Relevant characteristics include location, energy intensity and mix, process emissions intensity, and general production technology.
- Estimating facility-level annual physical production and total energy use by fuel type is possible using various **publicly-available data sources** (e.g., McMillan and Narwade 2018), **avoiding the need to purchase proprietary data.**

Approach: Focus Industries

- Initial set of focus industries were chosen based on their energy and GHG emissions intensity, and difficulty to electrify.
- Initial set of **focus industries**
  - Ammonia (natural gas, Haber-Bosch fertilizer facilities only)
  - Cement (clinker production only)
  - Iron and steel
- Planned additions to facility-level representation of
  - Wet corn milling
  - Soybean milling
  - Sugar refining
  - Ethylene cracking

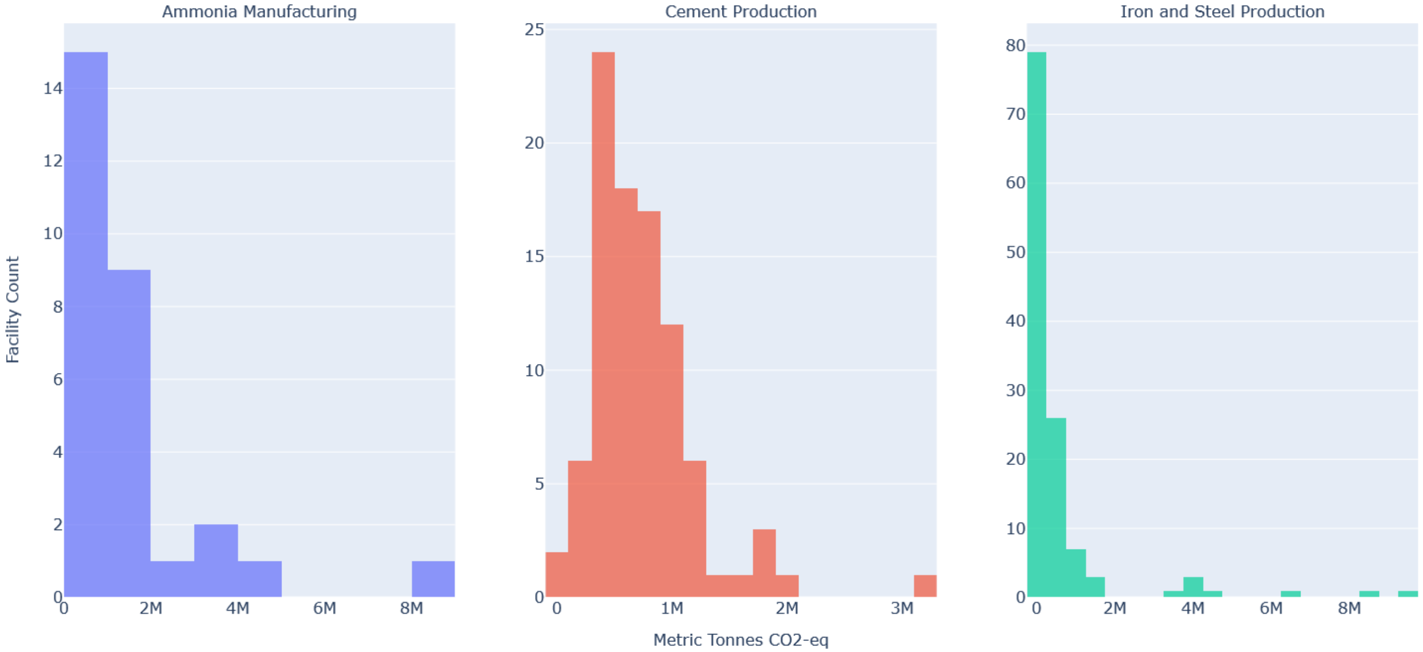
Approach: Focus Industries



Data from https://www.epa.gov/ghgreporting/data-sets and https://cfpub.epa.gov/ghgdata/inventoryexplorer/

- GHG emissions from focus industries and industry overall increased through 2019
- The **~240 focus industry facilities** consistently contribute ~11% of industrial sector total emissions

Approach: Focus Industries Emissions by Facility (2018)



Data from https://www.epa.gov/ghgreporting/data-sets

Total emissions from iron and steel industry are fat-tailed, due to large size and emissions intensity of integrated mills compared to electric arc furnace mills

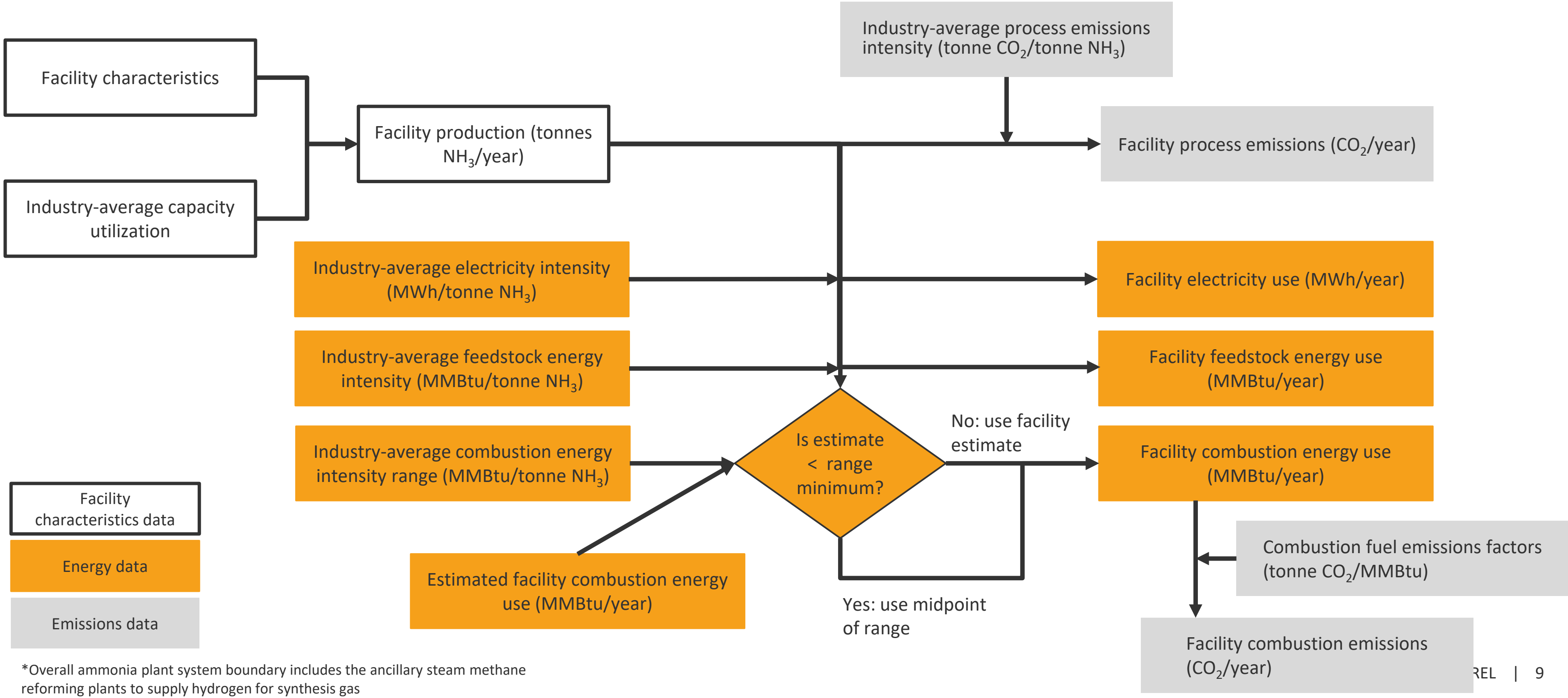
Note: figures do not include emissions that are transferred offsite or injected (i.e., GHGRP Subpart PP).

Approach: Focus Industries

- Existing and decarbonized facilities in focus industries are defined in terms of their **facility characteristics**, and **energy use and emissions characteristics**
- **Facility characteristics**
  - Location: latitude, longitude
  - Vintage: construction date
  - Capacity: physical annual production capacity
  - Production: physical annual production
  - Industry type: North American Industrial Classification (NAICS) code
- **Energy use and emissions characteristics**
  - Fuel use by type (e.g., electricity, natural gas)
  - Feedstock energy use by type (e.g., coking coal)
  - Process-specific emissions (e.g., CO_2 emissions from ironmaking)

Ammonia

Ammonia: Estimation Overview*



Facility characteristics

Industry-average capacity utilization

Facility production (tonnes NH_3/year)

Industry-average process emissions intensity (tonne CO_2/tonne NH_3)

Facility process emissions (CO_2/year)

Industry-average electricity intensity (MWh/tonne NH_3)

Facility electricity use (MWh/year)

Industry-average feedstock energy intensity (MMBtu/tonne NH_3)

Facility feedstock energy use (MMBtu/year)

Industry-average combustion energy intensity range (MMBtu/tonne NH_3)

Estimated facility combustion energy use (MMBtu/year)

Is estimate < range minimum?

No: use facility estimate

Yes: use midpoint of range

Facility combustion energy use (MMBtu/year)

Combustion fuel emissions factors (tonne CO_2/MMBtu)

Facility combustion emissions (CO_2/year)

Facility characteristics data

Energy data

Emissions data

*Overall ammonia plant system boundary includes the ancillary steam methane reforming plants to supply hydrogen for synthesis gas

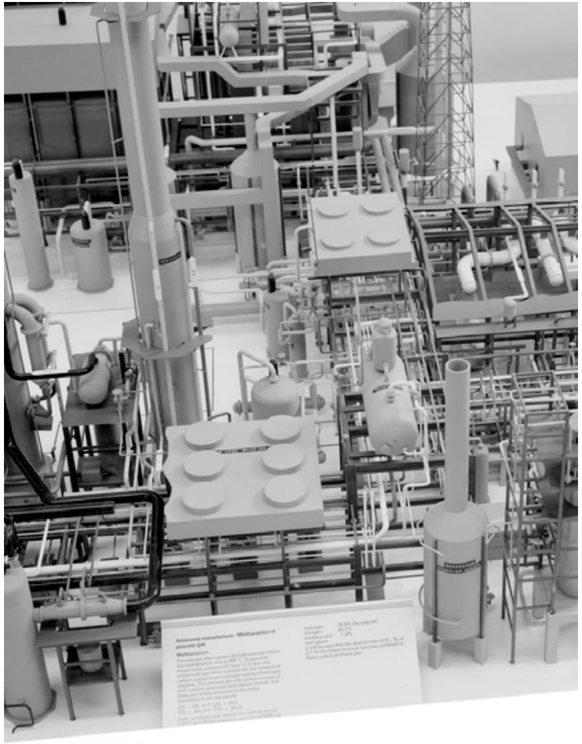
Ammonia

Existing facility characteristics

- Location (latitude and longitude, city, and state; EPA 2020)
- Capacity (tonnes NH_3 / year; Apodaca 2021)
- Capacity utilization, industry average (%; U.S. Census Bureau 2021)
- Vintage (Brown 2021)
- Only includes facilities that produce ammonia for fertilizer use
- Production is represented as NH_3; urea and urea-ammonium solutions (representing ~60% of U.S. fertilizer use [Apocada 2021]), as well as other N-containing fertilizers, are not distinguished

Existing facility energy use

- Combustion energy by fuel type, facility estimate (U.S. EPA 2020 applying method from McMillan et al. 2021)
- Combustion energy, industry average intensity (12.7 MMBtu natural gas / tonne NH_3; midpoint of range from Kermeli et al. 2017)
- Feedstock energy, industry average intensity (22.3 MMBtu natural gas/tonne NH_3; midpoint of range from Kermeli et al. 2017)
- Electricity, industry average intensity (0.110 MWh/tonne NH_3; U.S Energy Information Administration 2021 and Apodaca 2021)



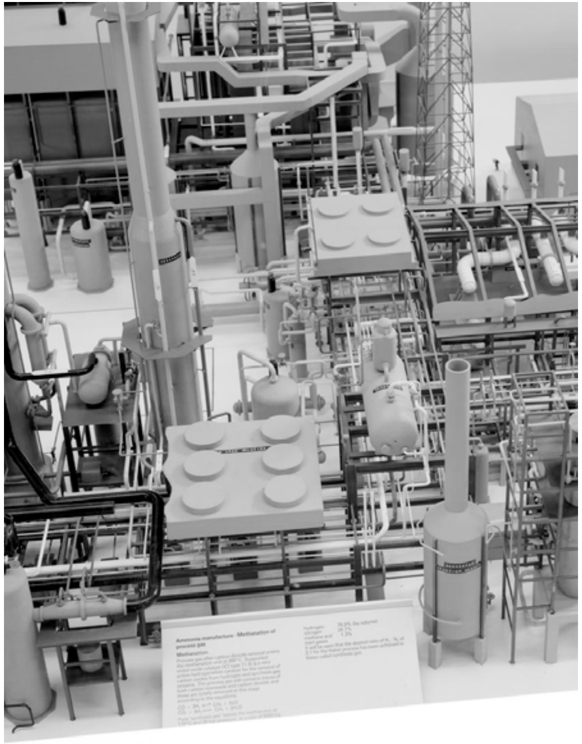
Ammonia

Existing facility direct GHG emissions

- Process emissions, industry average (0.767 tonnes CO_2/tonne NH_3; EPA 2022a and Apodaca 2021)
  - Process emissions are net of CO_2 used for urea production
- Combustion emissions (varies by fuel type; EPA 2022b)

BAT Steam Methane Reforming Haber Bosch

- Capacity (875,000 tonnes NH_3/year; IEA 2021)
- Electricity, intensity (0.083 MWh/tonne NH_3; IEA 2021)
- Natural gas combustion, intensity (10.5 MMBtu/tonne NH_3; IEA 2021)
- Natural gas feedstock, intensity (19.9 MMBtu/tonne NH_3; IEA 2021)

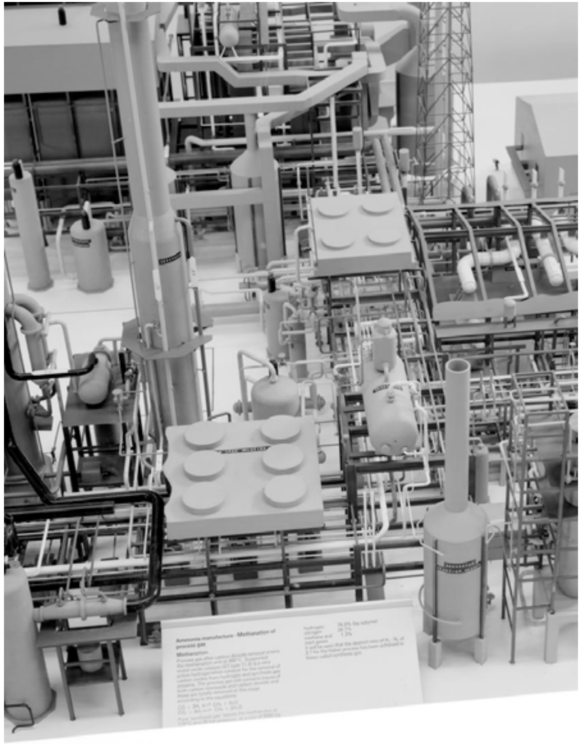


"Model of ICI Billingham 'Ammonia Four' Ammonia synthesis plant (model - representation)" by Cleveland Process Designs Limited is licensed under CC BY-NC-SA 4.0.

Ammonia

Decarbonization technologies: Steam Methane Reforming Haber-Bosch with Carbon Capture, Utilization and Storage (CCUS)

- Capacity (875,000 tonnes NH_3/year; IEA 2021)
- Natural gas combustion, intensity (10.5 MMBtu/tonne NH_3; IEA 2021)
- Natural gas feedstock, intensity (19.9 MMBtu/tonne NH_3; IEA 2021)
- Electricity, intensity (0.2778 MWh/tonne NH_3; IEA 2021)
- CO_2 capture rate (90%; IEA 2021)
- CAPEX (2,297 USD/tonne NH_3; IEA 2021)
- Fixed OPEX (59 USD/tonne NH_3/year; IEA 2021)



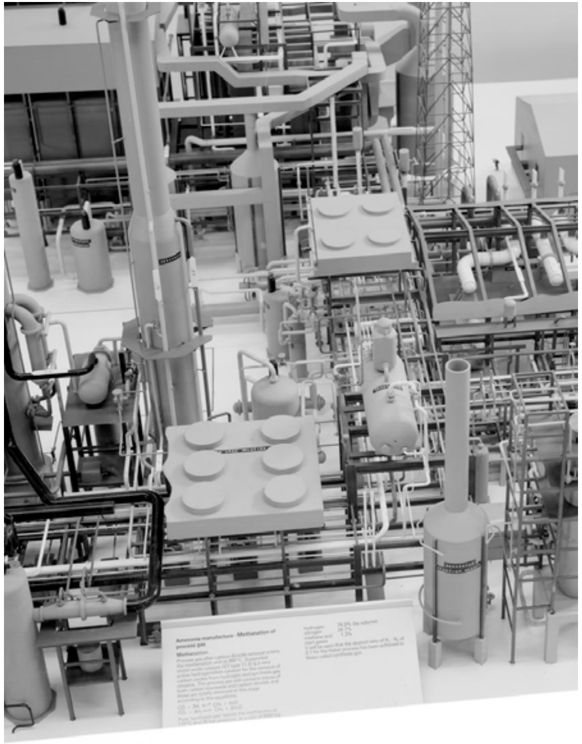
Ammonia

Decarbonization technologies: Steam Methane Reforming Haber-Bosch CCUS retrofit

- Electricity, intensity (0.2778 MWh/tonne NH_3; IEA 2021)
- CO_2 capture rate (90%; IEA 2021)
- CAPEX (383/tonne NH_3; IEA 2021)
- Fixed OPEX (11 USD/tonne NH_3/year; IEA 2021)

Decarbonization technologies: Electrolysis Haber-Bosch

- Capacity (875,000 tonnes NH_3/year; IEA 2021)
- Electricity, intensity (10 MWh/tonne NH_3; IEA 2021)
- CO_2 capture rate (90%; IEA 2021)
- CAPEX (2,360 USD/tonne NH_3; IEA 2021)
- Fixed OPEX (59 USD/tonne NH_3/year; IEA 2021)

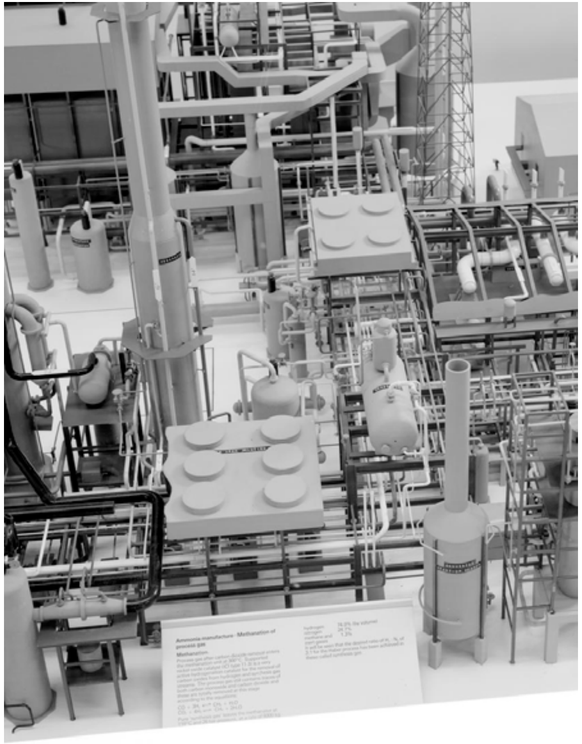


"Model of ICI Billingham 'Ammonia Four' Ammonia synthesis plant (model - representation)" by Cleveland Process Designs Limited is licensed under CC BY-NC-SA 4.0.

Ammonia

Decarbonization technologies: Electrochemical NH_3*

- Capacity (730,000 tonnes NH_3/year; assumed)
- Electricity, intensity (35 MWh/tonne NH_3; Badgett et al. 2021)
- CAPEX (3,000 USD/tonne NH_3; assumed)
- Fixed OPEX (5 USD/tonne NH_3/year; assumed)

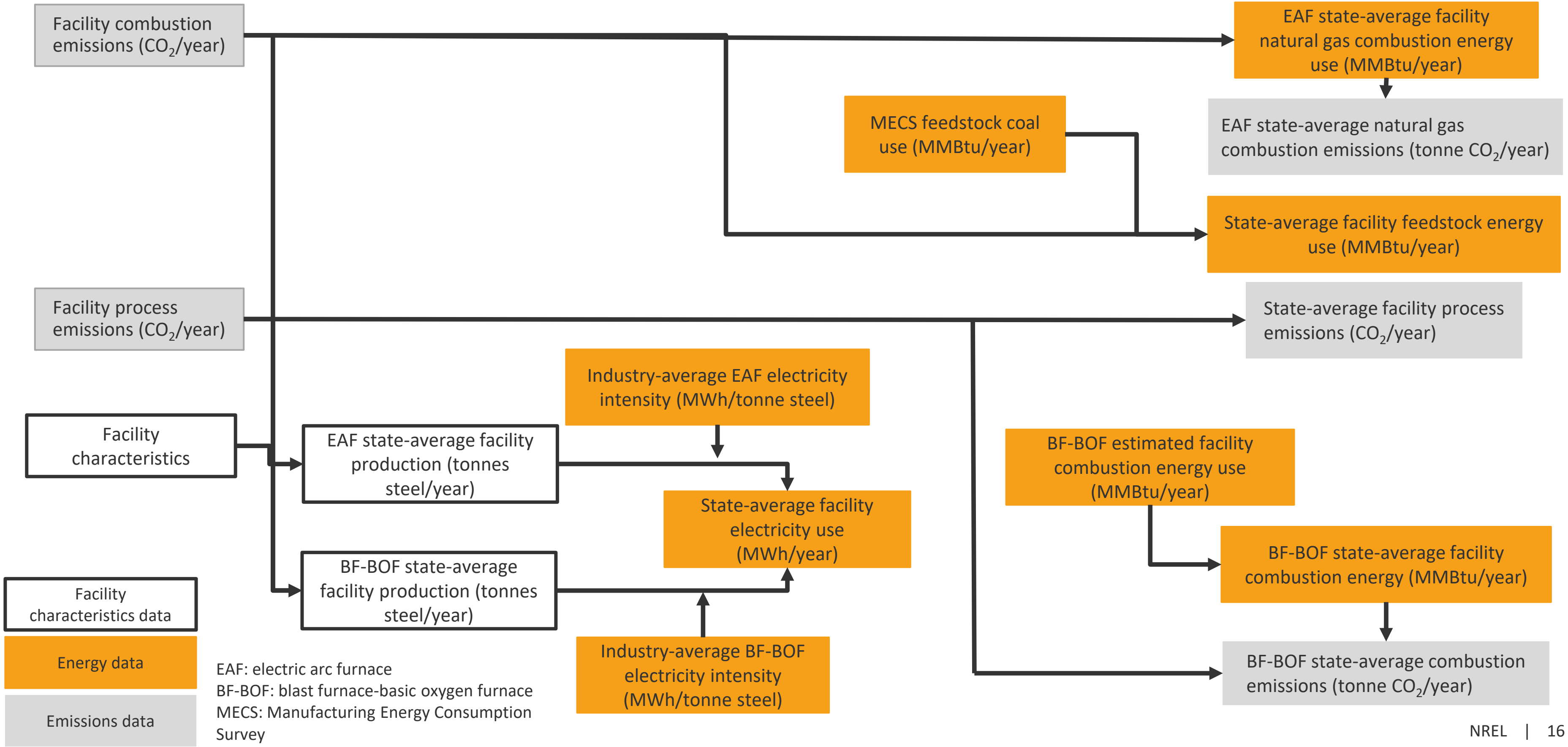


"Model of ICI Billingham 'Ammonia Four' Ammonia synthesis plant (model - representation)" by Cleveland Process Designs Limited is licensed under CC BY-NC-SA 4.0.

* Note: the technology and process design and optimization constraints are not yet well understood for ammonia electrosynthesis

Iron and Steel

Iron and Steel: Estimation Overview



Facility combustion emissions (CO_2/year)

Facility process emissions (CO_2/year)

Facility characteristics

EAF state-average facility production (tonnes steel/year)

BF-BOF state-average facility production (tonnes steel/year)

Industry-average EAF electricity intensity (MWh/tonne steel)

State-average facility electricity use (MWh/year)

Industry-average BF-BOF electricity intensity (MWh/tonne steel)

MECS feedstock coal use (MMBtu/year)

EAF state-average facility natural gas combustion energy use (MMBtu/year)

EAF state-average natural gas combustion emissions (tonne CO_2/year)

State-average facility feedstock energy use (MMBtu/year)

State-average facility process emissions (CO_2/year)

BF-BOF estimated facility combustion energy use (MMBtu/year)

BF-BOF state-average facility combustion energy (MMBtu/year)

BF-BOF state-average combustion emissions (tonne CO_2/year)

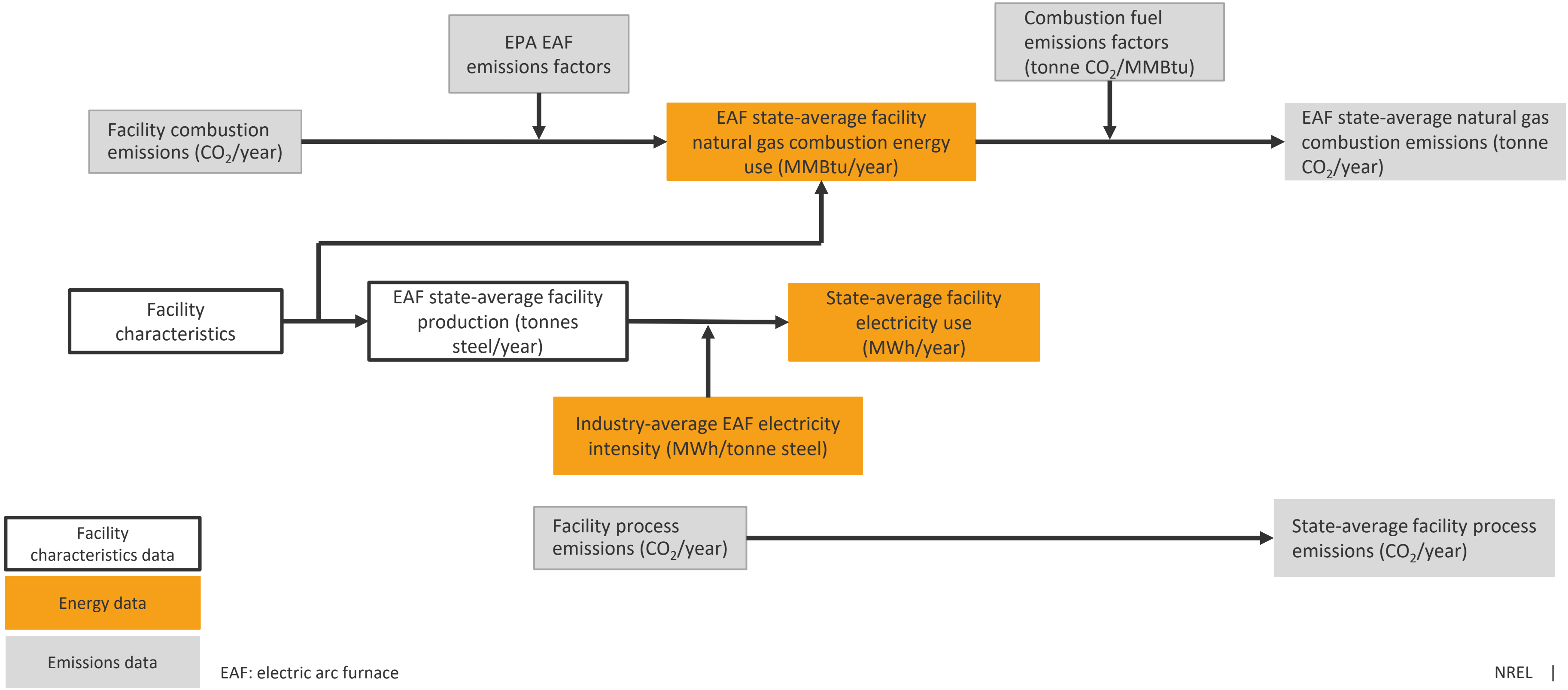
Facility characteristics data

Energy data

Emissions data

EAF: electric arc furnace
BF-BOF: blast furnace-basic oxygen furnace
MECS: Manufacturing Energy Consumption Survey

EAF Energy and Emissions Estimation



EPA EAF emissions factors

Combustion fuel emissions factors (tonne CO_2/MMBtu)

Facility combustion emissions (CO_2/year)

EAF state-average facility natural gas combustion energy use (MMBtu/year)

EAF state-average natural gas combustion emissions (tonne CO_2/year)

Facility characteristics

EAF state-average facility production (tonnes steel/year)

State-average facility electricity use (MWh/year)

Industry-average EAF electricity intensity (MWh/tonne steel)

Facility process emissions (CO_2/year)

State-average facility process emissions (CO_2/year)

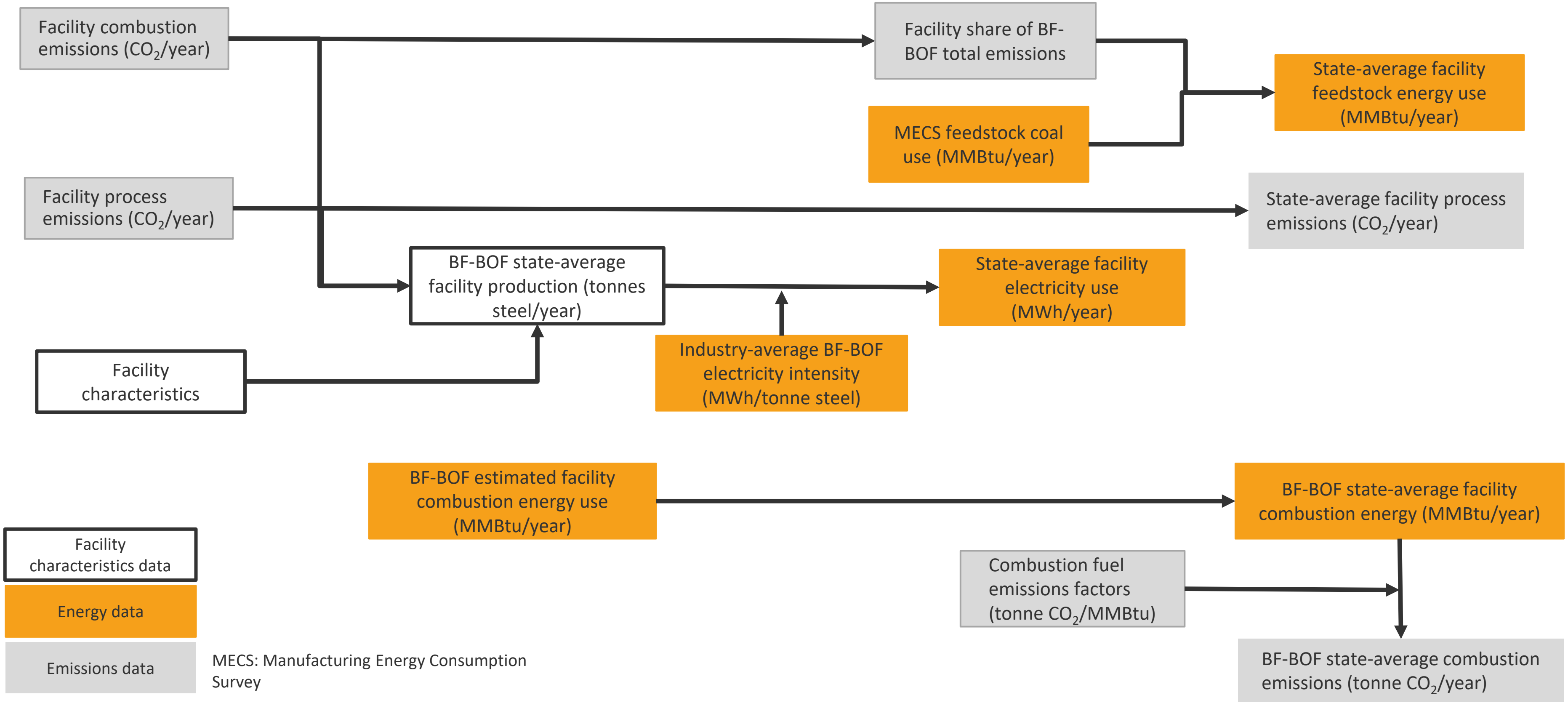
Facility characteristics data

Energy data

Emissions data

EAF: electric arc furnace

BF-BOF Energy and Emissions Estimation



Facility combustion emissions (CO_2/year)

Facility share of BF-BOF total emissions

State-average facility feedstock energy use (MMBtu/year)

MECS feedstock coal use (MMBtu/year)

Facility process emissions (CO_2/year)

State-average facility process emissions (CO_2/year)

BF-BOF state-average facility production (tonnes steel/year)

State-average facility electricity use (MWh/year)

Facility characteristics

Industry-average BF-BOF electricity intensity (MWh/tonne steel)

BF-BOF estimated facility combustion energy use (MMBtu/year)

BF-BOF state-average facility combustion energy (MMBtu/year)

Combustion fuel emissions factors (tonne CO_2/MMBtu)

BF-BOF state-average combustion emissions (tonne CO_2/year)

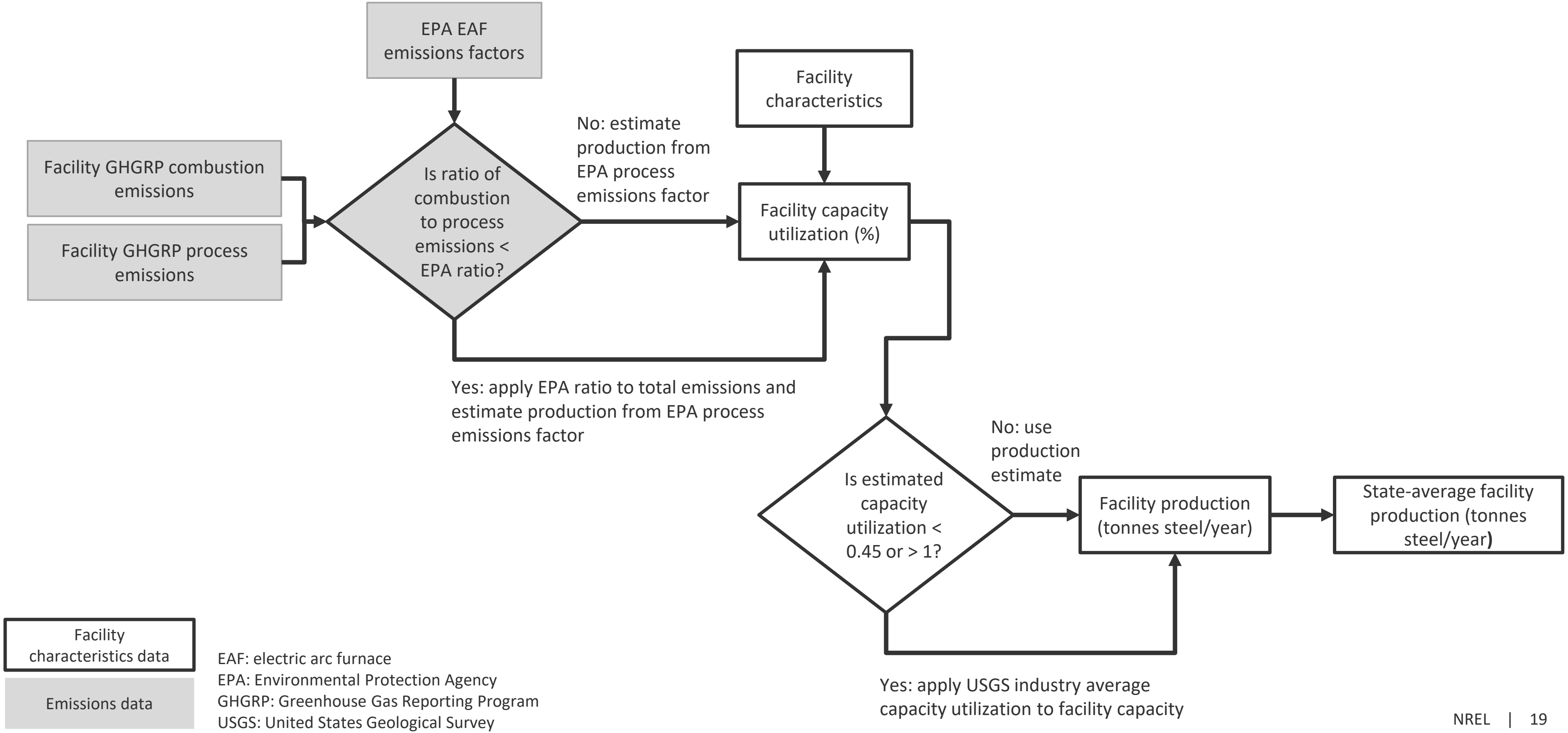
Facility characteristics data

Energy data

Emissions data

MECS: Manufacturing Energy Consumption Survey

EAF Production Estimation



EPA EAF emissions factors

Facility GHGRP combustion emissions

Facility GHGRP process emissions

Is ratio of combustion to process emissions < EPA ratio?

No: estimate production from EPA process emissions factor

Yes: apply EPA ratio to total emissions and estimate production from EPA process emissions factor

Facility characteristics

Facility capacity utilization (%)

Is estimated capacity utilization < 0.45 or > 1?

No: use production estimate

Yes: apply USGS industry average capacity utilization to facility capacity

Facility production (tonnes steel/year)

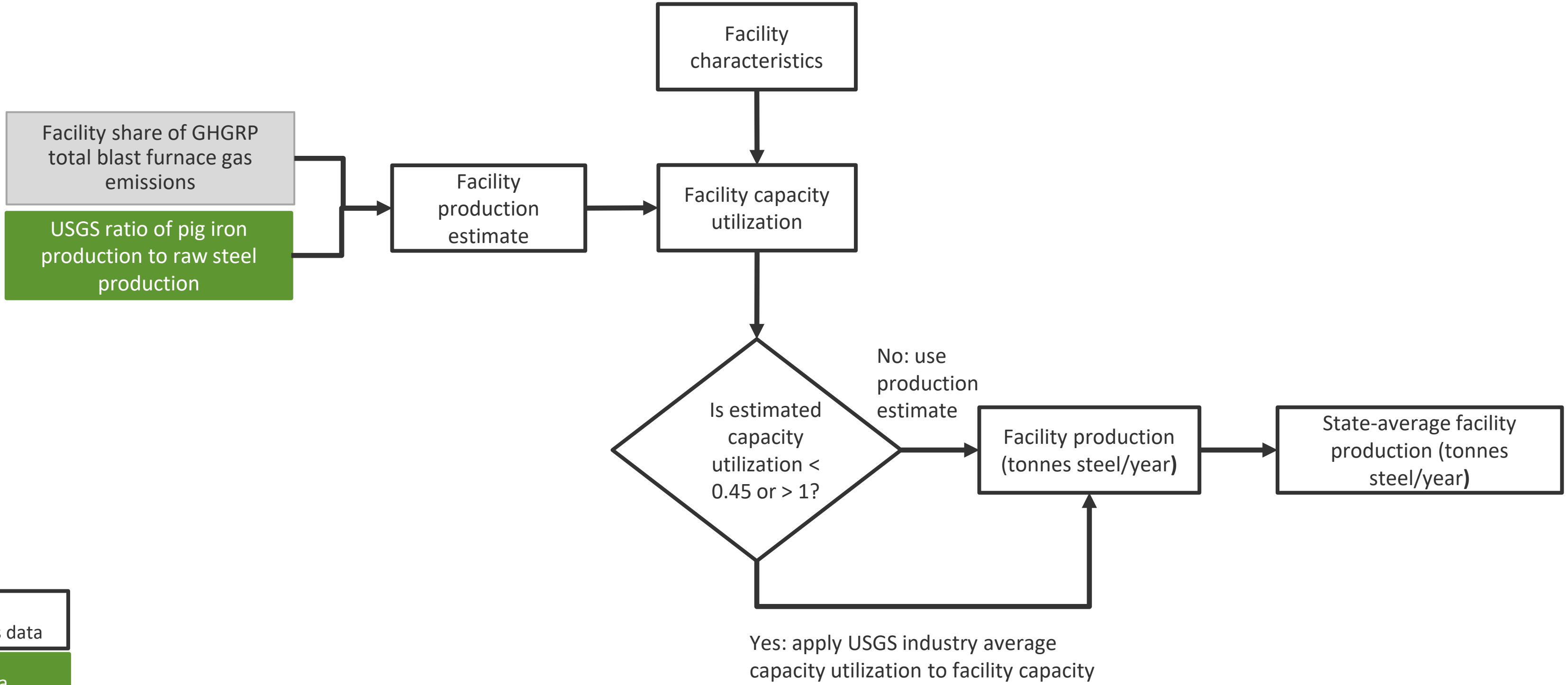
State-average facility production (tonnes steel/year)

Facility characteristics data

Emissions data

EAF: electric arc furnace
EPA: Environmental Protection Agency
GHGRP: Greenhouse Gas Reporting Program
USGS: United States Geological Survey

BF-BOF Production Estimation



Facility characteristics

Facility share of GHGRP total blast furnace gas emissions

USGS ratio of pig iron production to raw steel production

Facility production estimate

Facility capacity utilization

Is estimated capacity utilization < 0.45 or > 1?

No: use production estimate

Facility production (tonnes steel/year)

State-average facility production (tonnes steel/year)

Yes: apply USGS industry average capacity utilization to facility capacity

Facility characteristics data

Other data

Emissions data

BF-BOF: blast furnace-basic oxygen furnace
EPA: Environmental Protection Agency
GHGRP: Greenhouse Gas Reporting Program
USGS: United States Geological Survey

Iron and Steel

Existing facility characteristics

- Location (latitude and longitude, city, and state; EPA 2020)
- Capacity (tonnes steel / year; EPA 2009, McCarten et al. 2021a, and company websites)
- Vintage (McCarten et al. 2021a and company websites)
- Includes only facilities that produce steel with the BF-BOF or EAF process; finishing mills are not included

Existing facility energy use

- BF-BOF
  - Feedstock energy, coking coal (U.S. EIA 2021)
  - Combustion energy by fuel type, facility estimate (U.S. EPA 2020 applying method from McMillan et al. 2021)
  - Electricity, industry average intensity (0.243 MWh/tonne steel; U.S. DOE 2015)
- EAF
  - Process emissions factor (0.08 tonne CO_2/tonne steel; U.S. EPA 2009) and industry average natural gas intensity (5.4 MMBtu/tonne; U.S. EPA 2009)
  - Electricity, industry average intensity (0.458 MWh/tonne steel; U.S. DOE 2015)

Iron and Steel

Existing facility direct GHG emissions

- Process emissions, industry average
  - BF-BOF (0.11 tonnes CO_2/tonne steel; EPA 2009)
  - EAF(0.08 tonnes CO_2/tonne steel; EPA 2009)
  - DRI (0.0354 tonnes CO_2/tonne steel; Zang et al. 2023)
- Combustion emissions (varies by fuel type; EPA 2022b)

BAT steelmaking

- BF-BOF
  - Capacity (4,323,327 tonnes steel/year; Zang et al. 2022 and U.S. DOE 2015)
  - CAPEX (862 USD/tonne; Zang et al. 2022)
  - Fixed OPEX (338 USD/ tonne/year; IEA 2020)
  - Variable OPEX (243 USD/tonne/year; Zang et al. 2022)
  - Electricity, intensity (0.213 MWh/tonne steel; Zang et al. 2022 and U.S. DOE 2015)
  - Feedstock energy, intensity (16.8 MMBtu coal/tonne steel; Zang et al. 2022 and U.S. DOE 2015)
  - Combustion energy, intensity (5.80 MMBtu/tonne steel; Zang et al. 2022 and U.S. DOE 2015)

Iron and Steel

BAT steelmaking

- EAF
  - Capacity (4,920,000 tonnes steel/year; Zang et al. 2023 and U.S. DOE 2015)
  - CAPEX (120 USD/tonne ; Zang et al. 2022)
  - Fixed OPEX (8.10 USD/ tonne/year; Zang et al. 2022)
  - Electricity, intensity (0.573 MWh/tonne steel; Zang et al. 2023 and U.S. DOE 2015)
  - Combustion energy, intensity (1.69 MMBtu natural gas/tonne steel; Zang et al. 2022 and U.S. DOE 2015)

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Iron and Steel

BAT steelmaking

- DRI EAF (100% natural gas; 25% scrap)
  - Capacity (4,00,000 tonnes steel/year; Zang et al. 2023 and U.S. DOE 2015)
  - CAPEX (403USD/tonne ; Zang et al. 2023)
  - Fixed OPEX (13 USD/tonne/year; Zang et al. 2023)
  - Electricity, intensity (0.867 MWh/tonne steel; Zang et al. 2023 and U.S. DOE 2015)
  - Feedstock energy, intensity (6.88 MMBtu natural gas/tonne steel; Zang et al. 2023 and U.S. DOE 2015)
  - Combustion energy, intensity (3.05 MMBtu natural gas/tonne steel; Zang et al. 2023 and U.S. DOE 2015)
  - Process emissions, intensity (0.115 tonne CO_2/tonne raw steel; EPA 2009 and Zang et al. 2023)

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Iron and Steel

Decarbonization Technologies

- BF-BOF with CCS
  - CO_2 capture rate (69%; Zang et al. 2022)
  - Capacity (4,323,327 tonnes steel/year; BAT BF-BOF assumption)
  - Electricity, intensity (0.27 MWh/tonne steel; IEA 2013)
  - Feedstock energy, intensity (16.8 MMBtu coal/tonne steel; Zang et al. 2022 and U.S. DOE 2015)
  - Combustion energy, intensity (9.72 MMBtu/tonne steel; BAT BF-BOF assumptions with IEA 2013)
  - CAPEX (1,063 USD/tonne ; Zang et al. 2022)
  - Fixed OPEX (338 USD/ tonne/year; BAT BF-BOF assumption)
  - Variable OPEX (243 USD/ tonne/year; BAT BF-BOF assumption)

Iron and Steel

Decarbonization technologies

- Flash ironmaking
  - Capacity (4,330,000 tonnes raw steel/year; Zang et al. 2023)
  - CAPEX (418 USD/tonne; Zang et al. 2023)
  - Fixed OPEX (12.73 USD/tonne; Zang et al. 2023)
  - Hydrogen is purchased
  - Electricity, intensity (0.732 MWh/tonne raw steel; Zang et al. 2023)
  - Combustion energy, intensity (1.6 MMBtu/tonne raw steel; Zang et al. 2023)
  - Feedstock hydrogen, intensity (0.083 tonne H_2/tonne raw steel; Zang et al. 2023)
  - Feedstock emissions, intensity (0.1635 tonne CO_2/tonne raw steel; Zang et al. 2023)

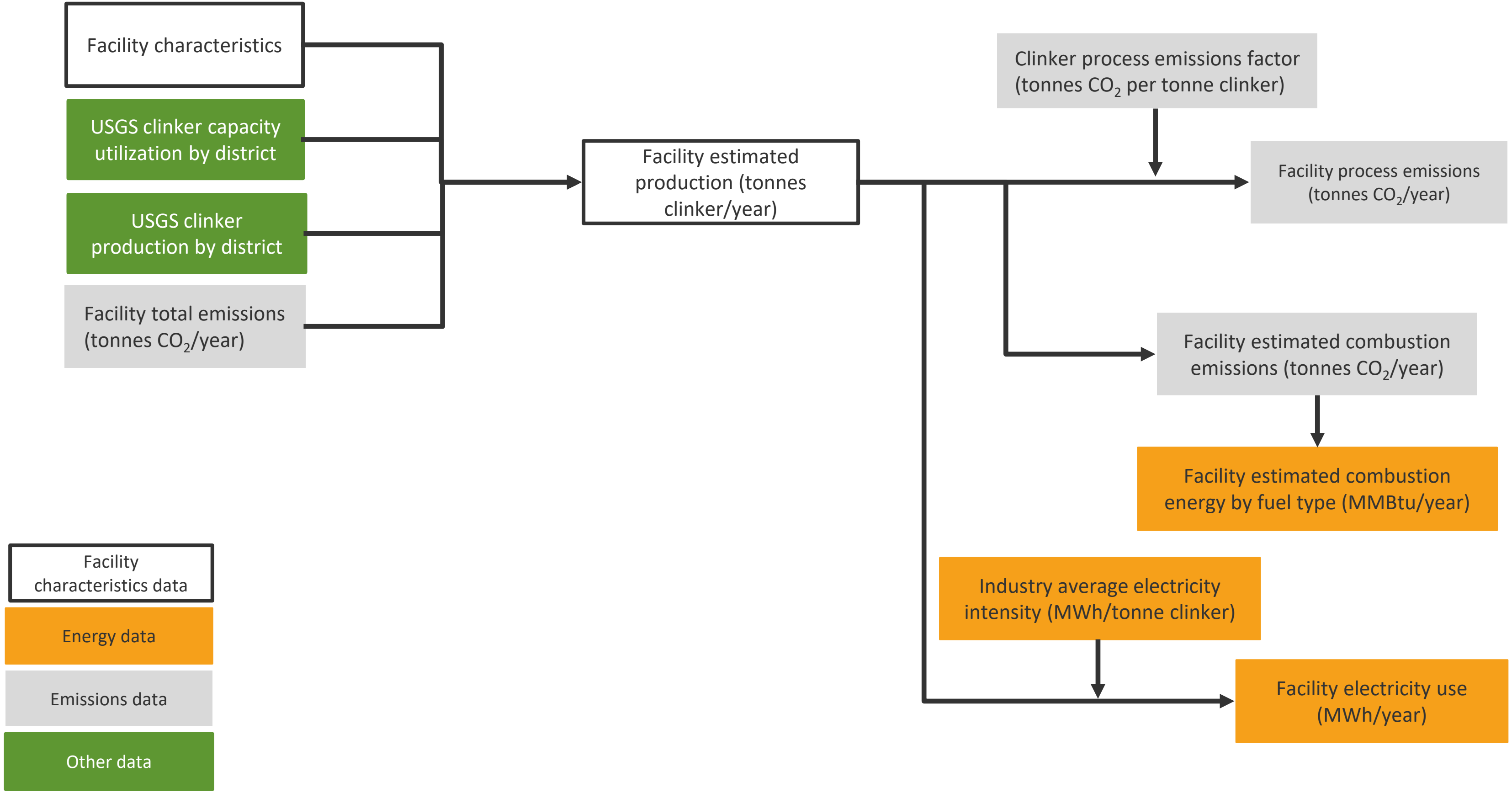
Iron and Steel

Decarbonization technologies

- Hydrogen direct reduction ironmaking and EAF
  - Capacity (4,000,000 tonnes raw steel/year; Zang et al. 2023)
  - CAPEX (403 USD/tonne; Zang et al. 2023)
  - Fixed OPEX (12.73 USD/tonne; Zang et al. 2023)
  - Hydrogen is purchased
  - Feedstock, intensity (0.061 tonne H_2/tonne raw steel; 1.18 MMBtu natural gas/tonne raw steel; 75% hydrogen, 25% natural gas mix; Zang et al. 2023)
  - Electricity, intensity (0.867 MWh/tonne raw steel; Zang et al. 2023)
  - Combustion energy, intensity (2.1 MMBtu/tonne raw steel; Zang et al. 2023)
  - Process emissions, intensity (0.08 tone CO_2/tonne raw steel; EPA 2009)

Cement

Cement: Estimation Overview



Facility characteristics

USGS clinker capacity utilization by district

USGS clinker production by district

Facility total emissions (tonnes CO_2/year)

Facility estimated production (tonnes clinker/year)

Clinker process emissions factor (tonnes CO_2 per tonne clinker)

Facility process emissions (tonnes CO_2/year)

Facility estimated combustion emissions (tonnes CO_2/year)

Facility estimated combustion energy by fuel type (MMBtu/year)

Industry average electricity intensity (MWh/tonne clinker)

Facility electricity use (MWh/year)

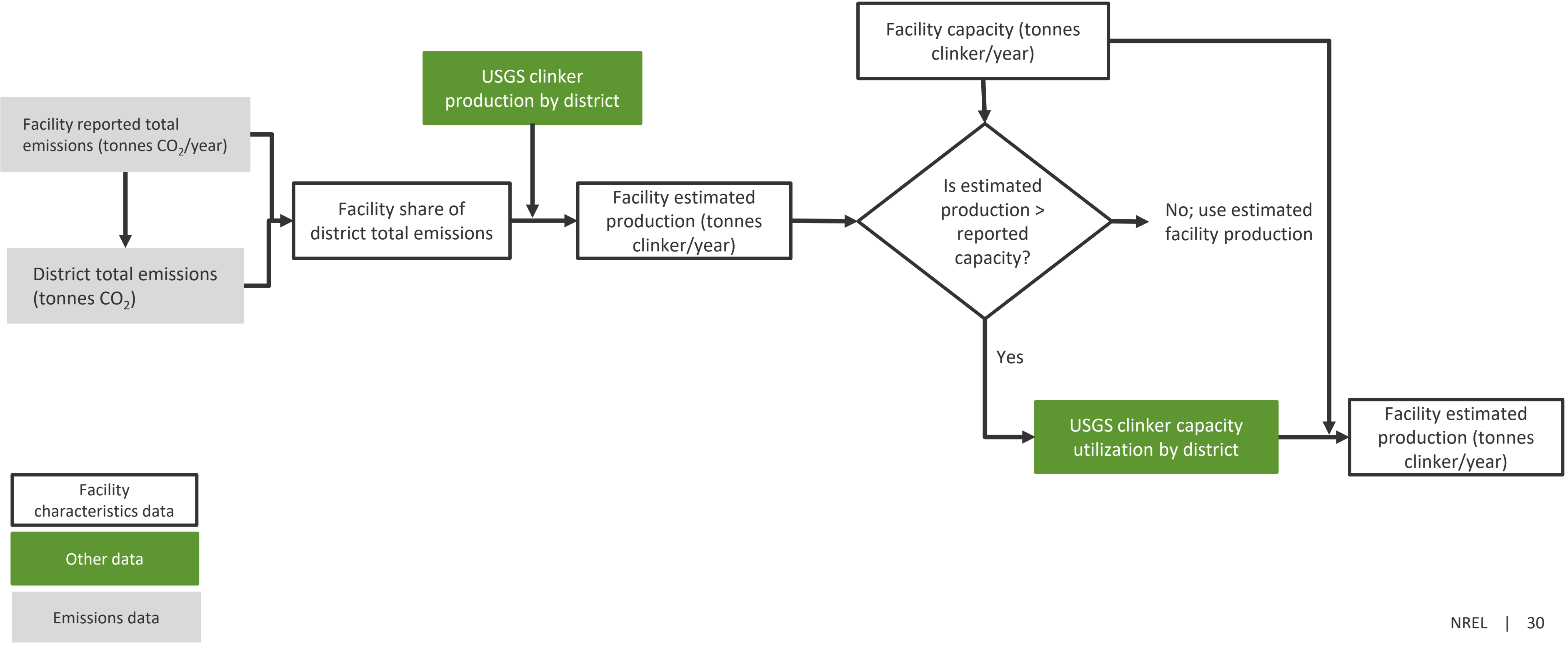
Facility characteristics data

Energy data

Emissions data

Other data

Clinker Production Estimation



Facility reported total emissions (tonnes CO_2/year)

District total emissions (tonnes CO_2)

Facility share of district total emissions

USGS clinker production by district

Facility estimated production (tonnes clinker/year)

Facility capacity (tonnes clinker/year)

Is estimated production > reported capacity?

No; use estimated facility production

Yes

USGS clinker capacity utilization by district

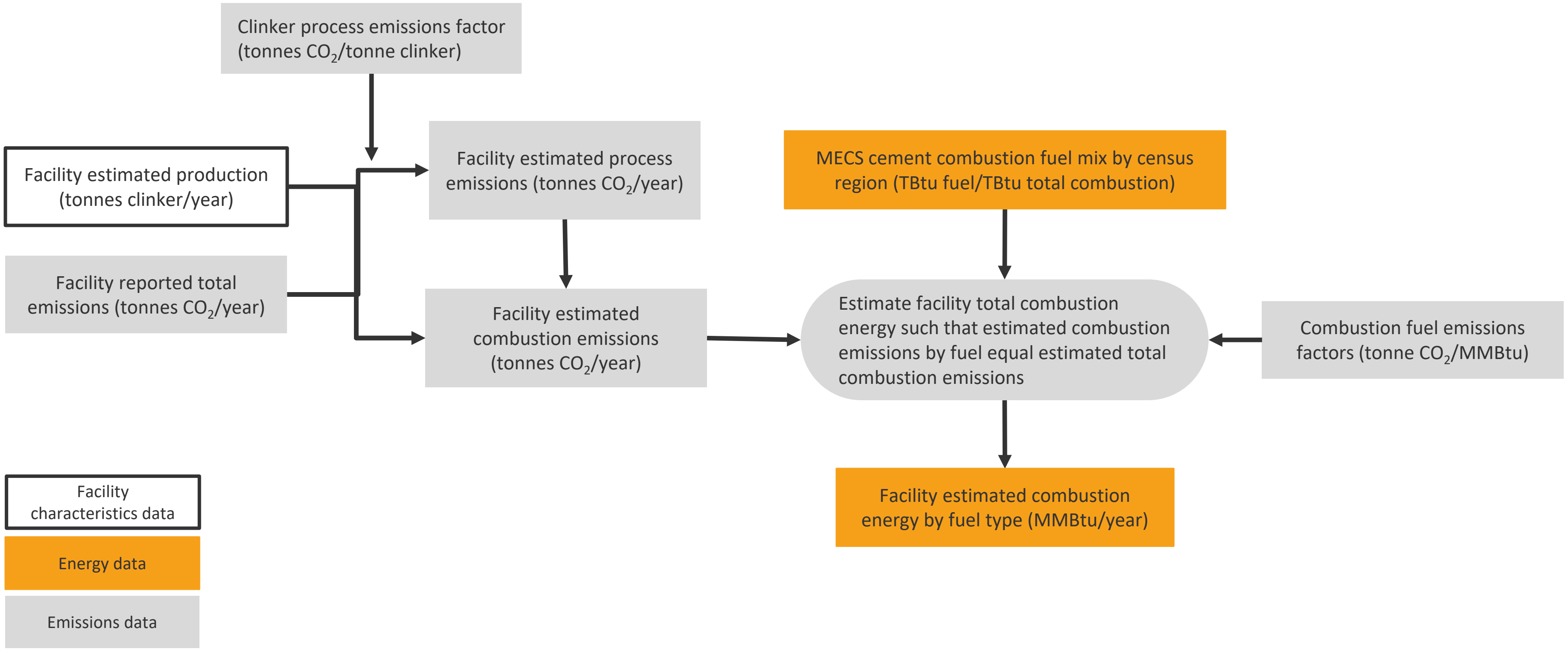
Facility estimated production (tonnes clinker/year)

Facility characteristics data

Other data

Emissions data

Cement: Combustion Energy Estimation



Clinker process emissions factor (tonnes CO_2/tonne clinker)

Facility estimated production (tonnes clinker/year)

Facility reported total emissions (tonnes CO_2/year)

Facility estimated process emissions (tonnes CO_2/year)

Facility estimated combustion emissions (tonnes CO_2/year)

MECS cement combustion fuel mix by census region (TBtu fuel/TBtu total combustion)

Estimate facility total combustion energy such that estimated combustion emissions by fuel equal estimated total combustion emissions

Combustion fuel emissions factors (tonne CO_2/MMBtu)

Facility estimated combustion energy by fuel type (MMBtu/year)

Facility characteristics data

Energy data

Emissions data

Cement

Existing facility characteristics

- Location (latitude and longitude, city, and state; EPA 2020)
- Capacity (tonnes clinker/year; McCarten et al. 2021b, and company websites)
- Vintage (McCarten et al. 2021b and company websites)
- No distinction between wet and dry processes (seven of 93 kilns use wet process [Curry 2021])

Existing facility energy use

- Electricity, census region average (EIA 2021) normalized by census region clinker production (Curry 2021)
- Combustion fuel mix, census region average (EIA 2021)
- Combustion fuel

Cement

BAT conventional technology

- Typical capacity (1,056,866 tonnes clinker/year; Lena et al. 2018)
- CAPEX (24 USD/tonne clinker; existing facility assumption)
- Fixed OPEX (21 USD/tonne clinker; existing facility assumption)
- Variable OPEX (2 USD/tonne clinker; De Lena et al. 2019)
- Electricity (0.1319 MWh/tonne clinker; Lena et al. 2018)
- Combustion fuel intensity (2.971 MMBtu/tonne clinker; Lena et al. 2018)
- Combustion fuel mix, census region average (EIA 2021)

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Cement

Decarbonization technologies

- Clinker substitution is not considered at this time.
- CCS with calcium looping (tail-end, 50% integrated)
  - Capacity (1,028,205 tonnes clinker/year; De Lena et al. 2019)
  - CAPEX (48 USD/tonne clinker; De Lena et al. 2019)
  - Fixed OPEX (34 USD/tonne clinker; De Lena et al. 2019)
  - Variable OPEX (3.2 USD/tonne clinker; De Lena et al. 2019)
  - Electricity, intensity (0.0425 MWh/tonne clinker; De Lena et al. 2019)
  - Combustion fuel intensity (6.73 MMBtu/tonne clinker; Lena et al. 2018)
  - Combustion fuel mix, census region average (EIA 2021)
  - CO_2 capture efficiency (94%; De Lena et al. 2019)

Cement

Decarbonization technologies

- CCS with calcium looping (100% integrated)
  - Capacity (1,028,205 tonnes clinker/year; De Lena et al. 2019)
  - CAPEX (50 USD/tonne clinker; De Lena et al. 2019)
  - Fixed OPEX (35 USD/tonne clinker; De Lena et al. 2019)
  - Variable OPEX (2.9 USD/tonne clinker; De Lena et al. 2019)
  - Electricity, intensity (0.128 MWh/tonne clinker; De Lena et al. 2019)
  - Combustion fuel intensity (5.16 MMBtu/tonne clinker; Lena et al. 2018)
  - Combustion fuel mix, census region average (EIA 2021)
  - CO_2 capture efficiency (95%; De Lena et al. 2019)

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