# EU industrial competitiveness: measures to address power sourcing costs whilst fostering decarbonisation

## Technical Appendix

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Agora Energiewende

Agora Industry

IDDRI

COMPASS LEXECON

# Introduction

**This technical appendix summarises the assumptions made and external sources leveraged in the course of performing the analysis for the Iddri, Agora Energie, Agora Industrie and Compass Lexecon study to which it is attached**

- It is not intended as a standalone document and should be read in conjunction with the full report.

# 1.

## Technical appendix 1 – Methodology and assumptions for the flexibility potential analysis

# Flexibility potential analysis (1/4) – Methodology

- We follow a two-step approach when analysing the flexibility potential:

1. First, we assess whether a process is technically able to react within required time-frames to participate on flexibility markets. The assessment is based on a literature review and expert interviews (see next slide).
2. Second, based on a subset of applications, we identify accessible revenues for industrial application in terms of €/kW of industrial load and assess whether they are large enough to close the decarbonisation cost gap.

- We focus on the inherent flexibility of the core upstream process which may include thermal or material storage. Flexibility from other production streams is not considered, i.e. office amenities/lights or optimising heating/cooling as well as previous or subsequent production steps.

**Building on the technical review across all case studies and the economic review on the subset of applications, we extrapolate the economic potential to assess whether each application can technically deliver flexibility and whether the associated revenues are likely to offset the costs and risks of providing flexibility.**

# Flexibility potential analysis (2/4) – Step 1: bibliography

| Sector | Industrial application | Selected decarbonised technology | Sources |
|---|---|---|---|
| **Chemicals and petrochemicals** | Steam cracking for olefines (ethylene) | H2 / Electric furnace | • Oliveira and Van Dril (2021) Decarbonisation options for large volume organic chemicals production<br>• Arteconi et al. (2023) Opportunities for high temperature heat pumps as grid flexibility providers<br>• Smith et al. (2020) Current and future role of Haber-Bosch ammonia in a carbon free energy landscape |
| | Low-temperature chemical steam supply | E-boiler / heat pump | |
| | Ammonia production | H2 / Electrolyser | |
| **Iron and steel** | Primary steel smelting | H2-DRI-EAF or NG-DRI-EAF | • Boldrini (2023) Flexibility options in a decarbonised iron and steel industry, Zhang et al (2016) Cost-effective scheduling of steel plants with flexible EAFs |
| | Secondary steel smelting | EAF | |
| | Post-production heating | Electric / H2 / hybrid furnace | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Aluminium** | Primary aluminium smelting | Electrolyser with inert anode | • Industry expert interview |
| | Secondary aluminium melting | Electric furnace | • Industry expert interview |
| | Alumina digestion | E-boiler | • European Aluminium (2025) Position paper Demand side Response & Flexibility |
| **Glass** | Container glass melting | Hybrid electric furnace | • Industry expert interview |
| | Flat glass melting | Hybrid electric furnace | |
| **Cement** | Cement clinker burning | Electric rotary kiln | • Industry expert interview |
| **Paper and pulp** | Steam generation for paper drying | E-boiler / heat pump | • Arteconi et al. (2023) Opportunities for high temperature heat pumps as grid flexibility providers ; Agora Industry (2022) Power-2-Heat direkte Elektrifizierung von Industrieller Prozesswärme |
| **Food and beverages** | Milk power production steam supply | E-boiler / heat pump | |
| **Data centres** | Data storage / AI computation | Electricity | • Industry expert interview |
| **Battery** | Cell manufacturing | Electric boiler | • Fraunhofer website- Energy efficient clean and dry rooms and mini environments |

# Flexibility potential analysis (3/4) – Step 2: key technical assumptions

| Industry | Flexible process step | Assumptions | | | | |
|---|---|---|---|---|---|---|
| | | Load flexibility share | Time between activations/frequency of activation | Required activation times | Duration | Power-On |
| **Iron and steel** | Electric arc furnace (EAF) | • 80% - full process | • 1.25 hours between activations as batches take 1h and filling next batch is assumed to take 0.25h | • 15 min | • 1h at opportunity cost ~550 €/MWh | • **EAF:** 52% + 22% charging (14% malfunction and maintenance, 12% planned maintenance) |
| **Aluminium** | High temperature electrolysis | • 5-88% full process | • 3/week for 5% load reduction<br>• 3/month for full shutdown (88%) | • 5 min | • 1h (ensuring that alumina does not solidify) at opportunity cost ~300 €/MWh | • **Electrolyser potline:** 95% (5% maintenance) |
| **Paper** | Hybrid steam production + accumulator | • 80% - paper machine | • 4 hours between activations to refill the accumulator (if fully empty) | • 5 min | • 15 min to 1 h (depending on accumulated steam volume) | • **Electric-boiler**: 95% (~8300h/a) |
| **Glass** | Container glass hybrid furnaces with electric boosters | • 5-15% - full process | • 3/month | • 5 min | • 15 min to 1 h | • **Electric booster:** 95% (5% maintenance)[4] but operations running 100% of the time |
| **Cement** | Raw material preparation and cement milling | • 75% - full process | • 4 hours between activations necessary to sufficiently dry fine cement in the milling process | • Instant | • 1h short interruptions (assumption that storage is equivalent of 1h of production)<br>• Additional time post 1h have opportunity cost ~400 €/MWh | • **Raw material preparation** (raw milling): 87% (average power-on 7000h/a)<br>• **Cement milling:** 50% (average power-on 4300h/a)<br>• Load adjusted weighted average: 65% |

*Sources: smartEn (2025) The business case for flexibility provision for energy-intensive industry*

# Flexibility potential analysis (4/4) – Step 2: possible revenues from flexibility provision in 2030 in the EU across selected industrial applications

| Industry | Flexible process step | Key modelling results | | | |
|---|---|---|---|---|---|
| | | Revenues from upward flexibility provision for a standalone exemplary plant | Number of activations | Share of annual energy consumption curtailed | Avoided $CO_2$ emissions in the power system |
| **Iron and Steel** | Electric arc furnace | 50 000 EUR/MW/a<br>15 EUR/t | 40-45./a | 0.3-0.4% | 3-4 $tCO_2/MW$<br>0.35 $tCO_2/t_{not\ produced}$ |
| **Aluminium** | High temperature electrolysis | 35 000 EUR/MW/a<br>55 EUR/t | 26-27./a | 0.1-0.2% | 4-6 $tCO_2/MW$<br>6.5 $tCO_2/t_{not\ produced}$ |
| **Paper** | Hybrid steam production + steam accumulator | 340 000 EUR/MW/a<br>57 EUR/t | 1000-1400./a | 15-20% (energy storage) | 480-640 $tCO_2/MW$<br>0.65 $tCO_2/t_{steam\ accumulator}$ |
| **Glass** | Container glass hybrid furnaces with electric boosters | 70 000 EUR/MW/a<br>7 EUR/t | 25-30./a | 0.3-0.4% | 1-2 $tCO_2/MW$<br>0.25 $tCO_2/t_{switch\text{-}to\text{-}gas}$ |
| **Cement** | Raw material preparation and cement milling | 300 000 EUR/MW/a<br>50 EUR/t | 560-920./a | 10-15% (material storage) | 260-380 $tCO_2/MW$<br>0.6 $tCO_2/t_{flexible}$ |

*Sources*: smartEn (2025) The business case for flexibility provision for energy-intensive industry

# On-site batteries flexibility revenues – methodology and assumptions

**Context**

- Energy-intensive industrials typically require continuous electricity supply. Depending on the industrial process there is some inherent flexibility which leads to cost-savings from lower electricity prices and participation on flexibility markets.
- To enhance revenues from inherent flexibility an on-site battery can be installed to provide peak-shaving to avoid most expensive hours on wholesale markets. In addition, the battery can participate on flexibility markets.
- Revenues that are earned on flexibility markets can cross-subsidise industrial production and ensure a more reliable electricity supply. These benefits will need to be offset by additional investment cost from battery.

**Modelling**

- Results are based on the modelling of a 2h battery's net revenues.
- From gross flexibility revenues, net revenues are calculated based on capital and operating cost of a battery as well as charging costs (average wholesale prices in relevant countries).
- Given the potential revenue per MWh of industrial load, sector specific cost reductions are calculated assuming that the battery can cover 20% of max hourly load. Cost reductions per MWh of industrial load are then expressed per tonnes of product or kWh of battery cell capacity manufactured.

**Battery-optimisation model set-up**

1. PLEXOS – Capacity market optimisation
2. Excel – Wholesale markets arbitrage revenues
3. PLEXOS – Intra-day optimisation
4. PLEXOS – Ancillary services optimisation
5. Excel – **Integration of results:**
   - Optimisation output: Gross revenue from flexibility
   - Transformation yearly revenue to revenue per MWh of industrial demand
   - Calculation net revenue: subtraction CAPEX, FOM and country specific energy procurement costs
   - Conversion of net revenue per MWh industrial load to net revenue per sector specific final unit of output (with country-specific energy costs and application-specific energy-requirements)
   - Battery capacity: max. 20% of installation's peak load

**Assumptions battery[1]**

- CAPEX: 926 EUR2024/kW
- FOM: 18 EUR2024/kW/y
- Lifetime: 15 years
- Duration: 2h

*Note: Plexos is an energy system modelling software that performs multiple integer linear programming (MILP) optimisation using the Gurobi algorithm.*
*[1] All assumptions taken from NREL 2025 Cost Projections for Utility-Scale Battery Storage: 2025 Update.*
*Abbreviations: FOM…fixed operational and maintenance costs, WACC…weighted average cost of capital*

# 2.

## Technical appendix 2 – Selected regions and energy prices assumptions for industrial bottom-up costs models

# Selection of areas - 2 relevant EU member states and 1 US and Chinese regions for each application

| Application | Relevant region | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | EU | Justification of selection | Source | US | Justification of selection | Source | China | Justification of selection | Source |
| Primary aluminium production | | • Large EU producer, south-eastern EU MS<br>• Large EU producer, large western EU MS | • *International Aluminium – Primary aluminium production* | **Kentucky** | • Largest among two active smelters (220k t/a) | • *Century aluminium – Kentucky plant* | **Inner Mongolia** | • Historically 3rd largest producers, has so called coal-aluminium industrial complex | Agora Energiewende / Agora Industry & regional expert opinion |
| Primary steel production | SE3 | • Largest EU steel producer, existing announcements for H2-DRI-EAF route<br>• Large EU steel producer, first EU H2-DRI-EAF plant expected in 2026 | • *WV Stahl (2025) Statistisches Jahrbuch* | **Indiana** | • Most employees in steel sector in the US | • US Census Bureau – Labour statistics | **Hebei** | • ~200 Mtpa primary crude steel capacity and slowly transitioning to EAF | |
| Steam supply for low T° chemicals | | • Largest EU chemicals producer, largest EU MS<br>• Large EU producer, large SW-EU MS | • *Cefic (2024) Facts and figures* | **Texas** | • Most employees in chemical sector in the US | | **Shandong** | • Province with largest chemical production capacity in China | |
| Paper drying | ITN | • Large EU producer eastern EU MS<br>• Large EU producer, southern EU MS | • *CEPI (2025) Key statistics 2024* | **Georgia** | • Most employees in paper and pulp sector in the US | | **Shandong** | • Biggest pulp pro- and consumer | |
| Battery cell manu-facturing | | • Since 2013 two new battery plants, large central EU MS<br>• Since 2018 two new battery plants, more plants to be finished, eastern EU MS | • *IPCEI (2024) Battery cell production in Europe* | **Michigan** | • Most employees in battery sector in the US | | **Henan** | • Long-term lead in electrode sector in China and willingness to maintain it with policy support | |

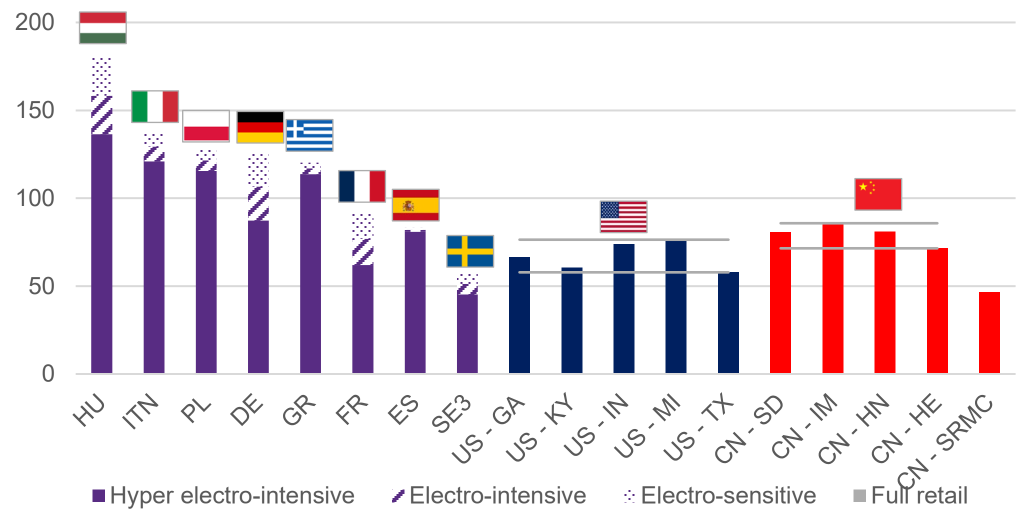


*Abbreviations: MS…Member state, ITN…Italy North (power market bidding zone), SE3…Sweden 3 (power market bidding zone), H2-DRI-EAF…Hydrogen direct reduced iron and electric arc furnace (primary steel production route)*

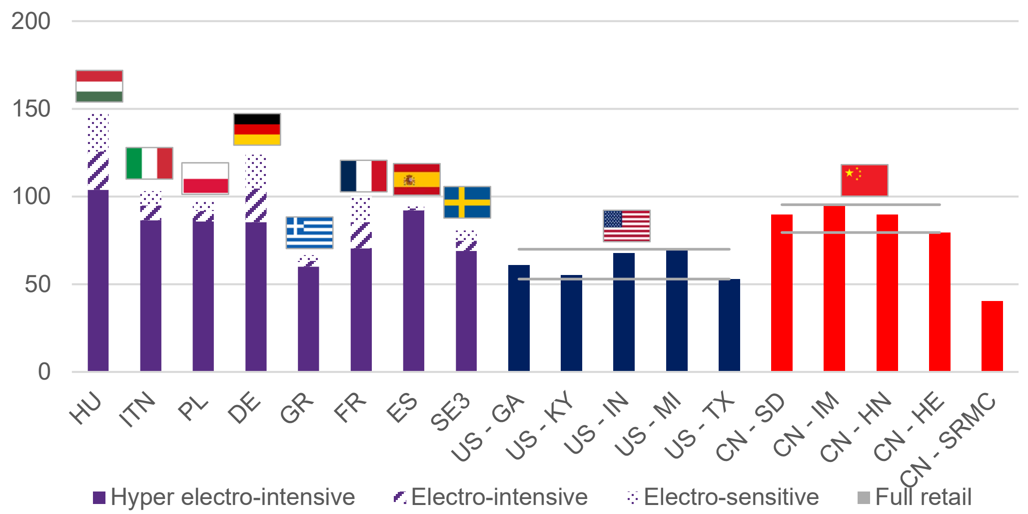
# Electricity prices – Assumptions vary according to the electro intensity of the processes and are based on reference external sources

- **Retail price assumptions:** industrial retail prices are differentiated between hyper electro-intensive, electro-intensive and electro-sensitive. Final retail rates include procurement costs, network costs as well as taxes levies and fees in Europe. For the US and China, we show relevant industrial retail rates which are equivalent to electro-sensitive rates in Europe.
  - For 2024, we rely on publicly available statistics.
  - For 2035 price assumptions for the EU rely on CL scenario modelling for IDDRI-Agora with main inputs from TYNDP24 and WEO24, US prices are based on the projections of industrial retail prices made by the EIA 2025 Energy Annual outlook and Chinese projections are based on AFRY projections.
- **Additional sensitivity China:** Historically, the Chinese government has subsidised coal-fired power generation, and some industrial facilities operate on-site coal plants. To reflect this, a Chinese "coal SRMC" sensitivity is included, assuming industrial users receive electricity at short-run marginal cost.

**Industrial electricity retail price assumptions, 2024, $€_{2024}$/MWh**




**Industrial electricity retail price assumptions, 2035, $€_{2024}$/MWh**

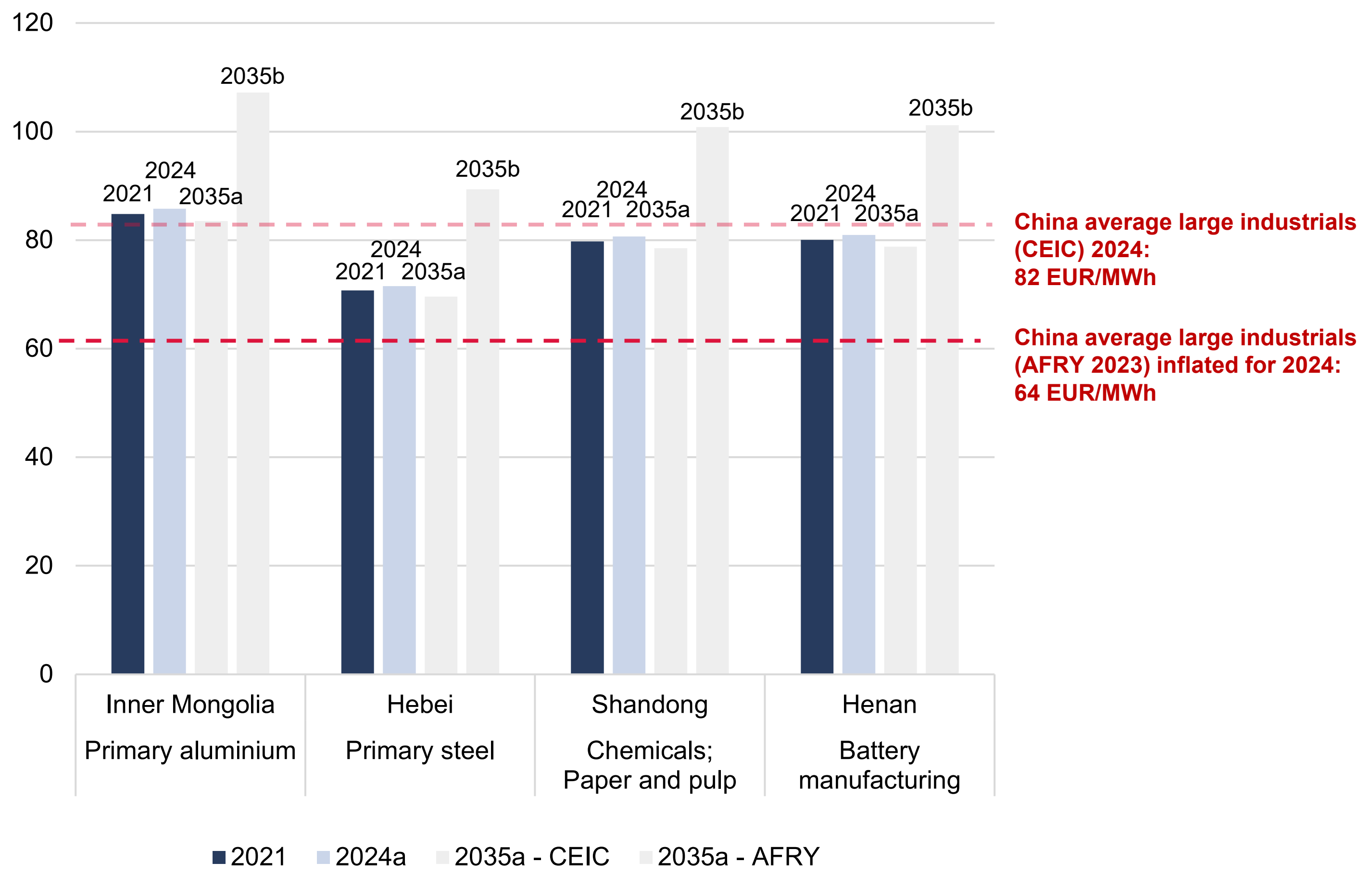



*Sources: CL EU competitiveness gap prices scenario, Eurostat, IEA (2024) World Energy Outlook,, EIA (2025) Annual Energy Outlook, , AFRY (2023) Internationaler Vergleich Industriestrompreise and Energy Market Price,*

***Notes**: EU 2024 procurement costs are based on annual average day-ahead prices, network costs and taxes are from Eurostat non-household consumers with a consumption >150 GWh/a US retail prices are based on to EIA 2024 average US Industrial price converted in EUR/MWh and China retail price Chinese retail rates are based on scholarly work publicly available reports, for more information see Technical Appendix. Retail prices for hyper electro-intensive industries reflect (i) the wholesale price and (ii) rebated non-energy charges. For France, Germany, Poland, and Spain, the rebate is based on the specific national discounts for EIIs. In other countries, an average discount is applied to Eurostat's 2024 data for non-energy charges. Electro-intensive and electro-sensitive industries follow the same methodology, but with half the discount and no discount on non-energy charges, respectively. Projections of electricity prices in the US in 2035 are calculated by applying the growth rate of industrial retail prices from the EIA 2025 Annual Energy Outlook report between 2024 and 2035 to each observed industrial retail price in the states of interest in 2024. Chinese short-run marginal costs are based on historic coal prices as reported on Zhangzou commodity exchange and assume 3 EUR/MWh variable operational costs. Efficiencies represent average between high and low efficiency plants to reflect diverse generation assets. **Abbreviations:** CN…China, GA…Georgia, KY…Kentucky, IN…Indiana, MI…Michigan, TX…Texas, SD…Shandong, IM…Inner Mongolia, HN…Henan, HE…Hebei, SRMC…Short run marginal costs*

# Electricity prices – Electricity costs to 2024 and 2035 are adapted from Chinese provinces data for large industrials in 2021

**Large industrial retail electricity prices China, historical and projections 2021, 2024 and 2035 EUR/MWh(1)**



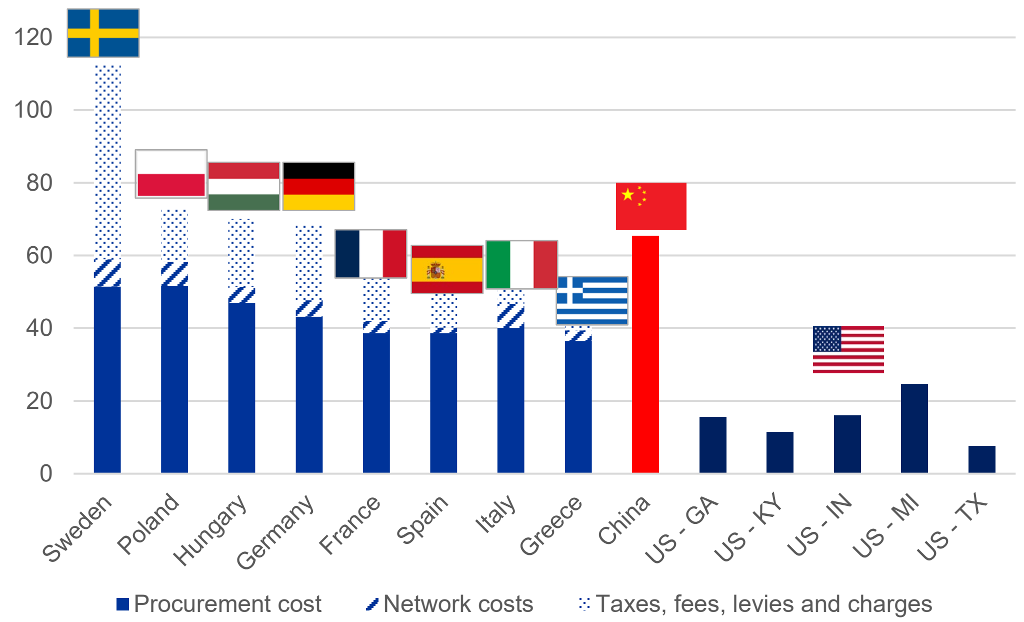

- Provincial electricity prices are derived from a 2024 research paper that sources their prices from latest available data up to 2021 on the official websites of State Grid of all provinces and municipalities.
- Chinese industrial electricity prices comprise 2 components: an energy-based component as well as a power factor clause. The data on the left shows both.
- Based on the data provided until 2021 we use available average price data from 2024 to calculate the average price increase from 2021 to 2024, and public reports for 2035:
  - **Provincial projection 2024** = (average CN electricity price 2024 / average CN electricity price 2021) * provincial price 2021
  - **Provincial projection 2035** = (average CN electricity price projection 2035 / average CN electricity price 2024 (CEIC and AFRY-based) * provincial price projection 2024
- Note, there was no AFRY data for 2021. Thus, 2021 prices cannot be transformed using this series. This yields the following factors
  - 2021 to 2024: 1.01 (CEIC averages)
  - 2024 to 2035a: 0.97 (CEIC average to 2035 projection)
  - 2024 to 2035b: 1.25 (AFRY average to 2035 projection)

*Sources: [1] Qiu et al. (2024) Analysis of Chinas electricity price and electricity burden of basic Industries under the carbon peak target before 2030. CEIC – 36- city price average for large industrial electricity consumers and ; AFRY (2023) Kurzstudie: Internationaler Vergleich von Strompreisen für die Industry*
*Notes: We use ECB exchange rates to transform CNY 2021 electricity prices to nominal EUR 2021 prices.*

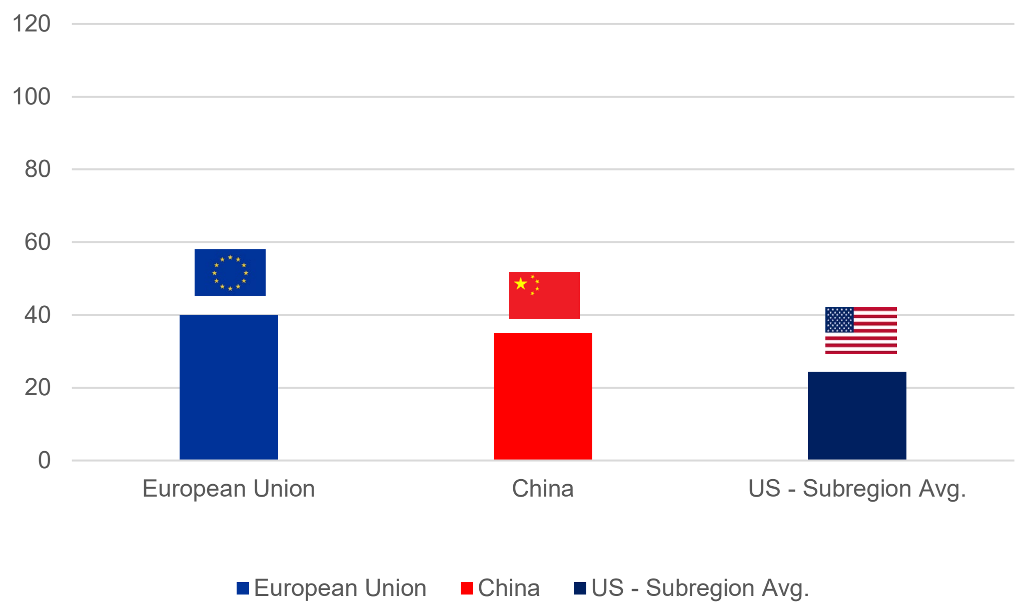
# Natural gas – Current and projected prices for natural gas  from reference sources

- For 2024, we use Eurostat data, “gas price component for non-household users with a consumption between 100 000GJ and 999 999GJ per year”, the highest consumption band with data available for all countries in scope. US prices correspond to the 2024 average US Industrial price converted in EUR/MWh and Chinese prices are based on IEA Q1 2023 Industry end-user prices for natural gas, which we have inflated using China 2024 Inflation consumer price of the World Bank.
- Industrial retail price calculations for 2035 are based on wholesale price projections from the World Energy Outlook 2024 for the EU and China. Industrial retail prices projections in the US are based on the EIA's 2025 Energy Annual Outlook.

**Natural gas retail price assumptions, 2024, EUR/MWh**




**Natural gas retail price assumptions, 2035, EUR/MWh**

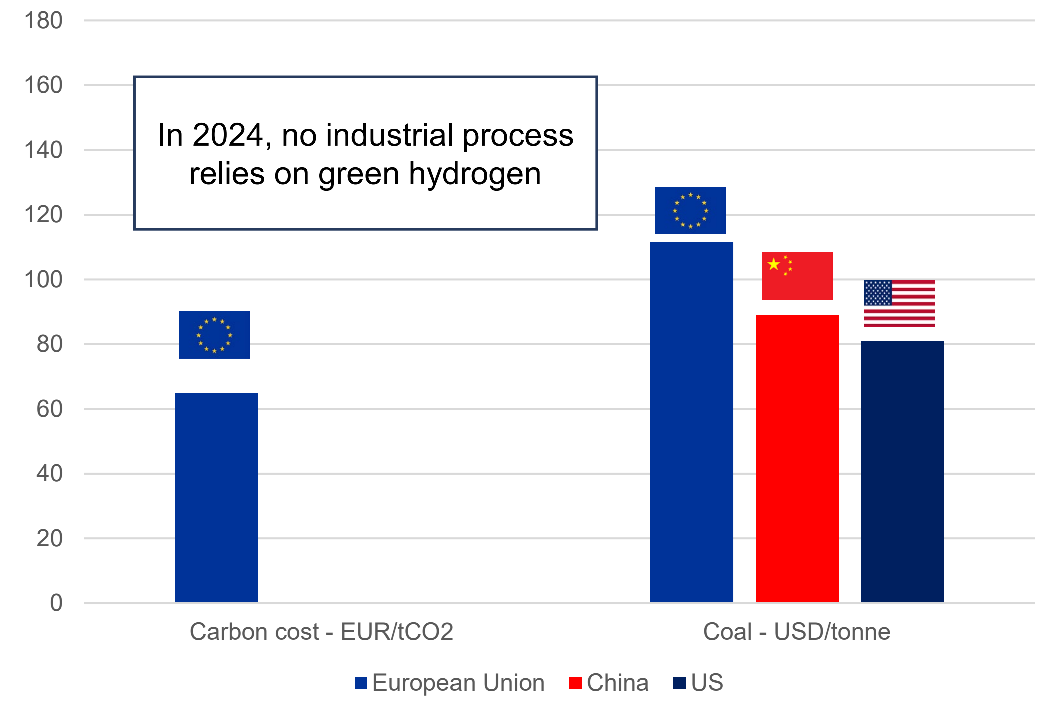



*Sources: Eurostat, IEA (2024) World Energy Outlook., EIA (2025) Annual Energy Outlook, and Energy Market Price,*
*Notes: Projections of industrial natural gas prices in the US for 2035 are calculated by applying the growth rate of industrial retail prices from the EIA 2025 Annual Energy Outlook report between 2024 and 2035 to each observed industrial retail price in the states of interest in 2024. US subregion average represents selected states only.*
*Abbreviations: CN…China, GA…Georgia, KY…Kentucky, IN…Indiana, MI…Michigan, TX…Texas, SD…Shandong, IM…Inner Mongolia, HN…Henan, HE…Hebei, SRMC…Short run marginal costs*

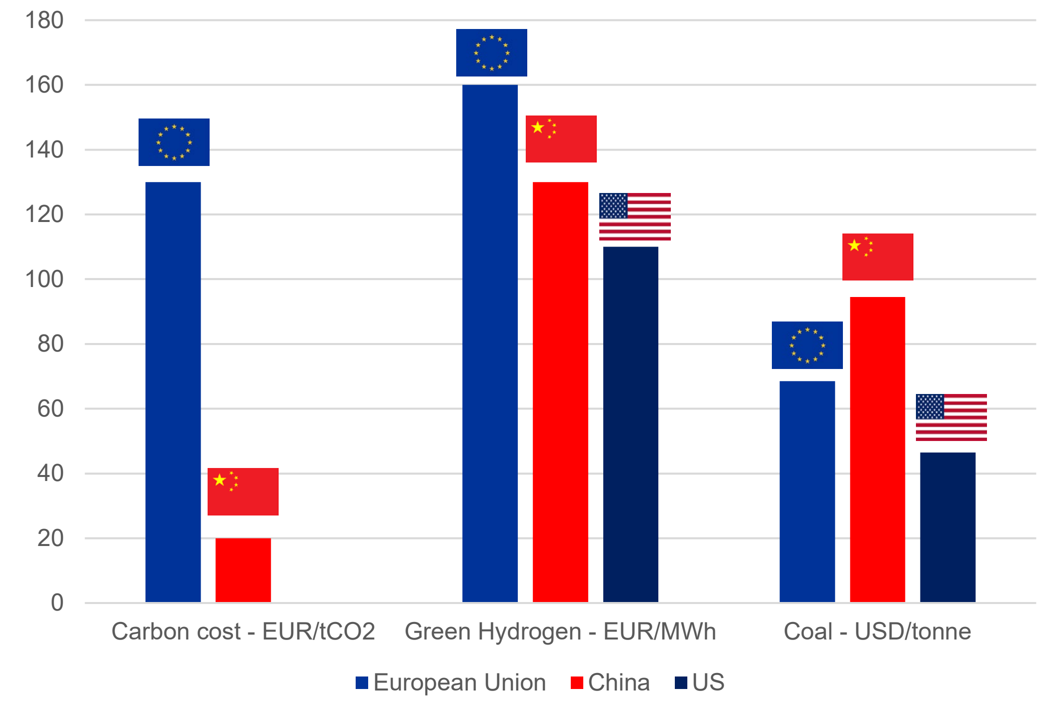
# Other commodities – Current and projected prices for green hydrogen, CO2 prices, and coal are taken from reference sources

- **Coal**: For 2024 we rely on the average EU ETS allowance price and for coal we use Europe coal ARA CIF (Amsterdam-Rotterdam-Antwerpen), China Qinhuangdao yearly average spot prices, including cost and freight (CFR), and US Central Appalachian coal spot price index (FOB).
- **$CO_2$:** For 2024, EU ETS allowance price at 65 EUR/t (average yearly market price). For 2035, EUA price at 130 EUR/t (WEO24 STEPS); China's carbon pricing is applied to industrials at 20 EUR/t (WEO24). No carbon pricing in the US.
- **$H_2$**: prices taken from IEA 2024 Global Hydrogen Review.

**Carbon cost and coal retail price assumptions, 2024, EUR/tCO2 and USD/tonne**




**Carbon cost, green H2 and coal retail price assumptions, 2035, EUR/tCO2, EUR/MWh and USD/tonne**






*Sources*: IEA (2024) World Energy Outlook, IEA (2024) Global Hydrogen Review, Zhengzou Commodity Exchange and Energy Market Price

# 3.

## Technical appendix 3 – Methodology and bibliography for bottom-up costs models

# Scope of models in 2024 and 2035

- We based the calculations of our bottom-up cost models on publicly available sources for each cost component and validated the key assumptions and results through interviews with industry stakeholders. The scope of the different cost components in 2024 and 2035 is explained below:

**Cost components differentiated across time**

| | 2024 | 2035 |
|---|---|---|
| **Energy costs** | • Gross prices for industrials (procurement costs, network charges, levies and taxes) based on external sources (see Technical appendix 2)<br>• Network and tax/levy rebates in EU and Indirect $CO_2$ cost compensation in relevant EU MS (emission costs from power generation) | • Gross prices for industrials (procurement costs, network charges, levies and taxes) based on reference sources (see Technical appendix 2)<br>• Network and tax/levy rebates in EU |
| **Carbon costs** | • EU ETS 1 cost (scope 1): average 2024 EUA price of 65 EUR/t<br>• Free allowances for relevant industries<br>• No emission costs in China and US | • Full EU ETS 1 cost (Scope1): 130 EUR/t (WEO2024)<br>• Chinese ETS cost for industrials (scope1): 20 EUR/t (WEO2024)<br>• CBAM: Direct (scope 1) / indirect (scope 2) for China and US |
| **+ Flexibility revenues from battery** | | **Flexibility revenues**<br>• For EU countries, flexibility revenues from on-site battery on electrified processes |

**+ Cost components assumed constant across time**

**Constant over time**

| | | |
|---|---|---|
| **CAPEX[1]**<br>Asset investment costs, integration costs, per t of final output, non-differentiated across regions, no subsidies | **Non-energy OPEX**<br>Differentiated across regions (EU, US and China) | **Transport costs**<br>Costs to ship to the EU per ton of final output |
| **Labour costs**<br>Differentiated across regions (EU, US and China) | **Financing costs**<br>Differentiated across regions (EU, US and China) | **Raw material costs**<br>(Raw material costs per ton of final output, differentiated per region) |

*Note: [1] Constant CAPEX is assumed in relation to time (i.e., no learning effects between 2024 and 2035). However, we distinguish between greenfield investment costs for fossil-based processes and decarbonised/electrified processes. Non-differentiated assumes that relevant cost component (capex, raw material requirement, energy requirement and emission intensity) is held constant across regions / timeframes due to limited data availability.*

*Abbreviations: MS…Member states, CBAM...Carbon border adjustment mechanism, ETS…Emissions trading system*

# Capital costs and financing

**We base our calculations on publicly available sources as follows:**

**Greenfield capital cost assumptions**

- Capital costs expenditure represent the overnight capital costs to build the installation on a greenfield site. Only incumbent primary steel production considers a retro-fit. We consider an EU average installation and thus show estimates rather than real site-level data. Due to limited data availability greenfield capital costs are not differentiated between regions.
- CAPEX are annualised using lifetimes for installations from literature (see right) and divided by output production in a year.

**Financing costs**

- We differentiate Weighted Average Cost of Capital per sector and per world region, based on data published by Damodaran et al. (here).
- For China, we assume that government guarantees or grants reduce the private investors' Damodaran et al.-based WACCs by a factor of two.

| Industrial application | Sources for CAPEX |
|---|---|
| **Steam cracking for ethylene production** | • Oliveira and Van Dril (2021) Decarbonisation options for large volume organic chemicals production<br>• Industry interview (2023 - confidential) |
| **Low-temperature chemicals steam supply** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung - steam generation for paper and<br>• Agora Industry, FutureCamp, Wuppertal Institute (2022): Power-2-Heat: Direct electrification of industrial process heat - transforation cost calculator |
| **Ammonia production** | • Industry interview (2023 - confidential) |
| **Primary steel production** | • Agora Industry, FutureCamp, Wuppertal Institut und Ecologic Institut (2021): Klimaschutzverträge für die Industrietransformation. |
| **Secondary steel production** | |
| **Post-production heating** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Primary aluminium smelting** | • European Aluminium (2023) Science-based decarbonisation pathways for the European aluminium industry and<br>• Boudreau et al. (2024) Techno-economic assessment of aluminum as a clean energy carrier to decarbonize remote industries |
| **Secondary aluminium melting** | • European Aluminium (2023) Science-based decarbonisation pathways for the European aluminium industry |
| **Alumina digestion** | • European Aluminium (2023) Science-based decarbonisation pathways for the European aluminium industry |
| **Container glass melting** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Flat glass melting** | |
| **Cement clinker burning** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung for rotary kiln and<br>• IEAGHG (2013) Deployment of CCS in the cement industry for raw material and cement milling |
| **Paper drying** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Milk powder production steam supply** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Data storage / AI computation** | • Turner and Townsend (2024) Data centre cost trend |
| **Cell manufacturing** | • Eurelectric (2025)The new industrial age - calculations are based on Hungary case study |

# Labour cost and non-energy opex

**We base our calculations on publicly available sources as follows:**

**Non-energy OPEX (incl. labour)**

- We first split labour costs and other fixed O&Ms based on EU literature (see table on the right).
- For sectors where non-energy OPEX did not include labour costs**,** labour costs are approximated by dividing total production in a representative country by number of sectoral employees and average sectoral compensation from Eurostat.

**Labour cost differentiation**

- For the five case study countries labour costs and non-energy OPEX were differentiated by region.
- In a first step the labour cost share in the non-energy OPEX aggregate value was approximated using representative splits observed in Europe as reported by literature.[2]
- In a second step, based on a data set of the International Labour Organisation (ILO)[1] that includes average monthly earnings by activity for EU, US and China a transformation variable was calculated. Based on this, EU labour cost estimations were adapted for China and the US.

| Industrial application | Sources for non energy OPEX |
|---|---|
| **Steam cracking for ethylene production** | • Industry interview (2023 - confidential) |
| **Low-temperature chemicals steam supply** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung - steam generation for paper and<br>• Agora Industry, FutureCamp, Wuppertal Institute (2022): Power-2-Heat: Direct electrification of industrial process heat - transforation cost calculator |
| **Ammonia production** | • Industry interview (2023 - confidential) |
| **Primary steel production** | • Agora Industry, FutureCamp, Wuppertal Institut und Ecologic Institut (2021): Klimaschutzverträge für die Industrietransformation. |
| **Secondary steel production** | |
| **Post-production heating** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Primary aluminium smelting** | • Boudreau et al. (2024) Techno-economic assessment of aluminum as a clean energy carrier to decarbonize remote industries |
| **Secondary aluminium melting** | • Kürschner et al. (2021) Branchenanalyse AluminiumIndustry |
| **Alumina digestion** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung (excluding labour) |
| **Container glass melting** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Flat glass melting** | • Rahmat et al. (2024) Power to X for sustainable glass production a techno-economic and life cycle assessment<br>• BV Glas Jahresbericht 2023 |
| **Cement clinker burning** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung for rotary kiln and<br>• IEAGHG (2013) Deployment of CCS in the cement industry for raw material and cement milling |
| **Paper drying** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung<br>• Die Papierindustrie - Leistungsbericht 2024 |
| **Milk powder production steam supply** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung (excluding labour cost) |
| **Data storage / AI computation** | • Bieser and Kunbaz (2018) The role of maintenance in data centres: a case study |
| **Cell manufacturing** | • Eurelectric (2025) The new industrial age - calculations are based on Hungary case study |

*Note: [1] ILO data base can be found here [2] Representative labour cost shares in non-energy OPEX are from the Energy Efficiency and Conservation Authority (EECA) Non-fuel operating cost tables*

# Raw material and transport costs

**We base our calculations on publicly available sources as follows:**

**Raw material costs**

- Raw material requirements per unit of output are as reported in EU literature. There is no differentiation per region.
- Raw material prices are differentiated per region (EU, US and China) for each case study sector based on regional price quotas obtained from available market data.

**Transport costs**

- For US and Chinese production, we include transport costs per final output to Europe based on a model of Panamax dry-bulk carrier with a cargo capacity of 80 000mt as found in Boudreau et al. (2024).[1]
- Carrier distances are based on Houston to Rotterdam for US production and Shanghai to Rotterdam for European production.

| Industrial application | Sources for raw material costs (requirements and prices) |
|---|---|
| **Steam cracking for ethylene production** | • Ray et al. (2014) Feedstock for the petrochemical industry<br>• Ren et al (2006) Olefines from conventional and heavy feedstocks: energy use in steam cracking and alternative processes<br>• JRC (2017) best available technologies: reference document for the production of large volume organic chemicals |
| **Low-temperature chemicals steam supply** | • Not applicable (steam as product) |
| **Ammonia production** | • Natural gas/hydrogen and nitrogen (air) forms basis of ammonia |
| **Primary steel production** | • Agora Industry, FutureCamp, Wuppertal Institut und Ecologic Institut (2021): Klimaschutzverträge für die Industrietransformation. |
| **Secondary steel production** | |
| **Post-production heating** | • Crude steel is reheated |
| **Primary aluminium smelting** | • ThyssenKrupp – How is aluminium made?<br>• Boudreau et al. (2024) Techno-economic assessment of aluminum as a clean energy carrier to decarbonize remote industries<br>• IMARC |
| **Secondary aluminium melting** | • IMARC |
| **Alumina digestion** | • Rio Tinto Fact Book 2023 |
| **Container glass melting** | • EC (2017) Cumulative cost assessment of the EU glass industry |
| **Flat glass melting** | • Britglass – Raw materials and costs flat glass industry<br>• BV Glas Broschüre Glas – Ein Werksstoff mit vielen Talenten<br>• IMARC |
| **Cement clinker burning** | • Agora Industry, FutureCamp, Wuppertal Institut (2022): Carbon Contracts for transforming industry: Calculator for estimating the transformation costs of climate-friendly cement production |
| **Paper drying** | • Przybysz et al. (2018) Yield of pulp, dimensional properties of fibers, and properties of paper produced from fast growing trees and grasses<br>• ERCST EU ETS softwood prices |
| **Milk powder production steam supply** | • Not applicable (steam as product) |
| **Data storage / AI computation** | • Shehabi et al. (2024) United states data center energy usage report 2024<br>• Berliner Wasserbetriebe (2024) Gebührenblatt 2024 |
| **Cell manufacturing** | • Eurelectric (2025)The new industrial age - calculations are based on Hungary case study |

*Note: [1] Boudreau et al. (2024) Techno-economic assessment of aluminum as a clean energy carrier to decarbonize remote industries*
*Abbreviations: DWT…deadweight tonnage*

# Energy OPEX and carbon costs

**We base our calculations on publicly available sources as follows:**

**Energy requirements**

- Energy needs for relevant energy carriers are based on EU literature and Expert interviews (see right), not differentiated across regions due to lack of data

**Energy costs**

- Energy costs are differentiated per region:
  - Electricity costs are used at member-state level in the EU, state level in the US and provincial level in China. They are retail prices for industrials.
  - Natural gas prices are used at national level for all regions and include retail charges for industrials.
  - Coal prices are used at national level at wholesale prices, due to the fact that transport costs from trading hubs (e.g. ARA) differ.
  - Hydrogen prices are used at world region level

**Carbon emissions**

- Application specific scope 1 emissions are based on publicly available EU reports and Expert interviews and not differentiated across regions (see right)

| Industrial application | Sources for energy requirements and scope 1 emissions |
|---|---|
| **Steam cracking for ethylene production** | • Rivera and Boulamanti (2016) Production costs from energy intensive industries in the EU and third countries;<br>• Ren et al (2006) Olefines from conventional and heavy feedstocks: energy use in steam cracking and alternative processes;<br>• JRC (2017) best available technologies: reference document for the production of large volume organic chemicals;<br>• Industry interview (2023 - confidential) |
| **Low-temperature chemicals steam supply** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung - steam generation for paper<br>• Agora Industry, FutureCamp, Wuppertal Institute (2022): Power-2-Heat: Direct electrification of industrial process heat - transformation cost calculator |
| **Ammonia production** | • IEA (2023) Towards hydrogen definitions based on their emission intensity<br>• Industry interview 2023 (confidential) |
| **Primary steel production** | • Agora Industry, FutureCamp, Wuppertal Institut und Ecologic Institut (2021): Klimaschutzverträge für die Industrietransformation.<br>• Industry interview (2024) |
| **Secondary steel production** | |
| **Post-production heating** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Primary aluminium smelting** | • European Aluminium (2023) Science-based decarbonisation pathways for the European aluminium industry<br>• Boudreau et al. (2024) Techno-economic assessment of aluminum as a clean energy carrier to decarbonize remote industries<br>• Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung<br>• Industry-interview (2025) |
| **Secondary aluminium melting** | • European Aluminium (2023) Science-based decarbonisation pathways for the European aluminium industry<br>• Dardor et al. (2024) Modelling the effect of future uncertainty in energy prices on decarbonization pathways for secondary aluminium production |
| **Alumina digestion** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Container glass melting** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung<br>• Industry-stakeholder interview (2025) |
| **Flat glass melting** | |
| **Cement clinker burning** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung<br>• Industry interview (2025) |
| **Paper drying** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung<br>• Industry-stakeholder interview (2025) |
| **Milk powder production steam supply** | • Fleiter et al. (2023) CO2-neutrale Prozesswärmeerzeugung |
| **Data storage / AI computation** | • Shehabi et al. (2024) United states data center energy usage report 2024 |
| **Cell manufacturing** | • Eurelectric (2025) The new industrial age<br>• Kuki et al. (2025) Energy Use and Environmental Impact of Three Lithium-Ion Battery Factories<br>• Degen (2023) Lithium-ion battery cell production in Europe |

*Note: Scope 1 emissions include direct greenhouse gas (GHG) emissions from sources that are owned or controlled by the organization, such as emissions from fuel combustion in company vehicles, boilers, or onsite manufacturing processes. Scope 2 emissions are indirect GHG emissions from the generation of purchased electricity, steam, heating, or cooling consumed by the organization.*
*Abbreviations: ARA…Amsterdam-Rotterdam-Antwerpen*

# CBAM charges estimates

## Our assumptions for sensitivities to CBAM costs

$$Scope\ 1 = \big((EU\ domestic\ CO_2\ price) - (Foreign\ CO_2\ price)\big) \times \boldsymbol{installation\ emission\ factor}$$

**+**

$$Scope\ 2 = EU\ domestic\ CO_2\ price \times Foreign\ average\ power\ emission\ factor \times \boldsymbol{installation\ power\ factor}$$

**Direct emission (scope 1): CBAM is mainly driven by carbon cost differences**

- To calculate the difference in regional carbon costs by 2035 we rely on an assumption in line with WEO24 STEPS ( EU: 130 €/t$CO_2$, CN: 20 €/t$CO_2$ and US: 0 €/t$CO_2$)
- Installation-specific power factors are based on our bottom-up cost model assumptions

**Indirect emissions (scope 2): we assume average foreign power factors**

- We rely on the IEA WEO24 STEPS scenario assumption of decreasing emissions in industrialised power systems of around 30% until 2035
- Installation-specific power factors are based on our bottom-up cost model assumptions and represents electricity needs of the imported product

**Our assumptions reflect the theoretical impacts of the CBAM Regulation Delegated acts published in December 2025:**

- **The use of default values for calculating CBAM duties is disincentivised (mark-ups)**
  - We assume actual embedded emissions are the basis for CBAM duty calculations
- **Embedded scope 2 emissions are determined using average $CO_2$ emission factor of power generation**
  - We replicate that methodology for CBAM costs on scope 2 emissions
- **An extension of CBAM to downstream products and additional measures will be implemented to avoid circumvention**
  - We assume CBAM applies to all embedded emissions in imported goods

*Sources: EC (2025) Report on the application of the regulation on CBAM (available here)*

# CBAM charges estimates

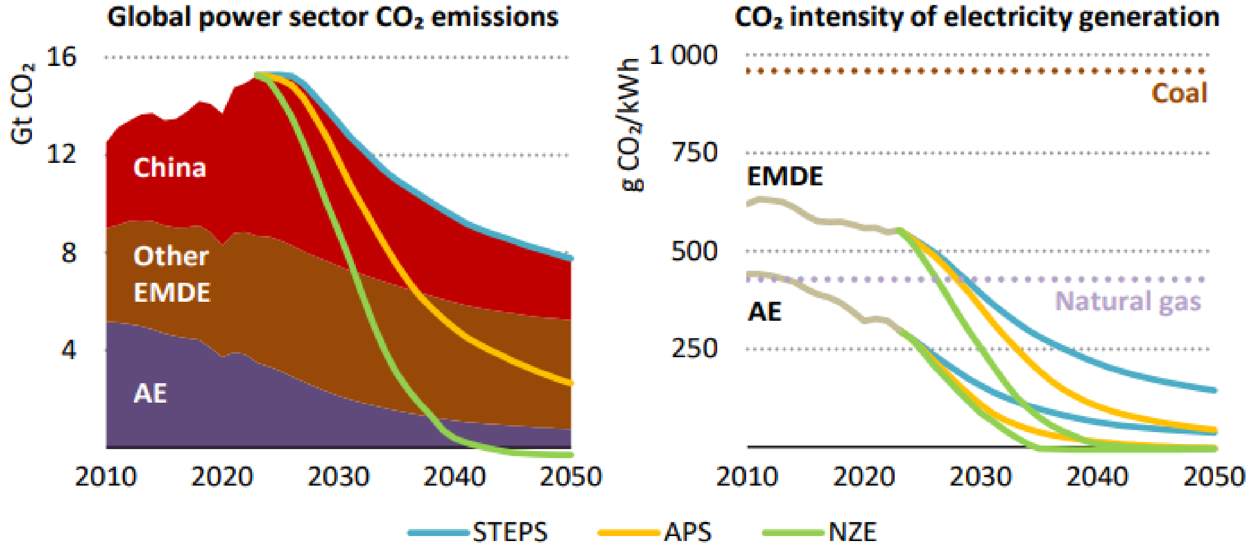
**CBAM on scope 1 emissions**

- The CBAM charge is ((EU domestic carbon price) – (foreign carbon price)) * (installation specific emission)

**CBAM on scope 2 emissions**

- The CBAM charge is calculated using the foreign average power system emission intensity times the EU ETS allowance price.
- For 2024, we used the IEA and Ember & Energy Institute (2025), Statistical Review of World Energy, as processed by Our World in Data.
- From the 2024, power system emission intensity, we apply a decrease based on WEO24 STEPS's power sector emission forecast in advanced economies:
  - **US**: as of 2023 the average power system emission intensity is at 0.36 tCO2/MWh. Emission intensity for 2035 results in: 0.36*(1 - 30%) = ~0.25 tCO2/MWh
  - **China**: as of 2024 the emission intensity is at 0.56 tCO2/MWh. Emission intensity for 2035 results in: 0.56*(1 – 30%) = ~0.4 tCO2/MWh

**Global power sector CO2-emissions and –intensity of electricity generation by region and WEO24 scenario, 2010-2050**




*Notes: AE… Advanced economies; EMDE… Emerging markets and developing economies*

# Free allowances – Free allowances for 2024 are calculated based on benchmarks published by the EC

**Based on EU delegated regulation, we estimate the free allocation of emission allowances. In practice, the historic installation specific production impacts allocation, which is disregarded in our calculation:**

$$Free\ allocation = Product\ benchmark \times yearly\ reduction\ factor \times CO_2\ price$$

- The product benchmark is based on publications EU Delegated Regulation 2019/331 between 2021 and 2030
- The yearly reduction factor is based on the same publication and assumes the highest yearly reduction factor
- Finally, we estimate the value of free allocations based on the observed 2024 EUA price
- In practice, the installation specific allocation of free allowances is also impacted by the historic production volumes. Decreasing production in one year would result in a reduction of allocation in the following years. We disregard this mechanic and assume a constant production rate.

| | Emission factor 2024 ($tCO2_{eq}/t_{production}$) *European Commission* | | | |
|---|---|---|---|---|
| **Application** | *Process* | *Product benchmark* | *Reduction factor* | *2024* |
| Primary aluminium | Smelter | 1.514 | 0.95 | 1.44 |
| Primary aluminium | Anodes | 0.324 | 0.95 | 0.31 |
| Primary aluminium | Total | | | **1.75** |
| Paper | Coated/uncoated fine paper | 0.318 | 0.95 | **0.30** |
| Primary steel - BOF | | 1.328 | 0.95 | **1.27** |
| Steam for low-temp. | Fuel benchmark | 56.1 | 0.95 | **0.14** |

**Source:** *COMMISSION DELEGATED REGULATION (EU) 2019/331*

# ICCC – ICCC in 2024 for EU electricity costs is computed using emission factors published by the EC for the Default methodology

**Based on state aid publications we approximate possible industrial indirect CO2 cost compensation using the following formula:**

$$Power\ price\ reduction = aid\ intensity \times CO_2\ price \times \mathbf{emission\ factor}$$

- For 2024, we rely on the default approach and use emission factors as published in the European Commission communication (2021/C 528/01)
- We use an Aid intensity of 75% in line with the same source
- For 2035, we use a sensitivity considering the emission factor would decrease in line with past trends

| | **Emission factor 2024 (*tCO2eq/MWh*)** *European Commission* |
|---|---|
| Methodology | *Default approach* |
| France | **0.44** |
| Germany | **0.72** |
| Poland | **0.81** |
| Spain | **0.53** |
| Greece | **0.73** |
| Italy | **0.7** |
| Sweden | (No scheme) |
| Hungary | (No scheme) |

**Sources**: Communication from the Commission supplementing the Guidelines on certain State aid measures in the context of the system for greenhouse gas emission allowance trading post-2021 (2021/C 528/01) and state aid decisions: France: SA.63404, Greece: SA.103180, Germany: SA.100559, Italy: SA.60787, Poland: SA.64719, Spain: SA.100004

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