

Integrating Carbon Accounting into Cost Estimation for IT Services, Hardware Systems, and AI Workloads

Updated full-lifecycle methods, AI case studies, and decision support

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Outline

1. Why carbon and AI matter now
2. LCA framework and recent calculator updates
3. Hardware end-of-life estimation
4. **Full-lifecycle AI carbon estimation**
5. Cases, reduction levers, and decision support

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Carbon Becomes a Decision Variable

Carbon footprint

Greenhouse gas emissions associated with a system across production, transportation, operation, and end of life.

Carbon cost

A financial value created by applying a carbon price or internal fee to the lifecycle footprint.

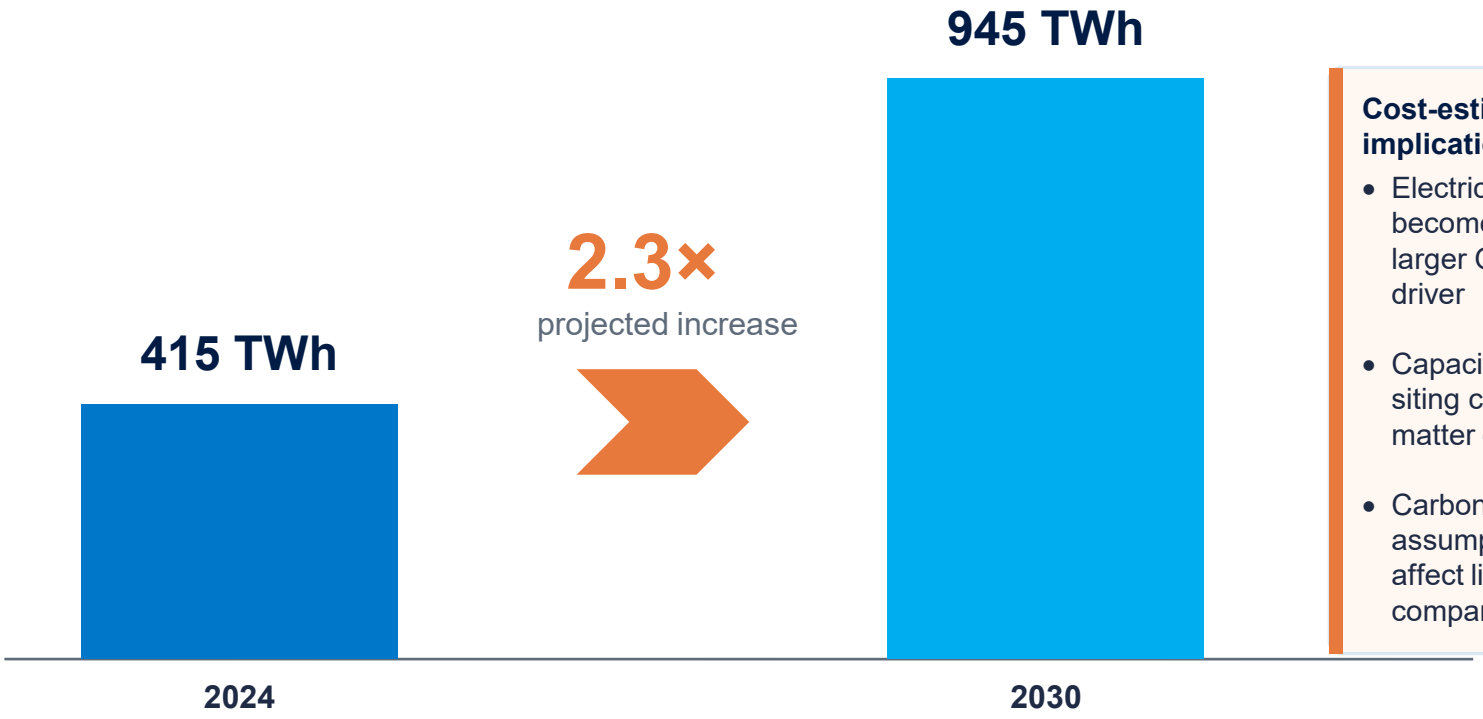
Engineering decision

A common trade space for direct cost, carbon cost, performance, schedule, and risk.

The goal is not carbon reporting alone. The goal is better engineering choices.

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Why AI Carbon Estimation Matters Now



Cost-estimating implication

- Electricity becomes a larger O&S driver
- Capacity and siting choices matter earlier
- Carbon assumptions affect lifecycle comparisons

https://www.iea.org/reports/energy-and-ai/executive-summary

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Why Carbon Matters to Cost Engineers

Energy efficiency	Reduces operating expense and operational emissions
Location and timing	Change both electricity cost and grid carbon intensity
Internal carbon price	Converts emissions into a comparable financial consequence
Lifecycle visibility	Prevents low-price options from hiding upstream or downstream impacts

Carbon information is most useful when it changes a decision.

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From Reporting Categories to Engineering Lifecycle Decisions

Previous focus: Scope 1 / 2 / 3

- Excellent for corporate inventories
- Organized by ownership and value-chain responsibility
- Less direct for component, logistics, and design trade studies



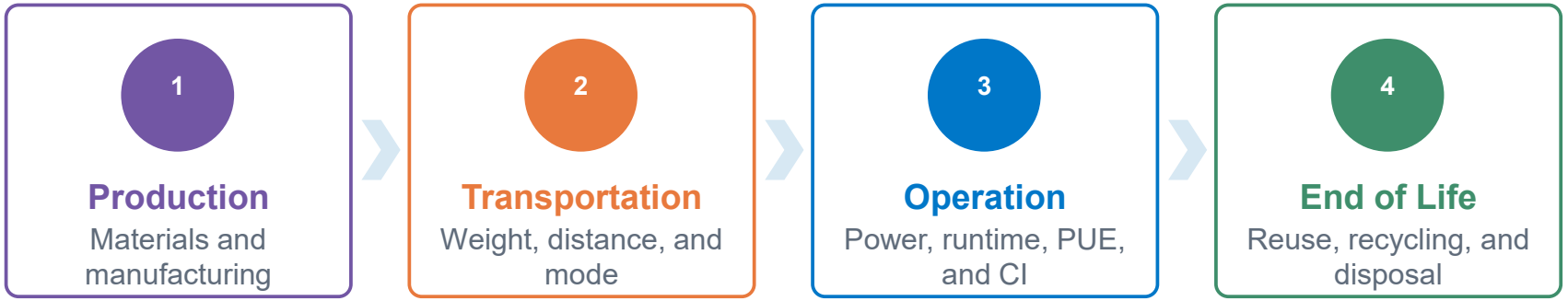
Current focus: LCA stages

- Production / embodied
- Transportation
- Operation / use phase
- End of life

LCA maps more directly to engineering levers.

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Integrated LCA Carbon-Cost Framework



Total lifecycle emissions → carbon cost → engineering trade study

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What Has Changed Since the Previous Version?

Hardware update

- Added explicit end-of-life estimation
- Recycling, reuse, landfill, and incineration pathways
- Treatment and transport emissions
- Recycling and reuse credits

AI update

- Five-component full-lifecycle model
- Allocated transportation and EOL
- Training and inference separated
- Cooling explicitly captured through PUE

Decision-support update

- Real lifecycle cases
- Sensitivity and reduction levers
- Functional-unit normalization
- Illustrative carbon-cost trade study

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IT Services

Operational and transportation emissions for infrastructure services

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IT Carbon Calculator: Infrastructure Service View

Operational emissions

- IT power × runtime
- PUE includes cooling and facility overhead
- Grid and on-site energy carbon intensity

Transportation emissions

- Hardware shipment weight
- Distance and transport mode
- Amortized to a reporting period when needed

Section Name	Input Field	Units
Transportation Emissions		
Shipped Weight	0.03	tonnes
Monthly Commute Length	**8,668.22**	km
Operational Emissions		
Monthly On-site Energy Production	0.00	kWh
On-site Carbon Intensity	300.00	
Carbon Intensity and Price Model	Jurisdictions	
Jurisdictions	US average	
Hours of Use Per Month	672.00	Hours
IT Equipment Utilization	41.00%	%
ICT Power Rating Model	Known Amount	
Known ICT Power Rating	1.00	kW
Monthly Facility Energy Draw Model	Known PUE	
Site PUE	1.580	
Quantity Deployed	5.00	
Estimate Server Energy Consumption	400.00	W
Power Load	50.00	kW

One infrastructure calculation can supply shared inputs to the AI calculator.

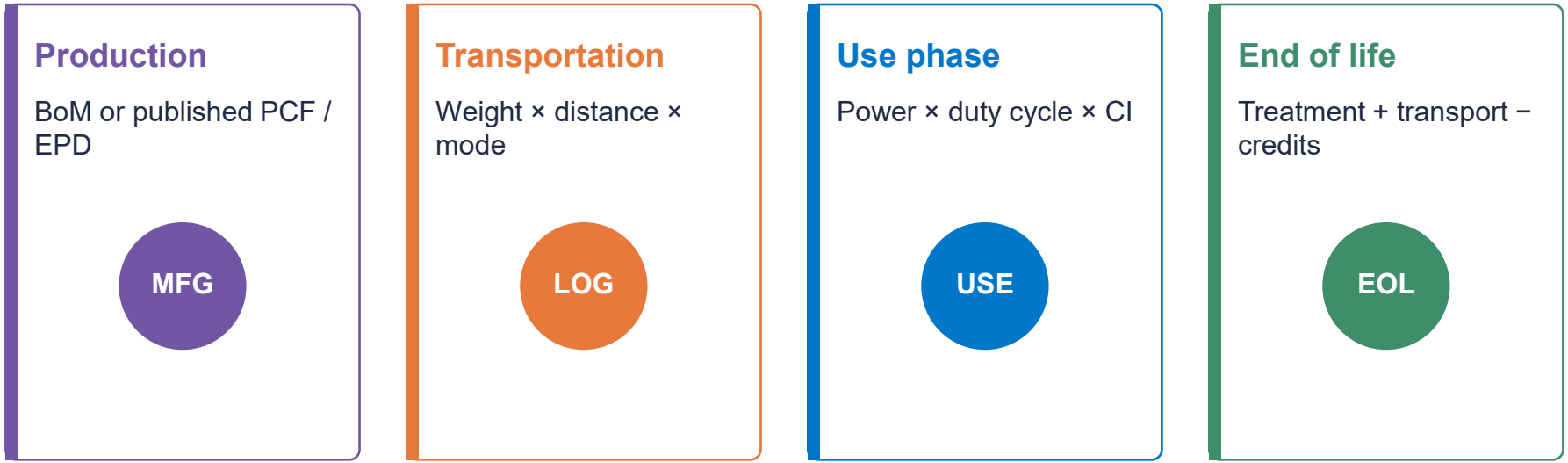
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Hardware

Production, transportation, use phase, and end-of-life updates

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Hardware Carbon Calculator — Updated Lifecycle Coverage



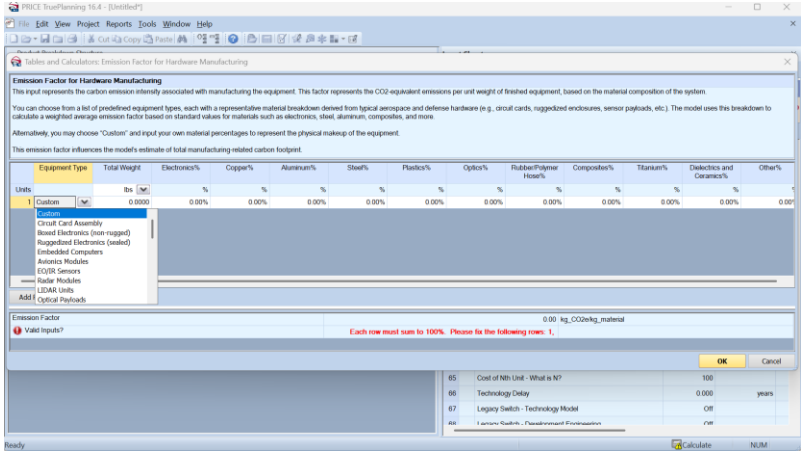
The calculator can start with screening defaults and mature toward supplier- and program-specific data.

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Hardware Production (Embodied) Emissions

$$CO_2e_{prod} = \frac{\sum_m mass_m \, EF_m}{1000}$$

- **Data pathways**
  - Bottom-up bill of materials
  - Published PCF or EPD for a comparable product
- **Key inputs**
  - Equipment type and weight
  - Material or component breakdown
  - Emission factors by material or subsystem
- **Output**
  - tCO2e per device or system



Production | Transportation | Use / Operation | End of Life

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Hardware Production (Embodied) Emissions

Emission Factors

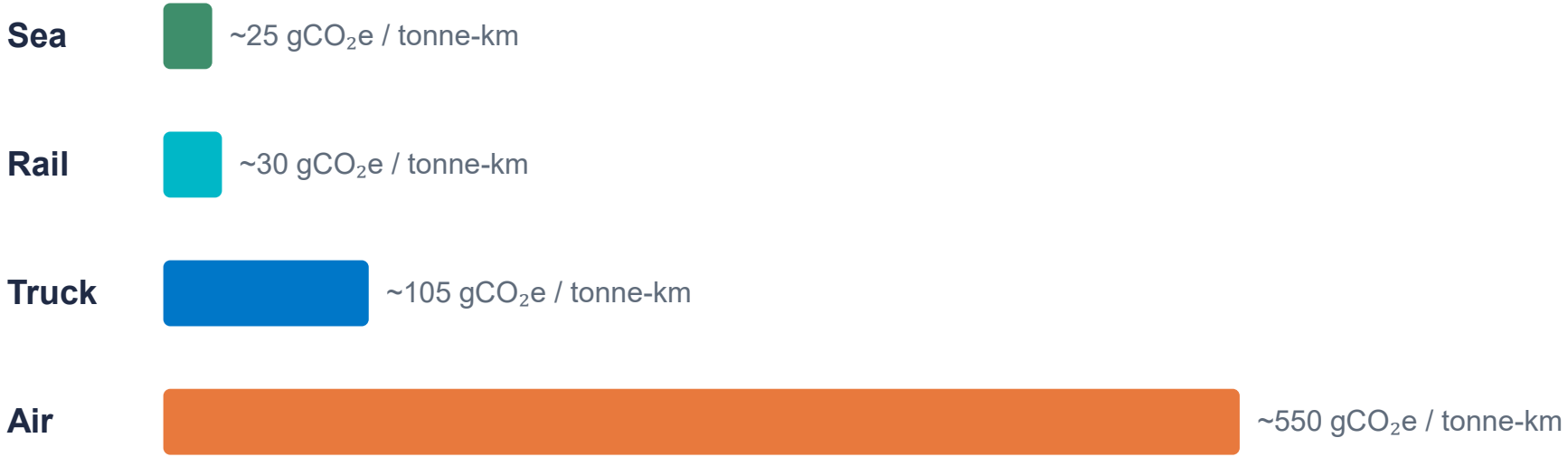
- Emission factors derived from ***ecoinvent, Climatiq,*** *Yulex…etc*
- Key factors: kg CO_2e per kg of aluminum, steel, plastics, copper, and composites.

Material	Emission Factor (kg CO_2e / kg material) - Average global	Data Link
Aluminum	8.243	Climatiq-Aluminum
Electronics	25	Maxey Moverley
Copper	2.886	Climatiq-Copper
Steel	1.4	SustainableShips
Plastics	3.165	Climatiq-Plastics
Optics (Glass)	1.437	Climatiq-Glass
Composites (CFRP / aerospace grade)	50	Das et al. (2016), "LCA of carbon fiber composites
Titanium	17	California Metal
Rubber/Polymer hose	5.55	YULEX Climatiq-Rubber
Dielectric/ceramic components	1.22	https://www.sciencedirect.com/science/article/abs/pii/S0955221912000817
Other (avg)	3.0	

Production | Transportation | Use / Operation | End of Life

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Hardware Transportation: Mode Can Dominate the Result



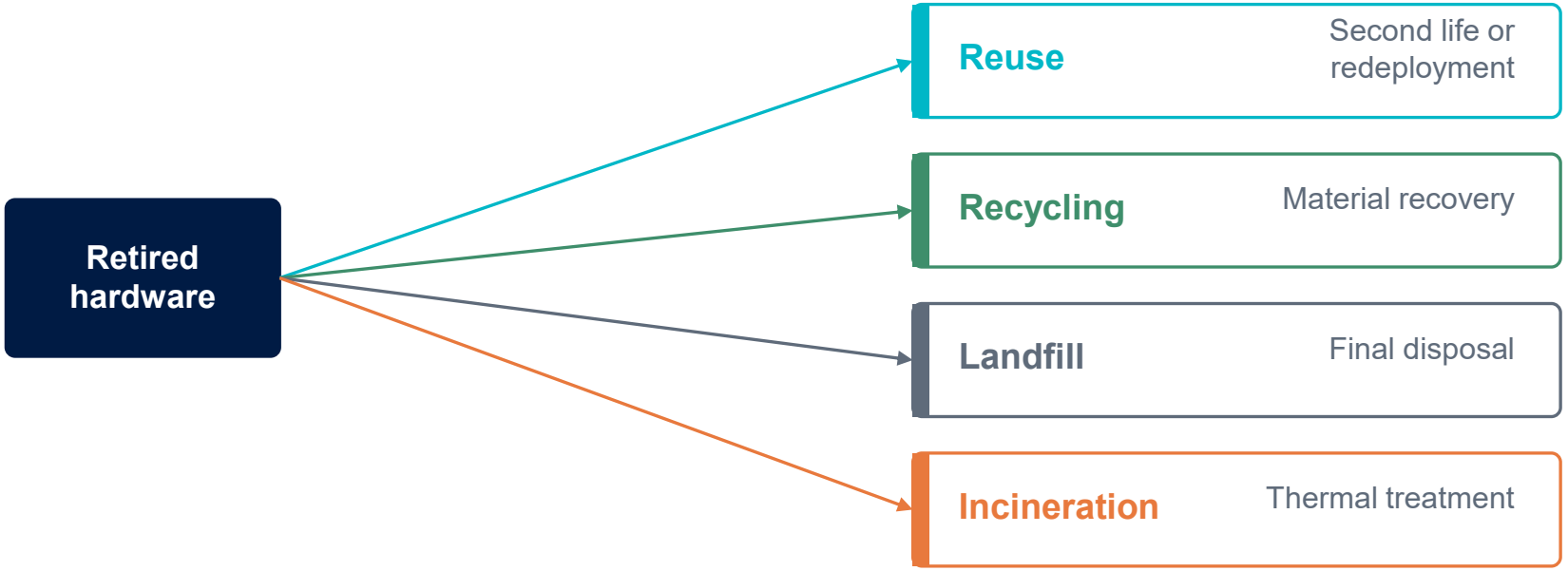
Illustrative midpoints from the mode ranges used in the calculator.

$$CO_2e_{trans} = \frac{\sum_i W_i D_i EF_{mode,i}}{1000}$$

Production | **Transportation** | Use / Operation | End of Life

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Hardware End-of-Life Update: Four Treatment Pathways



Model treatment emissions, transport to the EOL facility, and avoided-emission credits under a consistent system boundary.

Production	Transportation	Use / Operation	End of Life

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Hardware EOL: Equation, Inputs, and Output

$$CO_2e_{EOL,net} = \frac{CO_2e_{treat} + CO_2e_{transport} - Credit_{recycle} - Credit_{reuse}}{1000}$$

Treatment inputs

- Hardware mass
- Pathway shares
- Emission factor by pathway

Transport inputs

- Distance to recycler / disposal site
- Freight mode and factor
- Packaging or shipment weight

Credit inputs

- Recovered material credit
- Reuse / life-extension credit
- Credit method and system boundary

Output: net hardware EOL emissions in tCO2e

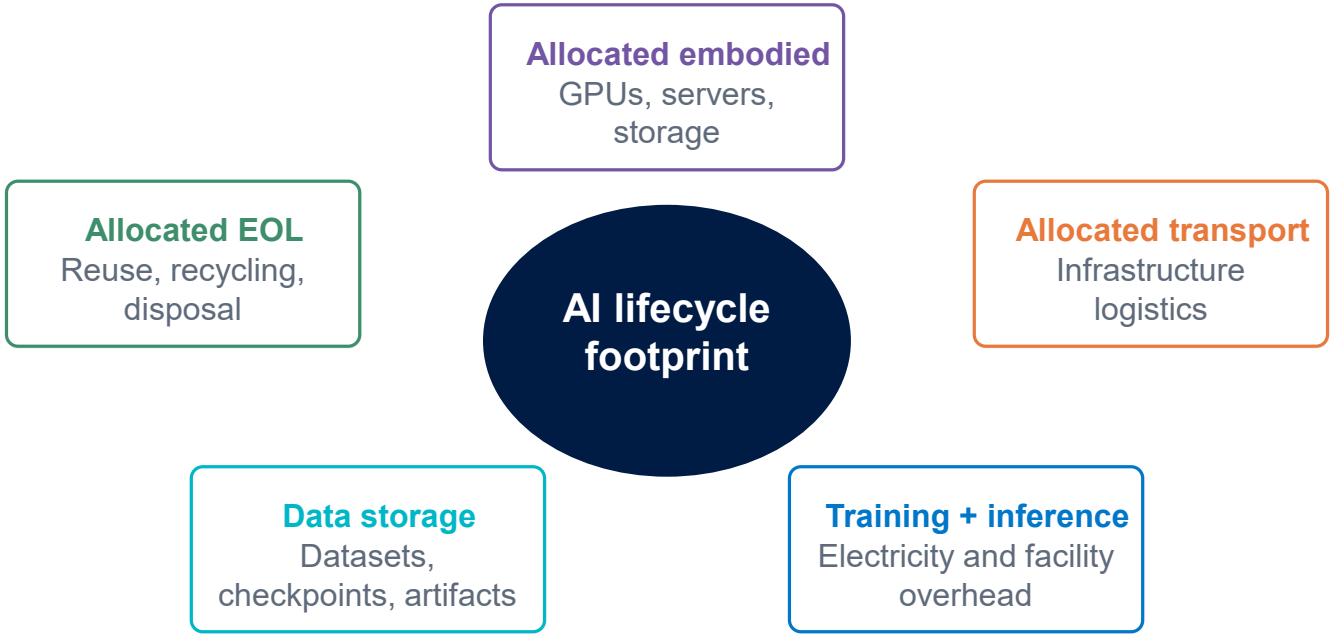
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AI

Full-lifecycle carbon estimation for training and inference

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AI Carbon Calculator — Full-Lifecycle Framework



$$CO_2e_{AI,total} = CO_2e_{emb} + CO_2e_{trans} + CO_2e_{train} + CO_2e_{inf} + CO_2e_{storage} + CO_2e_{EOL}$$

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Start with the Functional Unit and System Boundary

Per training run

Best for comparing model-development alternatives

Per model-month

Useful for lifecycle and recurring service estimates

Per 1 million inferences

Useful for production serving comparisons

Per year of service

Useful for program and portfolio decisions

Results are comparable only when the functional unit, reporting period, and boundary are consistent.

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Training Operational Emissions

$$P_{IT,avg} = N_g \times P_{g,avg} \times u$$

$$CO_2e_{train} = \frac{P_{IT,avg}\, t_{train}\, PUE\, CI}{1000}$$

Required inputs

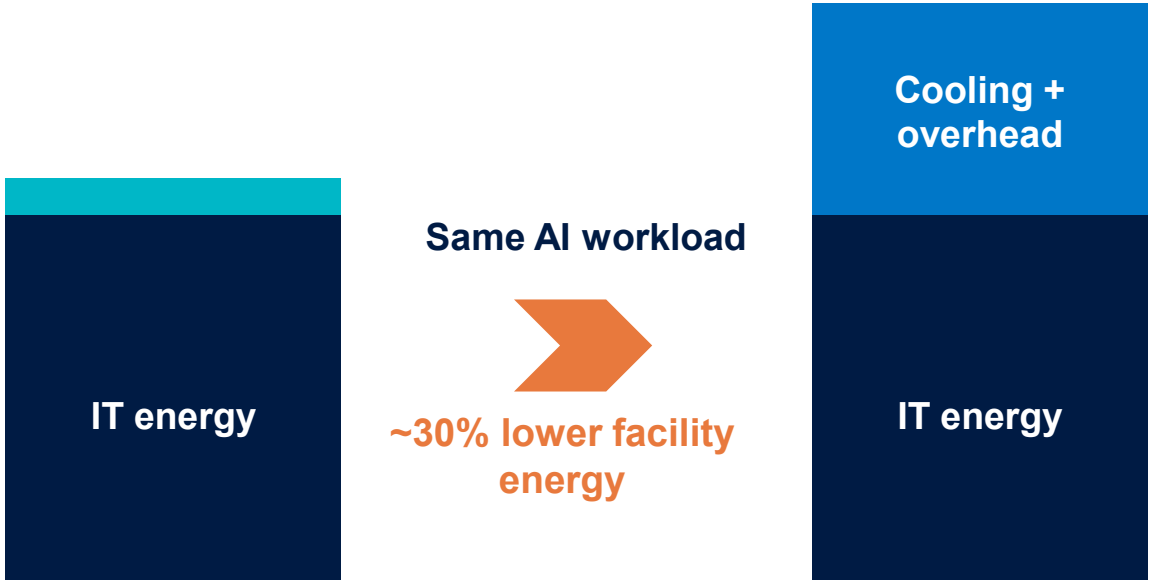
- Measured or modeled IT power
- Training runtime
- PUE
- Grid carbon intensity

Preferred hierarchy: measured rack/server energy → measured device power → nameplate power with utilization adjustment

Cooling and other facility overhead are included through PUE.

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Cooling Is Included Through Power Usage Effectiveness (PUE)



PUE includes cooling, fans, pumps, power-distribution losses, and other facility overhead.

https://sustainability.google/reports/google-2024-environmental-report/

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Inference Emissions

- They mainly come from:
  - **Operational electricity** to run GPUs/CPUs + memory + networking, plus facility overhead (PUE)
  - **Allocated embodied carbon** of the serving hardware
  - **Supporting storage** (model weights, feature stores, logs) and sometimes network transfer

Energy-per-request method

- Best when measured or benchmarked request energy is available
- Duration is already embedded in E_req
- Do not multiply by time again

$$CO_2e_{inf} = \frac{E_{req} N_{req} PUE\, CI}{1000}$$

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Allocated Embodied Emissions

$$CO_2e_{emb,alloc} = EC\left(\frac{t_{use}}{L}\right)\alpha$$

EC

Embodied carbon of the asset

t_use / L

Share of lifetime active hours

α

AI workload share of shared capacity

Recommended allocation hierarchy

Measured GPU-hours share → reserved capacity share → screening default

Allocation prevents assigning the full manufacturing burden of shared infrastructure to one workload.

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Other AI Lifecycle Terms: Storage, Transportation, and EOL

Data storage

- Persistent datasets
- Checkpoints and model artifacts
- Replication and backup
- Power × duration × PUE × CI

Allocated transportation

- Compute and storage shipments
- Weight × distance × mode
- Amortized over lifetime
- Allocated to the AI workload

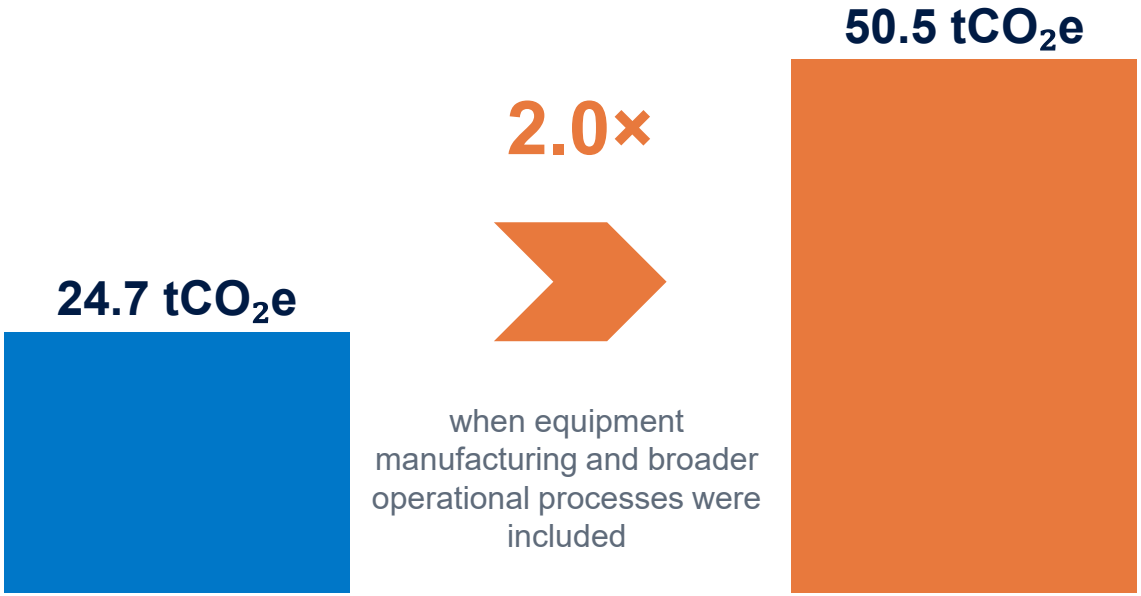
Allocated end of life

- Decommissioning and treatment
- Recycling, reuse, and disposal
- Detailed factors or screening factor
- Same lifetime and workload allocation

These terms are usually smaller than operation, but they complete the lifecycle and improve comparisons.

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Real Case: Broader Boundaries Changed the BLOOM Result



System boundary is not a documentation detail—it can change the answer materially.

https://jmlr.org/papers/v24/23-0069.html

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Inference at Scale: Small per Request Can Become Material

One median Gemini Apps text prompt

0.24 Wh energy
0.03 gCO_2e

Provider-reported, point-in-time estimate from May 2025.

Illustrative scale: 1 billion prompts

240 MWh energy
30 tCO_2e

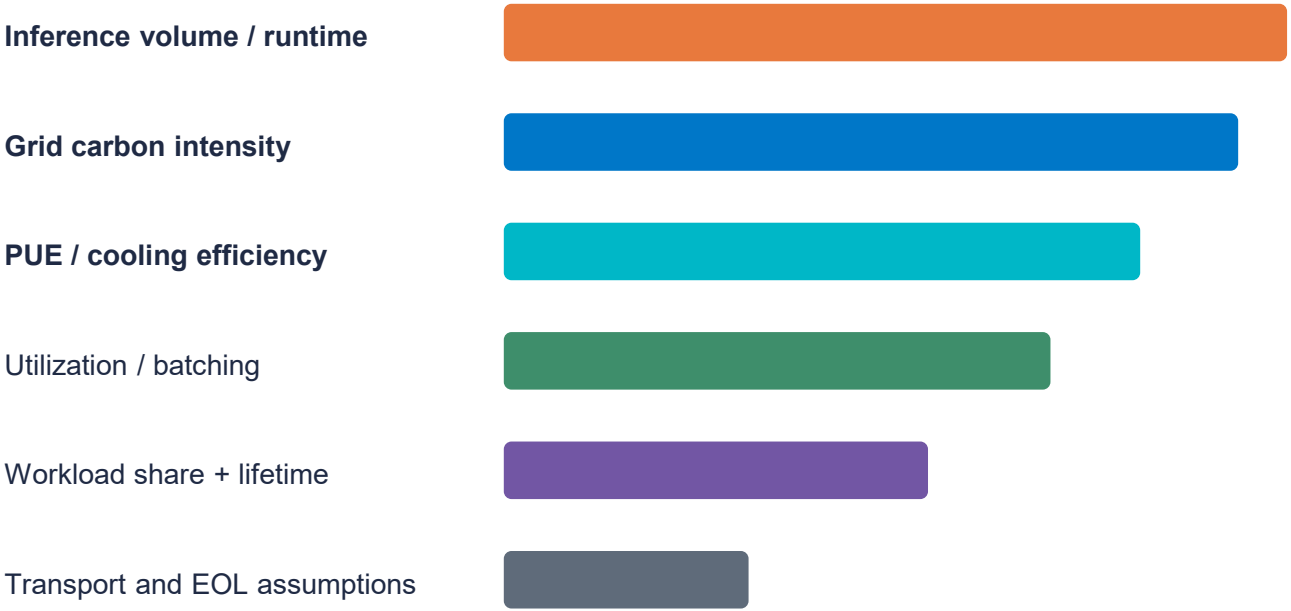
Same per-prompt assumption multiplied by usage volume.

Per-request efficiency and total demand must be evaluated together.

https://cloud.google.com/blog/products/infrastructure/measuring-the-environmental-impact-of-ai-inference

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Sensitivity: What Matters Most?



Improve first

- Use location-specific CI
- Measure production PUE
- Capture request volume
- Replace default allocation

Typical qualitative influence; actual ranking depends on workload, boundary, and reporting period.

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How Can AI Carbon Be Reduced?

Reduce demand	Improve serving	Improve facility	Clean the energy	Extend the lifecycle
Smaller fit-for-purpose models Shorter inputs and outputs Caching and request routing	Batching and consolidation Higher utilization Right-size accelerators	Lower PUE Efficient cooling Avoid thermal throttling	Lower-carbon regions Time-shift flexible workloads Increase clean-energy supply	Longer hardware life Reuse and refurbishment Avoid air freight

The calculator converts these engineering actions into measurable changes in model inputs and outputs.

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Water Should Be a Companion Metric—not Part of the CO_2e Total

Core carbon calculator

- Reports tCO_2e
- Cooling electricity included through PUE
- Carbon intensity converts energy to emissions
- Keep the LCA carbon total internally consistent

Optional water extension

- Reports liters or m³
- Use Water Usage Effectiveness (WUE)
- Track site water separately from grid water
- Evaluate carbon–water trade-offs

$$WUE = \frac{Site\ water\ use\ (L)}{IT\ energy\ (kWh)}$$

Recommendation: one core slide, one backup slide, and a separate output—not a new term in the carbon sum.

https://www.energy.gov/cmei/femp/cooling-water-efficiency-opportunities-federal-data-centers

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How a Cost Engineer Would Use This Framework



1 Define the decision

Functional unit, reporting period, alternatives

2 Populate lifecycle inputs

Production, transport, operation, EOL

3 Calculate carbon

IT, hardware, and AI modules

4 Apply carbon price

tCO_2e and carbon cost

5 Compare options

Cost, performance, schedule, and risk

Decision-ready output: lifecycle carbon by stage + carbon cost + traceable assumptions

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Illustrative Trade Study: Same AI Service, Two Hosting Alternatives

Metric	Option A Standard facility / higher-CI grid	Option B Efficient facility / lower-CI grid
Direct annual cost	$2.40M	$2.48M
Operational carbon	2,790 t	460 t
Other lifecycle carbon	150 t	150 t
Total carbon	**2,940 t**	**610 t**
Carbon cost @ $50/t	**$147k**	**$31k**
Total evaluated cost	**$2.547M**	**$2.511M**

Decision insight: Option B costs more directly, but becomes the lower evaluated-cost option when carbon is included.

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Key Takeaways and Next Steps

What is complete

- Common LCA framework
- Hardware production, transport, use, and EOL
- AI full-lifecycle calculator
- Cooling included through PUE

What matters most

- Demand / runtime
- Grid carbon intensity
- PUE and utilization
- Boundary and allocation choices

Next steps

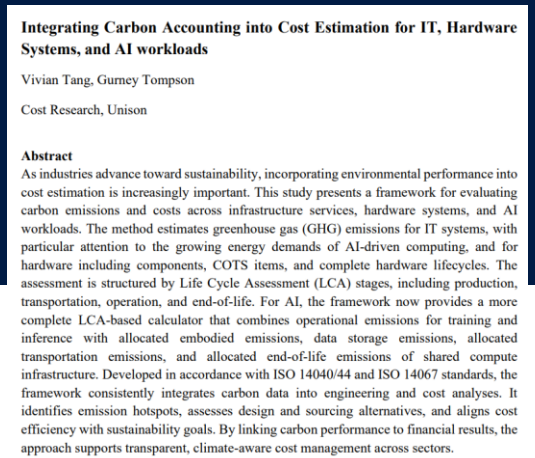
- Validate with telemetry
- Add supplier and recycler data
- Use time-varying carbon intensity
- Keep water as a separate companion metric

Carbon estimation becomes valuable when it changes an engineering or cost decision.

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Thank you for listening

Questions are welcome



Integrating Carbon Accounting into Cost Estimation for IT, Hardware Systems, and AI workloads

Vivian Tang, Gurney Tompson

Cost Research, Unison

Abstract

As industries advance toward sustainability, incorporating environmental performance into cost estimation is increasingly important. This study presents a framework for evaluating carbon emissions and costs across infrastructure services, hardware systems, and AI workloads. The method estimates greenhouse gas (GHG) emissions for IT systems, with particular attention to the growing energy demands of AI-driven computing, and for hardware including components, COTS items, and complete hardware lifecycles. The assessment is structured by Life Cycle Assessment (LCA) stages, including production, transportation, operation, and end-of-life. For AI, the framework now provides a more complete LCA-based calculator that combines operational emissions for training and inference with allocated embodied emissions, data storage emissions, allocated transportation emissions, and allocated end-of-life emissions of shared compute infrastructure. Developed in accordance with ISO 14040/44 and ISO 14067 standards, the framework consistently integrates carbon data into engineering and cost analyses. It identifies emission hotspots, assesses design and sourcing alternatives, and aligns cost efficiency with sustainability goals. By linking carbon performance to financial results, the approach supports transparent, climate-aware cost management across sectors.

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Backup: Data Sources and Default Hierarchy

Best available

- Measured energy and utilization
- Program logistics records
- Supplier PCF / EPD
- Recycler-specific pathway data

Intermediate

- Comparable product proxy
- Regional grid intensity
- Facility-reported PUE
- Mode-specific freight factors

Screening only

- Equipment-class defaults
- Industry-average PUE
- Generic material factors
- Low / base / high scenarios

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Backup: LCA vs. GHG Protocol

Life Cycle Assessment

- Organized by production, transportation, operation, and EOL
- Best for engineering, design, sourcing, and lifecycle optimization
- Primary analytical framework in this work

GHG Protocol

- Organized by Scope 1, 2, and 3
- Best for corporate reporting, disclosure, and target setting
- LCA results can be mapped to scopes when needed

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Backup: Key Operational Metrics

PUE

Total facility energy divided by IT energy. Captures cooling and facility overhead.

Carbon intensity

$kgCO_2e$ per kWh. Varies by region, generation mix, and time.

Utilization

Useful workload divided by provisioned capacity. Affects power per useful output.

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Backup: Full AI LCA Equation Summary

$$CO_2e_{AI,total} = CO_2e_{train} + CO_2e_{inf} + CO_2e_{storage} + CO_2e_{emb,alloc} + CO_2e_{trans,alloc} + CO_2e_{EOL,alloc}$$

Training

$$CO_2e_{train} = \frac{P_{IT}tPUECI}{1000}$$

Inference

$$CO_2e_{inf} = \frac{E_{req}N_{req}PUECI}{1000}$$

Embodied

$$CO_2e_{emb,alloc} = EC(t_{use}/L)\alpha$$

Storage

$$CO_2e_{storage} = \frac{D_{TB}P_{TB}tPUECI}{1000}$$

Transport

$$CO_2e_{trans,alloc} = \frac{\sum WDEF}{1000}(t_{use}/L)\alpha$$

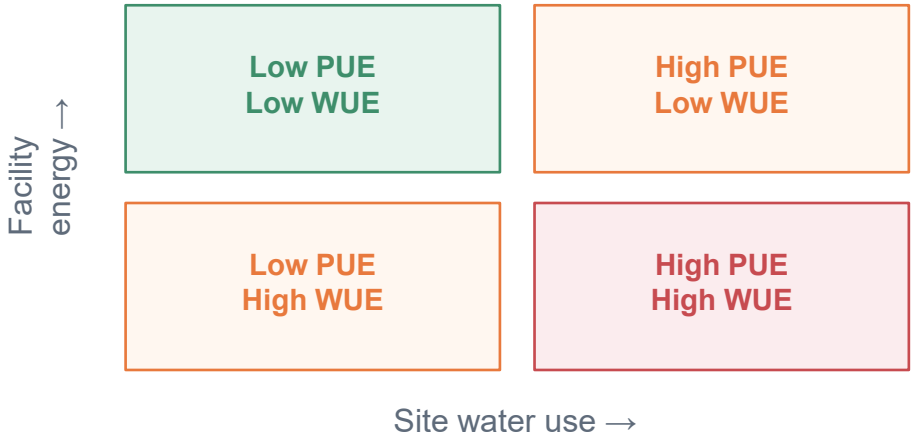
EOL

$$CO_2e_{EOL,alloc} = CO_2e_{EOL,total}(t_{use}/L)\alpha$$

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Backup: Water as a Separate Environmental Output

$$Water_{site}(m^3) = \frac{E_{IT}(kWh)\,WUE(L/kWh)}{1000}$$



Do not add water directly to CO_2e

- Different unit and impact category
- Report alongside carbon, not inside the sum

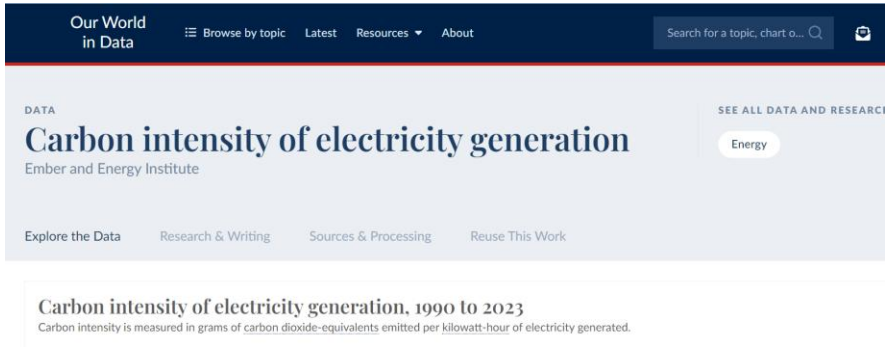
Use in trade studies

- Compare cooling alternatives
- Flag water-stressed locations
- Track reclaimed vs potable water
- Evaluate energy–water trade-offs

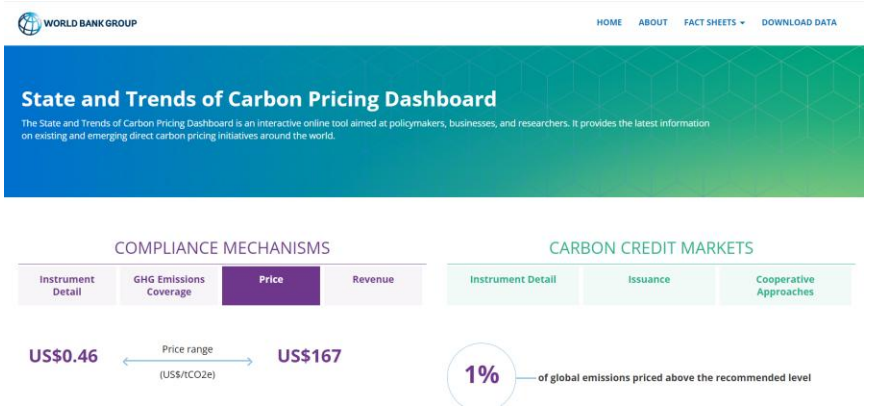
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Data Resources

Carbon Intensity



Carbon Unit Price



- Data is also released yearly by the EPA for every region in the US.