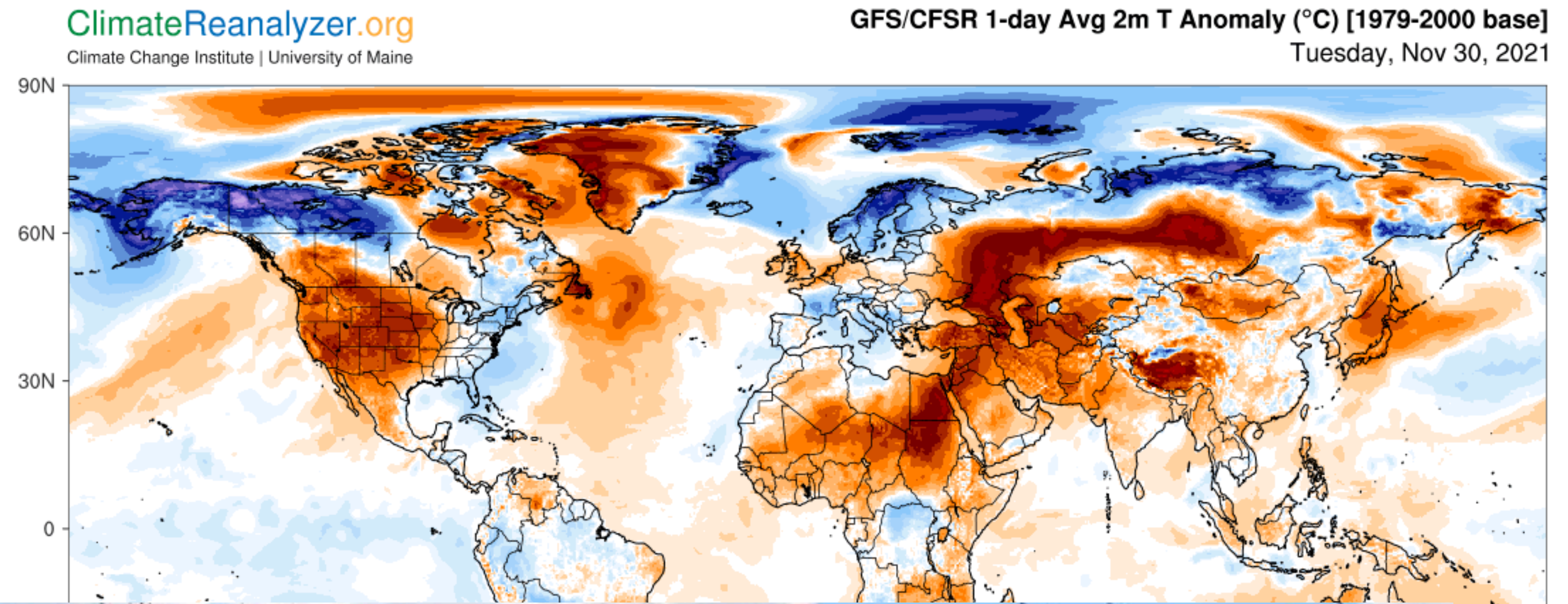
Carnegie Mellon University
Language Technologies Institute

Carbon and the Future

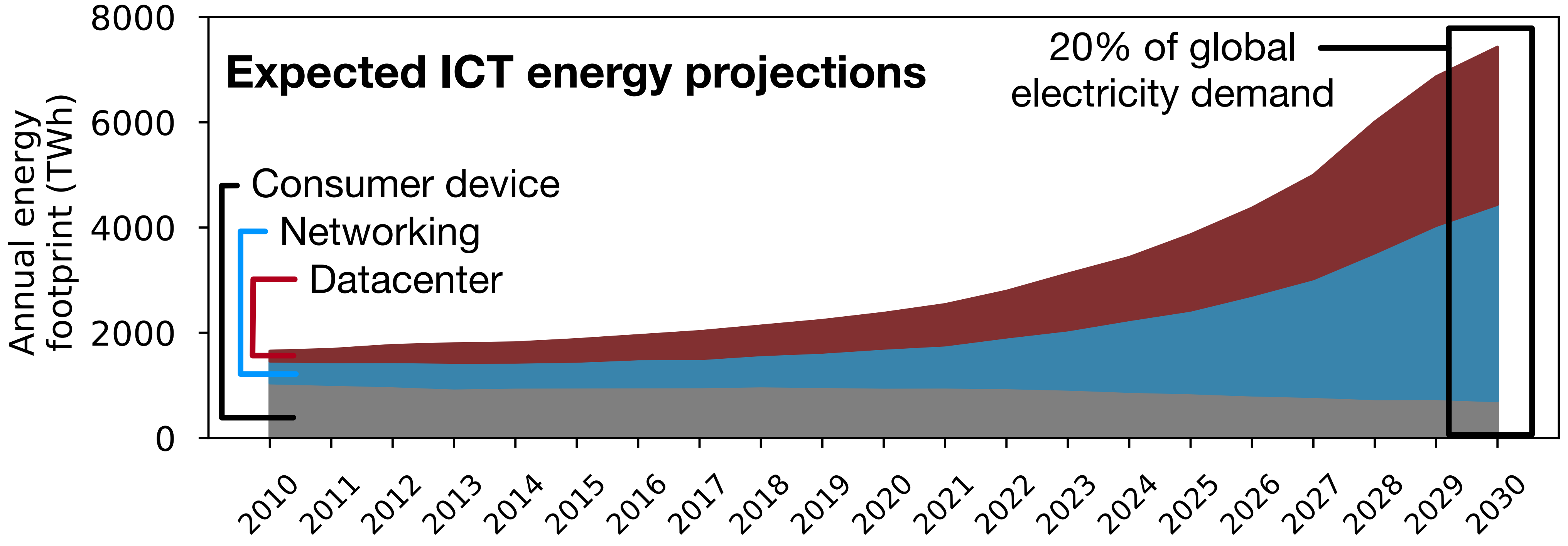
Emma Strubell & Yonatan Bisk

Climate change is real

- Humans have already caused 1ºC of global warming, likely to reach 1.5ºC between 2030–2052 at current rate.
- 1.5–2ºC seems to be an inflection point for catastrophic changes in weather, sea levels.
- Limiting global warming to 1.5°C will require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems. IPCC Special Report: Global Warming of 1.5ºC
- Computers use energy, but more importantly, digitization is (re-)shaping the economy. **AI has great potential for positive or negative impact on the climate**.



https://www.wesa.fm/environment-energy/2021-06-10/pittsburgh-area-coal-fired-power-plant-to-close



Gupta et al. Chasing Carbon: The Elusive Environmental Footprint of Computing. 2020.

The big picture

The Greenhouse Gas Protocol for quantifying organization-level emissions.

Scope 1

Direct emissions

- Raw material combustion, refrigerants in offices and facilities.
- Burning PFCs, chemicals and gasses in manufacturing.
- Cow farts.

Scope 2

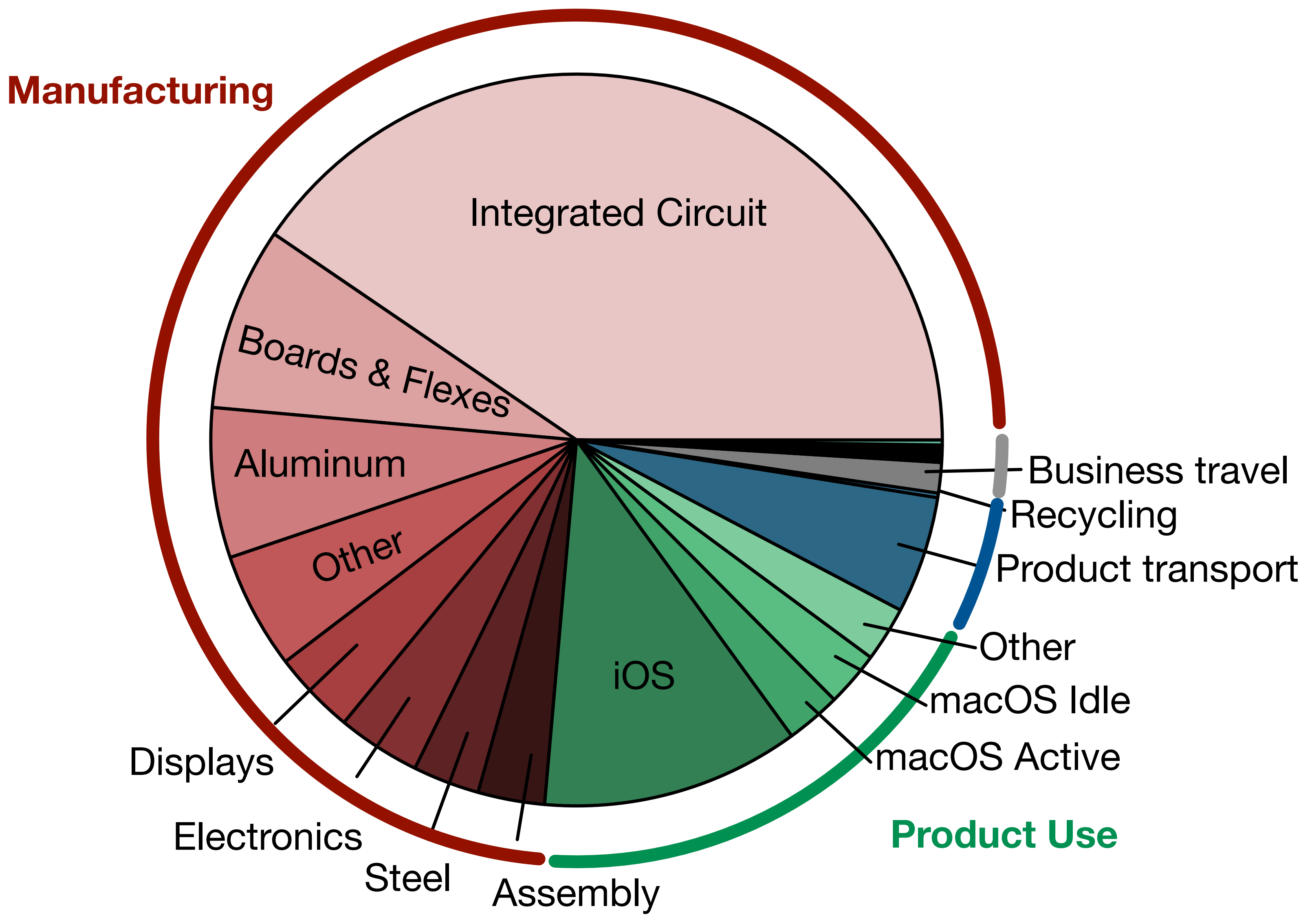
Indirect emissions

- Purchased energy for fabrication, heating and cooling offices, datacenters.
- Training, developing, running ML models.

Scope 3

Up- and down-stream supply chain

- Everything else.
- Facilities construction.



Apple's carbon emission breakdown: 98% due to hardware lifecycle

Calculated relative to a specific GHG-emitting entity.

Supply Chain

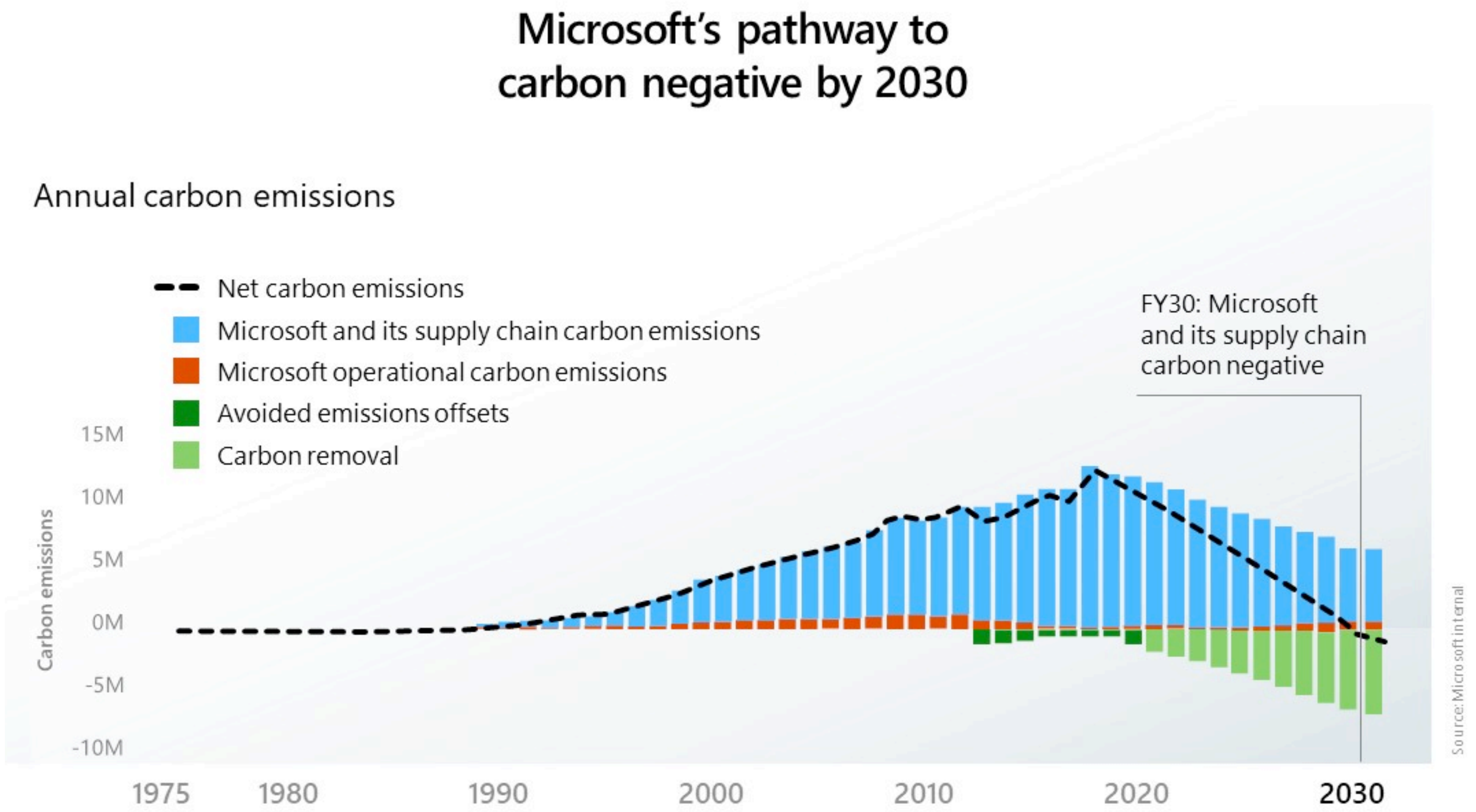
How much of your carbon footprint happens before you enter the picture?

13-inch MacBook Pro life cycle carbon emissions

76%	Production
6%	Transport
17%	Use
<1%	End-of-life processing

iPhone 13 life cycle carbon emissions

81%	Production
2%	Transport
16%	Use
<1%	End-of-life processing



https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/

Google: Operating Net Zero
https://sustainability.google/commitments/

Apple: Operating + Supply Chain Net Zero
https://www.apple.com/newsroom/2020/07/apple-commits-to-be-100-percent-carbon-neutral-for-its-supply-chain-and-products-by-2030/

Carbon Capture vs Carbon Offsets

CO_2 Removal

Carbon dioxide removal (CDR), also known as negative CO_2 emissions, is a process in which carbon dioxide gas (CO_2) is **removed from the atmosphere** and sequestered for long periods of time

https://en.wikipedia.org/wiki/Carbon_dioxide_removal

Plant a tree 🌲

Carbon Capture and Storage

Carbon capture and storage (CCS) or carbon capture and sequestration is the process of capturing carbon dioxide (CO_2) **before it enters the atmosphere**, transporting it, and storing it (carbon sequestration) for centuries or millennia.

https://en.wikipedia.org/wiki/Carbon_capture_and_storage

You burn it? Catch it!

Carbon Offsets

A carbon offset is a reduction or removal of emissions of carbon dioxide or other greenhouse gases made in order to **compensate for emissions made elsewhere**

https://en.wikipedia.org/wiki/Carbon_offset

It's complicated…

Carbon Offsets

Guiding Philosophy: Someone needs to pay (also idea behind a carbon tax)

Burn all the coal ➡ Pay for a wind farm that will hopefully someday replace you

Take that vacation ➡ Pay for a materials science research lab on battery tech

Build a house ➡ Donate to forest preservation

Problem: We need right column regardless, so it doesn't really "cancel" out column A

The big picture

The Greenhouse Gas Protocol for quantifying organization-level emissions.

Scope 1
Direct emissions

Scope 2
Indirect emissions

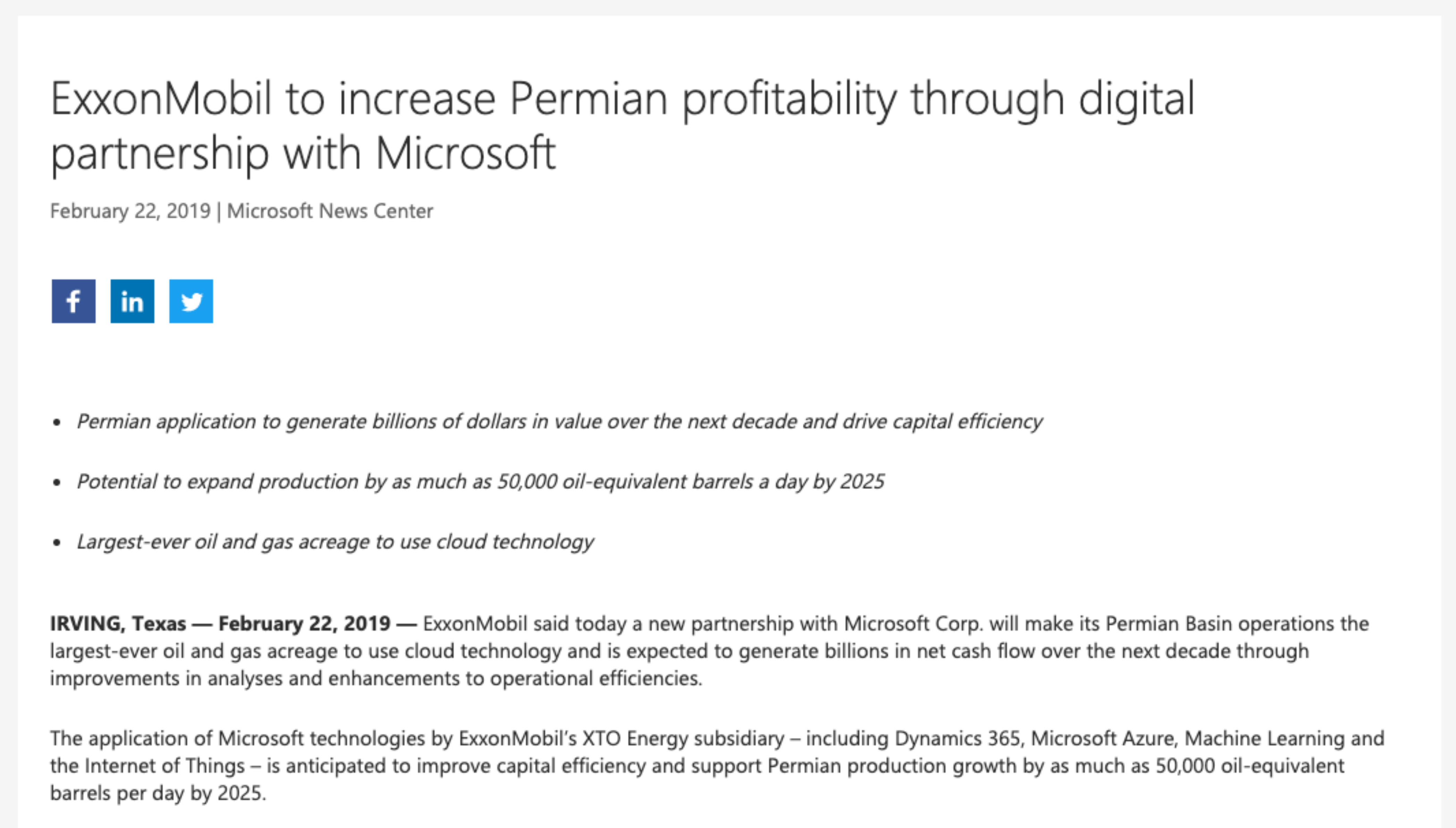

Microsoft will be carbon negative by 2030

Jan 16, 2020 | Brad Smith - President & Vice Chair

Microsoft will be carbon negative by 2030

Scope 3
Up- and down-stream supply chain

- Everything else.


ExxonMobil to increase Permian profitability through digital partnership with Microsoft

February 22, 2019 | Microsoft News Center

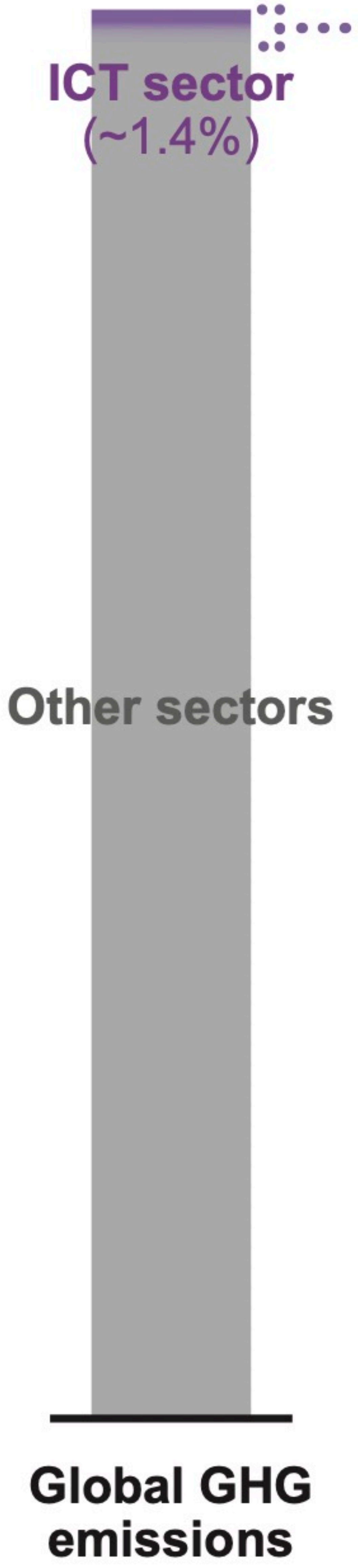
- *Permian application to generate billions of dollars in value over the next decade and drive capital efficiency*
- *Potential to expand production by as much as 50,000 oil-equivalent barrels a day by 2025*
- *Largest-ever oil and gas acreage to use cloud technology*

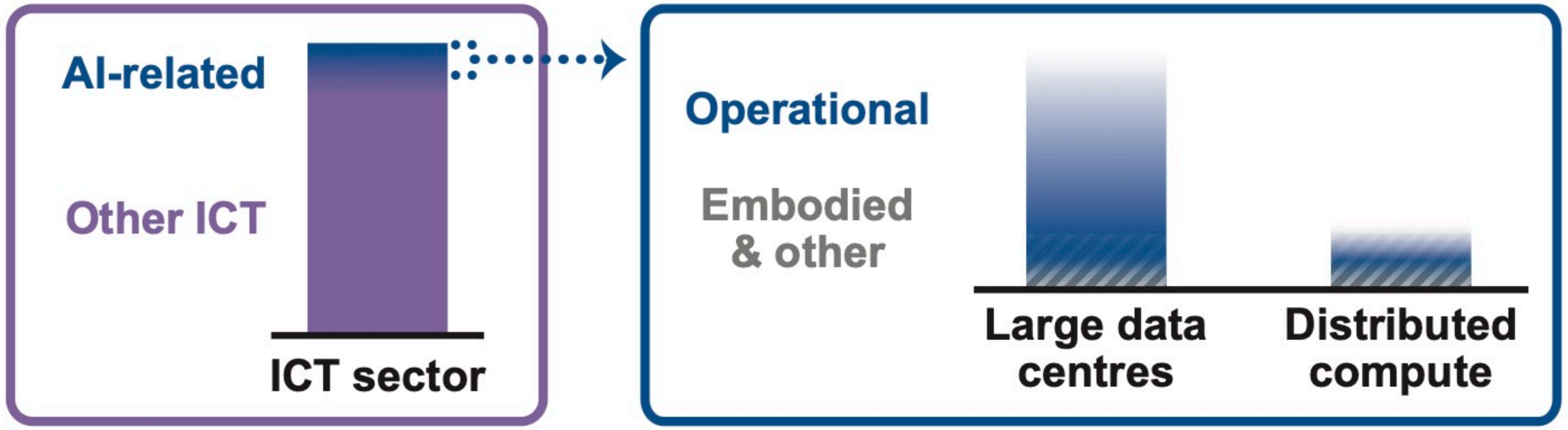
IRVING, Texas — February 22, 2019 — ExxonMobil said today a new partnership with Microsoft Corp. will make its Permian Basin operations the largest-ever oil and gas acreage to use cloud technology and is expected to generate billions in net cash flow over the next decade through improvements in analyses and enhancements to operational efficiencies.

The application of Microsoft technologies by ExxonMobil's XTO Energy subsidiary – including Dynamics 365, Microsoft Azure, Machine Learning and the Internet of Things – is anticipated to improve capital efficiency and support Permian production growth by as much as 50,000 oil-equivalent barrels per day by 2025.

ExxonMobil to increase Permian profitability through digital partnership with Microsoft

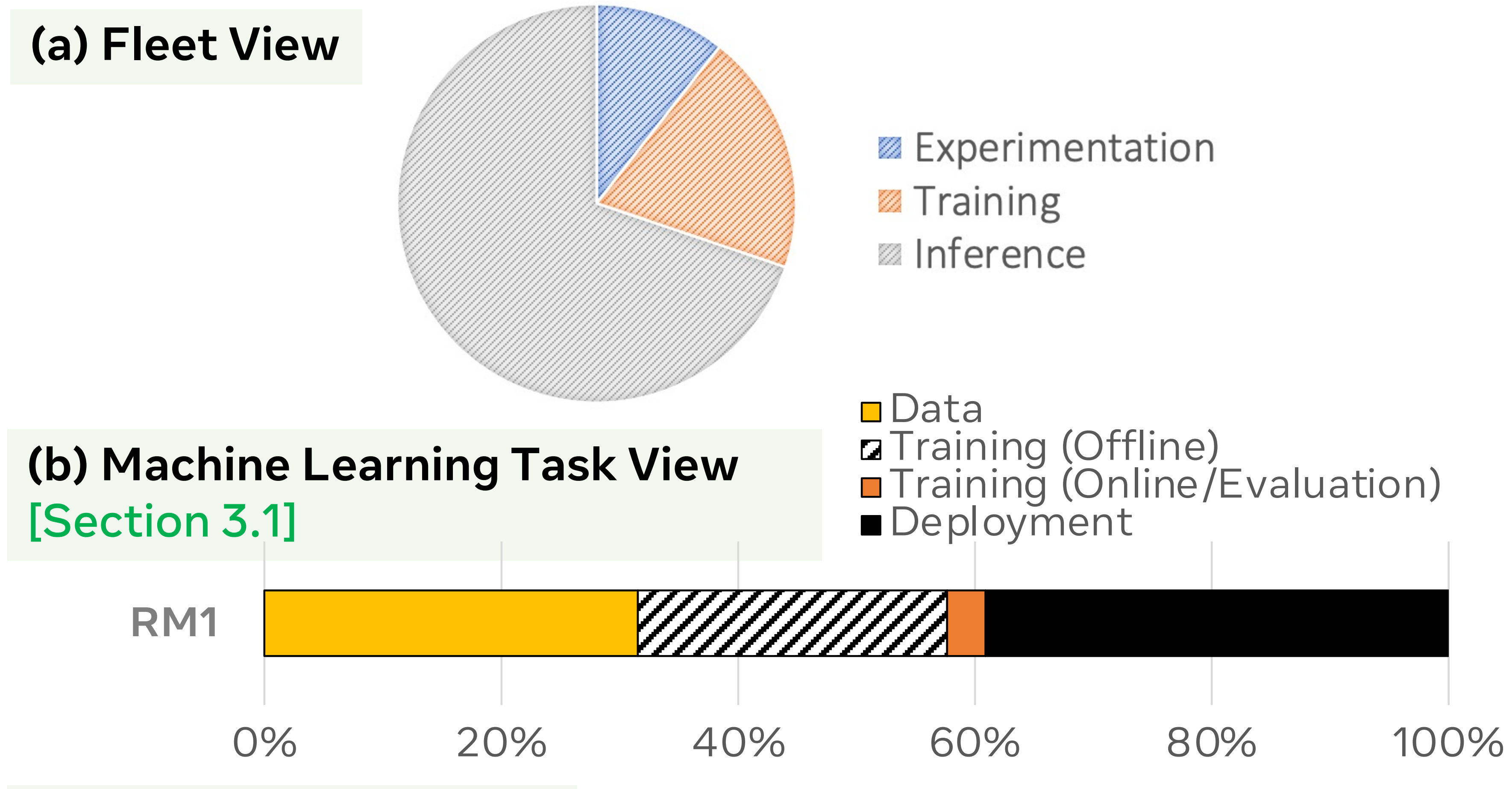
Operational emissions: ML model lifecycle





ML workloads make up 10-15% of Google's total energy consumption 2019—2021. 1.5-2TWh in 2020.

Energy use breakdown at Meta:

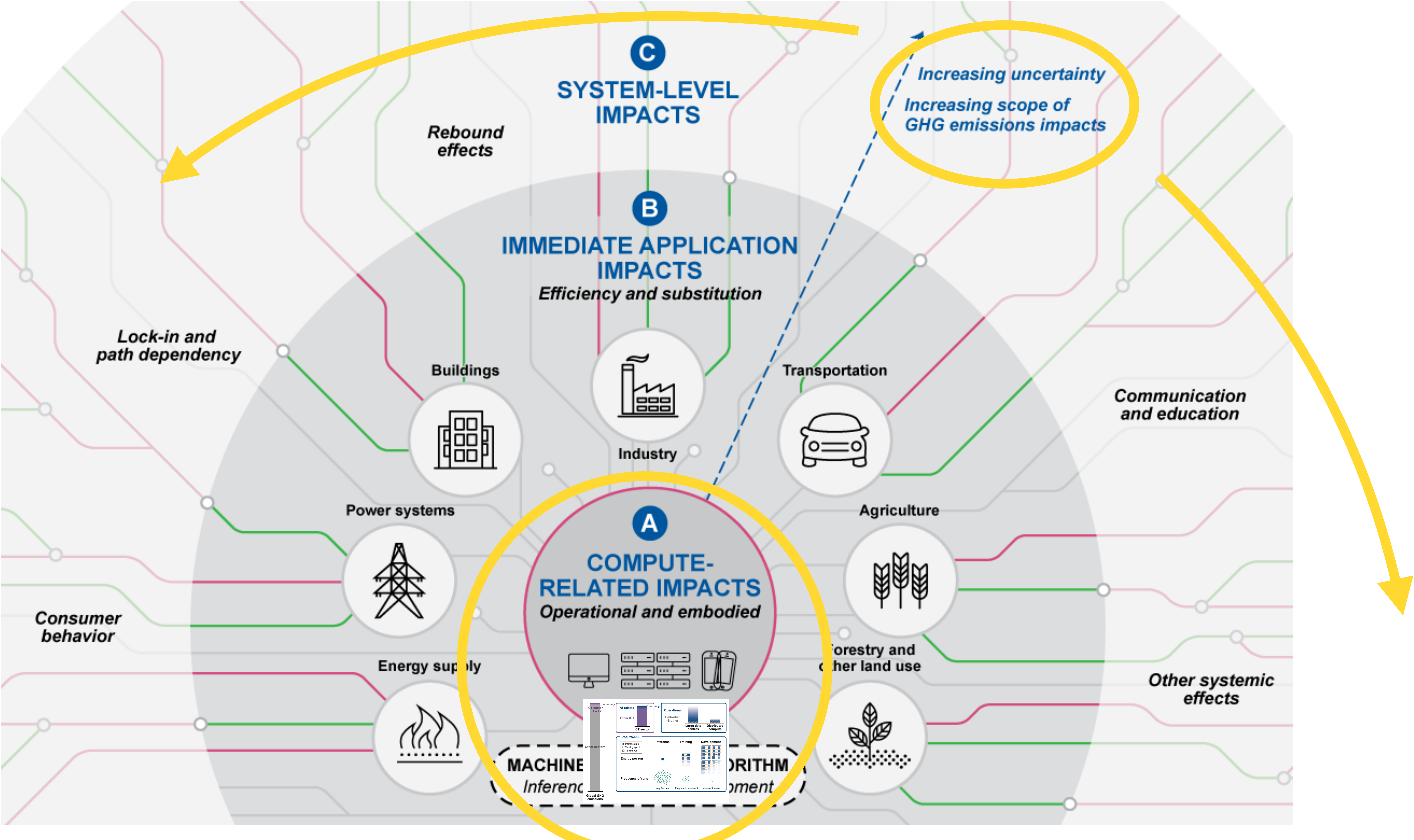


Meta: Carole-Jean Wu, et al. Sustainable AI: Environmental Implications, Challenges and Opportunities. MLSys, 2022.

Google: D. Patterson et al. The Carbon Footprint of Machine Learning Training Will Plateau, Then Shrink. IEEE Computer, 2022.

Figure: L. Kaack, P. Donti, E. Strubell, G. Kamiya, F. Creutzig, D. Rolnick Aligning artificial intelligence with climate change mitigation. Nature Climate Change, 2022.

The big picture: Framework for AI + climate



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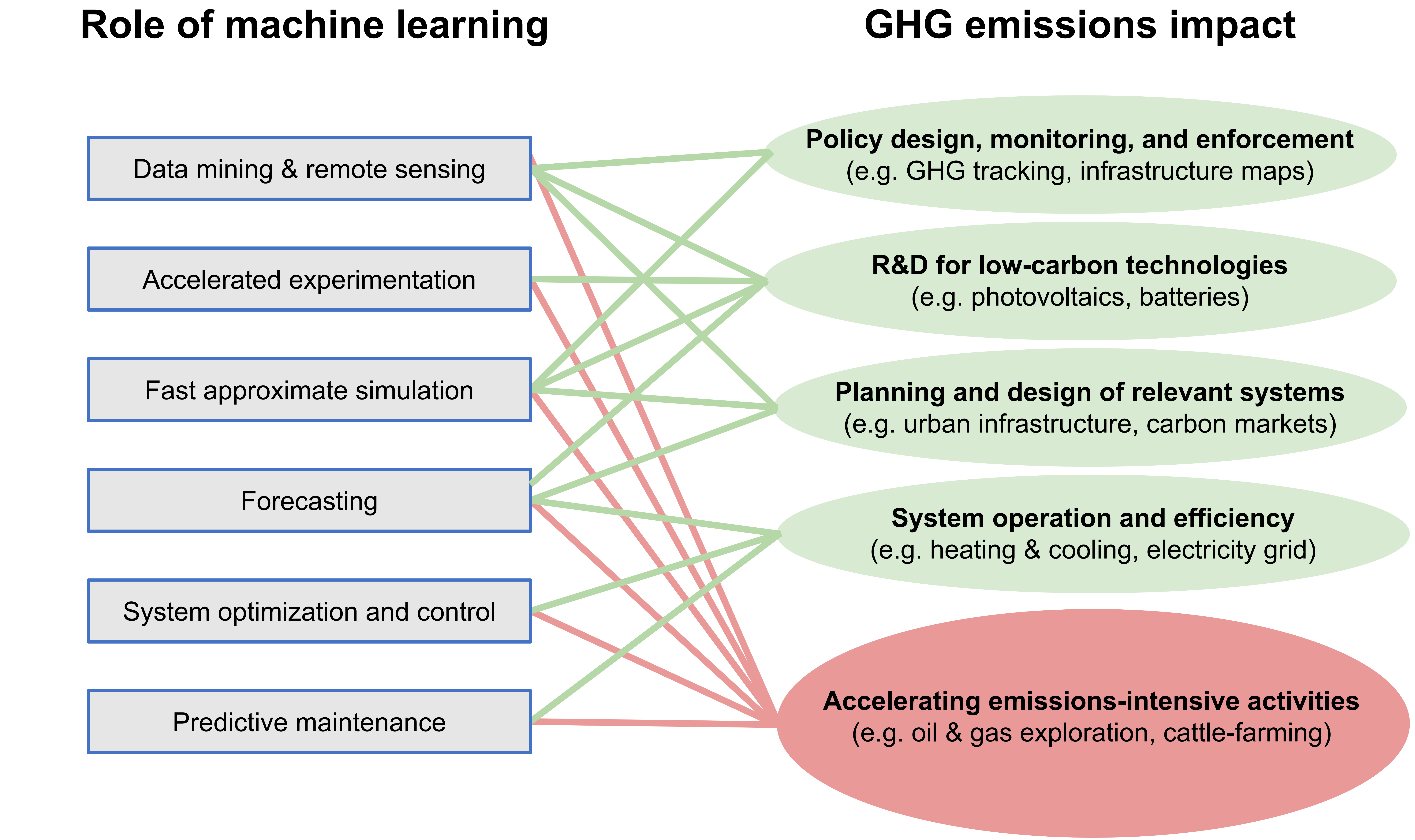

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Discovering and decarbonizing materials

Materials synthesis

Photovoltaics, batteries and compute hardware.

Materials decarbonization

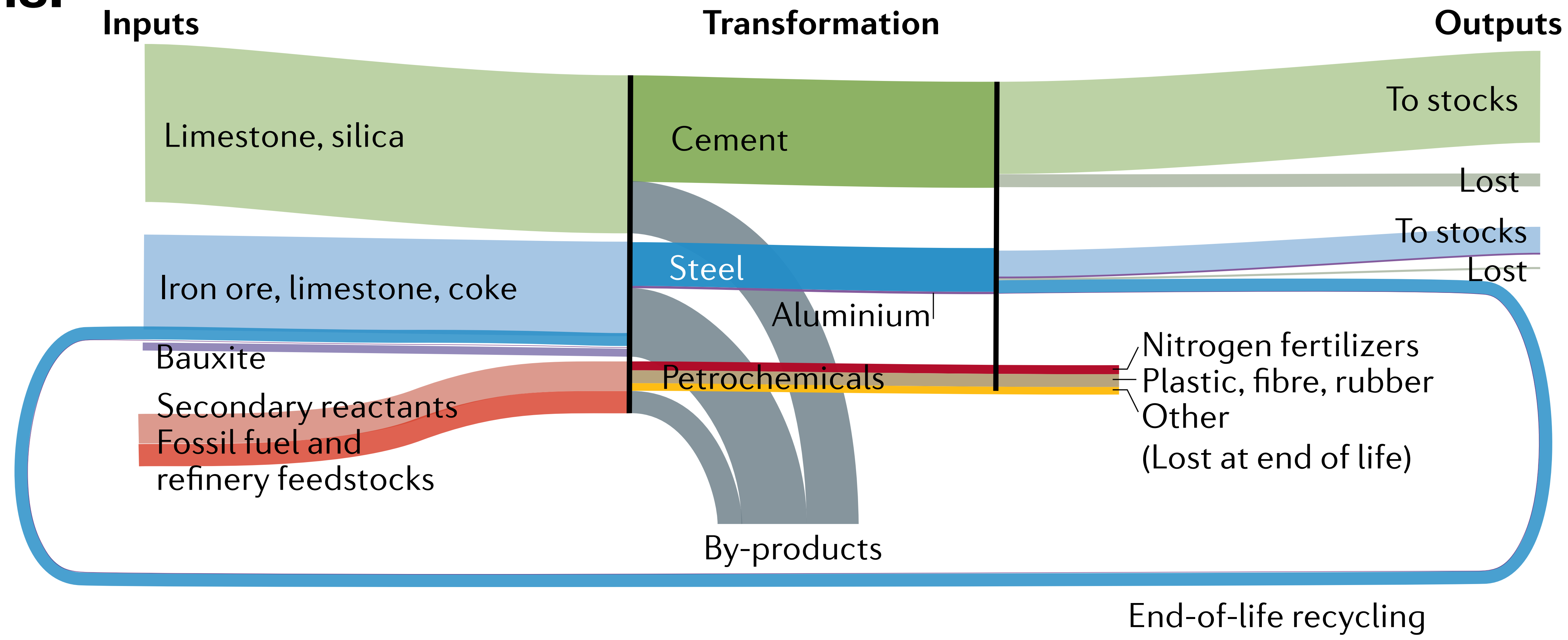
Cement, steel and petrochemicals

Global GHG emissions:

7-8%

~10%

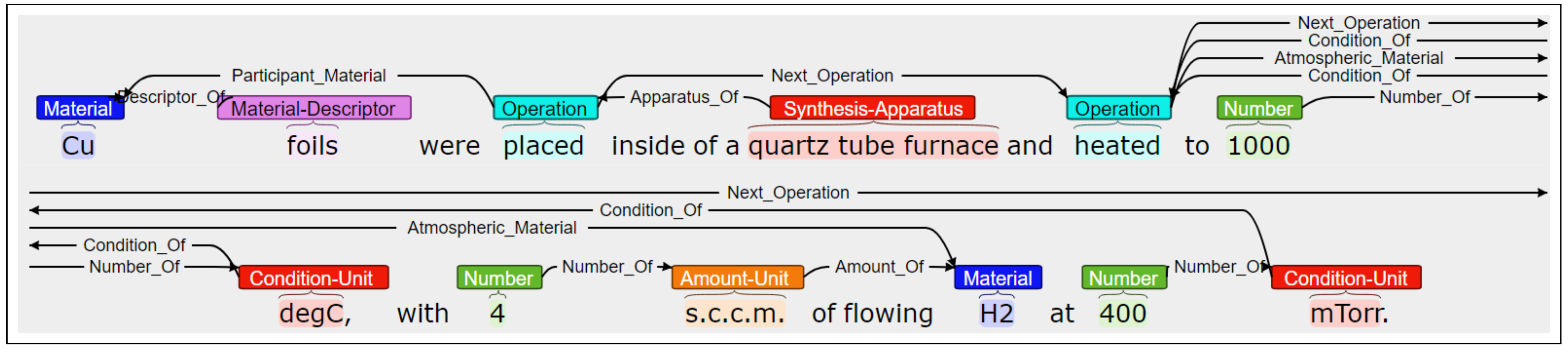
5%



K. Daehn, R. Basuhi, J. Gregory, M. Berlinger, V. Somjit & E. A. Olivetti. Innovations to decarbonize materials industries. Nature Reviews Materials, 2022.

R. Yokoi, T. Watari, M. Motoshita. Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals. Energy Environ. Sci., 2022.

NLP for accelerating scientific discovery



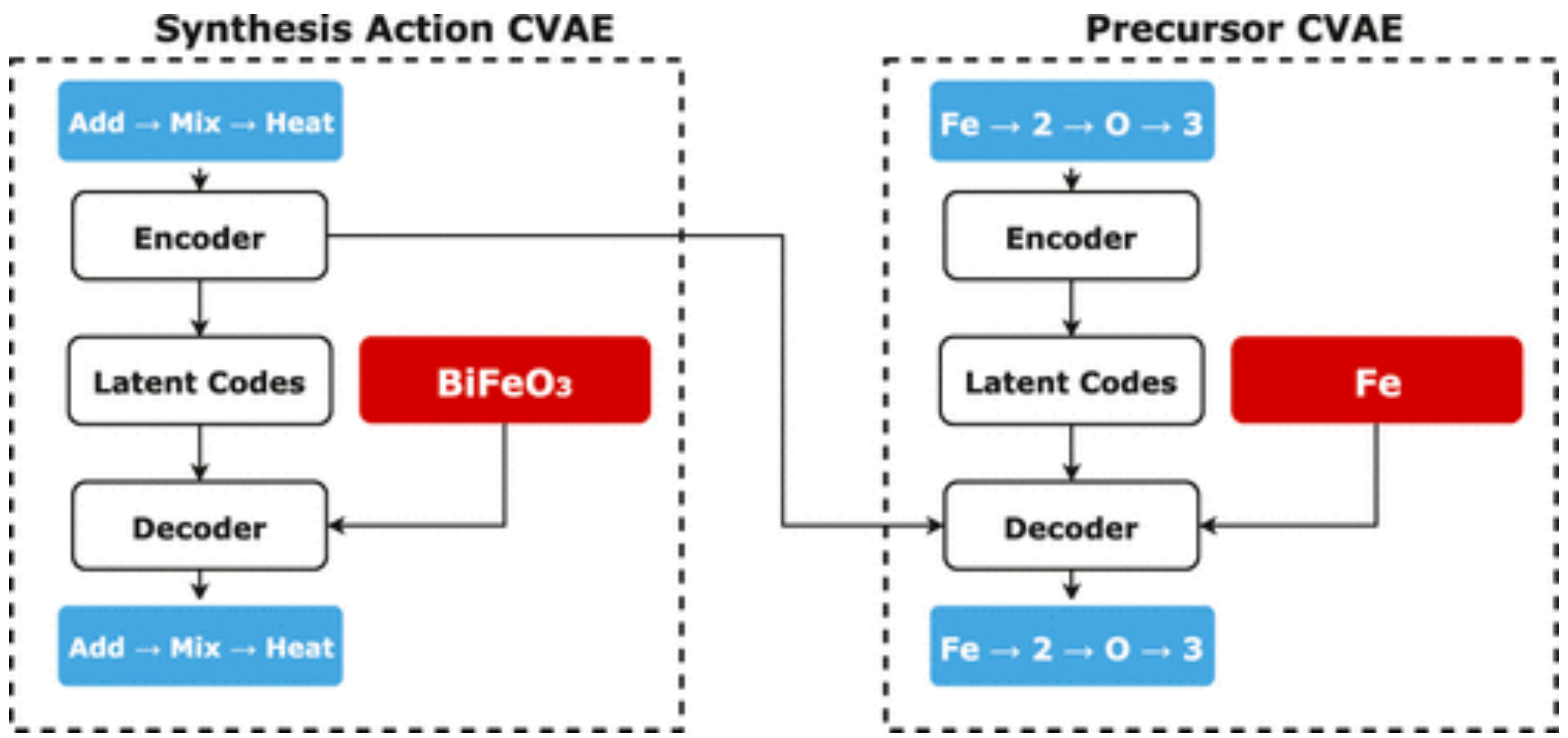
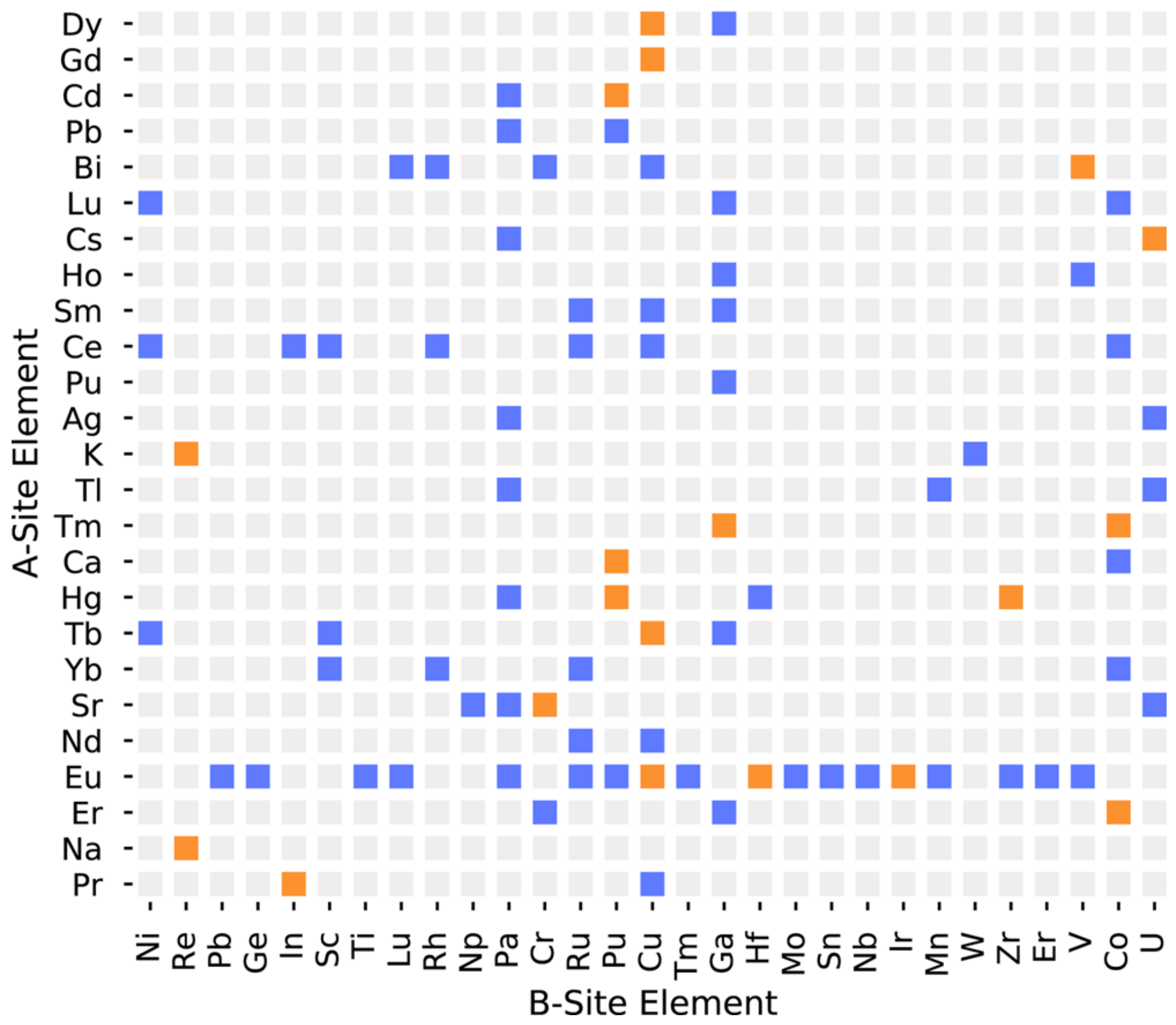


Table 1. Generated Precursors for $InWO_3$ and $PbMoO_3$, Drawn from the CVAE Model[a]

target material	precursors
$InWO_3$	$In_2S_3 + WCl_4$
	$In(NO_3)_3 + WCl_4$
	$In_2O_3 + WO_2$
	$In_2O_3 + WN$
	[b]$InCl_3 + Na_2WO_4$
$PbMoO_3$	$PbCl_2 + MoCl_2$
	$PbSO_4 + MoCl_2$
	[c]$PbO + MoO_2$

[a]The CVAE model was trained on synthesis routes published during or before 2005. [b]Precursors match Kamalakkannan et al. (2016).[31] [c]Precursors match Takatsu et al. (2017).[32]



S. Mysore, Z. Jensen, E. Kim, K. Huang, H. Chang, E. Strubell, J. Flanigan, A. McCallum, E. Olivetti. The Materials Science Procedural Text Corpus: Annotating Materials Synthesis Procedures with Shallow Semantic Structures. LAW, 2019.

E. Kim, Z. Jensen, A. van Grootel, K. Huang, M. Staib, S. Mysore, H. Chang, E. Strubell, A. McCallum, S. Jegelka, E. Olivetti. Inorganic Materials Synthesis Planning with Literature-Trained Neural Networks. J. Chem. Inf. Modeling, 2020.

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- **Training, developing, running ML models.**

Scope 3

Up- and down-stream supply chain

- Everything else.
- Facilities construction.
- Business travel, commuting, logistics.
- Raw materials.
- Downstream use.

Calculated relative to a specific GHG-emitting entity.

Calculating Carbon

- How we estimated carbon emissions due to model training (Strubell et al. 2019).
- Assumes you have access to power draw (device: RPi4, Jetson 4GB)

power draw

$$p_t = \frac{\overset{\text{PUE}}{1.58}\ \overset{\text{training time}}{t}\ (\overset{\text{CPU}}{p_c} + \overset{\text{DRAM}}{p_r} + \overset{\text{GPU}}{g p_g})}{1000} \quad \text{kWh}$$

power consumption during training

WattTime

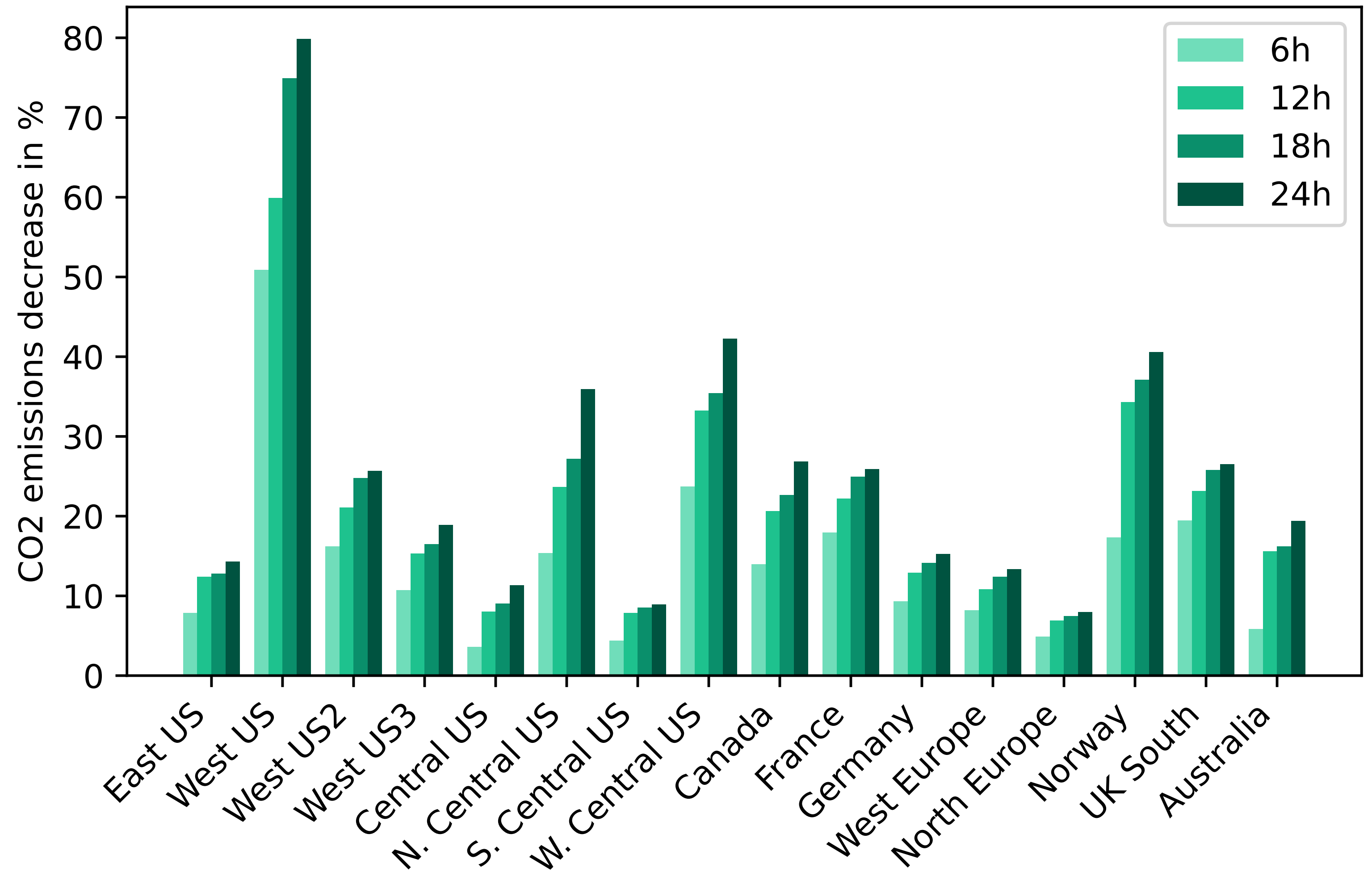
U.S. average emissions (EPA)

$$CO_2e = 0.954 p_t \quad \text{pounds}$$

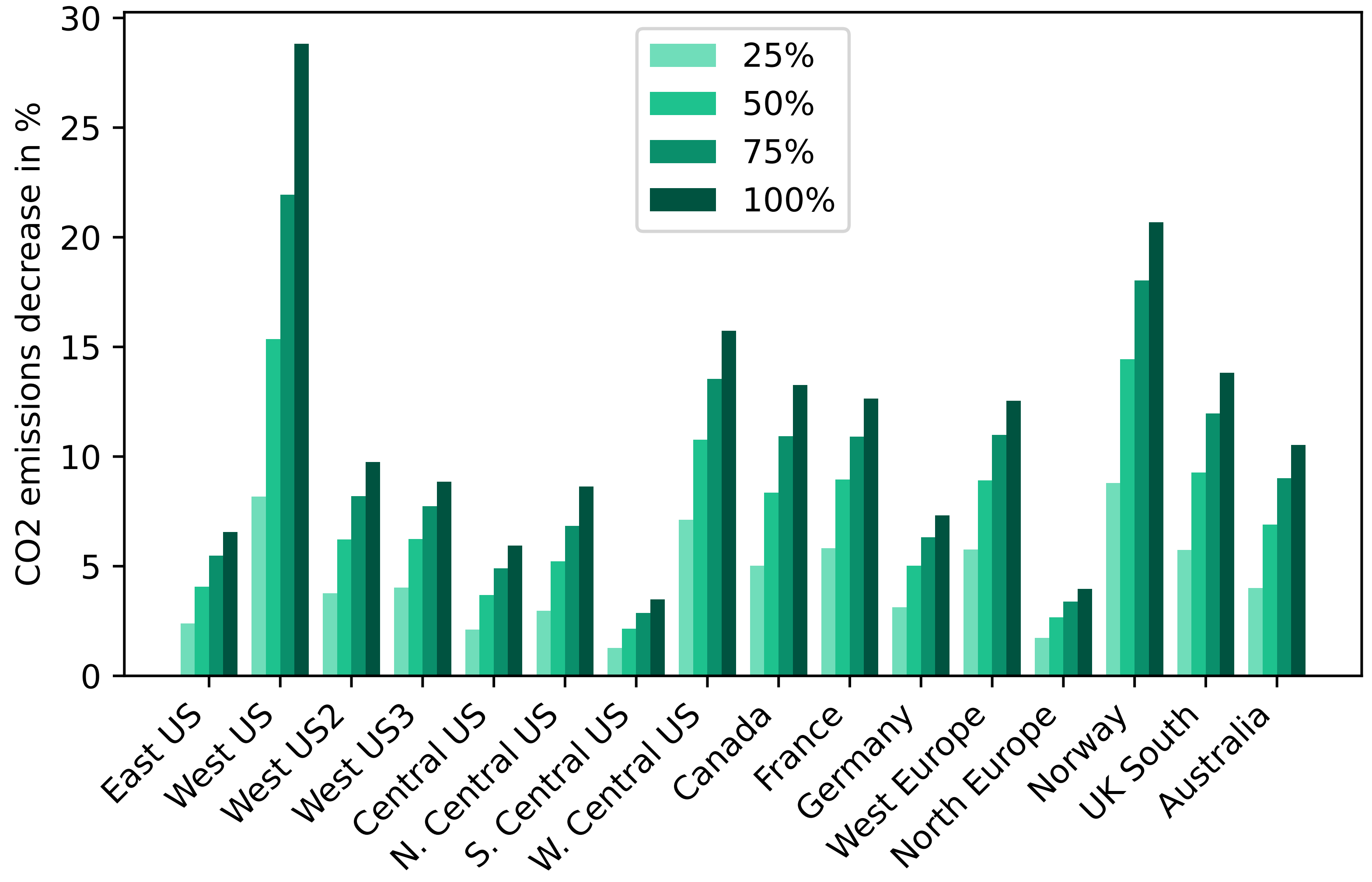
carbon emissions

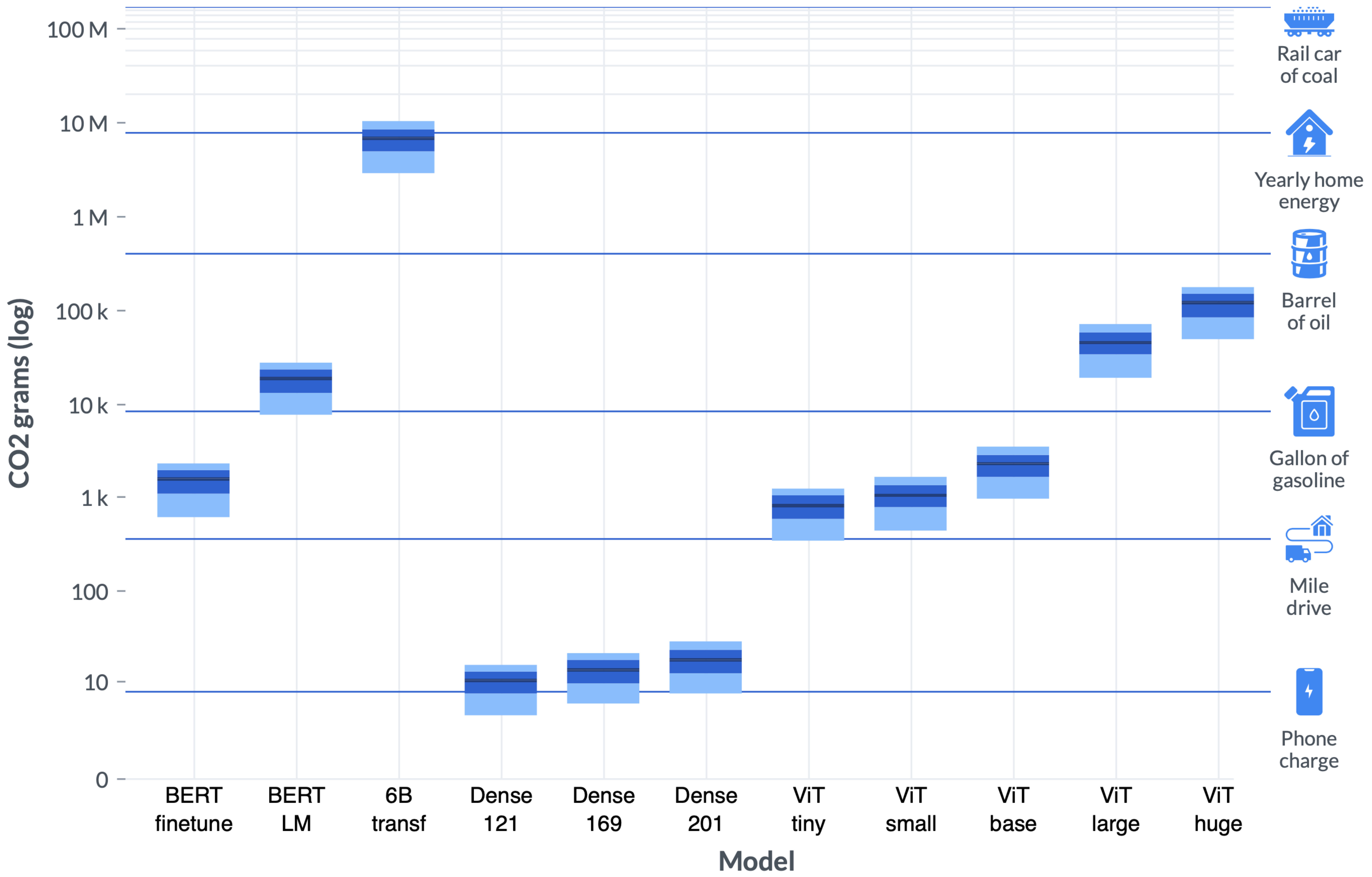
Case study: Training large models at Microsoft

DenseNet 201: Flexible Start



6B Transformer: Pause & Resume





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J. Dodge, T. Prewitt, R. Tachet Des Combes, E. Odmark, R. Schwartz, E. Strubell, A. S.Luccioni, N. A. Smith, N. DeCario, W. Buchanan. Measuring the Carbon Intensity of AI in Cloud Instances. ACM FAccT, 2022.

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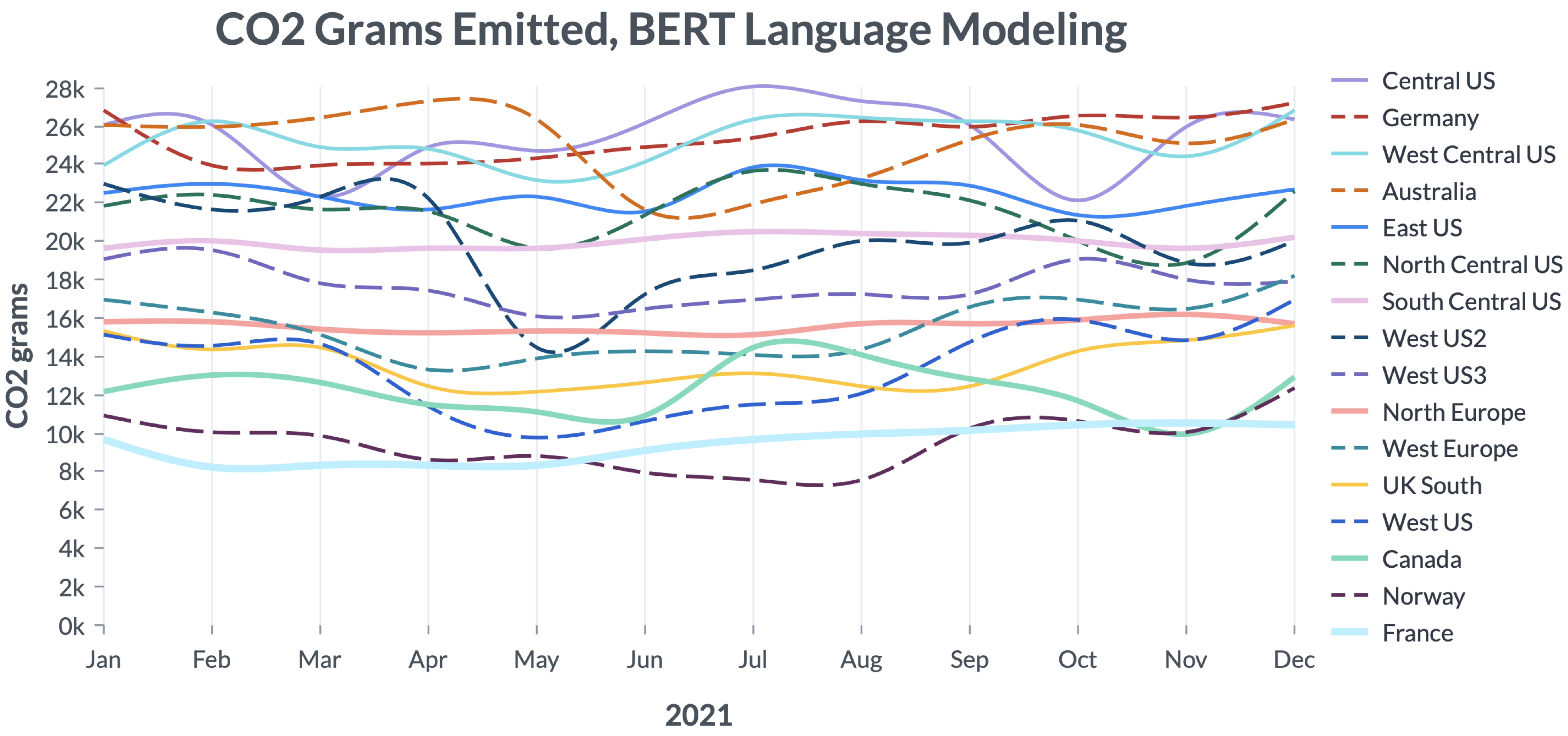

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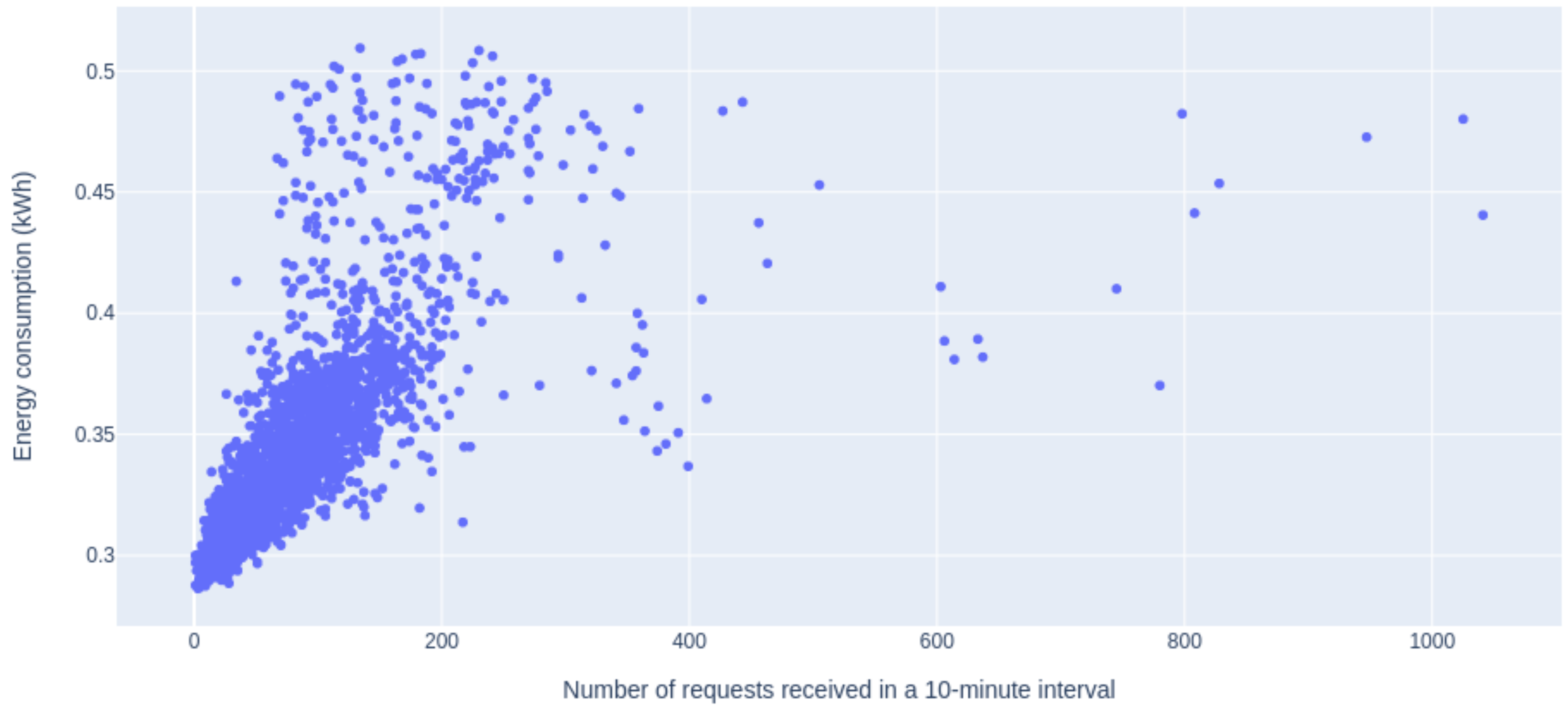
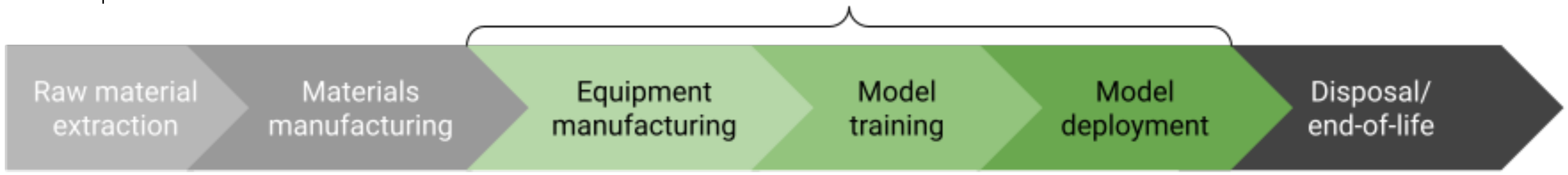
Case study: Training BLOOM (176B params)

Total training time	118 days, 5 hours, 41 min
Total number of GPU hours	1,082,990 hours
Total energy used	433,196 kWh
GPU models used	Nvidia A100 80GB
Carbon intensity of the energy grid	57 gCO_2eq/kWh

Process	**CO_2emissions (CO_2eq)**	**Percentage of total emissions**
Embodied emissions	11.2 tonnes	22.2 %
Dynamic consumption	24.69 tonnes	48.9 %
Idle consumption	14.6 tonnes	28.9 %
Total	**50.5 tonnes**	**100.00%**



19 kgs CO_2 emitted per day of deployment
75% of energy due to serving the model



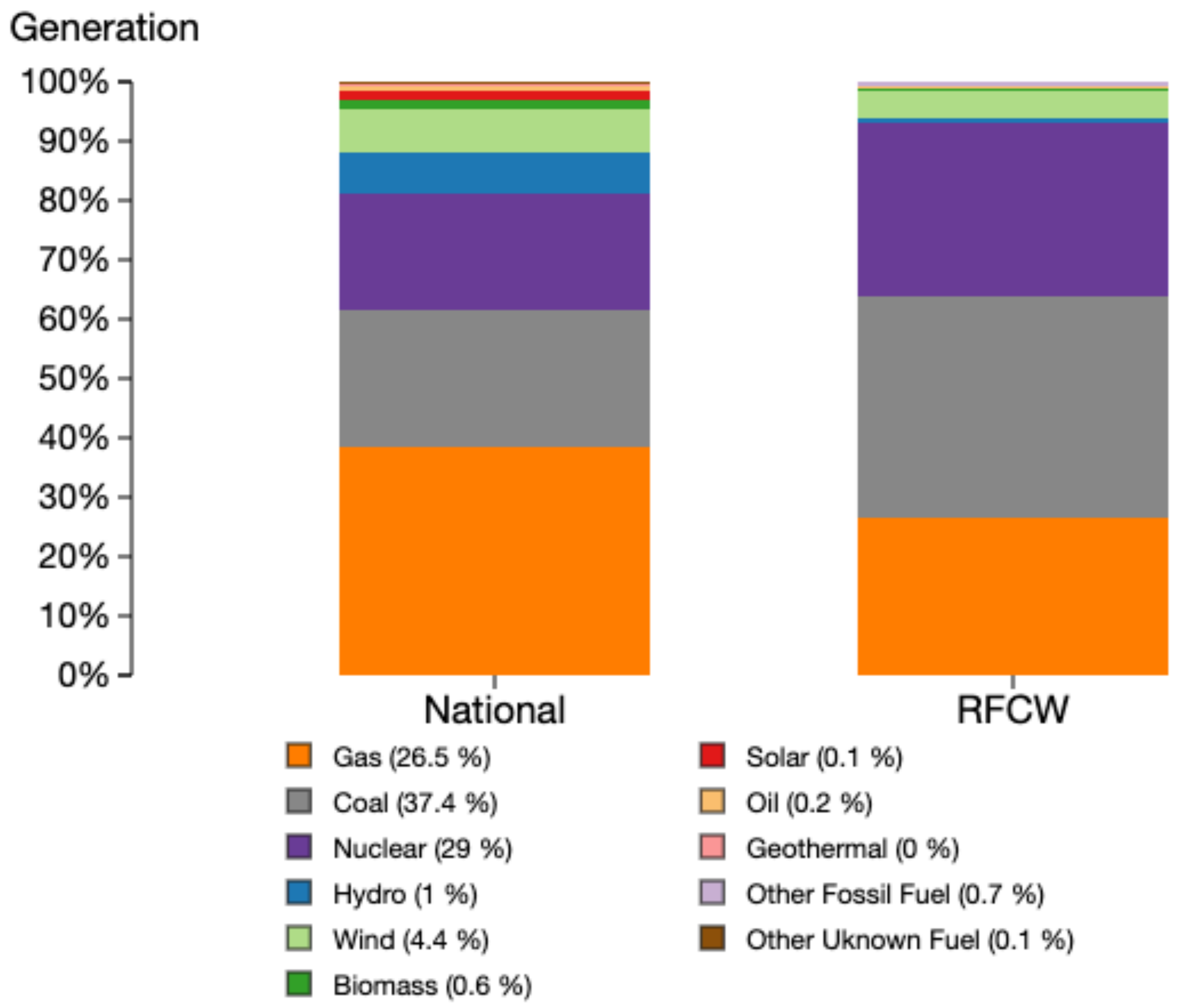
A. S. Luccioni, S. Viguier, A.-L. Ligozat. Estimating the Carbon Footprint of BLOOM, a 176B Parameter Language Model. 2022.

Calculating Carbon

- Most accurate: Direct measurement at the wall using meter
- Jetson 2GB: this is your only option. Others: can compare!
- Still need to convert to emissions.
  - Coarse: https://www.epa.gov/egrid/power-profiler
  - Fine-grained: WattTime API

Fuel Mix

This chart compares fuel mix (%) of sources used to generate electricity in the selected eGRID subregion to the national fuel mix (%).



RFCW Emission Rates

CO_2

1,067.7

(lbs/MWh)

Calculating Carbon

- In the cloud: Machine Learning Emissions Calculator (Lacoste et al. 2019).
- On device: CodeCarbon