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Pathways to Sustainability: Carbon-Aware Routing for Global AI Data Transfers

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Background

- Deep learning enables advances in pathology and demands substantial computational power, resulting in considerable **carbon dioxide equivalent (CO_2eq) emissions**.
- The energy required to **transfer large datasets** between infrastructures may further add to CO_2eq emissions and deserves closer attention in sustainable AI research.

Question

- How can carbon-aware routing of data transmission across global internet infrastructures **reduce the carbon emissions** (CE) associated with AI training and inference?
- When is the **optimal time** to transfer data to reduce CE?

Methods

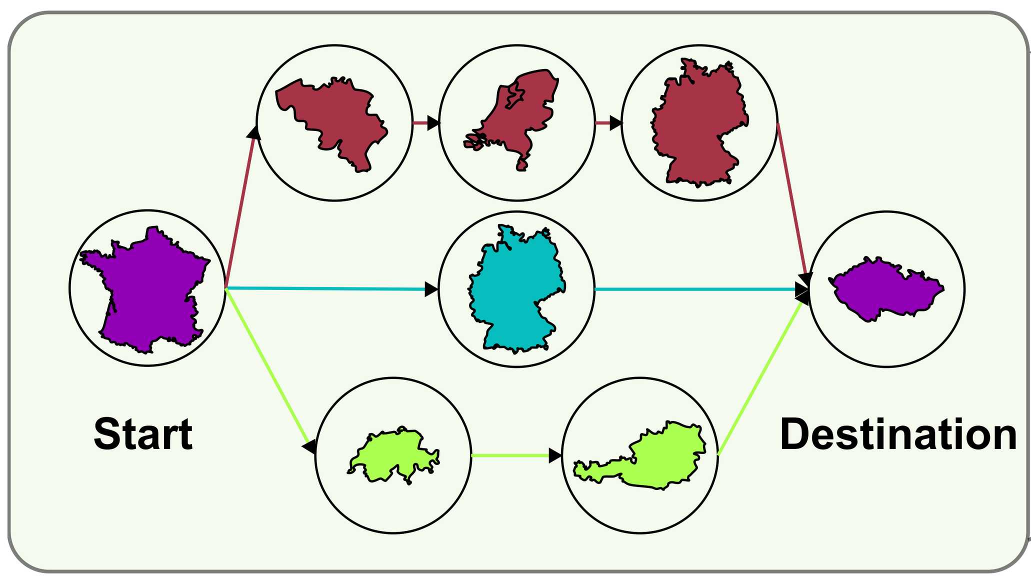
Routing Algorithms

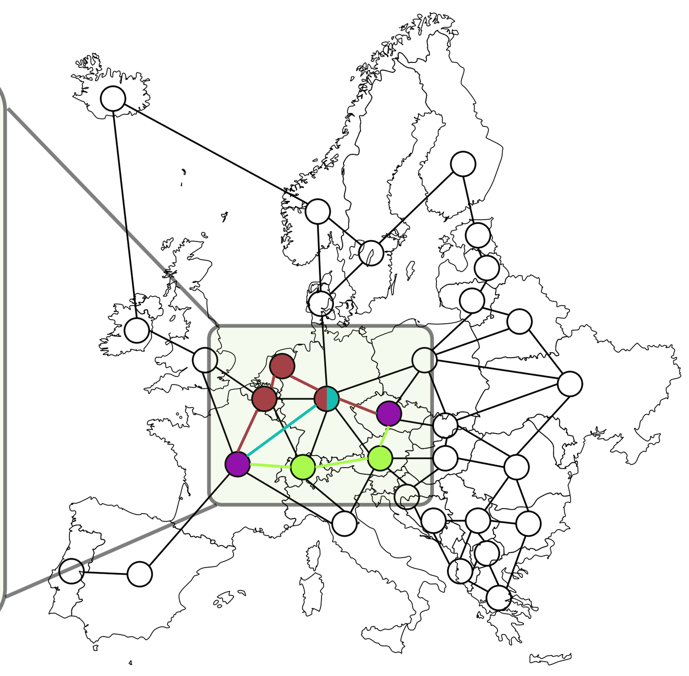
Dijkstra's shortest path algorithm was applied to compute the paths with the lowest total weights.
We've evaluated three methods:

Baseline: Traceroute hop sequence with minimum CI routing between traced hops.

Shortest: path with minimum total distance.

Lowest CI: path minimizing carbon intensity.





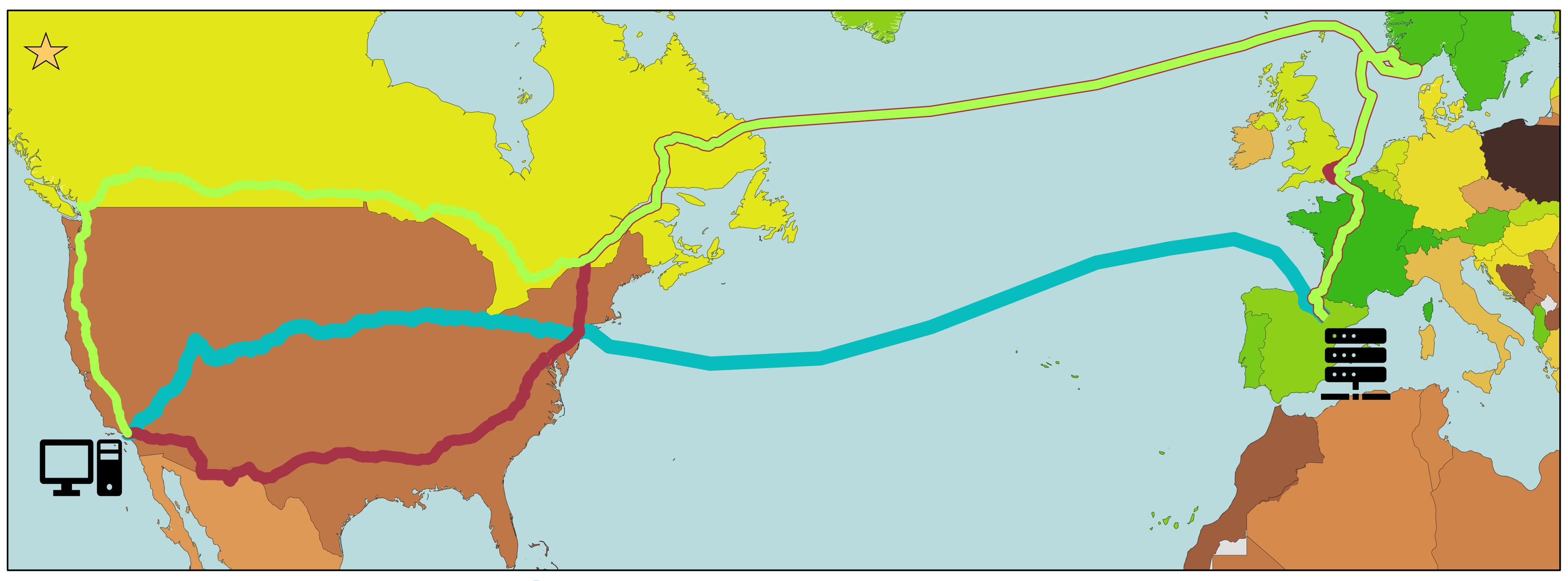
Weights of CE graph are calculated using the following formula:

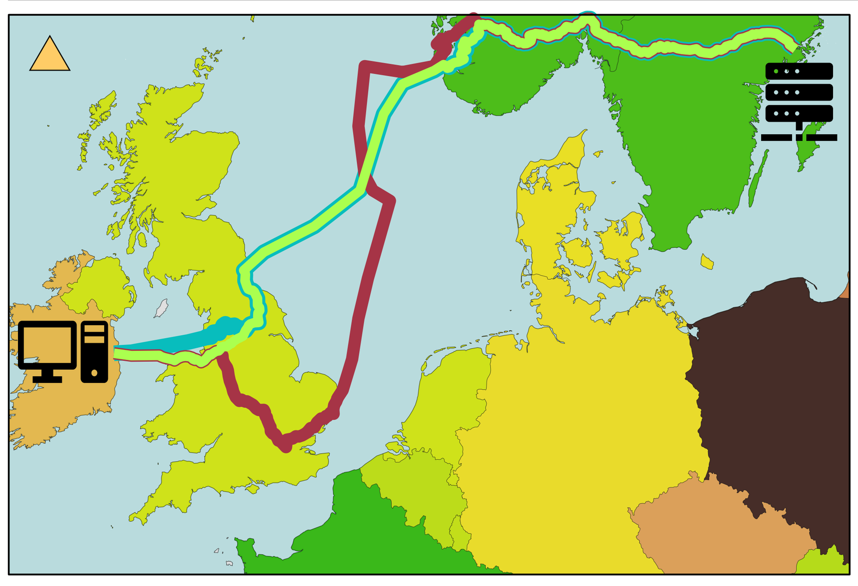
$$w_e = \text{Energy consumption metric}\left(\frac{\text{kWh}}{\text{GB}\cdot\text{km}}\right) \times \text{Cable length}_e(\text{km}) \times \text{Data volume (GB)} \times \text{Carbon Intensity}_{c,t}\left(\frac{\text{gCO}_2}{\text{kWh}}\right)$$

Weights of shortest graph are the cable lengths:

$$w_S = \text{Cable length}_S(\text{km})$$

Results

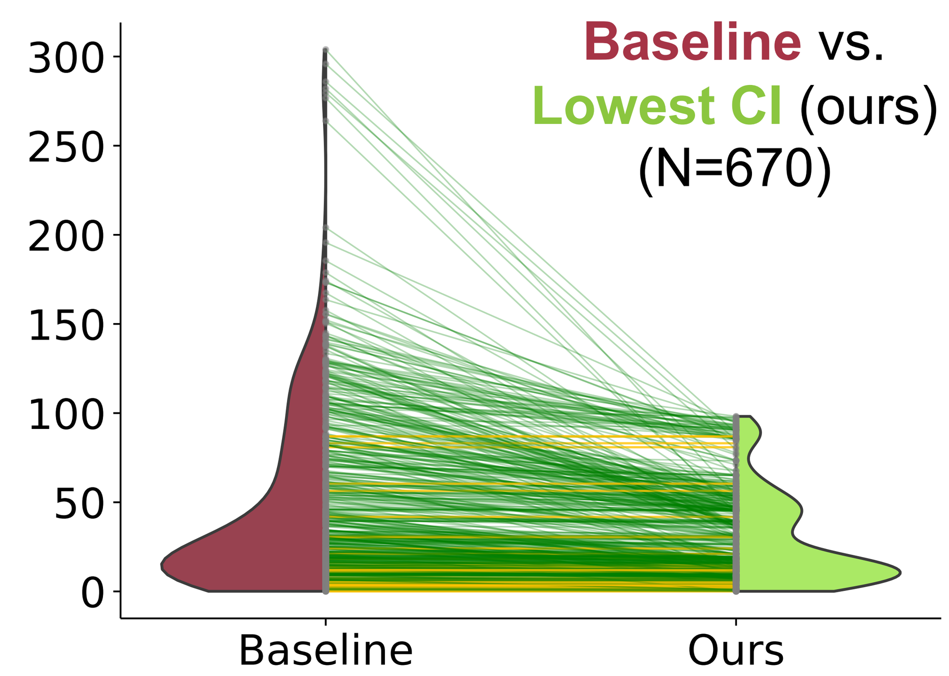




Pairwise Route Comparison

Corresponding pairs of routes are connected by lines. Green lines: reduction in CE; yellow lines: equal CE.

Mean (std dev) emissions for:
Baseline: 46.89 (49.05),
Lowest CI: **28.1** (25.34),
Shortest: 43.98 (32.68).



Visualized Routes

☆ Los Angeles, USA to Zaragoza, Spain with carbon costs 38.16, 51.67 (+35.4%), **22.41** (-41.3%)

△ Dublin, Ireland to Stockholm, Sweden with carbon costs 2.93, 2.55 (-13.1%), **2.07** (-29.5%)

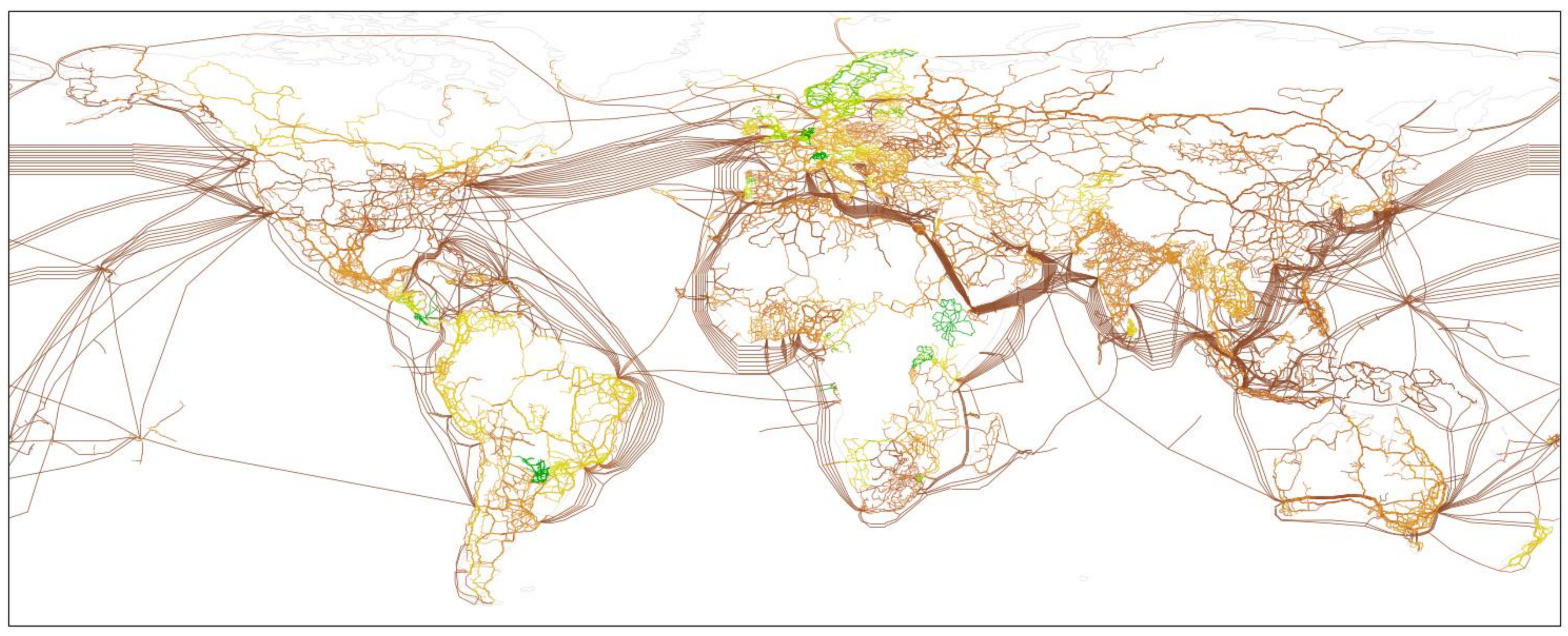
AWS S3 Server

PerfOps MTR node

CI in gCO_2eq/kWh

0 – 700

Cable Graph Colored by CE



From City	To City	Baseline		Shortest			Lowest CI (ours)		
		gCO2/GB	std (±)	gCO2/GB	$\Delta_{Base.}$ (%)	std (±)	gCO2/GB	$\Delta_{Base.}$ (%)	std (±)
Tokyo	São Paulo	76.77	4.08	78.26	1.95	12.72	58.05	**-24.39**	5.57
Singapore	Zürich	32.77	4.19	55.65	69.80	2.51	31.95	**-2.51**	3.31
Amsterdam	San Jose	39.07	3.44	45.69	16.92	4.26	18.06	**-53.79**	1.99
Chicago	Jakarta	124.02	9.18	88.35	-28.76	5.05	46.66	**-62.37**	2.97
Los Angeles ☆	Zaragoza	38.16	1.58	51.67	35.38	2.77	22.41	**-41.29**	1.39
Seattle	Stockholm	15.28	1.81	9.09	-40.51	0.88	9.07	**-40.67**	0.88
Dublin △	Stockholm	2.93	2.09	2.55	-13.14	1.61	2.07	**-29.54**	1.32
Frankfurt am Main	Dār Kulayb	13.20	2.66	19.71	49.33	0.91	13.20	**0.00**	2.66
Athens	Milan	8.40	0.97	4.37	-47.95	0.48	3.77	**-55.14**	0.36
Frankfurt am Main	Melbourne	101.49	15.60	94.11	-7.27	6.68	76.99	**-24.14**	8.38

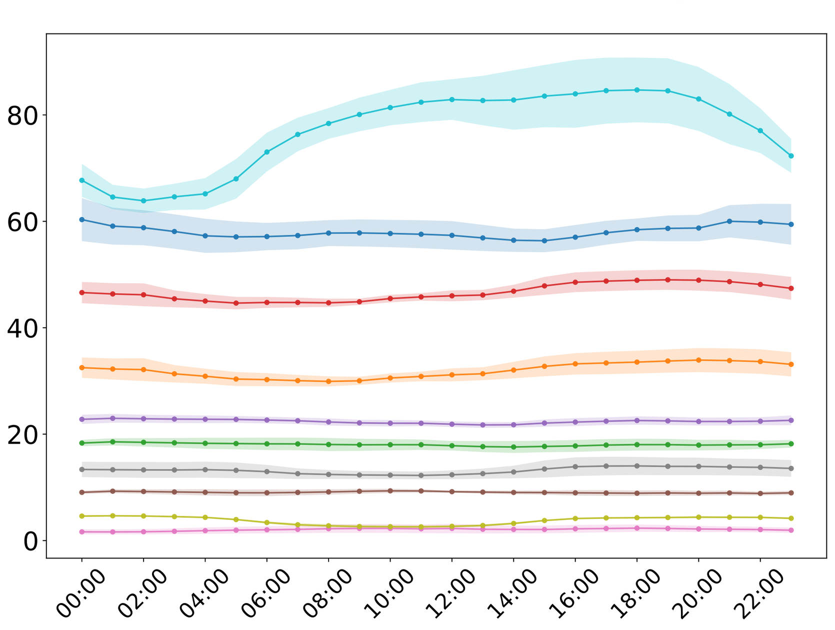
Results for Selected Routes

Table with CE of ten exemplary paths between city pairs for all three routing methods. The change of the carbon cost compared to the baseline method in percent is shown in columns $\Delta_{Base.}$.

The data is averaged over 24h across four days in four different months (January, April, June, October).

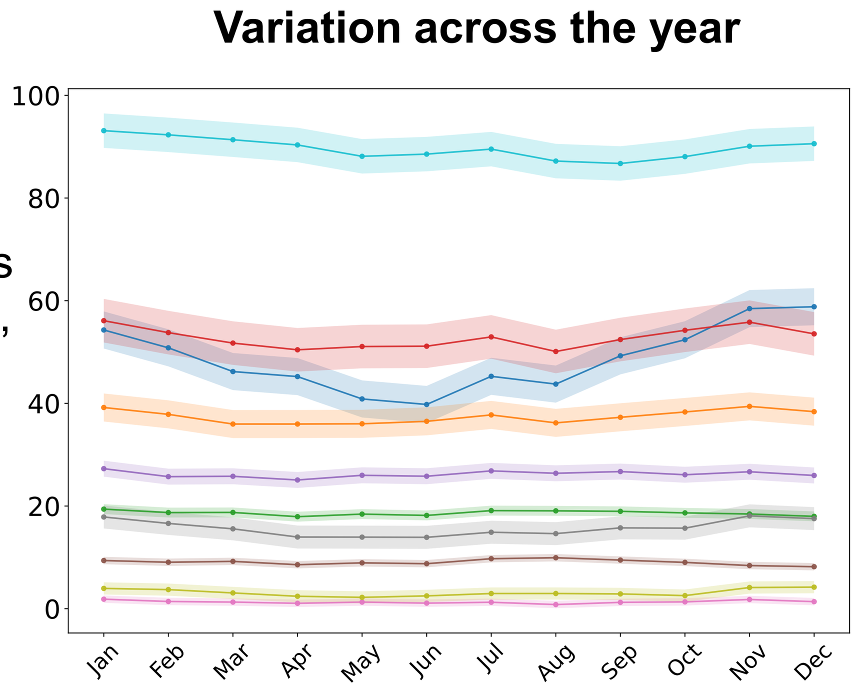
CE over Time

Variation across the day



gCO_2/GB for four days across all seasons, mean and SEM of **Lowest CI** paths

Variation across the year



gCO_2/GB for a single hour across all days of the year 2024, mean and SD of **Lowest CI** paths

Routes and their distances (km):

From City	To City	Baseline	Shortest	Lowest CI
Frankfurt am Main	Melbourne	33647	20678	32433
Tokyo	São Paulo	35292	24342	26568
Chicago	Jakarta	35606	20968	31944
Singapore	Zürich	19929	12016	19408
Los Angeles	Zaragoza	14761	11048	15414
Amsterdam	San Jose	24981	11106	13501
Frankfurt am Main	Dār Kulayb	9988	5743	9988
Seattle	Stockholm	15365	11475	11493
Athens	Milan	3105	1824	1905
Dublin	Stockholm	2671	2149	2156

NEURAL INFORMATION PROCESSING SYSTEMS

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