ORCA

Outcome-aware
Regional
Compute
Allocation

Sustainability-Aware Workload Shifting Beyond Carbon Intensity

Geerd-Dietger Hoffmann <didi@green-coding.io>
Verena Majuntke <verena.majuntke@htw-berlin.de>

GREEN CODING;
Universität Potsdam
Hochschule für Technik und Wirtschaft Berlin
University of Applied Sciences

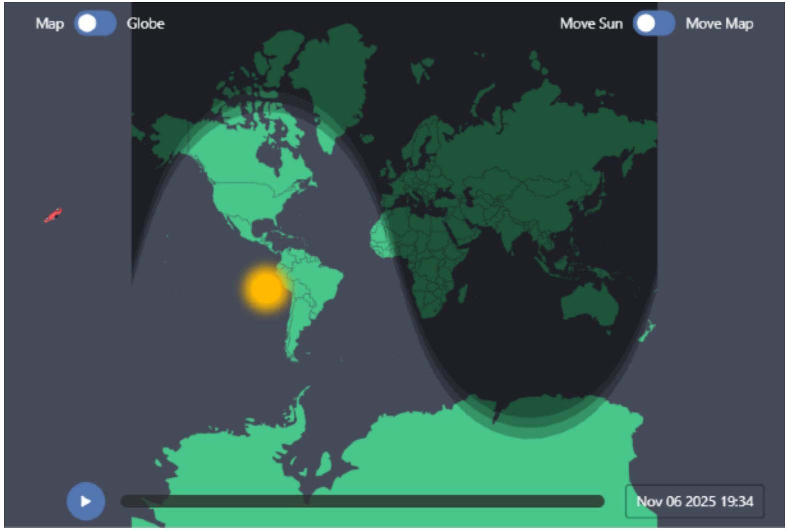
Sustainability-Aware Workload Shifting Beyond Carbon Intensity

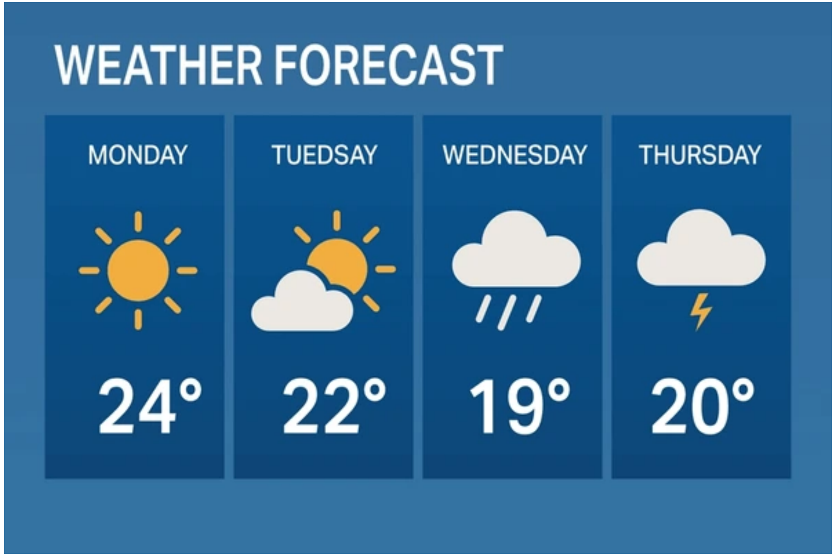
RQ1: How can workload shifting consider local impacts in addition to CO2?

RQ2: When does CO_2-optimal shifting increase local burdens?

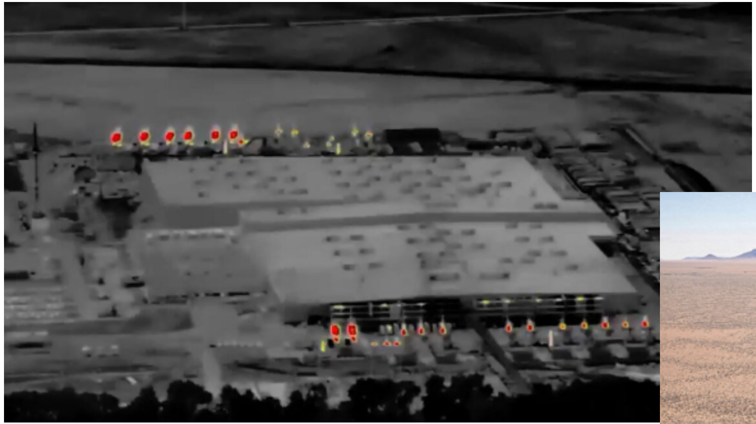
RQ3: How does zone-aware workload placement compare to CO2-only workload placement?

Location and Time shifting





Not only CO2 is harming people



https://arstechnica.com/tech-policy/2025/04/elon-musks-xai-accused-of-lying-to-black-communities-about-harmful-pollution/
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https://datacentremagazine.com/news/how-google-is-lowering-data-centre-emissions-amid-ai-growth

Google is just great

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Google is just great, thx Max

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The AI boom is built on the back of the down trodden

NAACP lawsuit accuses Elon Musk's xAI of polluting Black neighborhoods near Memphis

Suit alleges the billionaire's AI company is illegally spewing toxic pollutants from its datacenter in the Memphis area

CLOSE ALL TABS

How the AI Data Center Boom Impacts Black Communities

LISTEN

By Morgan Sung, Maya Cueva, Chris Egusa, Chris Hambrick Feb 4, 2026 Updated Mar 10, 2026 Save Article

Tech Policy Press

Data Center Boom Risks Health of Already Vulnerable Communities

This analysis aims to build awareness of the environmental and health risks that generative AI's energy expansion poses to marginalized communities.

12.06.2025

https://naacp.org/articles/elon-musks-xai-threatened-lawsuit-over-air-pollution-memphis-data-center-filed-behalf

https://www.canarymedia.com/articles/fossil-fuels/how-the-data-center-boom-could-harm-black-communities

What are other impacts

1. Embodied Emissions
    1. Metals and other Elements
    2. Transportation
2. Electricity ✓
3. Water ✓
4. Land usage
5. Rare earths
6. Waste management
7. Air Pollution ✓
8. Human

New factors emerging:

- Noise
- Light
- Refrigerant leakage
- Metal for construction
- Social / Society

CO2 vs the others

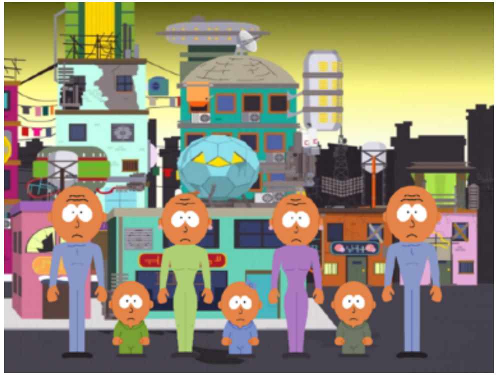
How should we rate which one is more important?

Climate change

Water

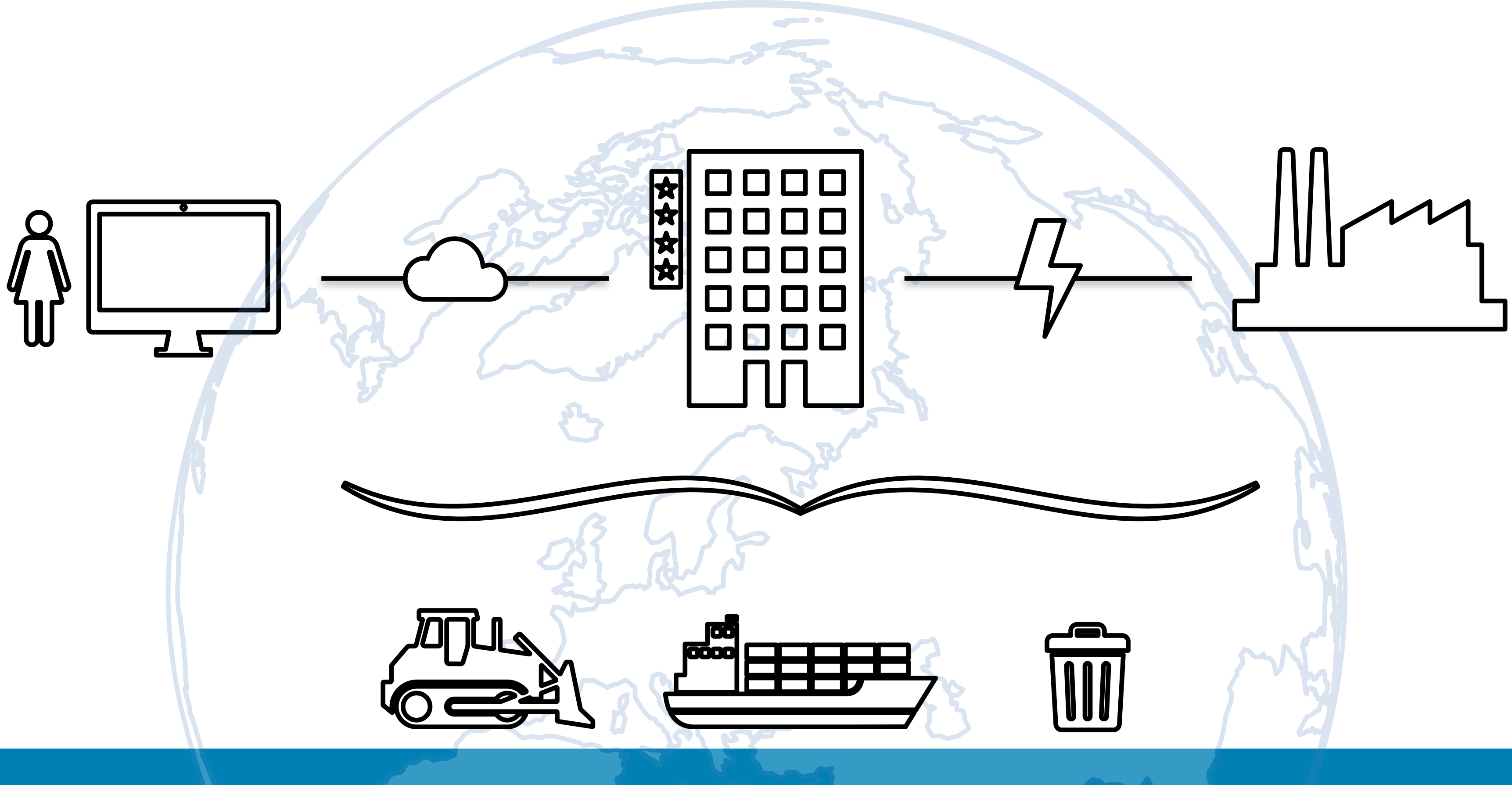
Noise Air pollution CO2 Nuclear Waste

Now Future



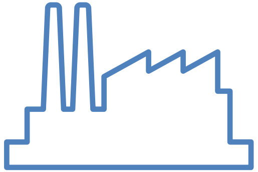
https://www.deviantart.com/hazlamglorius/art/GooBacks-to-the-Future-1073075354

Actors

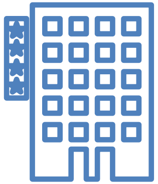


New Concept => Impact Zones

Global Zone: CO2 -eq (g/kWh)



Energy Production Zone: SO2 -eq (g/kWh) CO (g/kWh)



Data-Centre Zone: NO2 (µg/m3) PM2.5 (µg/m3) Price (EUR) Water

Orca decision model: from workload traces to auditable placement

1. **Workload resource profile**
   energy curve u(i)
   network transfer
   Sin/Sout
2. **Region-time impact signals**
   CO2, water, air pollution,
   price / grid stress
3. **Schedule accounting**
   execution term + transfer term
4. **Optimization & governance**
   Weights, optional caps

Decision variable: choose one data-centre d and one feasible start time τ for a non-migratory workload.

Formalization:

Schedule-induced burden per dimension

$$I_e(d,\tau) = \underbrace{\sum_{i=0}^{n-1} u(i)\cdot g_{d,e}(\tau + i\Delta)}_{\text{execution term}} + \underbrace{T_e(o,d)}_{\text{transfer term}}\ .$$

Weighted objective over normalized loads

$$J(d,\tau) = \sum_{e\in\mathcal{E}} \omega_e \frac{I_e(d,\tau)}{s_e}$$

Constraint layer: $I_e(d, \tau) \leq Cap_e(zone(d,e))$ for each dimension e

Caps prevent global optimization from violating local burden limits.

Experiment

Locations (all northern hemisphere)

DE	Europe (Frankfurt)
JP	Asia-Pacific (Tokyo)
CA	U.S. West (Northern California)

2 Dates:

- 01.07.2025 (summer)
- 01.01.2026 (winter)

Workload - Django unit tests

$H = 883.26$ s

$E_{exec} = 6905.28$ mWh = 0.00690528 kWh

Very Uniform workload

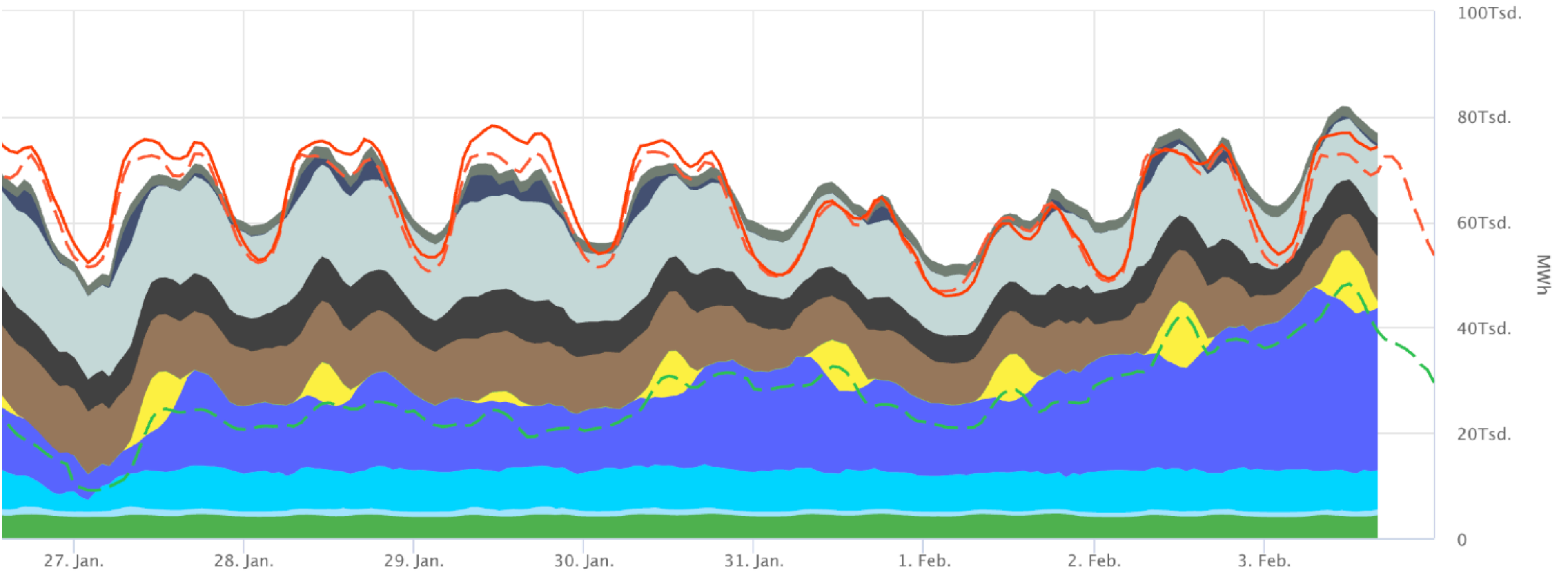
$S_{in} = 51.70$ MB

$S_{out} = 0$ MB

≈0.46 gCO_2e

Other impacts are for future work

Grids are really complex



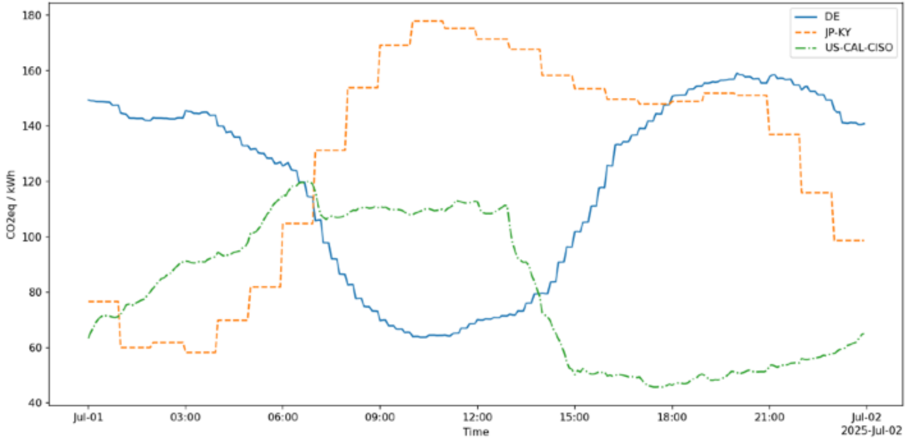
There is not only CO2

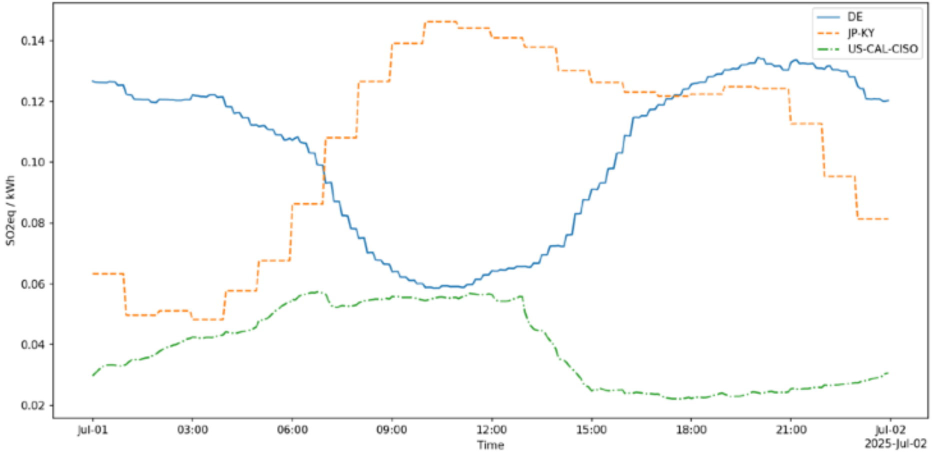
TABLE II: Emissions in g per kWh electricity

Energy Source	CO_2-eq	CO_2	CH4	N2O	SO_2-eq	SO_2	NOx	CO	NM-VOC
nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
geothermal	26.68	24.854	0.05	0.002	0.037	0.015	0.031	0.024	0.002
biomass	12.871	11.989	0.024	0.001	0.018	0.007	0.015	0.012	0.001
coal	398.36	394.95	0.002	0.013	0.387	0.196	0.279	0.114	0.005
wind	0.87	0.81	0.002	0.0	0.001	0.0	0.001	0.001	0.0
solar	0.44	0.41	0.001	0.0	0.001	0.0	0.001	0.0	0.0
hydro	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
hydro discharge	8.89	8.28	0.017	0.001	0.012	0.005	0.01	0.008	0.001
gas	212.3	202.77	0.295	0.005	0.095	0.001	0.136	0.05	0.005
oil	268.78	266.47	0.023	0.006	0.505	0.169	0.482	0.198	0.0

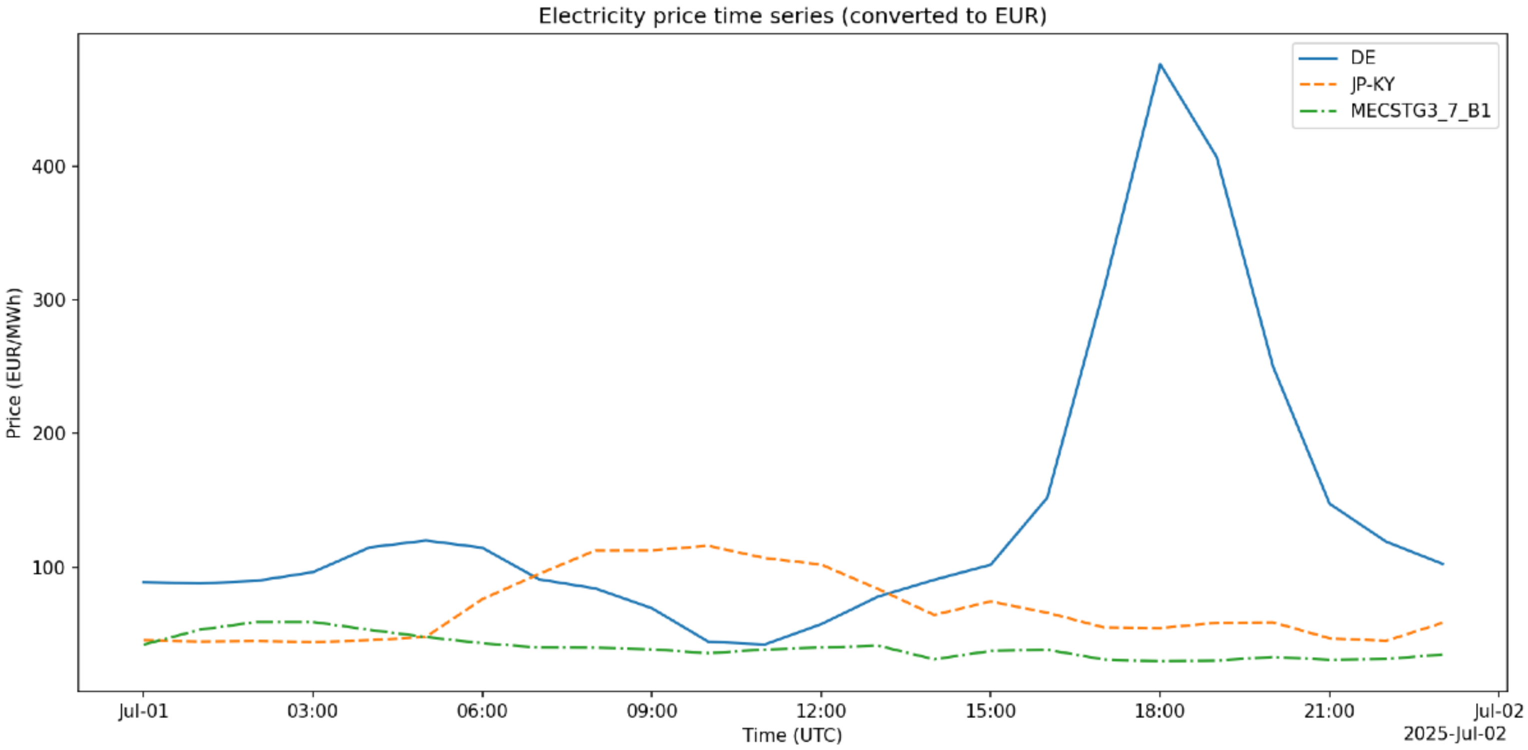
https://www.umweltbundesamt.de/system/files/medien/11850/publikationen/03_2025_cc_emissionsbilanz_erneuerbarer_energien_2023.pdf

CO2eq vs SO2eq

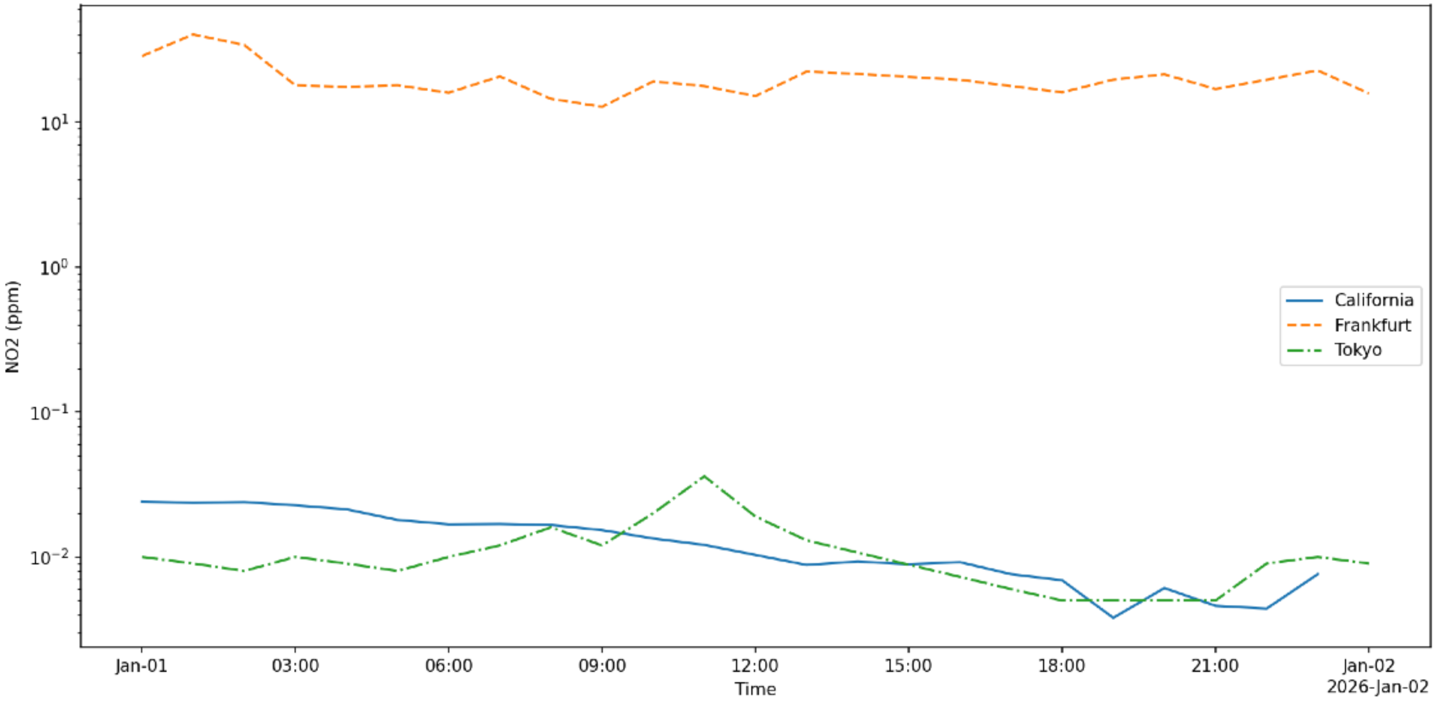




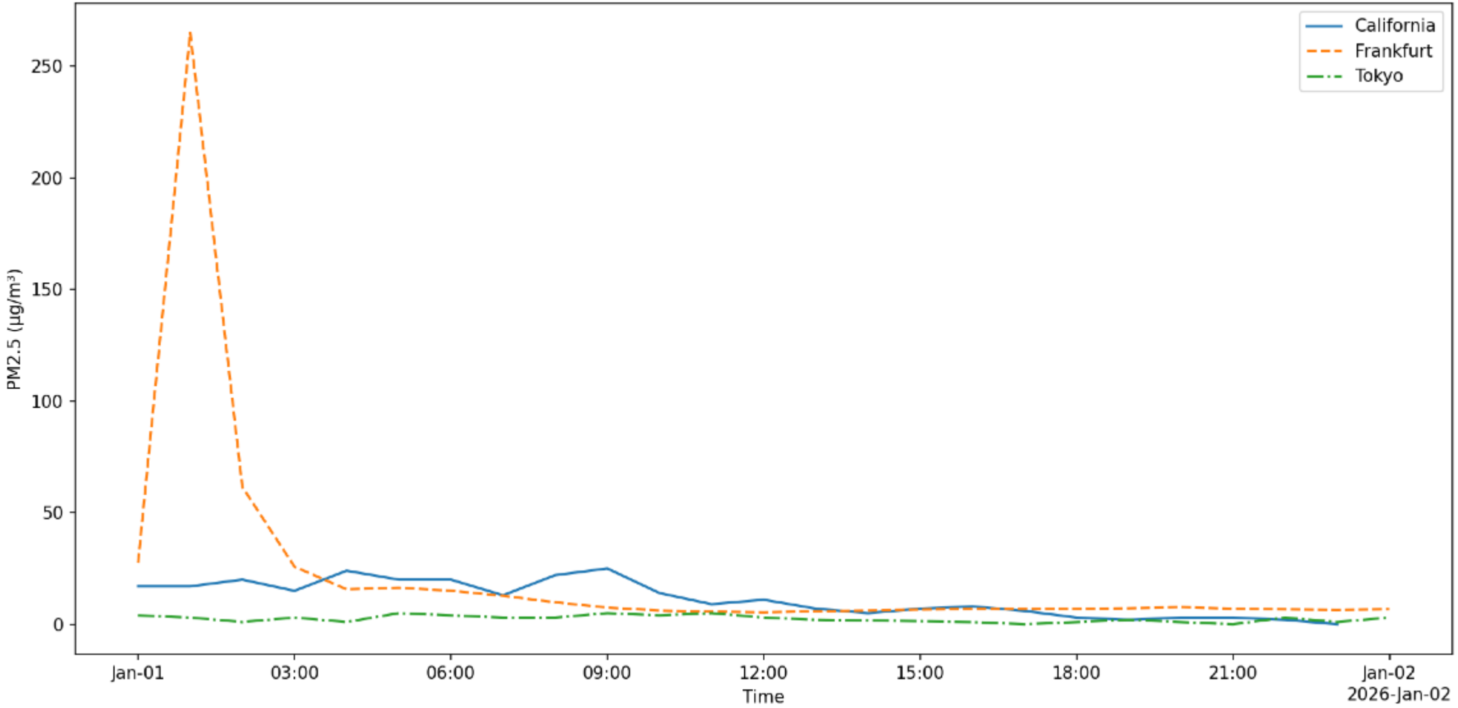
Electricity Price



Air NO2 - OpenAQ



Air PM2.5 - OpenAQ



Water

Europe (Frankfurt)	0.01
Asia-Pacific (Tokyo	0.91
U.S. West (Northern California)	0.51

TABLE III: Water scarcity risk levels by region and date.

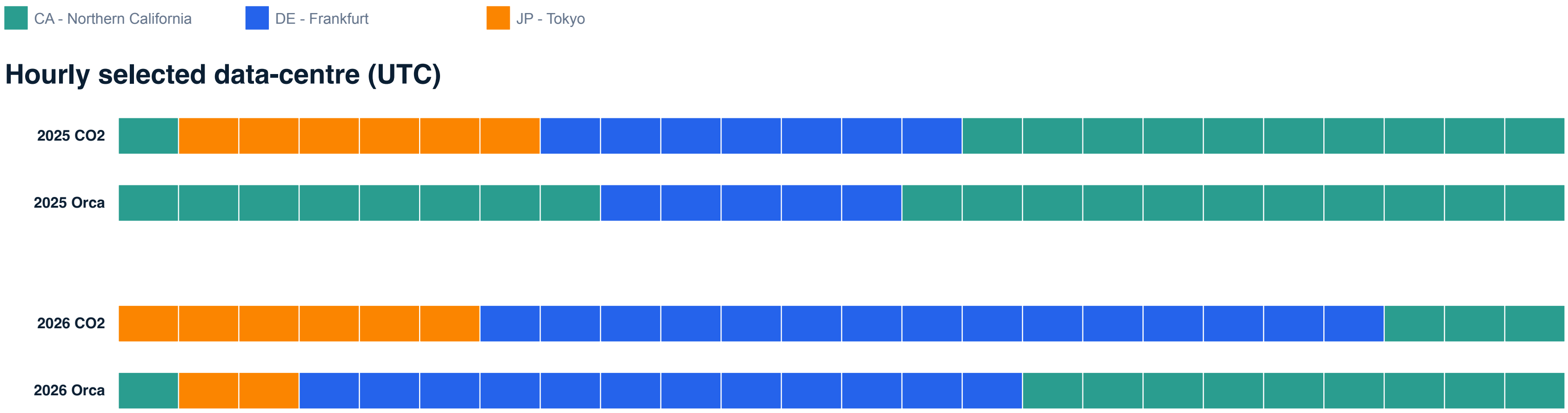
Date	Frankfurt	Tokyo	Northern California
01.01.2026	Medium–High	Medium–High	Low
01.07.2025	High	Medium–High	Medium–High

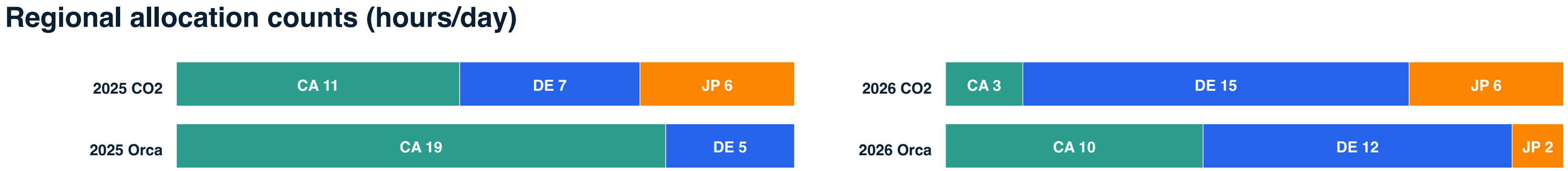
https://www.wri.org/applications/aqueduct/water-risk-atlas/#/?advanced=false&basemap=hydro&indicator=w_awr_def_tot_cat&lat=50.6607789125291&lng=29.992675781250004&mapMode=view&month=1&opacity=0.5&ponderation=DEF&predefined=false&projection=absolute&scenario=optimistic&scope=baseline&threshold&timeScale=annual&year=baseline&zoom=4

TABLE V: Hourly intensities by region with lowest values highlighted

	Global Zone			Energy Production Zone						Data-Centre Zone											
Time (h)	CO_2-eq (g/kWh)			SO_2-eq (g/kWh)			CO (g/kWh)			NO_2 ($\mu g/m^3$)			$PM_{2.5}$ ($\mu g/m^3$)			Price (EUR)			Water		
	CA	DE	JP	CA	DE	JP	CA	DE	JP	CA	DE	JP	CA	DE	JP	CA	DE	JP	CA	DE	JP
2025																					
00:00	**69.57**	148.57	76.64	**0.03**	0.13	0.06	**0.02**	0.04	0.02	**0.01**	15.10	0.01	**1.00**	5.86	12.00	**42.37**	89.10	45.64	1.53	**0.04**	2.73
01:00	76.20	143.08	**60.01**	**0.04**	0.12	0.05	0.02	0.04	**0.02**	**0.01**	11.13	0.01	5.00	**4.58**	13.00	53.52	88.08	**44.69**	1.53	**0.04**	2.73
02:00	86.44	142.85	**61.83**	**0.04**	0.12	0.05	0.02	0.04	**0.02**	**0.01**	9.22	0.01	**3.00**	3.93	13.00	59.27	90.01	**45.17**	1.53	**0.04**	2.73
03:00	91.35	144.72	**58.24**	**0.04**	0.12	0.05	0.02	0.04	**0.02**	**0.01**	10.80	0.01	**4.00**	4.12	15.00	59.27	96.50	**44.25**	1.53	**0.04**	2.73
04:00	94.65	136.68	**69.78**	**0.04**	0.12	0.06	0.02	0.04	**0.02**	**0.01**	8.00	0.01	5.00	**3.99**	13.00	53.40	114.97	**45.64**	1.53	**0.04**	2.73
05:00	107.05	129.23	**81.89**	**0.05**	0.11	0.07	0.03	0.04	**0.02**	**0.01**	15.18	0.01	6.00	**4.38**	14.00	**48.04**	120.11	48.13	1.53	**0.04**	2.73
06:00	118.23	121.14	**104.73**	**0.06**	0.10	0.09	**0.03**	0.03	0.03	**0.01**	27.11	0.01	5.00	**4.87**	15.00	**43.40**	114.72	76.38	1.53	**0.04**	2.73
07:00	108.37	**95.54**	131.24	**0.05**	0.09	0.11	**0.03**	0.03	0.04	0.01	37.98	**0.01**	6.00	**5.60**	11.00	**40.19**	91.19	95.08	1.53	**0.04**	2.73
08:00	110.02	**77.10**	153.89	**0.05**	0.07	0.13	0.03	**0.02**	0.04	0.01	48.72	**0.01**	10.00	**5.85**	11.00	**39.97**	84.31	112.77	1.53	**0.04**	2.73
09:00	109.71	**67.44**	169.15	**0.06**	0.06	0.14	0.03	**0.02**	0.05	**0.01**	39.01	0.01	8.00	**5.98**	10.00	**38.84**	69.56	112.86	1.53	**0.04**	2.73
10:00	109.45	**64.11**	177.95	**0.06**	0.06	0.15	0.03	**0.02**	0.05	**0.01**	41.34	0.02	7.00	**6.79**	13.00	**35.95**	44.54	116.21	1.53	**0.04**	2.73
11:00	111.89	**66.23**	175.39	**0.06**	0.06	0.14	0.03	**0.02**	0.05	**0.01**	35.91	0.02	**5.00**	6.45	13.00	**38.67**	42.47	107.05	1.53	**0.04**	2.73
12:00	109.79	**70.59**	171.40	**0.05**	0.06	0.14	0.03	**0.02**	0.05	N/A	32.35	**0.01**	**3.00**	6.36	9.00	**40.15**	57.65	102.16	1.53	**0.04**	2.73
13:00	90.07	**75.11**	167.73	**0.04**	0.07	0.14	0.02	**0.02**	0.05	0.01	N/A	**0.01**	**7.00**	N/A	9.00	**41.61**	78.14	84.02	1.53	**0.04**	2.73
14:00	**63.18**	87.62	158.29	**0.03**	0.08	0.13	**0.02**	0.03	0.05	**0.01**	33.56	N/A	8.00	**7.02**	N/A	**31.38**	90.80	64.58	1.53	**0.04**	2.73
15:00	**51.07**	108.98	153.54	**0.03**	0.10	0.13	**0.01**	0.03	0.04	**0.01**	25.50	N/A	10.00	**5.42**	N/A	**37.62**	102.02	74.63	1.53	**0.04**	2.73
16:00	**49.72**	132.52	149.74	**0.02**	0.11	0.12	**0.01**	0.04	0.04	**0.01**	25.52	0.02	6.00	**5.29**	11.00	**38.54**	152.08	66.21	1.53	**0.04**	2.73
17:00	**46.53**	143.27	148.05	**0.02**	0.12	0.12	**0.01**	0.04	0.04	**0.01**	35.31	0.02	**6.00**	6.24	10.00	**31.24**	307.27	55.22	1.53	**0.04**	2.73
18:00	**47.95**	152.48	148.86	**0.02**	0.13	0.12	**0.01**	0.04	0.04	**0.01**	39.53	0.01	8.00	**6.23**	9.00	**29.92**	476.19	54.71	1.53	**0.04**	2.73
19:00	**49.36**	156.26	151.91	**0.02**	0.13	0.12	**0.01**	0.05	0.04	**0.01**	37.98	0.01	**6.00**	6.71	9.00	**30.50**	406.81	58.62	1.53	**0.04**	2.73
20:00	**51.24**	157.31	151.07	**0.02**	0.13	0.12	**0.01**	0.05	0.04	**0.01**	56.31	0.01	**7.00**	8.36	12.00	**33.12**	250.01	58.98	1.53	**0.04**	2.73
21:00	**53.79**	156.82	137.01	**0.03**	0.13	0.11	**0.01**	0.04	0.04	**0.01**	72.99	0.01	**6.00**	12.26	11.00	**31.02**	147.65	47.07	1.53	**0.04**	2.73
22:00	**56.46**	151.80	115.87	**0.03**	0.13	0.10	**0.01**	0.04	0.03	**0.01**	68.92	0.01	**11.00**	11.89	12.00	**31.59**	119.29	45.17	1.53	**0.04**	2.73
23:00	**61.06**	142.09	98.69	**0.03**	0.12	0.08	**0.01**	0.04	0.03	**0.01**	40.16	0.02	9.00	**8.84**	12.00	**35.00**	102.70	58.65	1.53	**0.04**	2.73
2026																					
00:00	96.24	77.54	**59.26**	**0.05**	0.07	0.05	0.02	0.02	**0.02**	0.02	28.55	**0.01**	17.00	27.55	**4.00**	**38.46**	42.40	44.72	0.51	**0.03**	2.73
01:00	93.33	72.62	**21.13**	0.05	0.06	**0.02**	0.02	0.02	**0.01**	0.02	40.24	**0.01**	17.00	265.15	**3.00**	38.50	**19.57**	43.98	0.51	**0.03**	2.73

Result: Orca chooses different locations than CO2-only routing





What we answered

RQ1: How can workload shifting consider local impacts in addition to CO2?

=> Zones

RQ2: When does CO_2-optimal shifting increase local burdens?

=> Heavily depends on the local setting but can be modeled

RQ3: How does zone-aware workload placement compare to CO2-only workload placement?

=> Heavily depends on the weighting between impacts but there is a difference

Limitations: the model is exact about accounting, not omniscient about signals

Feasibility boundary
Assumes legal, latency, deployment and service constraints are already applied.

Non-migratory jobs
No preemption, checkpoint/restart, or live migration in the base model.

Transfer simplification
Per-MB proxy ignores path, caching, congestion, and transfer time.

Average vs marginal mix
Average generation mix is illustrative; marginal damage signals are better when available.

Data quality
Missing, stale, or sparse local signals can bias normalized objectives.

Embodied impacts
Omitted from example; can be added via amortized hardware burden terms.

> **The case study is a transparent demonstration of a decision model, not a universal operational recommendation for these three regions.**

Conclusion

1. We can show that there are other values than CO_2 that can be relevant
2. Emissions are not always global but increase burdens locally
3. Zones can model this
4. When taking into account other impacts routing decisions change

Next Paper: Why are people not migrating workloads?

I will need your help with this one

Questions?

https://www.linkedin.com/in/dietgerhoffmann/
https://www.linkedin.com/in/verena-majuntke/

didi@green-coding.io
verena.majuntke@htw-berlin.de

https://www.uni-potsdam.de/de/cs-se/team/geerd-dietger-hoffmann
https://www.htw-berlin.de/hochschule/personen/person/?eid=11866