The Carbon Footprint of the Electron-Ion Collider

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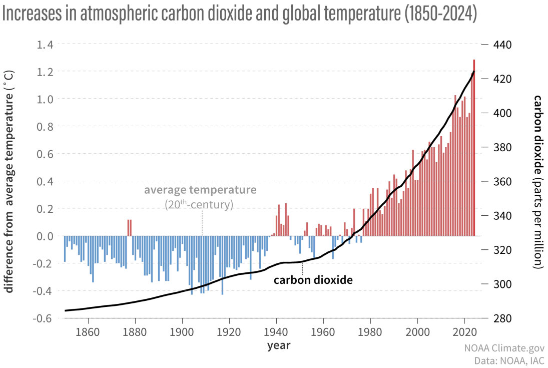
These preliminary results are for research purposes only and do not reflect the EIC Project nor its funding agencies.

Climate Change

- **Carbon dioxide** (CO_2) is a greenhouse gas
- 1000 gigatonnes CO_2 = 0.27-0.63°C rise in global temperature [9]
- Want to keep warming under 1.5°C = requires annual per capita emissions to be **less than 1.1 tonne CO_2** [9]
- Average US car emits 4.3 tonnes per year [37]



Atmospheric CO_2 levels compared with global temperature increase over the last 175 years [23].

Motivation

- Electron-Ion Collider (EIC) has the attention of scientific community
- Collaboration has the opportunity to prioritize sustainability
  - Practically: economic and social obstacles on the horizon

What are the EIC's largest emission sources and how can we reasonably mitigate them?

Motivation

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What are the EIC's largest emission sources and how can we reasonably mitigate them?

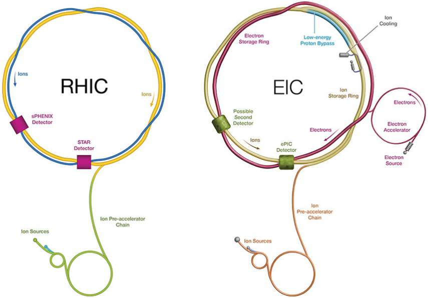
- **Takeaways:**
  - Sustainability is being talked about in particle physics community
  - Understand where EIC fits in the broader picture
  - Effective action comes from individuals

Methodology

- **tCO_2e** = tonnes carbon dioxide equivalent
  - Allows us to standardize emissions
- **Embodied Carbon Factor:** Amount of CO_2e per unit of a material, process, etc.
  - Aluminum: 13.06 kg CO_2e / kg of Al
- **Process:**
  1. Review Technical/Conceptual Design Report (TDR, CDR), collaboration records, etc. to determine the quantity of a material/process
  2. Multiply by embodied carbon factor
  3. Compare to other sources
- Only using publicly accessible information
- Keeping EIC separate from Brookhaven National Lab (BNL) whenever possible
- Construction, operation, community

Construction

- **Accelerator:** Constructing new Electron Storage Ring (beampipe) and Rapid Cycling Synchrotron (tunnel and beampipe) [38]
    - Reusing Hadron Storage Ring, reusing magnets from Argonne [28]
- **Detector:** Constructing ePIC [13]
    - Reusing Barrel Hadron Calorimeter from sPHENIX
- **Facilities:** 34 new buildings (336,000 ft^2), 8000ft of roads [17, 39]



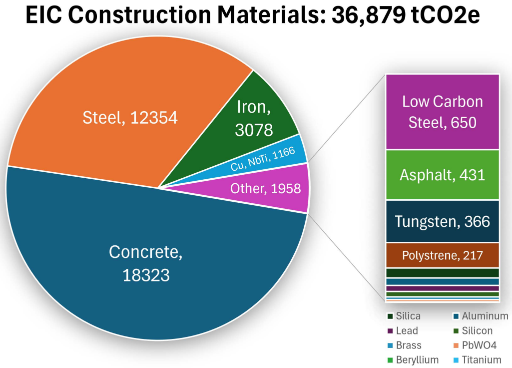
The EIC will reuse some of RHIC's infrastructure [16].

Construction

Estimating 36.9 ktCO_2e

→ LEP3 @ CERN: 61 ktCO_2e [5]

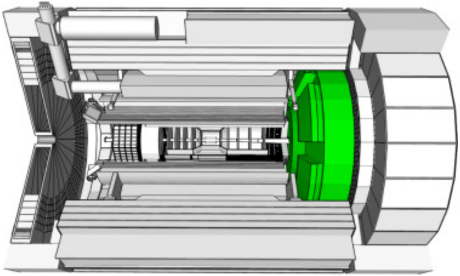
- Facilities (including tunnel): 62%
- Accelerator: 29%
- Detector: 9%
- Reusing HCal and magnets saves over 1,650 tCO_2e



Construction footprint primarily attributed to concrete and steel.

Operations: Cryogenics and Detection

- **Cryogenics**:
  - Liquid helium for superconducting magnets
  - Sourced from natural gas — production is expensive and unsustainable
  - Once produced, easily recycled
  - EIC not responsible for end-of-life
  - Neglible footprint (90 tCO_2e per year)
- **Detection**:
  - C_2F_6 = hexafluoroethane
  - "Forever chemical"
  - 1 tonne C_2F_6 = 12,400 tonnes CO_2
  - Assuming 20 m^3 per year [13]



The dual-radiator Ring Imaging Cherenkov detector in ePIC [12].

1.6 $ktCO_2e$ per year

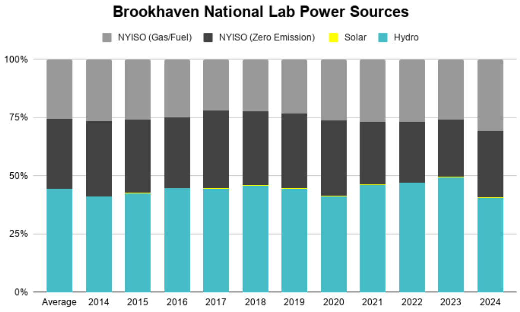
→ CERN reported 75,177 tCO_2e for total PFC use in 2024 [10].

Operations: Electricity

- Only ~ 25.6% of BNL's energy comes from gas/fuel [6, 30]
- Assuming full luminosity EIC with ePIC detector
  - 43.5 MW at any given time [17]
  - Higher than RHIC (25 MW) [6]
  - 26-week operation period

34.7 ktCO_2e per year

→ Powering 4,600 American homes [37]



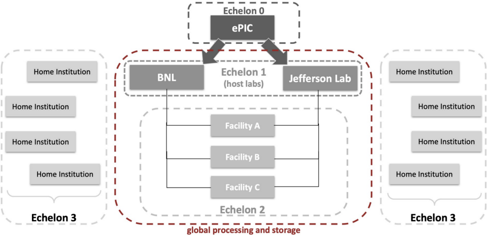
Brookhaven's fuel mix over the last ten years.

Community: Computing

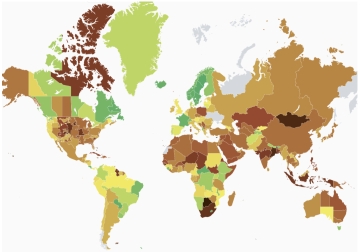
- Follows "butterfly model"
- Echelon 1: 220 PB/year, 400,000 core-years
- Echelon 2: 180 PB/year, 640,000 core-years [14]
- Echelon 3: Negligible
- Carbon emissions dependent on regional fuel mix

33.2 ktCO_2e per year

→ Training Chat-GPT 4 took ∼ 15 ktCO_2e [26]



EIC's computation hierarchy [4].



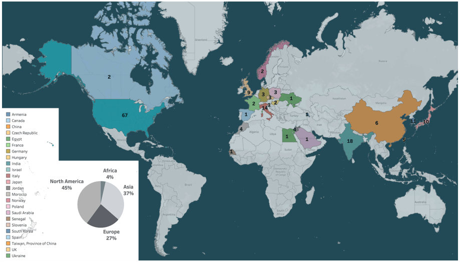
Electricity-related emissions by region [1].

Community: Conference Travel

- $\sim$ 15 EIC-specific conferences, $\sim$ 875 participants per year
- Assume everyone flew (driving, trains are more sustainable)
- Resulted in $\sim$ 1 tCO_2e per participant
  - Compare to 1.1 tCO_2e per capita budget

0.897 $ktCO_2e$ per year

$\rightarrow$ From $\sim$ 400 domestic flights, $\sim$ 230 international flights



Map of EIC's international collaborators [16].

Where Do We Fit In?

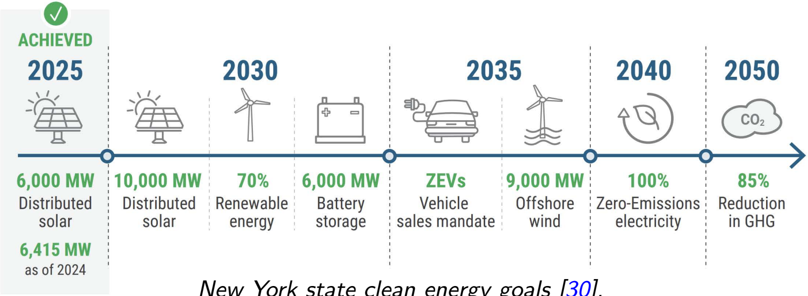
Annual per capita carbon footprint by region [31]

Region	Average (tCO_2e)	EIC Physicist (tCO_2e)
Africa	0.99	44.25
Asia	4.87	48.13
Europe	6.54	49.80
North America	9.99	53.25
Oceania	9.53	52.79
South America	2.55	45.81

- 64,891.7 tCO_2e annual footprint (operation + community), 1,500 collaborators, **additional 43.3 tCO_2e per capita**

→ CERN's per capita footprint estimated to be $\sim$ 33 tCO_2e per year [10, 22]

What Is Already Being Done?

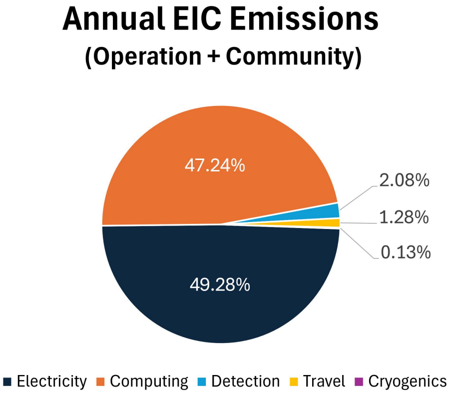


New York state clean energy goals [30].

- Within EIC:
  - R&D into C_2F_6 alternatives (pressurized argon) [13]
  - At least 60% of conference have hybrid options — likely to increase
- Externally:
  - New York (and other grids) on path to zero-emission
  - PFCs continue to be restricted [3]

Conclusion

- Demonstrated EIC's hot spots
- Improving results → accelerator materials, computing demands
- Currently investigating mitigation strategies
  - Balancing efficacy and practicality
  - Focusing on computing
  - Ex: 20% fewer core-years in Echelon 2 → 5.9% decrease in annual footprint
  - Optimizing code, hardware, job submissions, etc.



EIC's annual footprint dominated by electricity and computing expenses.

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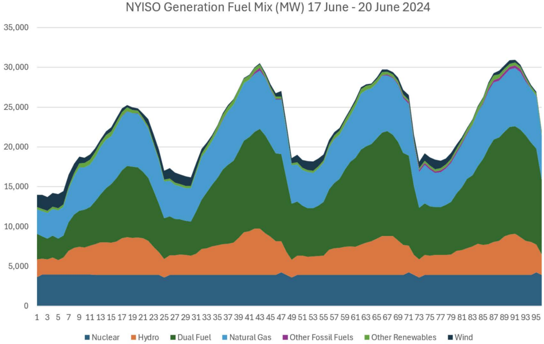
Mitigation Predictions

- Collaboration can "control" computing and travel
- 50% less travel → 0.69% decrease in annual footprint
- 20% more efficient computing at Echelon 2 facilities → 5.9% decrease in annual footprint
  - Preferential computing?
  - Nighttime job submission?
  - ARM vs. CPU vs. GPU?
  - Clean up code?

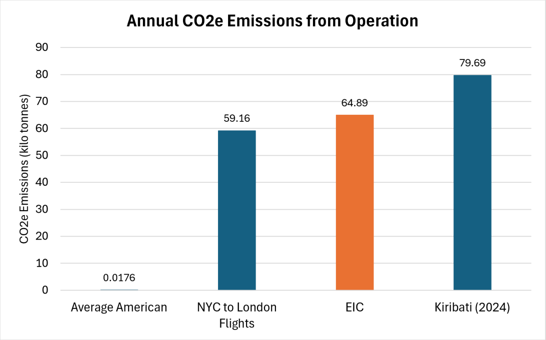


New York's fuel mix over a 4-day period in June 2024 [8].

Comparisons

EIC's emissions summary

	Category	tonnes CO_2e
Construction	Tunnel	172.35
	Accelerator	10,657.27
	Detector	3,353.73
	Facilities	22,695.53
	Total	**37,878.88**
Operation	Cryogenics	90.72
	Detection	1,465.23
	Electricity	34,653.98
	Annual Total	**36,209.93**
Community	Computing	33220.46
	Travel	897.06
	Annual Total	**34,117.52**



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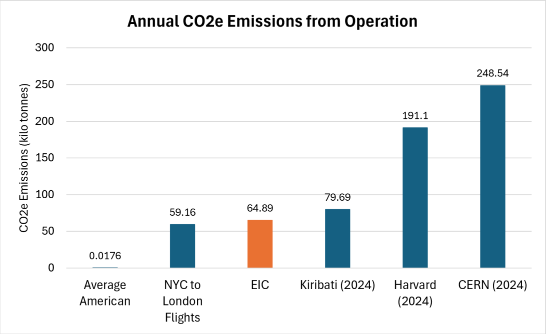

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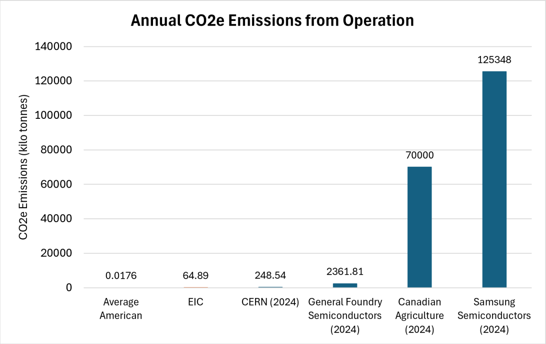
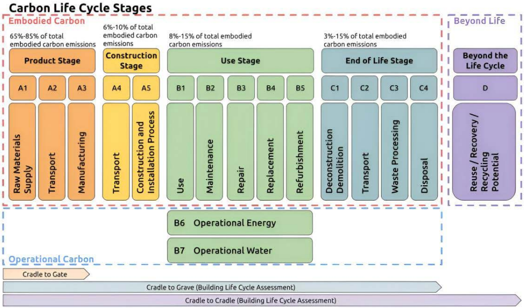


Embodied Carbon Factors

- Represent how much carbon a material produces (kg of CO_2e / kg of material) throughout lifespan
- LCA: Life Cycle Assessment
    - A1-A3: Production
    - A4: Transport
    - A5: Construction
- Factors only consider A1-A3
- Used Inventory of Carbon and Energy database for majority of factors, cross-referenced whenever possible



Stages of LCA from the US General Services Administration.

Selected Embodied Carbon Factors

Material	Unit	Carbon Factor ($\frac{kgCO_2e}{unit}$)	Source
Aluminum	kg	13.06	[19]
Asphalt	kg	0.059	[33]
Beryllium	kg	100	[21]
C_2F_6	m^3	12,400	[18]
Concrete	kg	1	[19]
Iron	kg	2	[19]
Lead	kg	1.67	[19]
Liquid helium	L	0.5	[15]
Niobium-titanium	kg	75	[5]
$PbWO_4$	kg	8.83	[21]
Polystyrene	kg	3.4	[19]

Material	Unit	Carbon Factor ($\frac{kgCO_2e}{unit}$)	Source
Silicon	kg	98.91	[7]
Steel 1020	kg	2.4	[19]
Titanium	kg	31.55	[19]
Tunnel construction	km	121.29	[24]
Gas/Fuel electricity	kWh	0.601	[36]
Cargo ship	km	0.016	[35]
Semi-truck	km	0.69	[35]
Domestic travel	$\frac{passenger}{km}$	0.246	[35]
International travel	$\frac{passenger}{km}$	0.150	[35]

Example: Conference Calculations

Year	Month	Meeting	Location	Participant Number	Hybrid	Host Institution	North America	Asia	Europe	Africa	Australia	South America
2024	April	ePIC Software & Computing	CERN	103	Yes!	4	29	18	15	2	0	0
	June	CFNS Summer School on Physics of EIC	Stony Brook, NY	57		6	15	6	8	0	1	0
	June	MC4EIC	Durham, UK	17	Yes!	2	2	0	11	0	0	0
	June	Diffraction and gluon saturation at the LHC and the EIC	Trento, Italy	34		4	10	0	20	0	0	0
	July	Synergies between LHC and EIC for Quarkonium Physics	Trento, Italy	36		8	1	2	25	0	0	0
	July	EICUG AI WG meeting on RAG-based Summarization for EIC	Online		Online							
	July	EICUG/ePIC	Bethlehem, Pennsylvania	271	Yes!	19	173	10	53	7	0	0
	July	Heavy Ion Physics in the EIC Era	Seattle, Washington	56		4	43	1	9	0	0	0
	September	Precision QCD predictions for ep physics at the EIC (III): opportunities with a second IR	Stony Brook, NY	35	Yes!							
	November	Uncovering New Laws of Nature at the EIC	Long Island, NY	83	Yes?	46	30	3	3	0	0	1
	November	Hadron Physics in the EIC era	Huizhou, China	165		122	9	15	15	0	0	3
	December	Second ePIC AI Town Hall	Online		Online							

NA Emssions	Asia Emissions	Europe Emissions	Africa Emissions	Australia Emissions	SA Emissions	Total Emissions (kg) x2 for round trip	Emissions (tonnes) per participant				
34800	25110	3321	847.2	0	0	128156.4	1.244236893		Domestic flight	0.246	kg CO2 / passenger / km
8487	10710	8280	0	2400	0	59754	1.048315789		Long-haul flight	0.15	kg CO2 / passenger / km
1260	0	3788.4	0	0	0	10096.8	0.5939294118				
12750	0	3099.6	0	0	0	31699.2	0.9323294118		Europe Location	Vienna, Austria	
1275	2700	3874.5	0	0	0	15699	0.4360833333		North America Location	Witchita, Kansas	
				0		0			Asia Location	Shanghai, China	
80860.2	17400	55650	9660	0	0	327140.4	1.207160148		South America Location	Sao Paulo, Brazil	
30676.2	1380	11610	0	0	0	87332.4	1.559507143		Australia Location	Sydney, Australia	
				0		0					
16974	5310	3060	0	0	1140	52968	0.6381686747			58.33%	hybrid/online
16065	4797	19575	0	0	8100	97074	0.5883272727	**2024 Total (kg)**	**2024 Total (tonnes)**	822	participants
				0		0		**809920.2**	**809.9202**	0.9853043796	tonnes / participant

Detector Assumptions

Component	Material	Mass (kg)	Emissions (tCO_2e)	Source
Forward Endcap EMCal ScFi	Tungsten powder	18200	364	[13], p. 205
	Polystyrene	2800	9.52	[13], p. 208
Forward Endcap HCal	Steel 1020	156643	375.9	[13], p. 254
	Polystyrene	55137	187.5	[13], p. 254
Forward Endcap Supports	Iron	160884	326.6	[20]
Magnet Thermal Shield	Al3003	971	12.68	[13], p. 31, 37
Magnet Vacuum Vessel	Al6061	3789	49.5	[13], p. 31, 37
Magnet Coil	Cu, NbTi	10389	310.0	[13], p. 31, 37
Magnet Mandrel	Brass 7030	8416	22.2	[13], p. 31, 37
Magnet Barrel Yoke	Steel 1020	454495	1090.8	[13], p. 31, 37
Magnet Plates	Steel 1020	1755	4.2	[13], p. 31, 37
Cooling Pipes	Titanium	11.5	363.3	[13], p. 134
Barrel EMCal Pb/ScFi	Lead	29886	49.9	[13], p. 185
	Polystyrene	3900	13.3	[13], p. 204
Barrel EMCal Supports	Steel 1020	14798	35.5	[20]
Tracking Electronics	Silicon	453	44.8	[20]
DIRC PID	Silica	862	85.3	[13], p. 141
dRICH	C_2F_6	116	1445.8	[13], p. 169
Backward Endcap EMCal	$PbWO_4$	1992	17.6	[27]
Backward Endcap HCal	Steel 1020	18463	44.3	[13], p. 218, 231
	Polystyrene	1481	5.0	[13], p. 218, 231
Backward Endcap Supports	Iron	136618	277.3	[20]

Accelerator and Construction Assumptions

Component	Material	Mass (kg)	Emissions (tCO_2e)	Source
IR Beampipe	Beryllium	0.405	0.041	[29]
ESR Vacuum	Copper	700	2.1	[38], p. 241
RCS Vacuum	Copper	14	0.042	[38], p. 625
Cryogenics	Liquid He	22679	90.72	[2]
IR Magnets	Cu, NbTi	18733	851.9	[38], p. 481-540
IR Yokes	Low-carbon steel	188891	648.2	[38], p. 481-540
IR Normal Magnets	Iron	77260	154.5	[38], p. 544, 547-563
ESR Magnets	Iron	3324	2108.5	[38], p. 547-563
RCS Magnets	Iron	1023	726.6	[32]
Supports	Steel 1020	2784493	6682.8	[38]

Above calculations do not account for recycled magnets. 400 quadrupoles and 280 sextupoles constitute 258720kg of iron and save 517.44 tCO_2e through their reuse [28].

Component	Amount	Unit	Emissions (tCO_2e)	Source
Cut-and-cover tunnel	1.421	km	172.3	[32]
Asphalt roads[1]	8000	ft	428.6	[6]
Buildings[2]	336000	ft^2	22266.9	[39]

[1] Assuming roads are 27ft (8.5m) across and 0.5ft (0.1524m) deep

[2] Assuming "new buildings will be constructed of concrete slab on-grade with footings and conventional steel frame" [6]. Buildings have 10in (0.254m) concrete foundation and follow the "rule of thumb" that 1 ft^2 of construction corresponds to 5kg of steel [34].

Power Assumptions

- From reviewing 10 years of environmental reports, BNL averaged 271 GWh annually. 119.5 GWh came from their hydroelectric contract, 0.73 GWh came from their on-site solar farm, and the remaining 151 GWh came from New York Independent System Operator (NYISO). Over the last 10 years, NYISO averages 55% zero-emission sources [6, 25, 30].
- Assuming BNL's hydro contract scales with time, 44.24% of BNL's power will come from hydro, 0.26% from solar, 29.91% from NYISO zero-emission, and 25.58% from NYISO gas-fuel.
- Assuming EIC is operational for six months out of the year (4368 hours)

Operating Condition [6]	**EIC Power (MW)**	**EIC Demand (GWh)**	**Gas-Fuel Fraction (GWh)**	**Emissions (tCO_2e)**
10 GeV, no ePIC	27.4	119.7	30.6	18995
10 GeV	33.9	148.1	42.4	25518
18 GeV, full lumi	43.5	190.0	57.64	34654
18 GeV, full lumi, 2 detectors	50	218.4	68.5	41377

Computing Assumptions

- Assuming respective Echelon storage and computation requirements split evenly between the institutions (eg. 110 PB/year and 200,000 core-years at both BNL and JLab)
- Assuming 17 Echelon 2 facilities across Canada, US, Italy, Taiwan, UK, and France [4]
- Based on JLab's Scientific Computing hardware, scaled accordingly [11]

Computing Node Hardware [11]	Number of Nodes	Total Power (W)	Watts per Core	Electricity (GWh)
dual 48 core Xeon Platinum 8558 (Emerald Rapids) (4 Nvidia A800 40GB)	2	5280	27.5	0.486
single 32 core AMD EPYC 7513 (Milan) (8 Nvidia A800 40GB)	2	6900	107.8	1.91
dual 16 core AMD EPYC 7313 (Milan) (4 Nvidia A100 80GB)	1	2415	75.6	0.667
dual 32 core AMD EPYC 7502 (two 16xT4, one 8xT4)	3	6270	48.9	0.866
dual 32 core Xeon(R) Gold 6130 4 Nvidia TitanRTX	2	5292	41	0.61
dual 32-core AMD EPYC 9354 (Genoa)	30	25200	13.13	3.48
dual 64 core AMD EPYC 7763 (Milan)	25	21000	6.56	1.45
dual 32 core AMD EPYC 7502 (Rome)	100	54000	8.4	7.46
dual 20 core 2.4 GHz Xeon (Skylake)	36	16200	11.25	3.58

- For storage, we assume 87.3% tape storage and 12.6% disk storage, per the distribution at JLab. The tape is assumed to be IBM4500 LTO-8 tape with 1.5 watts/TB and the disks are assumed to be Western Digital 24TB drives with 2.35 watts/TB.
- From this mix, we determine 101.1 kWh per core-year and 25353 kWh per PB of data stored. This was applied to the respective demands at each institution.
- After determining the electricity demand, we applied the yearly fuel mix factor for each region [1].
    - Ex: BC and MB, Canada (0.07 kgCO_2e/kWh) vs. Taiwan (0.519 kgCO_2e/kWh)