CARBON EMISSIONS
DIGITAL RESEARCH INFRASTRUCTURE UNDERSTANDING AND REDUCTION

Andy Turner, EPCC

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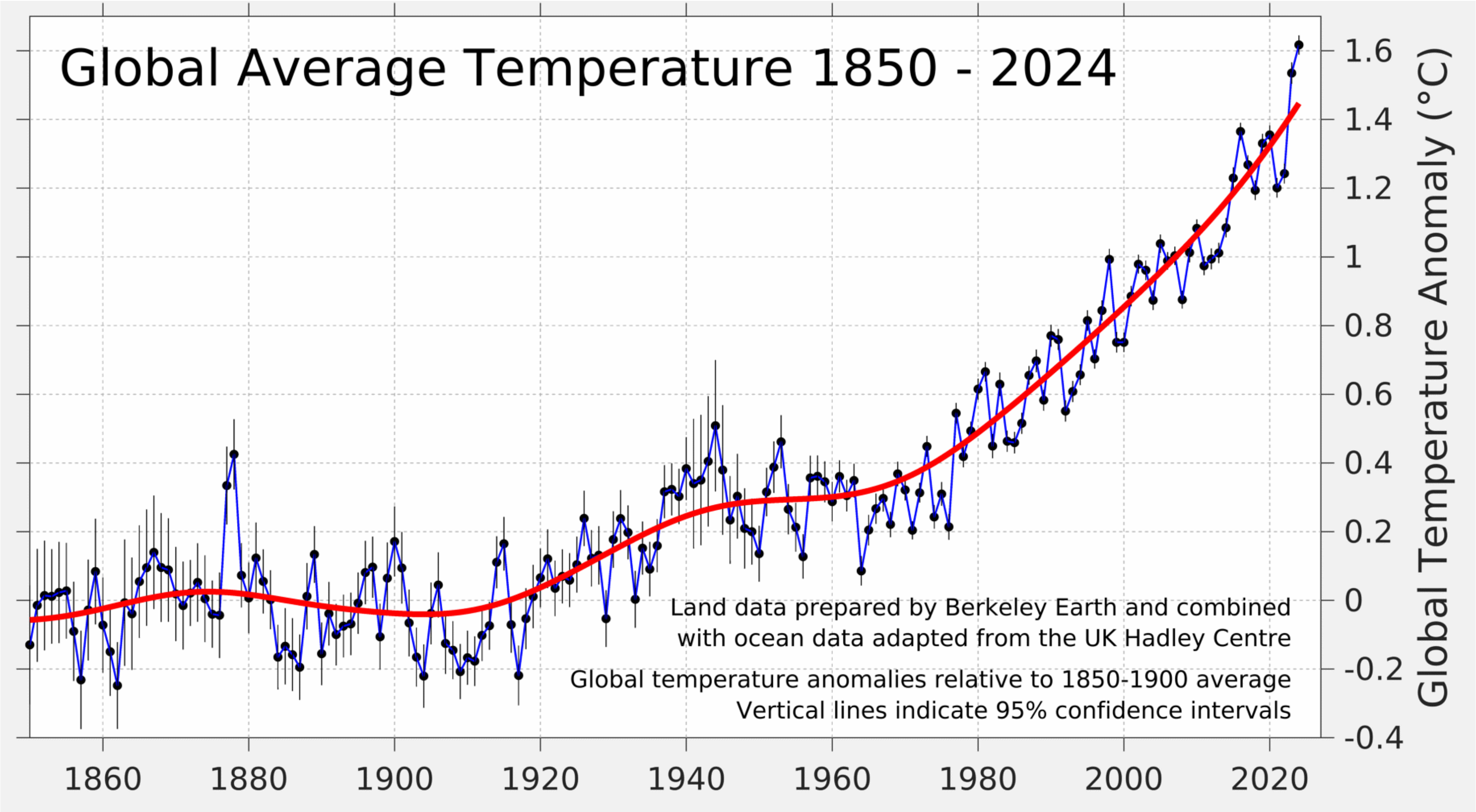
Overivew

- Why work to estimate and reduce emissions?
- Estimating emissions from HPC systems
    - Operational and embodied emissions, GHG Protocol
    - Case study: ARCHER2
    - HPC-CI emissions metric
- Estimating emissions from your work
    - Emissions categories
    - Case study: me!

WHY ESTIMATE AND REDUCE YOUR EMISSIONS?

Global temperature increase



Global Temperature Report 2025, Berkeley Earth
https://berkeleyearth.org/global-temperature-report-for-2024/

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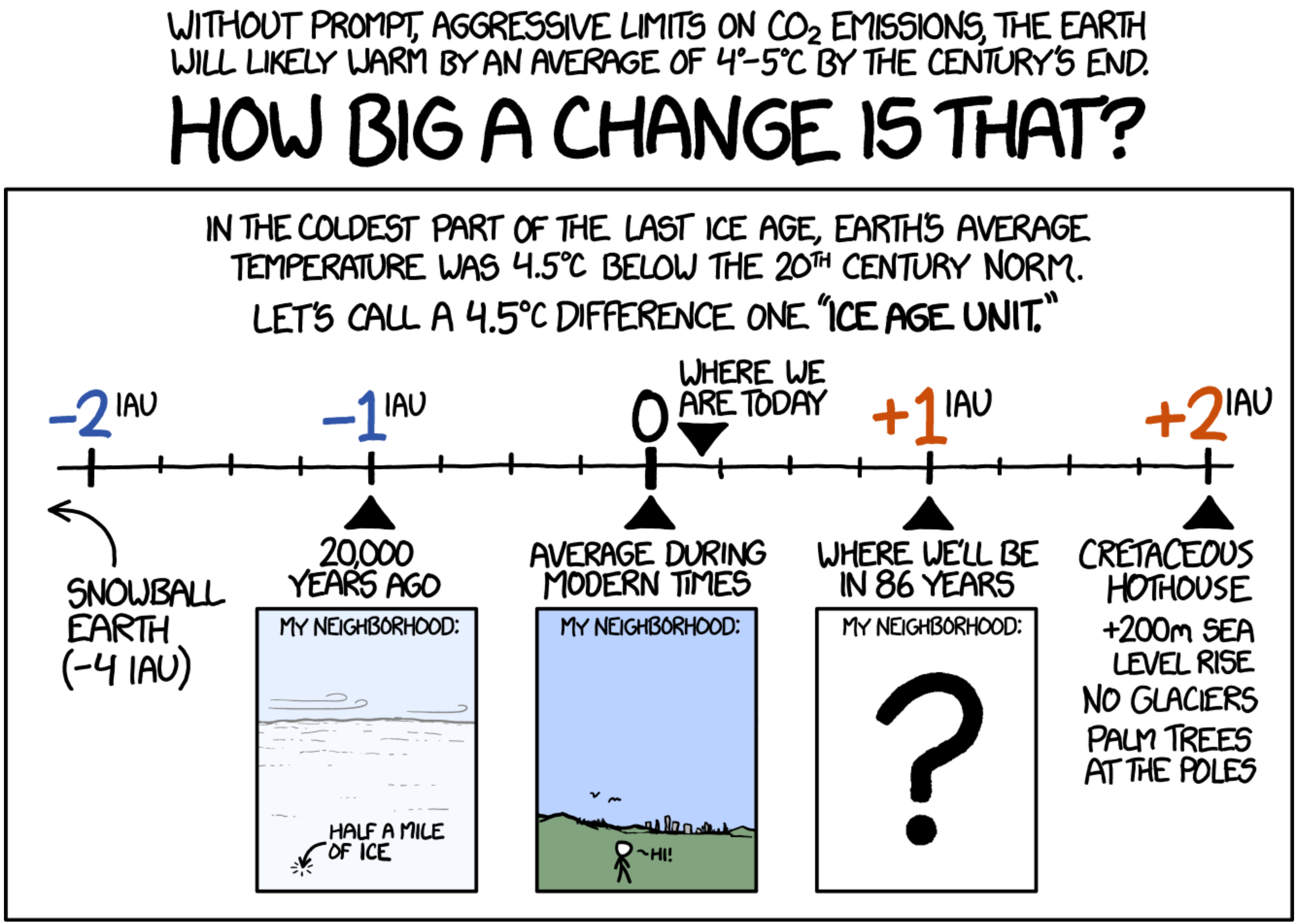


https://xkcd.com/1379/

Why does individual action matter?

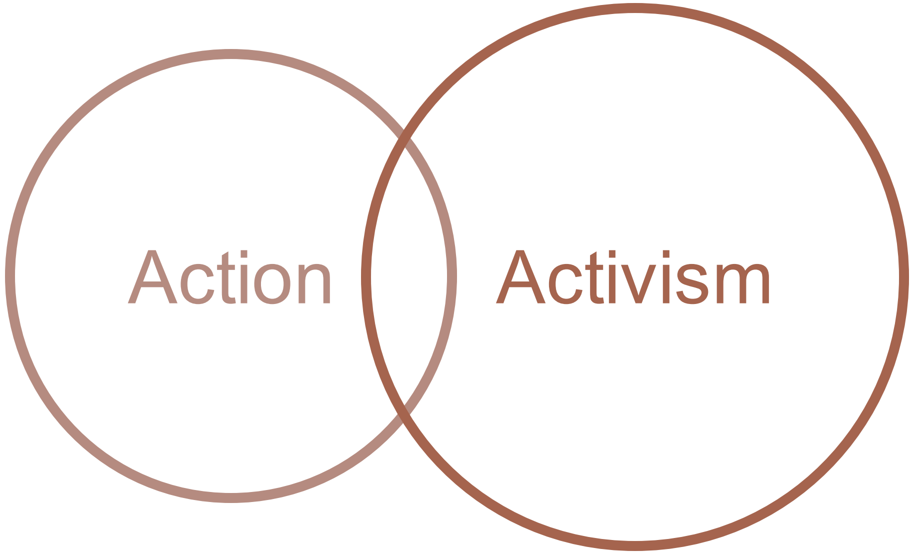
- Common comments:
  - *"It is a global challenge, my individual action does not matter."*
  - *"The UK emissions are small compared to China or the USA, why should we act first and create hardship for ourselves?"*
- Taking no action is not a reasonable response – things we do as individuals have a real impact and we can be a meaningful force for change by:
  - Working to cut our carbon emissions
  - Leading by example
  - Exerting pressure on workplaces, councils, governments, companies, etc. to make changes

Steps for having an impact

1. Understand your emissions profile
2. Pick your battles
3. Get started with taking action on your emissions profile
4. Get involved in activism and pushing for change

Action cycle:

1. Measure
2. Prioritise
3. Implement
4. Measure impact
5. Reflect and review



Can take many forms:

- Discussions with friends and family
- Activism at your workplace
- Activism within your communities
- Political activism
- Climate protests

Estimating emissions from HPC systems

Emission sources (Greenhouse Gas Protocol)

GREENHOUSE GAS PROTOCOL

https://ghgprotocol.org/

- Scope 1 (not usually important for HPC systems)
  - Direct emissions from the system (e.g. if you had your own energy generation)
- Scope 2
  - Emissions associated with energy generation to run the system
  - Should also include overheads (e.g. plant energy consumption, losses due to energy transformation)
- Scope 3
  - Emissions associated with manufacture, shipping, disposal etc. of system
  - Ideally, also include emissions associated with construction of datacentre
- For ARCHER2, we have looked at Scope 2 and Scope 3 emissions

Scope 3 (embodied) emissions

Caveat: data sources are often uncertain, so this is a rough estimate

	Compute Nodes	Interconnect	Lustre HDD	Lustre SSD	NFS HDD	
Count	5,860 nodes	768 switches	19,759,200 GB	1,900,800 GB	3,240,000 GB	
$kgCO_2e$ per unit	1,100	200	0.02	0.16	0.02	
$kgCO_2e$ Total	6,400,000	150,000	400,000	300,000	70,000	7,320,000 Total
%	87%	2%	6%	4%	1%	100%*

- Compute nodes dominate by far
  - Used high end estimates for compute node emissions, could be as much as 30% lower
- Even large amounts of storage have a relatively small contribution
- Note that solid state storage has much larger embodied emissions per GB
- Other components (login nodes, cables, CDU, racks) likely contribute smaller amounts and we will try to include these in future work.

Scope 2 (energy) emissions: power draw

	Compute Nodes	Interconnect	Lustre File System	Home File System	Coolant distribution Units	
Count	5,860 nodes	768 switches	5 File systems	2 File systems	6 CDUs	
Idle (each)	1,300 kW (0.22kW)	170 kW (0.22 kW)	40 kW (8 kW)	16 kW (8 kW)	96 kW (16 kW)	1,600 kW Total
Loaded (each)	2,400 kW (0.41 kW)	240kW (0.24 kW)	40 kW (8 kW)	16 kW (8 kW)	96 kW (16 kW)	2,800 kW Total
%	86%	9%	1%	0%	3%	100%

- Energy use **dominated by compute cabinets**; storage power not important
- Idle power draw of **compute nodes is high** – likely dominated by memory and NIC
  - High system utilisation is critical to both energy and emissions efficiency

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Scope 2 emissions scenarios

	Green energy	South Scotland	UK	World
gCo2/kWh	~0	26[2,3]	154[2]	481[4]
Scope 2 Emissions: per annum[1] (kgCO_2e)	~0	638,000	3,780,000	11,800,000
Scope 2 Emissions: 6 years (kgCO_2e)	~0	3,830,000	22,680,000	70,800,000
Scope 3 Emissions (kgCO_2e)	7,320,000	7,320,000	7,320,000	7,320,000
% Scope 2 of total emissions over 6 years	0%	34%	77%	91%

[1] Assuming 2.8 MW power draw
[2] Median value from 12 months: 1 Apr 2023 – 31 Mar 2024. https://electricityinfo.org/
[3] UK Government guidance is to report using location-specific grid carbon density values: (p48, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/850130/Env-reporting-guidance_inc_SECR_31March.pdf
[3] https://ourworldindata.org/grapher/carbon-intensity-electricity

- In low emissions energy scenarios, **emissions are dominated by Scope 3 (embodied) emissions**
- As the energy grid decarbonises, **Scope 3 emissions become more and more important**
- When Scope 3 emissions dominate, **running the system for as long as possible and getting the most out of it gives the best emissions efficiency**
- University of Edinburgh supplied 100% certified renewable energy via a large-scale power purchase agreement

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Providing emissions information to users

- Ideally:
  - Compute Scope 2 emissions associated with every job based on energy use and data feed on carbon density from national grid
  - Also include Scope 3 emissions amortised across lifetime of service
  - Include information in standard reports to users and PIs
  - Captures differences in power density between different use cases and changes in carbon density on national grid
  - Challenges:
    - Energy reporting per job is not always available and may need to be supplemented with energy use from other components (for large scale HPC, compute nodes typically dominate)
    - Scope 3 (embodied) emissions data quality is currently poor
- More approximate approaches are also available
  - Make more approximations about Scope 2 emissions – may not be a big issue given uncertainty in quality of Scope 3 emissions data

Example for ARCHER2 use

```
Period details:
                   Project:                  e05
              Period start:     2025-01-01T00:00
                Period end:     2025-03-29T00:00
                      Jobs:                79073
                        CU:          2105162.837
   Compute node energy use:           863116.763 kWh
  Other hardware energy use:          129467.514 kWh (estimated)
       Overhead energy use:            99258.428 kWh (estimated)
          Total energy use:          1091842.706 kWh (estimated)

Emissions estimates:
    Scope 2:      0.000 kgCO2e (ARCHER2 is on 100% certified
              renewable energy contract so scope 2 emissions are zero)
    Scope 3:  50523.908 kgCO2e (24.0 gCO2e/CU)
      Total:  50523.908 kgCO2e

    Indicative emissions estimates for UK national grid energy mix
    in S. Scotland at start of job if ARCHER2 was not using
    renewable energy
        Scope 2:  33548.999 kgCO2e (1091842.706 kWh)
           Carbon Intensities (gCO2e/kWh): Q1: 4.0, Median: 16.0, Q3: 57.0
        Scope 3:  50523.908 kgCO2e (24.0 gCO2e/CU)
          Total:  84072.908 kgCO2e

    Scope 2 carbon intensity values from carbonintensity.org.uk
```

Computed assuming 6 years of service (1 CU == 1 nodeh)

Values for EH26 from carbonintensity.org.uk at job start time

$$Scope\ 3\ Rate = \frac{7{,}320{,}000\ kgCO_2e}{(6\ years\ \times 365\ days \times 24\ hours \times 5{,}860\ nodes)} = 0.024\ kgCO_2e/nodeh$$

Reducing emissions from HPC

- One of the most important techniques is to minimise the amount of resource you use to reduce emissions
- Metric to enable track improvement of emissions efficiency

$$HPC\!-\!CI = \frac{(E \times CI) + M}{R}$$

E – Energy consumed
CI – Carbon intensity
M – Embodied emissions
R – Functional unit (e.g. iterations, systems modelled, papers produced)

- Only way to improve HPC-CI metric is through carbon abatement activities or improved efficiency - not offsets
  - Improve energy efficiency – reduce ***E***
  - Improve efficiency of hardware use – reduce ***M***
  - Demand shifting or shaping – reduce ***CI***
  - Improve performance – increase ***R***

HOW DO HPC EMISSIONS COMPARE TO OTHER SOURCES?

Professional/personal emissions

- In reality, these cannot be properly separated
  - You should look at your emissions across all activities
- Perfection is the enemy of progress
  - Having broad ideas of your emissions profile is good enough to identify areas and take action
- Some good tools available for estimating emissions from your life as a whole
  - WWF Footprint Calculator: https://footprint.wwf.org.uk/
  - How Bad Are Bananas? (Mike Berners-Lee): https://howbadarebananas.com/
- To meet global temperature increase targets, it is estimated that each person's annual emissions should total around 2,000 kgCO_2e

Carbon literacy

- Many people struggle to grasp how the emissions from different sources compare to each other.
- While financial costs and benefits are intuitive, carbon costs and benefits are not for most people.
- most of us have intuitive financial literacy but lack a similar *Carbon Literacy*.
- Part of the benefit of looking at your emissions is that you start to develop carbon literacy and can pass this on to other people.

Professional emissions categories

- Working location (home/office/hybrid)
- Commute
- Work travel
- Consumables: laptops, software, etc.
- Research facility use: HPC, research ships, beamlines, etc.
- Commercial cloud use

- Excluded from this analysis:
  - Downstream emissions from software you develop and release
  - See: https://greensoftware.foundation/

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Research Facility Use

- Base data:
  - ARCHER2: 0.023 $kgCO_2e$/nodeh
  - Source: https://docs.archer2.ac.uk/user-guide/energy/#archer2-emissions
- Useful links:
  - BAS Carbon Footprint 2023-2024: https://www.bas.ac.uk/science/science-and-innovation/towards-net-zero-fit-for-the-future/bas-carbon-emissions/
  - NCAS Carbon Footprint: https://ncas.ac.uk/national-centre-for-atmospheric-science-carbon-footprint/
  - Chemistry Lab Carbon Footprint:
    - ~4000 kgCO2e per person per annum
    - https://pubs.rsc.org/en/content/articlehtml/2024/gc/d3gc03668e
- My calculation (1 Apr 2024 – 1 Apr 2025)

Facility	Units	Emissions per unit ($kgCO_2e$)	Units used	Emissions (year, $kgCO_2e$)
ARCHER2	nodeh	0.024	45,110	1,082

Summary

Category	Annual Emissions (kgCO2e)	% Emissions
Work travel	3823	64.0%
HPC use	1082	18.0%
Working location	654	10.9%
Commute	260	4.3%
Commercial cloud use	134	2.2%
Consumables	66	1.0%
Total	**6018**	**100.0%**

https://edin.ac/4jZ7H6o

- Heavily dominated by emissions from travel
  - Reducing frequency of international trip to once every 5 years saves ~900 kgCO_2e (15% reduction in total annual emissions)
  - Travelling by train for European trip reduces emissions by around ~800 kgCO_2e (13% reduction in total annual emissions)

“We seem to need reminding that computing is not exempt from having to drastically reduce emissions. Instead of assuming computing can innovate the path to a greater future, the bravest and most heroic action the computing sector could take is to show restraint and leadership, …”

Bran Knowles *et al.*

https://dl.acm.org/doi/pdf/10.1145/3503916

EMISSIONS CALCULATION DETAILS

Working location

- Base data:
  - From:
  - Office working: 0.438 $kgCO_2e$ per person per hour
    - Includes: IT equipment, heating and lighting; assumes mid point office density (universities likely a bit higher due to lower office density)
  - Home working: 0.334 $kgCO_2e$ per person per hour
    - Includes: IT equipment, heating and lighting
    - DEFRA 2023 conversion factors
  - From: https://circularecology.com/news/the-carbon-emissions-of-homeworking-and-office-working

- My calculation (7.78 hours per day, 221 days per year)

Location	Days per week	Days per year	Hours per year	Emissions (year, $kgCO_2e$)
Office	2	98.2	764.2	334.7
Home	2.5	122.8	955.2	319.0
Total	**4.5**	**221.0**	**1719.4**	**653.8**

Commute

Mode	Unit	Emissions ($kgCO_2e$/mile)	Notes
Petrol/diesel car	Per vehicle	0.53	1.60 $kgCO_2e$/mile if congested
Electric car	Per vehicle	0.18	
Bus	Per person	0.05	Assumes half-full, hybrid Routemaster
Train	Per person	0.08	Electric
Tram/light rail	Per person	0.07	Electric
Electric bicycle	Per vehicle	0.05	Includes charging emissions and food emissions for pedalling
Bicycle	Per vehicle	0.10	Includes food emissions for pedalling

Source: How Bad Are Bananas (Mike Berners-Lee, 2020)

- My calculation

Mode	Miles per day	Days per week	Days per year	Miles per year	Emissions (year, $kgCO_2e$)
Bicycle	18	2	144.44	2600	260

Work Travel

Mode	Unit	Emissions ($kgCO_2e$/mile)	Notes
Petrol/diesel car	Per vehicle	0.53	1.60 $kgCO_2e$/mile if congested
Electric car	Per vehicle	0.18	
Bus	Per person	0.05	Assumes half-full, hybrid Routemaster
Train	Per person	0.08	Electric
Short haul flight	Per person	0.90	<1,860 miles, economy class
Long haul flight	Per person	0.58	>=1,860 miles, economy class

Source: How Bad Are Bananas (Mike Berners-Lee, 2020)

Flying in business or first class increases emissions rate significantly due to lower occupancy rate
Sharing cars reduces emissions rate per person

Item	Unit	Emissions ($kgCO_2e$/night)	Notes
Hotel	Per person per night, B&B	30.0	

Source: How Bad Are Bananas (Mike Berners-Lee, 2020)

Trip	Frequency	Type	Units	Emissions per unit ($kgCO_2e$)	Emissions ($kgCO_2e$)	Emissions (year, $kgCO_2e$)
International conference	Once every 3 years	Return flight Edinburgh to London	664 miles	0.90	597.6	
		Return flight London to New York	6930 miles	0.58	4019.4	
		Return flight to Denver	3218 miles	0.58	1866.4	
		Hotel stay	7 nights	30.0	210.0	
	Total				6693.4	2231.1
European conference	Once per year	Return flight to Amsterdam	830 miles	0.90	747.0	
		Hotel stay	7 nights	30.0	210.0	
	Total				957.0	957.0
UK conference	Once per year	Return train to Birmingham	500 miles	0.08	40.0	
		Hotel stay	5 nights	30.0	150.0	
	Total				190.0	190.0
UK overnight trip	4 times per year	Return train to London	664 miles	0.08	53.1	
		Hotel stay	1 night	30.0	30.0	
	Total				83.1	332.4
UK day trip	4 times per year	Return train to Manchester	350 miles	0.08	28.0	112.0
Total						**3822.5**

Consumables

- Base data:
  - Laptop:
    - 330 $kgCO_2e$ per laptop
  - Workstation:
    - ~700 $kgCO_2e$ workstation, monitor, keyboard, mouse
  - Emissions from energy use already included in office/home emissions
  - Source: How Bad Are Bananas (M. Berners-Lee, 2020)

- My calculation

Item	Unit	Units per year	Emissions per unit ($kgCO_2e$)	Emissions (year, $kgCO_2e$)
Laptop	1 every 5 years	0.2	330	66

Commercial Cloud Use

- Useful tools:
  - Website Carbon Calculator: https://websitecarbon.com/
  - Cloud Carbon Footprint: https://www.cloudcarbonfootprint.org/
  - Data Carbon Scorecard: https://digitaldecarb.org/data-carbon-scorecard/

- My calculation (example, using Website Carbon Calculator using 10,000 views per month):

Facility	Emissions Rating	Emissions (year, $kgCO_2e$)
ARCHER2 website	C	53.3
ARCHER2 Documentation	A	18.2
Cirrus website	D	62.2
Total		133.7

Commercial cloud use: Other items

- Could not find good information on other items
  - Online repository tools (e.g. Github, Gitlab)
  - Online tools (e.g. Office 365)
  - Online storage (e.g. Sharepoint)