From Error Budgets to Carbon Budgets

Empowering SRE for Eco-Efficiency

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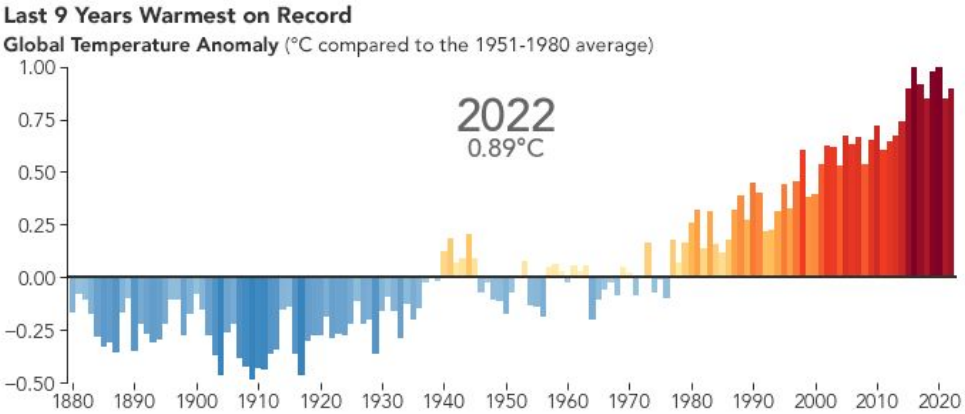
THE CARBON FOOTPRINT OF EVERYTHING

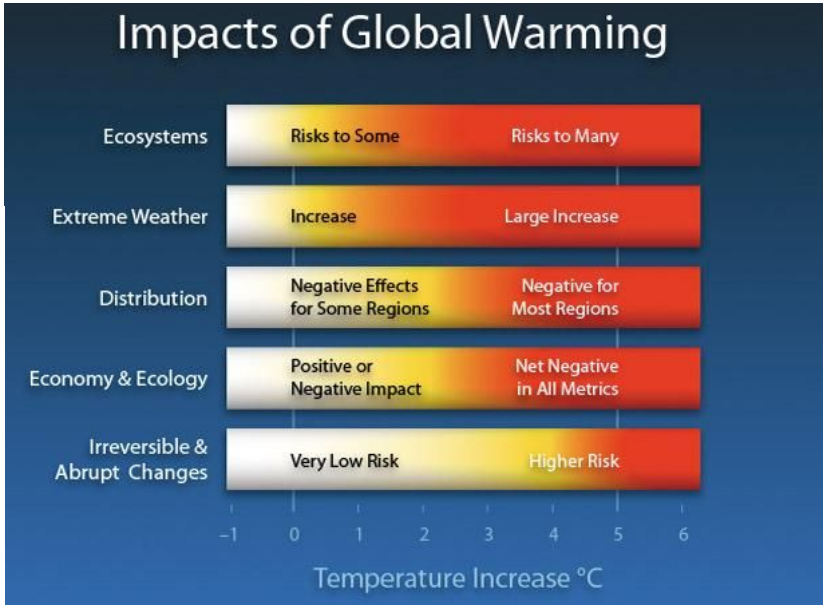
MIKE BERNERS-LEE

NEW EDITION – UPDATED AND EXPANDED

Why?

Is the Climate really changing?





https://www.sciencetopia.net/geography/effects-climate-change
https://earthobservatory.nasa.gov/world-of-change/global-temperatures

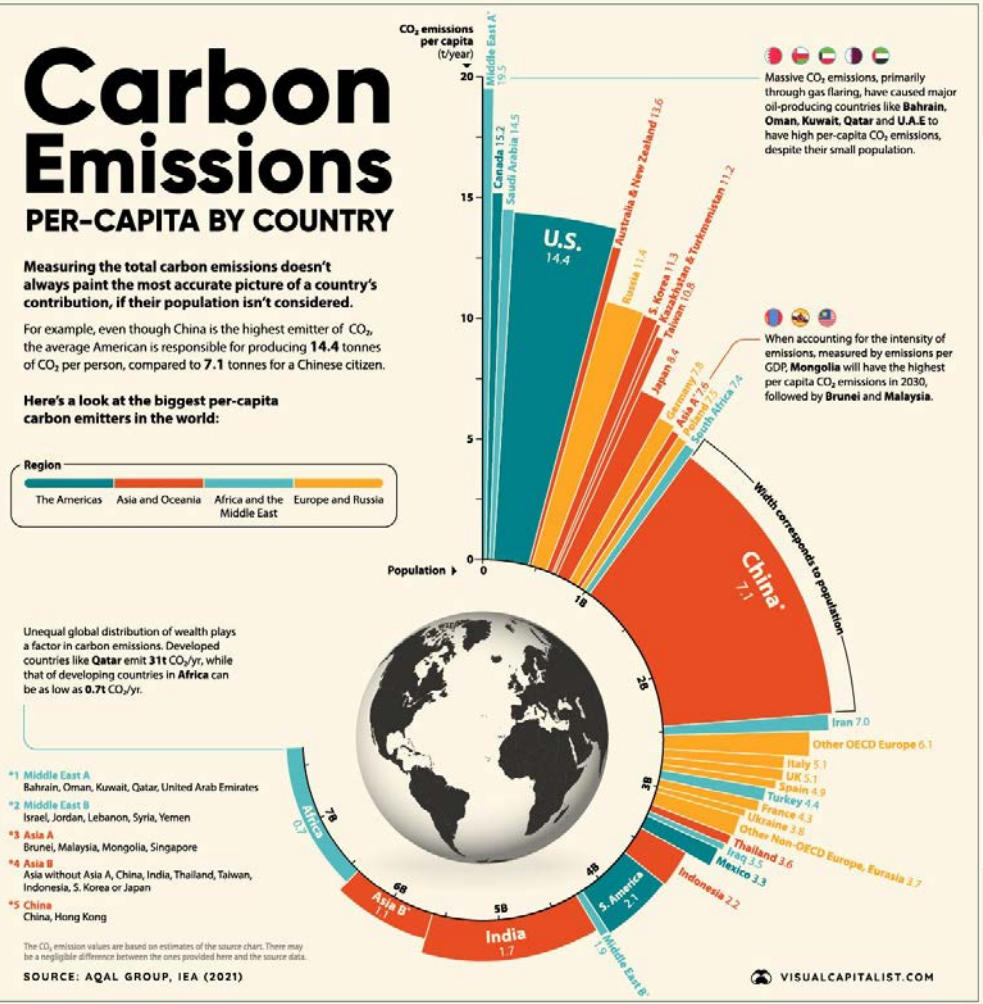
Carbon Emissions

PER-CAPITA BY COUNTRY

Measuring the total carbon emissions doesn't always paint the most accurate picture of a country's contribution, if their population isn't considered.

For example, even though China is the highest emitter of CO_2, the average American is responsible for producing **14.4** tonnes of CO_2 per person, compared to **7.1** tonnes for a Chinese citizen.

Here's a look at the biggest per-capita carbon emitters in the world:



Unequal global distribution of wealth plays a factor in carbon emissions. Developed countries like **Qatar** emit **31t** CO_2/yr, while that of developing countries in **Africa** can be as low as **0.7t** CO_2/yr.

*1 Middle East A
Bahrain, Oman, Kuwait, Qatar, United Arab Emirates
*2 Middle East B
Israel, Jordan, Lebanon, Syria, Yemen
*3 Asia A
Brunei, Malaysia, Mongolia, Singapore
*4 Asia B
Asia without Asia A, China, India, Thailand, Taiwan, Indonesia, S. Korea or Japan
*5 China
China, Hong Kong

The CO_2 emission values are based on estimates of the source chart. There may be a negligible difference between the ones provided here and the source data.

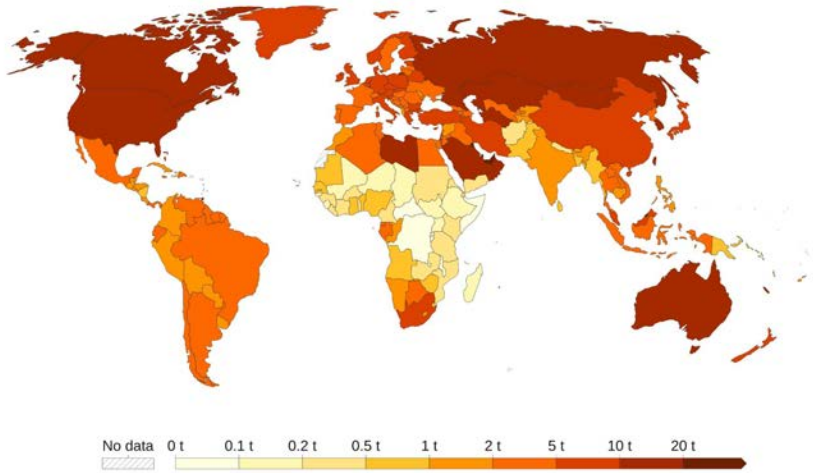
SOURCE: AQAL GROUP, IEA (2021)

VISUALCAPITALIST.COM

Per capita CO_2 emissions, 2021

Carbon dioxide (CO_2) emissions from fossil fuels and industry[1] . Land use change is not included.

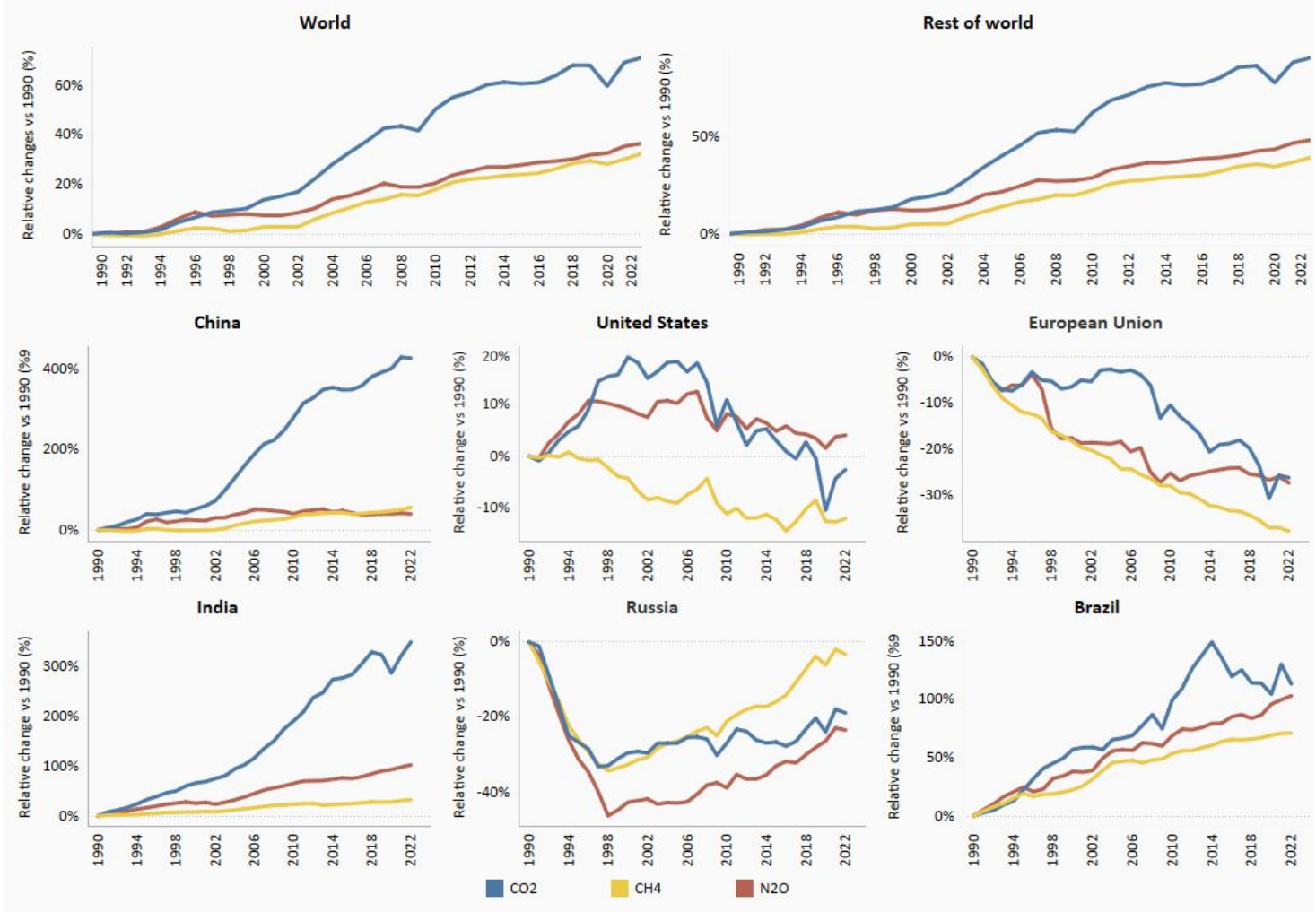
Our World in Data



Data source: Global Carbon Budget (2022); Population based on various sources (2023)
OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

1. Fossil emissions: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

Trends of CO_2, CH_4 and N_2O emissions in world total, rest of the world and top six emitting econom i e s ,



Regulation

What governments are doing?

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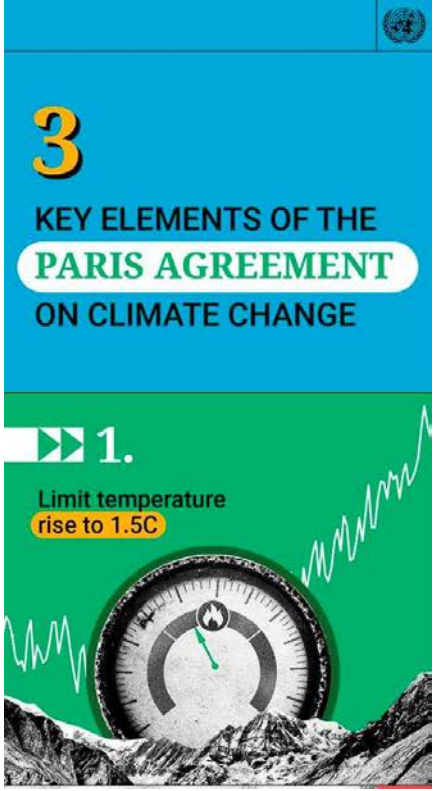
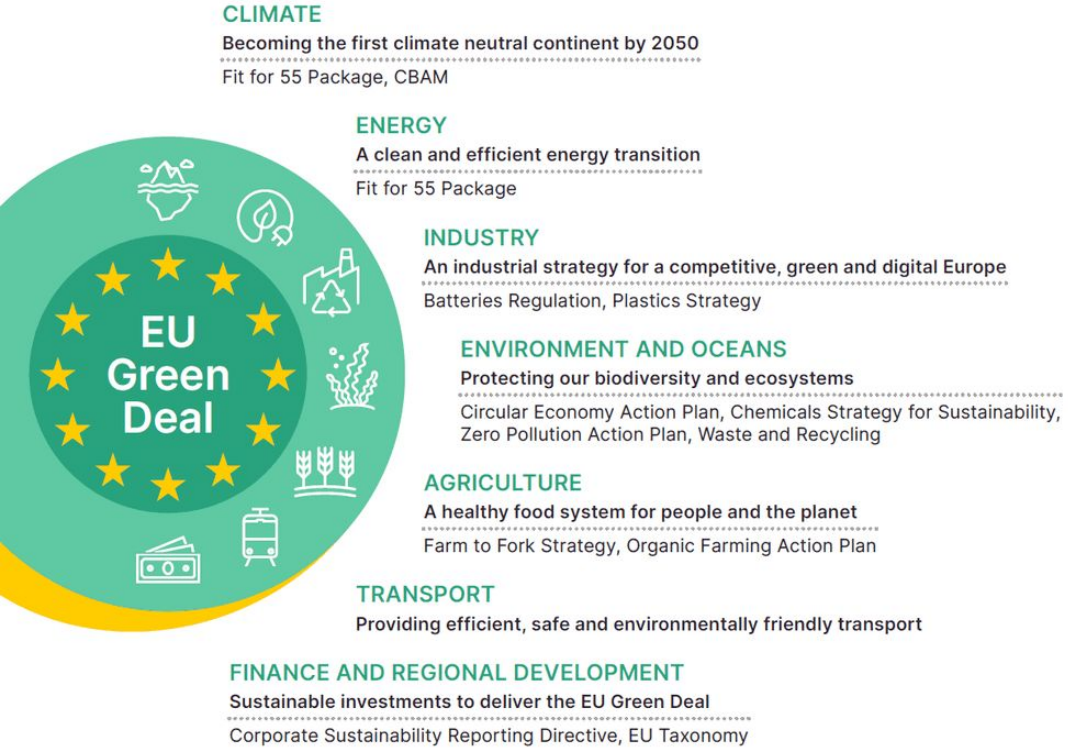
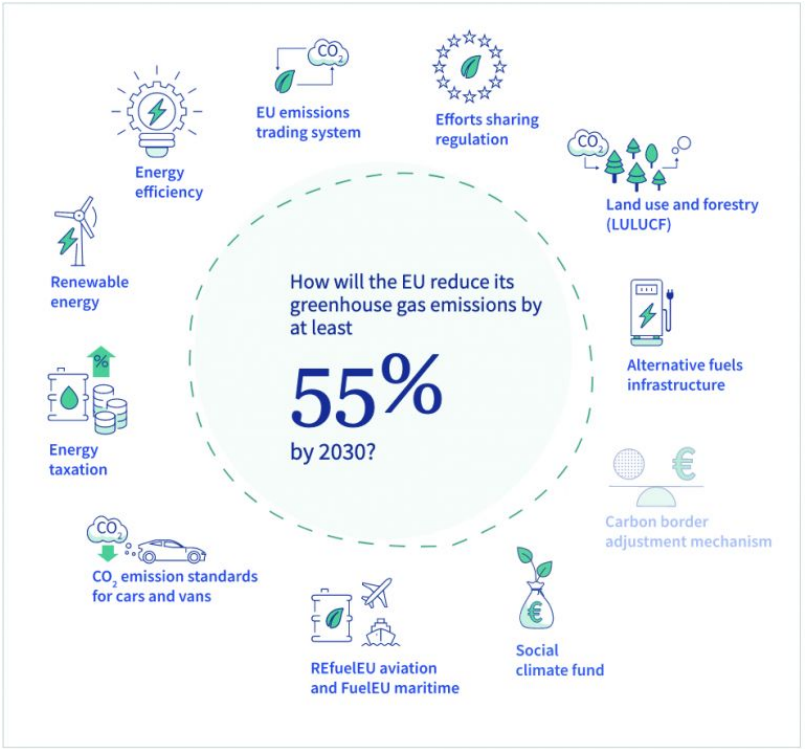

3
KEY ELEMENTS OF THE
PARIS AGREEMENT
ON CLIMATE CHANGE
1.
Limit temperature
rise to 1.5C


SUSTAINABLE DEVELOPMENT GOALS
1 NO POVERTY
2 ZERO HUNGER
3 GOOD HEALTH AND WELL-BEING
4 QUALITY EDUCATION
5 GENDER EQUALITY
6 CLEAN WATER AND SANITATION
7 AFFORDABLE AND CLEAN ENERGY
8 DECENT WORK AND ECONOMIC GROWTH
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
10 REDUCED INEQUALITIES
11 SUSTAINABLE CITIES AND COMMUNITIES
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION
14 LIFE BELOW WATER
15 LIFE ON LAND
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
17 PARTNERSHIPS FOR THE GOALS
SUSTAINABLE DEVELOPMENT GOALS


ESG
ENVIRONMENTAL
Climate change strategy,
Biodiversity,
Water efficiency,
Energy efficiency,
Carbon intensity,
Enviromental
management system
SOCIAL
Equal opportunities,
Freedom of association,
Health and safety,
Human rights,
Customer &
products resposibility,
Child labour
GOVERNANCE
Business ethics,
Compliance,
Board independence,
Executive compensation,
Shareholder democracy

Fit for 55: The EU's plan for a green transition



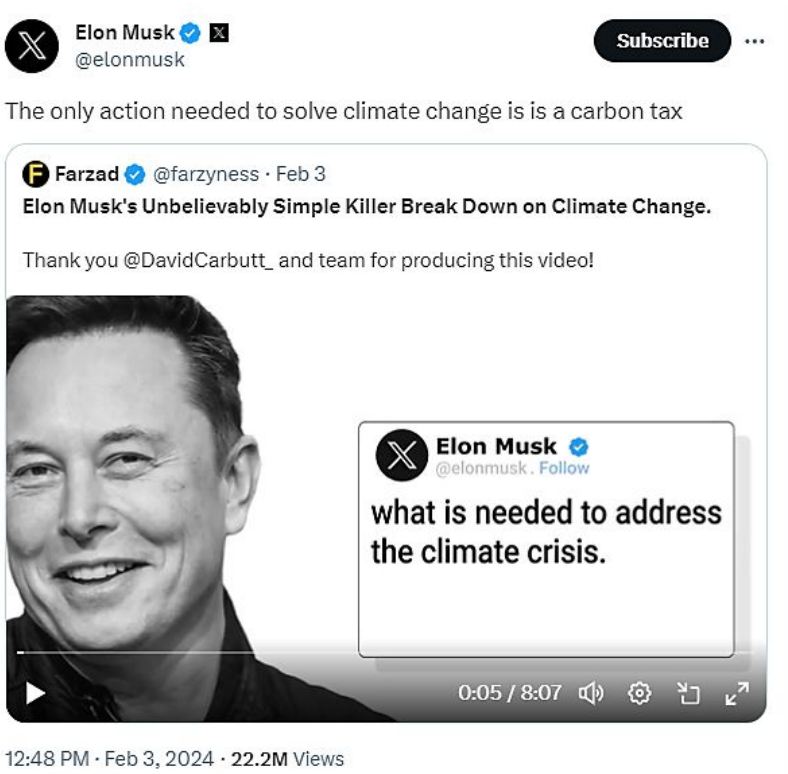


https://renewable-carbon.eu/news/fit-for-55-the-eus-plan-for-a-green-transition/

	Previous Framework NFRD	New Framework CSRD
Applies to	Approx. 12,000 companies	Approx. 50,000 companies
Reporting	Doesn't specify the format of disclosure and standards	Does specify the format of disclosure and standards
Enviromental	Doesn't require details on their impact on the environment or climate-related risks	Requires details on their impacts on the environment and climate-related risks
Format	Non-standardised data format	Standardised data format
Assurance	Doesn't require assurance on disclosed information	Requires assurance on disclosed information

Fines and Carbon Taxes?

Not yet, but coming soon!



Understanding IT emissions

And calculating

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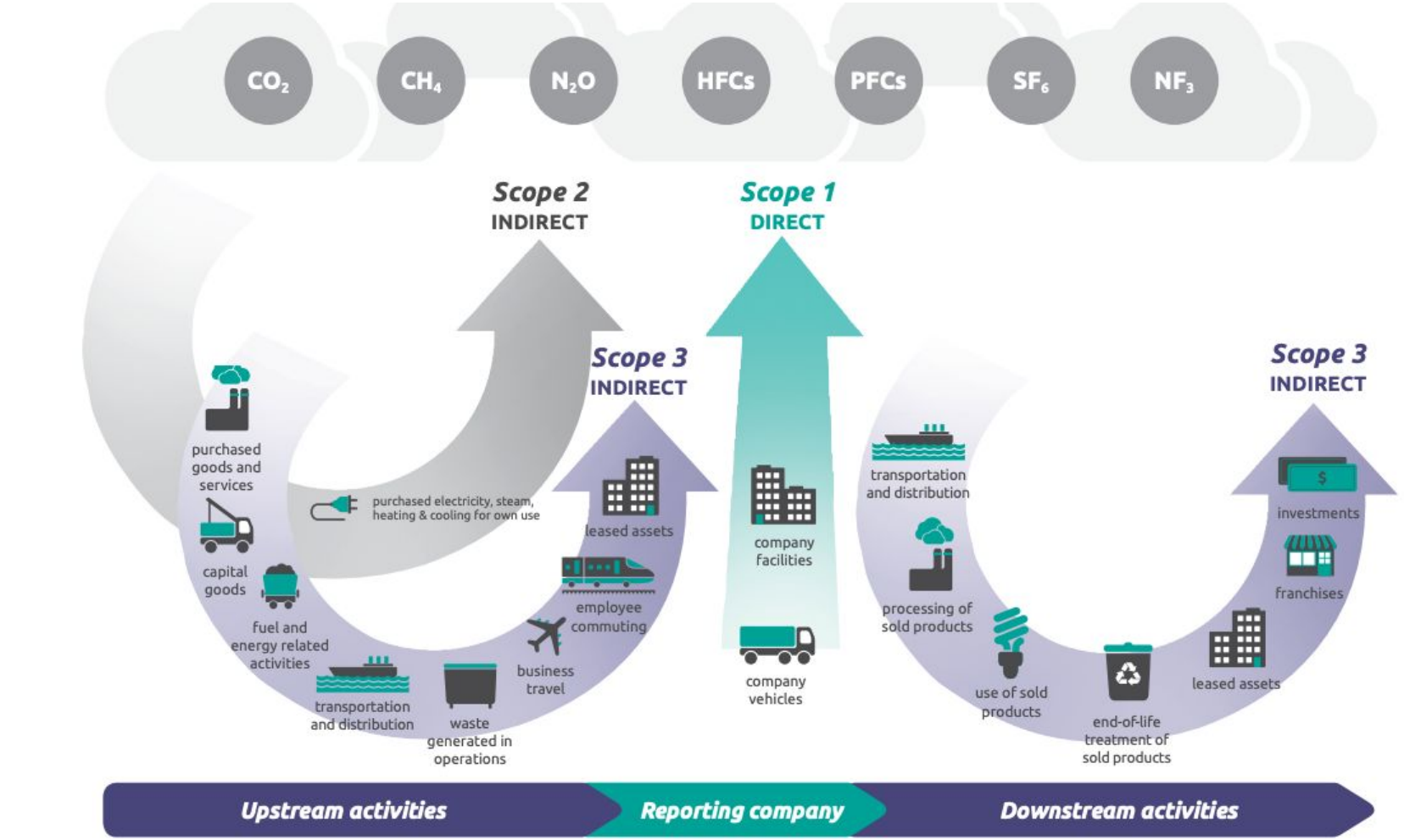
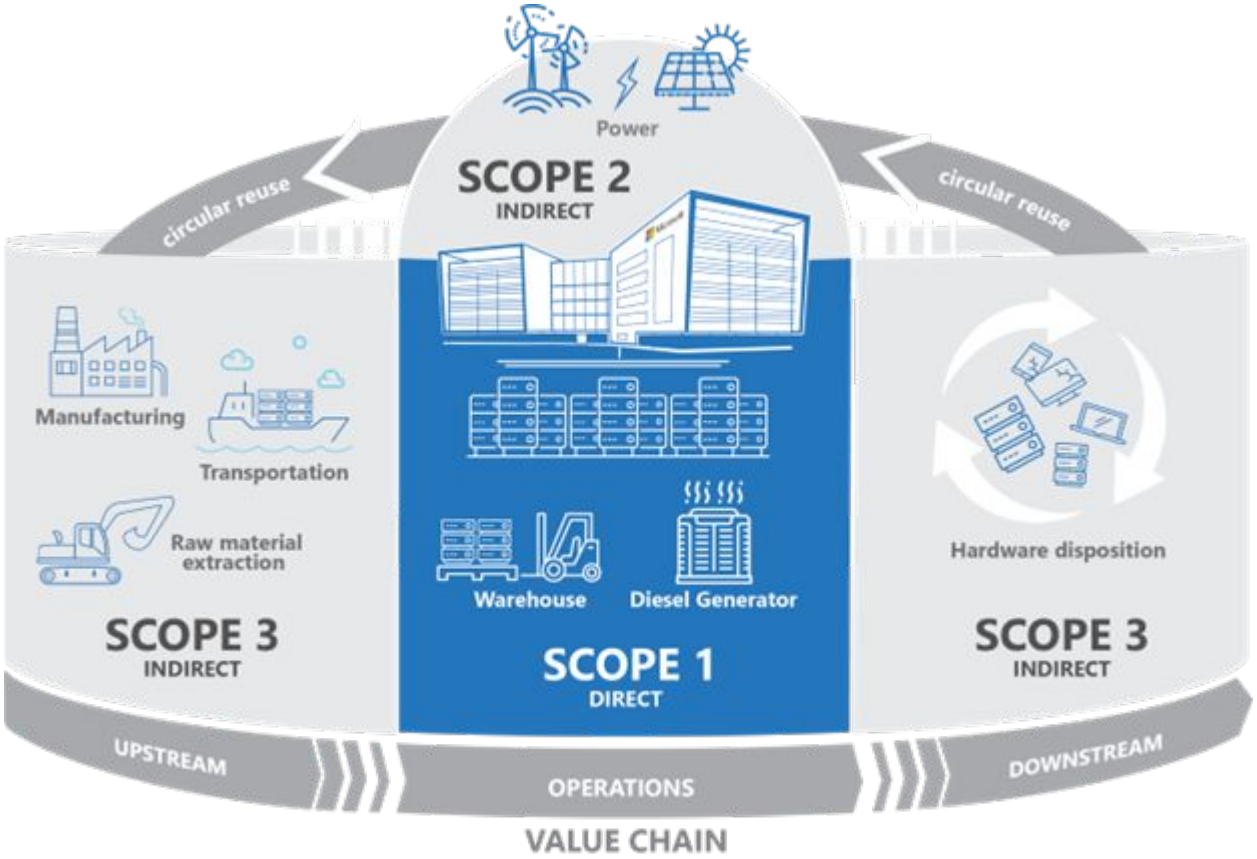
Data Centers could account for 13% of annual global electricity consumption and 6% of carbon footprint by 2030

Source: On Global Electricity Usage of Communication Technology: Trends to 2030, Huawei Technologies (Anders S. G. Andrae and Thomas Edler, 2015, Worst case scenario)



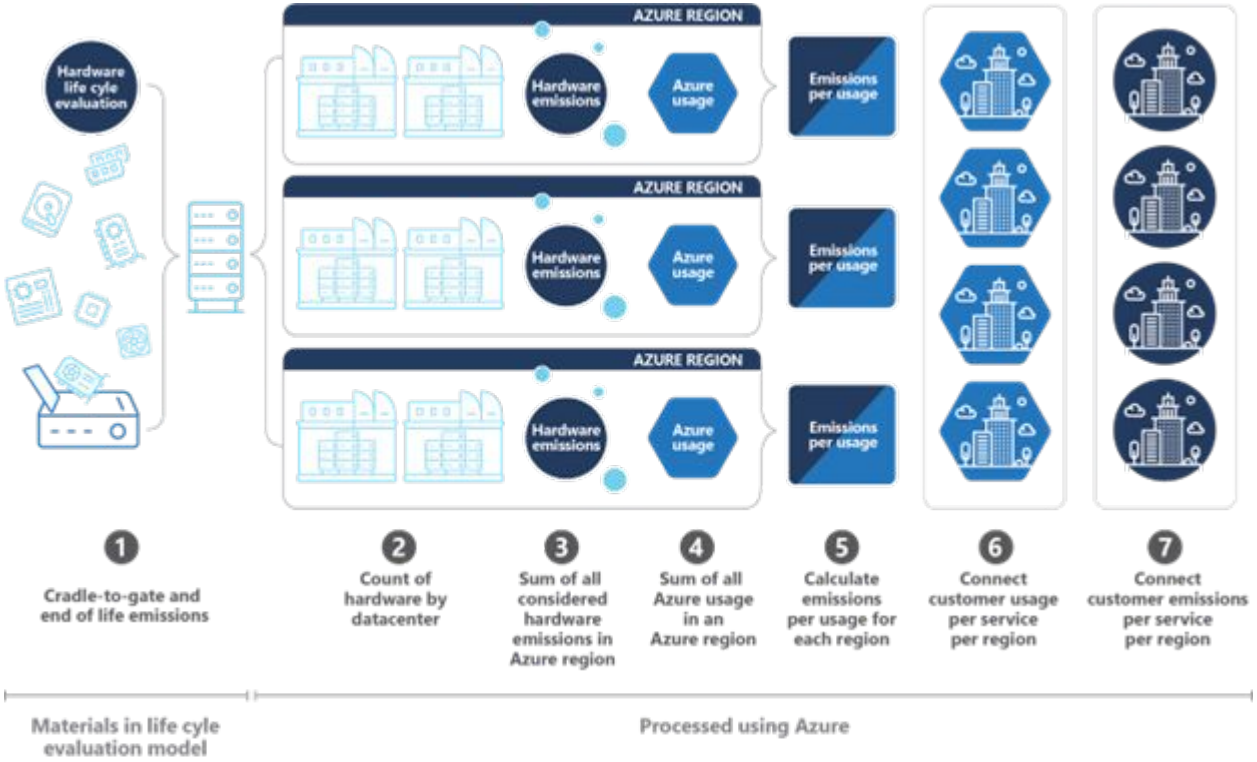
https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf



https://learn.microsoft.com/en-us/industry/sustainability/api-calculation-method

	DC hardware manufacturing	Cloud operations	Hardware disposition
Server manufacturer	Scope 1 and 2	Scope 3 downstream	Scope 3 downstream
Microsoft	Scope 3 upstream	Scope 1 and 2	Scope 3 downstream
Circularity partner	N/A	N/A	Scope 1 and 2
Cloud customer	Scope 3 upstream	Scope 3 upstream	Scope 3 upstream

https://learn.microsoft.com/en-us/industry/sustainability/api-calculation-method



https://learn.microsoft.com/en-us/industry/sustainability/api-calculation-method

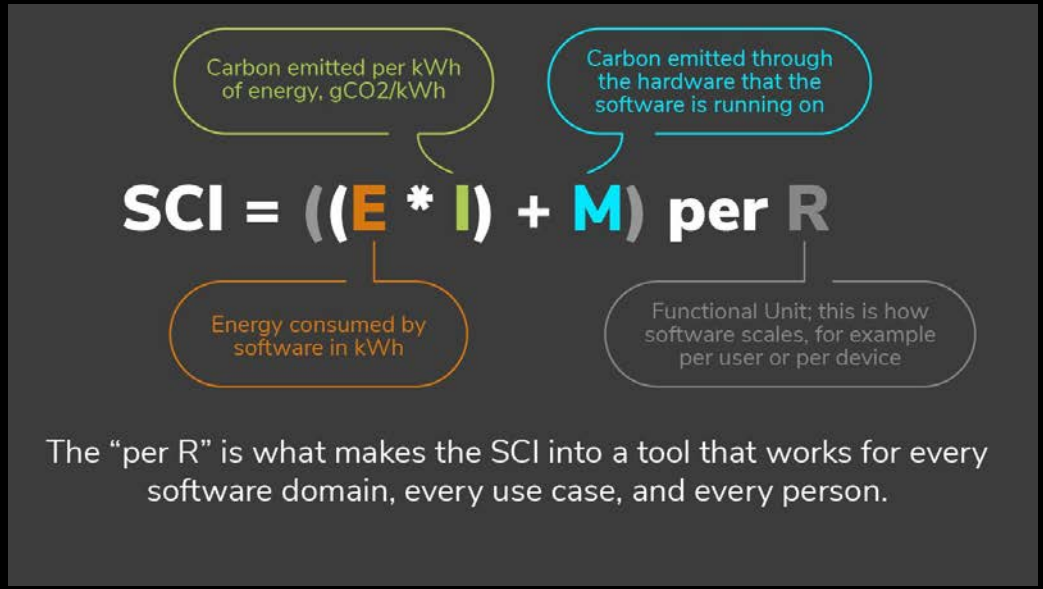
https://www.future-processing.com/blog/how-to-build-green-software-development/

Software Carbon Intensity (SCI) Specification

A specification and standardized protocol to calculate a carbon intensity score for software applications.

We can now measure the rate of carbon emissions for any type of application: console games, cloud applications, mobile applications, web applications, or internet of things devices.

The purpose is to help users and developers make informed choices about which tools, approaches, architectures, and services they use in the future. It is a score rather than a total; lower numbers are better than higher numbers, and reaching 0 is impossible.



Wrong ways to reduce emissions

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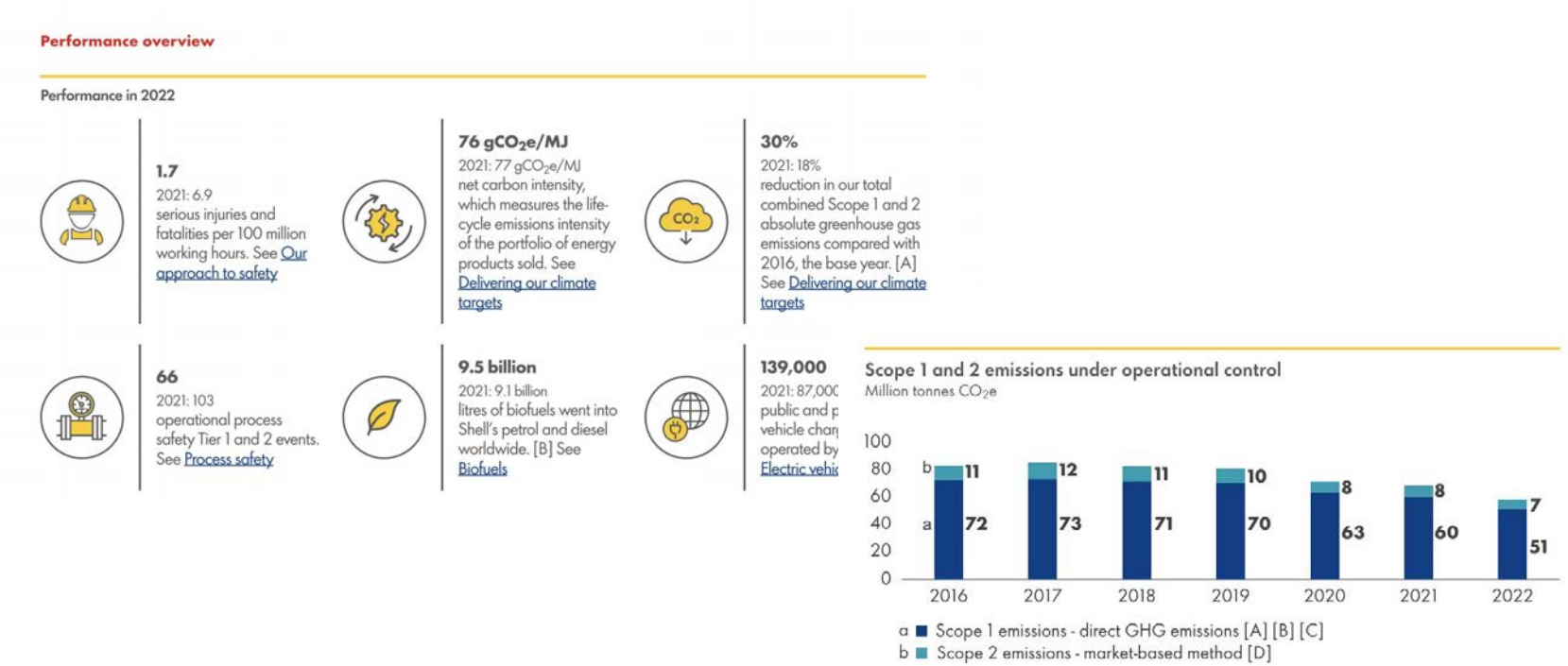
Greenwashing

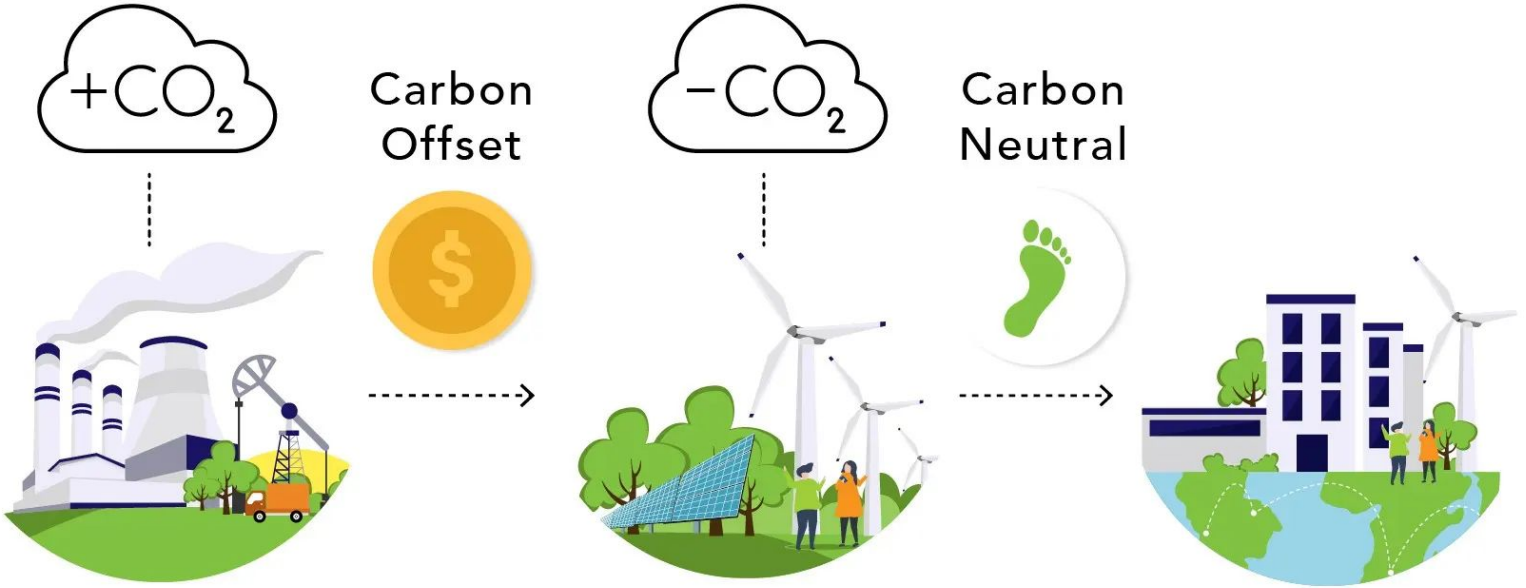


https://www.clientearth.org/projects/the-greenwashing-files/shell/

Greenwashing fines

Volkswagen	$34.69 billion	Implementing software that falsified data and helped evade emissions tests on its vehicles
Toyota	$180 million	Delayed sharing of emissions-related reports
DWS	$25 million	Potentially marketing ESG funds as 'greener' than they actually were
Eni	$5.6 million	Claiming its palm oil diesel was 'green'
Kohl's & Walmart	$5.5 million (combined)	Both claimed their products were made from environmentally friendly bamboo when they were made from other materials
Goldman Sachs	$4 million	Failing to follow ESG investment policies and misleading its customers
Keurig	$2.2 million	Making misleading claims about its single-use coffee pods, suggesting they were recyclable when recyclers don't widely accept them

Carbon Offsets



Carbon Offsets

Carbon Offsets: Last Week Tonight with John Oliver (HBO)
https://www.youtube.com/watch?v=6p8zAbFKpW0

More

- Follow the Sun (mixed benefits)

A better process

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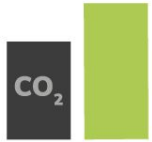
Green Software Principles

Energy Efficiency

Consume the least amount of electricity possible

Hardware Efficiency

Use the least amount of embodied carbon possible



Carbon Awareness

Do more when the electricity is clean and less when it's dirty

	ASPIRING	AWARE	ACTING	AWESOME	INSPIRING
commitments	none	carbon neutral	carbon zero with offsets	10% (offset)	1% (offset)
footprint	unknown	know scope 1&2	reducing per unit	reducing absolutely	~zero
metrics	none	report scope 1&2	daily scope 1&2&3	realtime	predicted
carbon ops	none	manual	lightswitch ops	auto-rightsizing	carbon SRE
energy	none	green hosting	dynamic management	demand shaping	24/7 Carbon Free Electricity
devices	none	some targets	10y/90%	10y/100%	rolling repair
utilization	none	some multi-tenant	all multi-tenant	max orchestration	edge integration
products	none	carbon awareness	demand shaping	feature tracking	feature carbon error budgets
training	ad hoc	basic/champions	advanced	you are the trainer	you are the leader

https://maturity-matrix.greensoftware.foundation/

Focus areas

Knowledge & Org

- Build internal knowledge base
- Leadership and Board commitment
- Implement in the whole business - the annual Co2 report can't stand alone

Data and Reporting

- Get your data sorted and make a strategy for this business area. It's at least an annual reporting thing!
- Automate your Co2 data collection
- The better data, the better reporting, the better decisions you make

SRE

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Purpose of SRE

SRE is a job function, a mindset, and a set of engineering practices to run reliable production systems. Google Cloud helps you implement SRE principles through tooling, professional services, and other resources.

Strike the balance between speed and reliability

But what about Sustainability?

Google

https://cloud.google.com/sre

Key Metrics in SRE

Google’s Golden Signals

- **Latency**: The time it takes for a system to respond to a request.
- **Traffic**: The volume of requests that a system is handling.
- **Errors**: The rate of requests that fail.
- **Saturation**: The percentage of available resources that are being consumed.

Key Metrics in SRE

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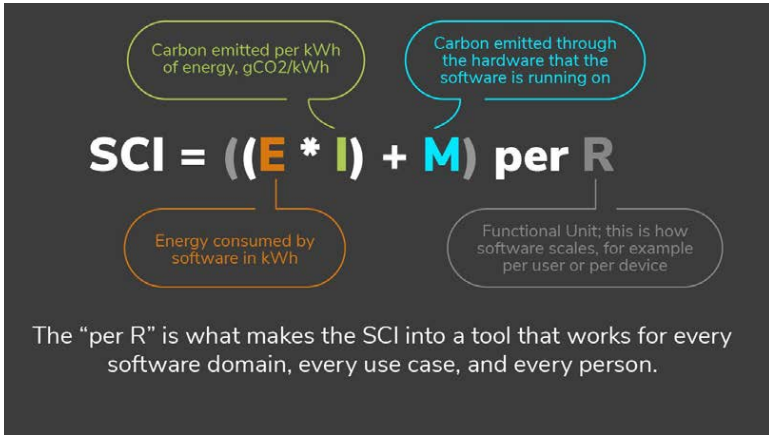
Fifth Golden Signal

- **SCI**: Software Carbon Intensity, or CO2e emitted by a unit of software.



SLO

Keep the planet inhabitable

- Reduce CO2e emissions inline with international agreements (or faster).

SLA & SLI

Drive positive change

- Measure current CO2e emissions and set that level as initial SLA
- Find anti-patterns and eliminate obvious waste
- Systematically reduce SLA to drive incremental improvements
- Nudge engineering teams when SLA is broken

Measurement Tools

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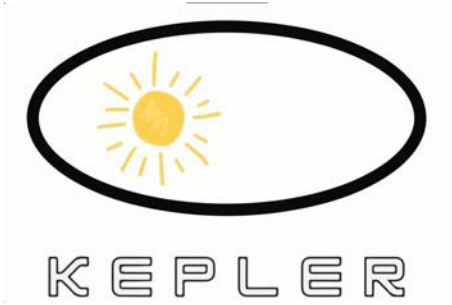
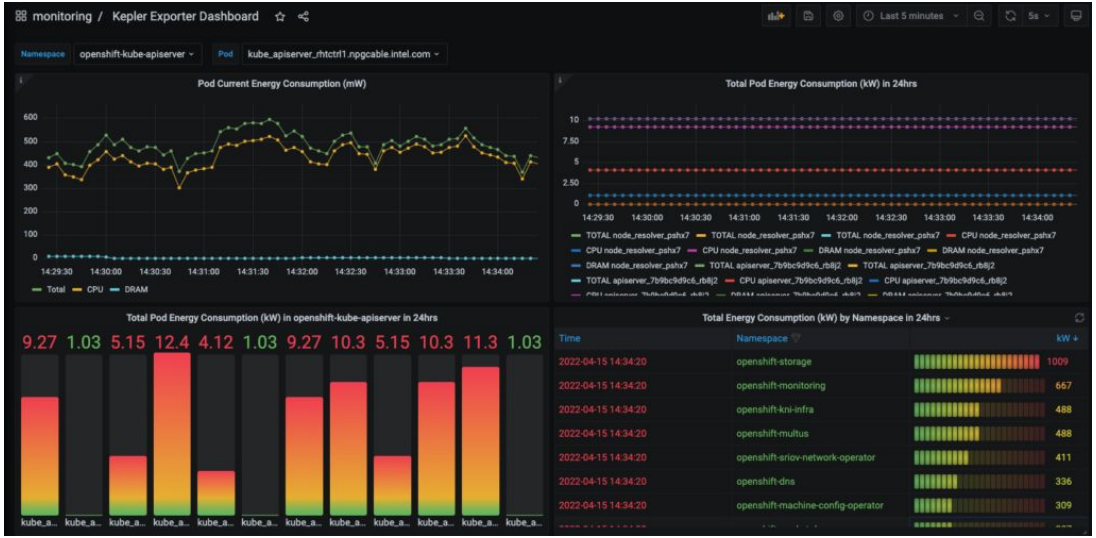


Kubernetes Efficient Power Level Exporter

Kepler (Kubernetes-based Efficient Power Level Exporter) is a Prometheus exporter. It uses eBPF to probe CPU performance counters and Linux kernel tracepoints.



Scaphandre

Energy consumption metrology agent.
Let "scaph" dive and bring back the metrics that will help you make your systems and applications more sustainable !

Aether – Carbon Observability

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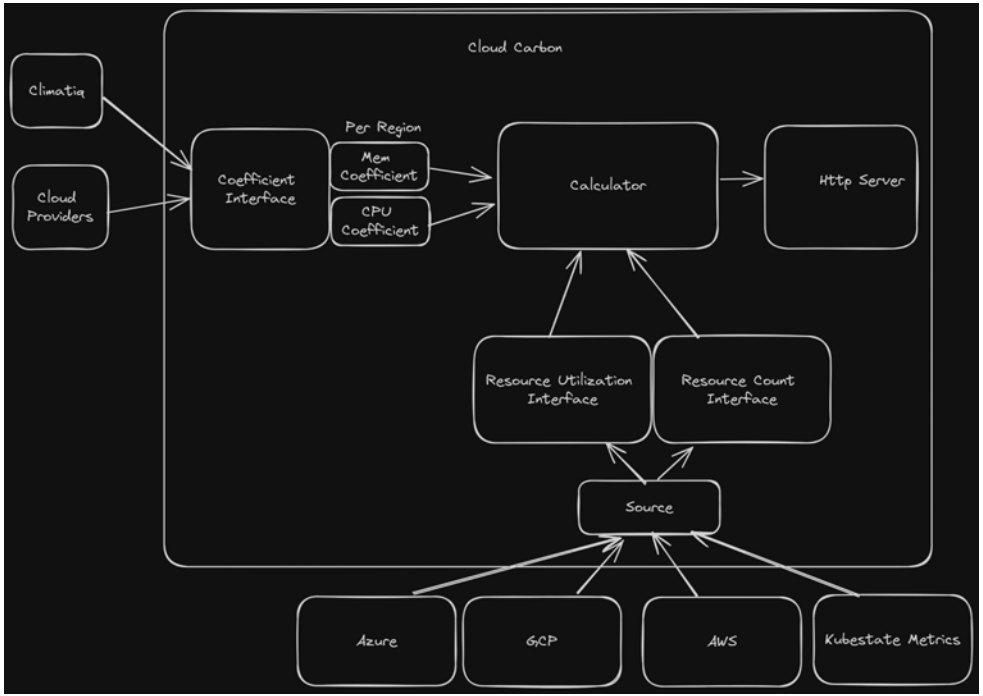


aether.green

https://github.com/re-cinq/aether
https://blog.re-cinq.com/posts/cloud-cpu-energy-consumption/

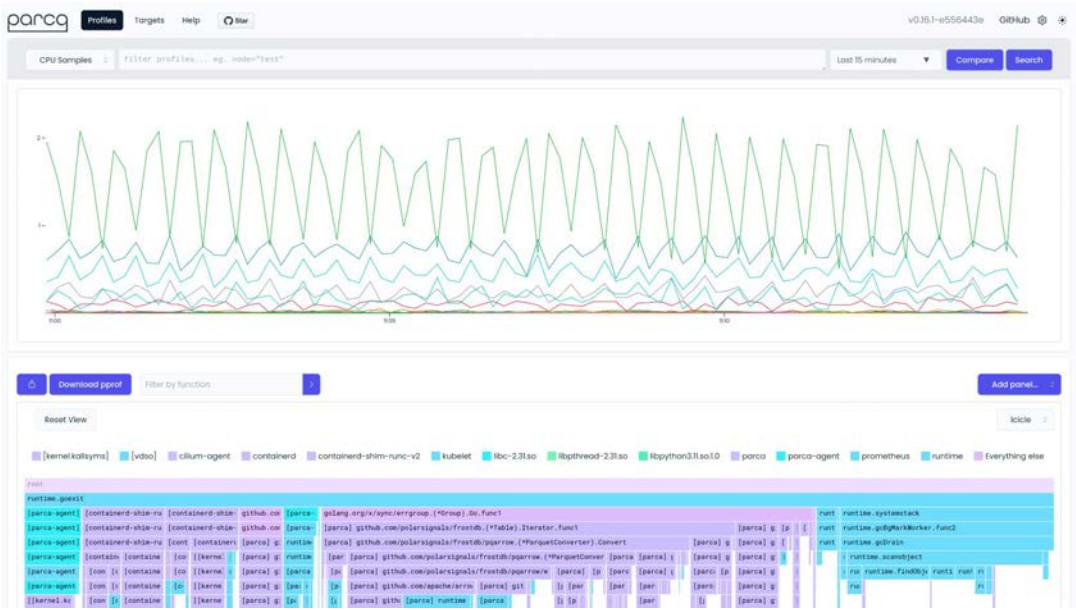
Aether – Carbon Observability

re:cinq

https://github.com/re-cinq/aether
https://blog.re-cinq.com/posts/cloud-cpu-energy-consumption/

Continuous Profiling

Continuous profiling for analysis of CPU, memory usage over time, and down to the line number.

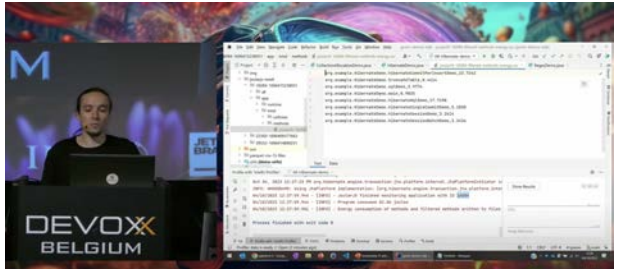


Another 20-30% of savings

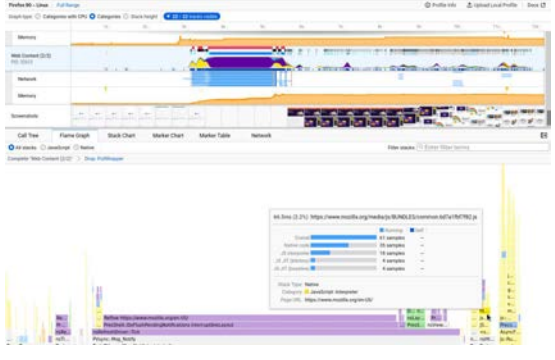
- Reducing carbon emissions
- Saving infrastructure costs
- Improving performance and reliability

Profiling talks

Talk by ING:
https://github.com/high-performance-green-code
https://www.youtube.com/watch?v=CbYZQl27ko8



Talk by Firefox:
https://docs.google.com/presentation/d/17UdQO9Nr3rg4uEcfxyhQrrqec1sSDeG-_T1Hks4BhNU/edit
https://profiler.firefox.com/
https://github.com/firefox-devtools/profiler
https://share.firefox.dev/3l5H1aF



How to achieve even more

Choose your language,
but mind the refactoring gap

Table 4. Normalized global results for Energy, Time, and Memory

Total					
	Energy		Time		Mb
(c) C	1.00	(c) C	1.00	(c) Pascal	1.00
(c) Rust	1.03	(c) Rust	1.04	(c) Go	1.05
(c) C++	1.34	(c) C++	1.56	(c) C	1.17
(c) Ada	1.70	(c) Ada	1.85	(c) Fortran	1.24
(v) Java	1.98	(v) Java	1.89	(c) C++	1.34
(c) Pascal	2.14	(c) Chapel	2.14	(c) Ada	1.47
(c) Chapel	2.18	(c) Go	2.83	(c) Rust	1.54
(v) Lisp	2.27	(c) Pascal	3.02	(v) Lisp	1.92
(c) Ocaml	2.40	(c) Ocaml	3.09	(c) Haskell	2.45
(c) Fortran	2.52	(v) C#	3.14	(i) PHP	2.57
(c) Swift	2.79	(v) Lisp	3.40	(c) Swift	2.71
(c) Haskell	3.10	(c) Haskell	3.55	(i) Python	2.80
(v) C#	3.14	(c) Swift	4.20	(c) Ocaml	2.82
(c) Go	3.23	(c) Fortran	4.20	(v) C#	2.85
(i) Dart	3.83	(v) F#	6.30	(i) Hack	3.34
(v) F#	4.13	(i) JavaScript	6.52	(v) Racket	3.52
(i) JavaScript	4.45	(i) Dart	6.67	(i) Ruby	3.97
(v) Racket	7.91	(v) Racket	11.27	(c) Chapel	4.00
(i) TypeScript	21.50	(i) Hack	26.99	(v) F#	4.25
(i) Hack	24.02	(i) PHP	27.64	(i) JavaScript	4.59
(i) PHP	29.30	(v) Erlang	36.71	(i) TypeScript	4.69
(v) Erlang	42.23	(i) Jruby	43.44	(v) Java	6.01
(i) Lua	45.98	(i) TypeScript	46.20	(i) Perl	6.62
(i) Jruby	46.54	(i) Ruby	59.34	(i) Lua	6.72
(i) Ruby	69.91	(i) Perl	65.79	(v) Erlang	7.20
(i) Python	75.88	(i) Python	71.90	(i) Dart	8.64
(i) Perl	79.58	(i) Lua	82.91	(i) Jruby	19.84

https://greenlab.di.uminho.pt/wp-content/uploads/2017/10/sleFinal.pdf

The Sustainable IT 50 % Challenge

The low-hanging fruits

Zombies

Identify and switch off those zombie servers that aren't doing anything

Right-Sizing

Do a right-sizing exercise on all your servers because everything tends to be overprovisioned to start with.

Cloud

Because of multi-tenancy, cloud already uses only a fraction of the electricity of an on prem DC. AWS claims to be 3.4 times more energy efficient.

Autoscaling

Make use of auto-scaling at peak and scale down to the bare minimum.

CPU Architecture

x86 vs. ARM

Other waste patterns

Ways to reduce emissions (examples)

- Separate spiky and stable loads to reduce cluster size (running routine stable load and heavy butch jobs in the same cluster may lead to significant over-provisioning)
- Only request resources you really need (monitor CPU, RAM, etc.)
- Optimize resource utilisation in deployment and runtime (container images, JVM settings, etc.)
- Minimize provisioning of test environments
- Match SLOs to business objectives (99.999% uptime leads to higher emissions than 99.999%)
- Replace or retire complex tools, DBs etc. (requires CSI benchmarking)
- And a lot more …

Other useful patterns at GSF: https://patterns.greensoftware.foundation/

PowerEdge R630

Report produced January, 2019

From design to end-of-life and everything in between, we work to improve the environmental impact of the products you purchase. As part of that process, we estimate the specific impacts throughout the lifecycle. This includes the contributions from materials, manufacturing, distribution, use and end-of-life management.

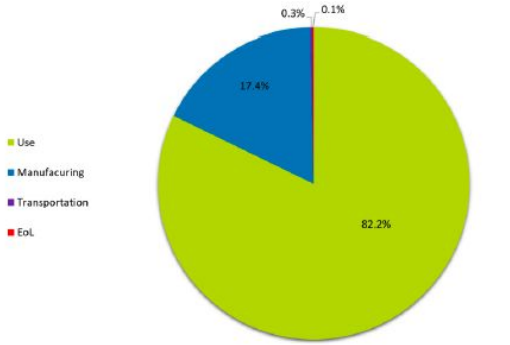
This product's estimated carbon footprint:

7260 kgCO2e *

Estimated impact by lifecycle stage:

Dell uses PAIA (Product Attribute to Impact Algorithm) to perform product carbon footprints. PAIA is a streamlined LCA tool developed by MIT's Materials System Laboratory. It takes into consideration important attributes of the product which can be correlated to activities in order to calculate the product carbon footprint.

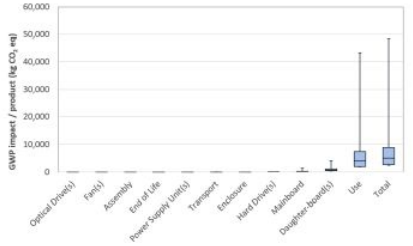
Due to high configurability of servers, the information provided here was calculated based on the products highest selling configuration (see assumptions on page 2).



Enterprise Equipment Name

* This product has an estimated standard deviation of +/- 7580 kgCO2e

As part of our commitment to transparency, the chart to the right demonstrates the degree of uncertainty that exists within the PAIA model for product carbon footprinting, based on assumptions we have made for select variables.



Assumptions for calculating product carbon footprint:

Product Weight	18.6 kg	**Server Type**	Rack	**Assembly Location**	EU
Product Lifetime	4 years	**Use Location**	EU	**Energy Demand (Yearly TEC)**	1433.574 kWh
HDD/SSD Quantity	x4 1.2TB 2.5" HDD	**DRAM Capacity**	16GB	**CPU Quantity**	2

7260 kgCO2e

To help our customers and other stakeholders contextualize product carbon footprint values, we provide these approximate equivalencies. Please remember these are estimates and should not be used for emission inventory or formal carbon footprinting exercises.

1 of these products… has a footprint approx. equivalent to **driving 17,787 miles** in a passenger car.

10 of these products… have a footprint approx. equal to what **85 acres of US forests** can absorb in a year.

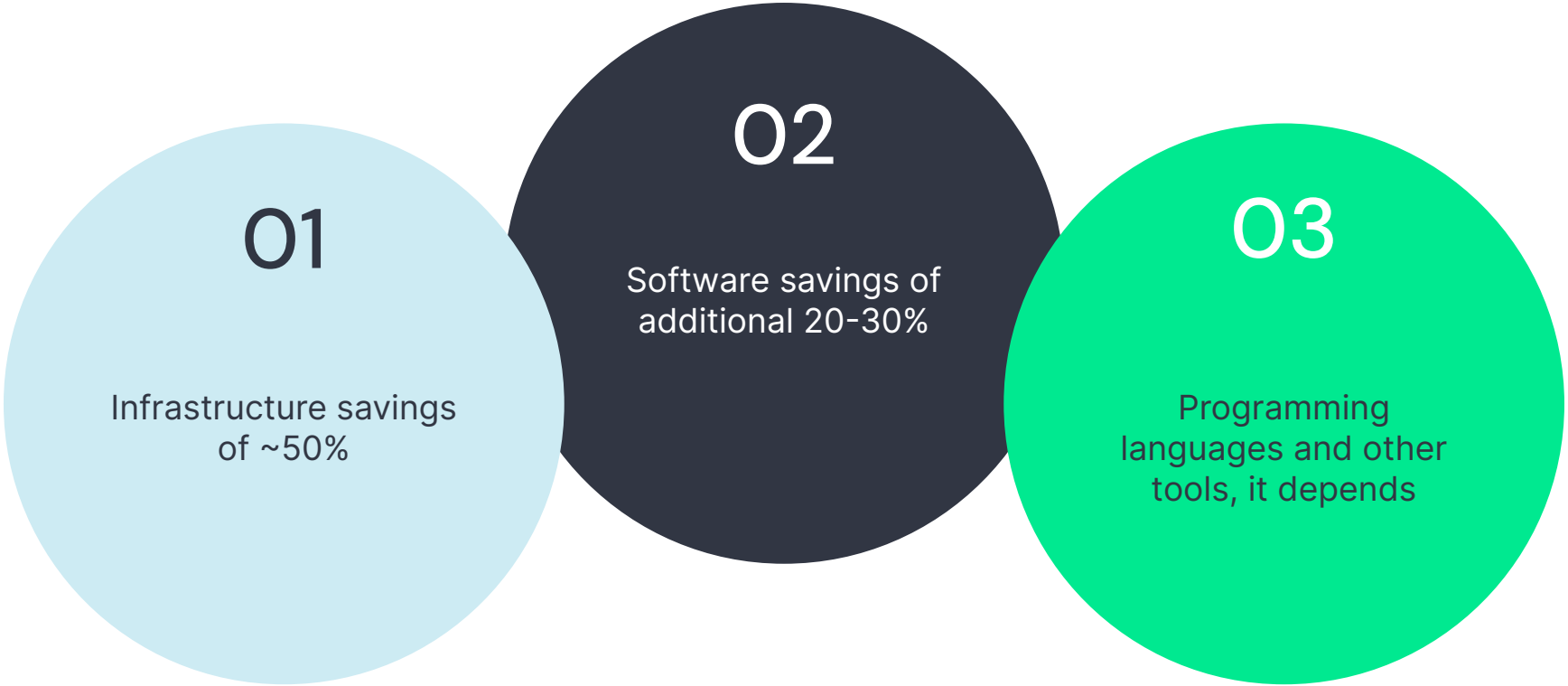
100 of these products… have a footprint about the same as the annual average carbon footprint of **145 people.**

Calculations are based on the following methodologies: 2.45 miles driven per 1 kg co2e (source: U.S. EPA); approx. 850 kg co2e absorbed per acre of forests over a year (source: U.S. EPA); global personal carbon footprint estimated at 5 MTco2e per person (source: World Bank).

Extending Hardware Life

Saves $$$ and Carbon

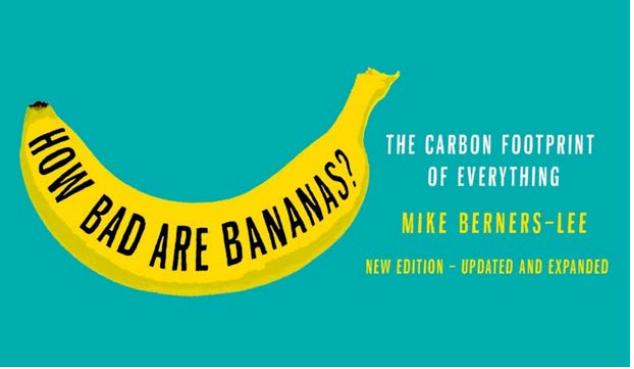
Wrapping Up


01
Infrastructure savings of ~50%
02
Software savings of additional 20-30%
03
Programming languages and other tools, it depends

Some random examples

Bananas and more

re:cinq



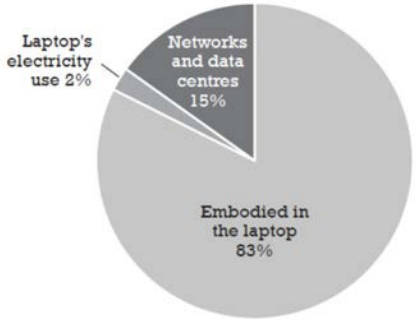
A banana

110g CO_2e each (or 670g CO_2e per kilo)[1]

To answer the question in the title of this book: bananas aren't bad at all

An email

0.03g CO_2e spam email picked up by your filters
0.2g CO_2e short email going from phone to phone
0.3g CO_2e short email sent from laptop to laptop
17g CO_2e long email that takes 10 minutes to write and 3 minutes to read, sent from laptop to laptop
26g CO_2e an email that takes you 10 minutes to write, sent to 100 people, 99 of whom take 3 seconds to realise they should ignore it and one of whom reads it[4]



Cycling a mile

40g CO_2e powered by bananas
70g CO_2e powered by cereals with cow's milk
190g CO_2e powered by bacon
310g CO_2e powered by cheeseburgers
4.7kg CO_2e powered by airfreighted asparagus
+ 10-100g CO_2e per mile for the bike's embodied carbon[10]

Cryptocurrencies

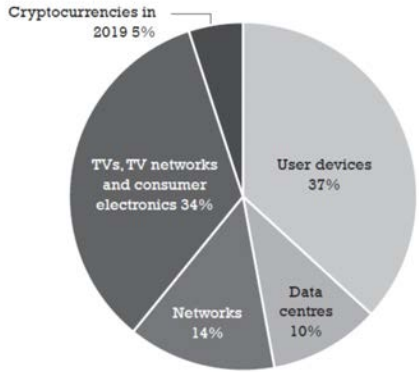
46 million tonnes CO_2e Bitcoin in 2019
68 million tonnes CO_2e all cryptocurrencies in 2019[8]

In just a decade, cryptocurrencies have eaten up 0.12 per cent of the world's carbon footprint[9]

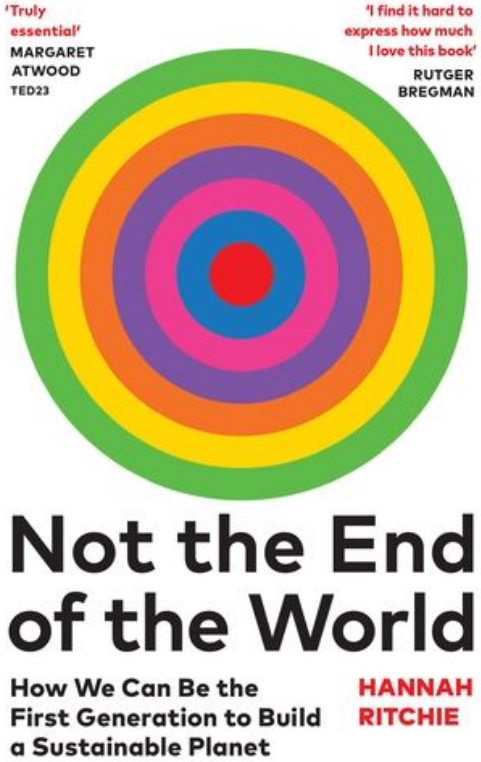
The Cloud and the world's data centres

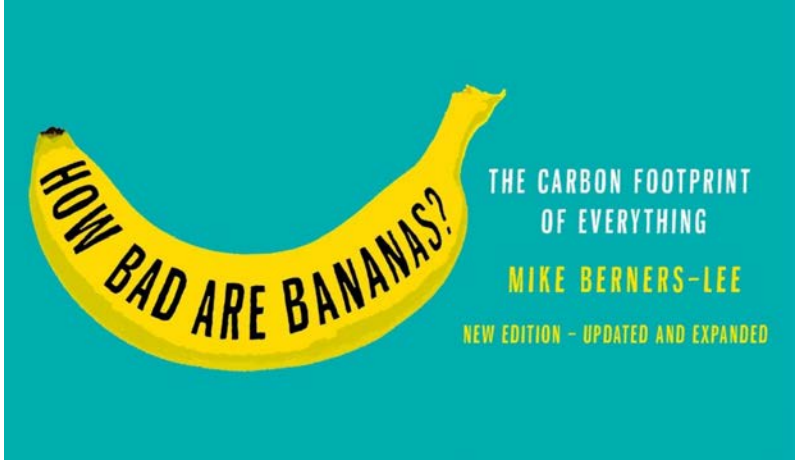
160 million tonnes CO_2e in 2020[14]

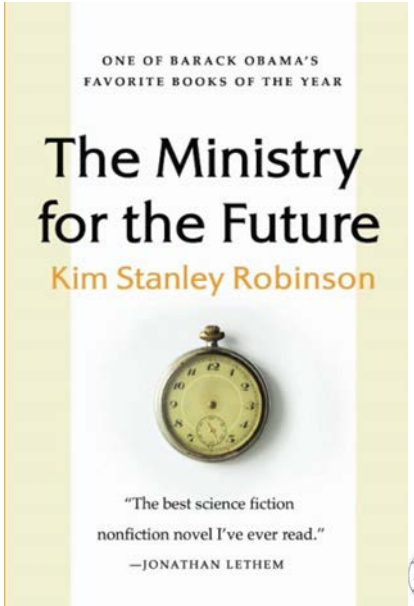
Data centres use about 1 per cent of global electricity and 0.25 per cent of its footprint[15]

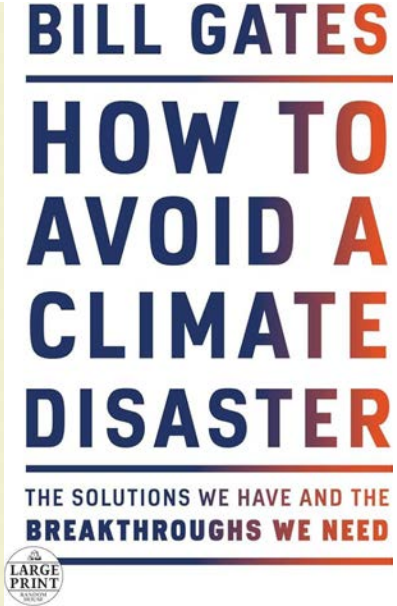


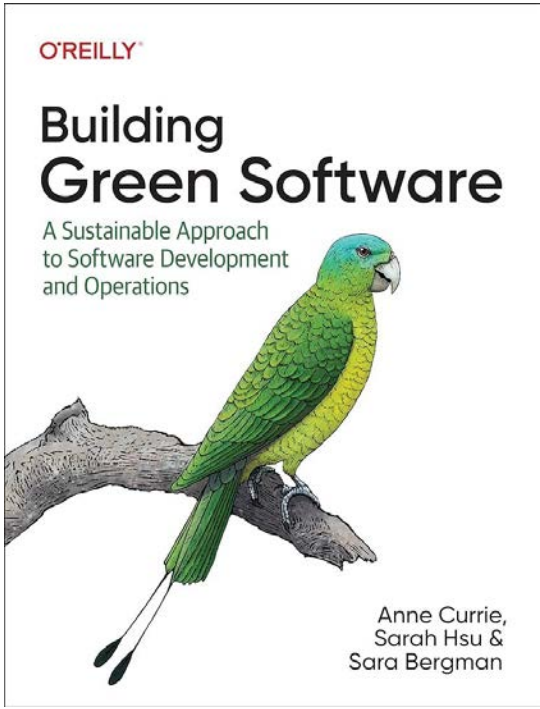
The world's ICT footprint (1.4 billion tonnes CO_2e), 2020


'Truly essential'
MARGARET ATWOOD
TED23
'I find it hard to express how much I love this book'
RUTGER BREGMAN
Not the End of the World
How We Can Be the First Generation to Build a Sustainable Planet
HANNAH RITCHIE


HOW BAD ARE BANANAS?
THE CARBON FOOTPRINT OF EVERYTHING
MIKE BERNERS-LEE
NEW EDITION - UPDATED AND EXPANDED


ONE OF BARACK OBAMA'S FAVORITE BOOKS OF THE YEAR
The Ministry for the Future
Kim Stanley Robinson
"The best science fiction nonfiction novel I've ever read."
—JONATHAN LETHEM


BILL GATES
HOW TO AVOID A CLIMATE DISASTER
THE SOLUTIONS WE HAVE AND THE BREAKTHROUGHS WE NEED
LARGE PRINT


O'REILLY
Building Green Software
A Sustainable Approach to Software Development and Operations
Anne Currie, Sarah Hsu & Sara Bergman

What can I do now?

- Read “Building Green Software”
- Start measuring

- Talk to re:cinq