Sustainable Computing

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Twitter: @rybizki

Teaser

- What do you think is sustainable computing?
- Please vote via handsraising

Bitcoin

Climate modelling

Neutrino Science

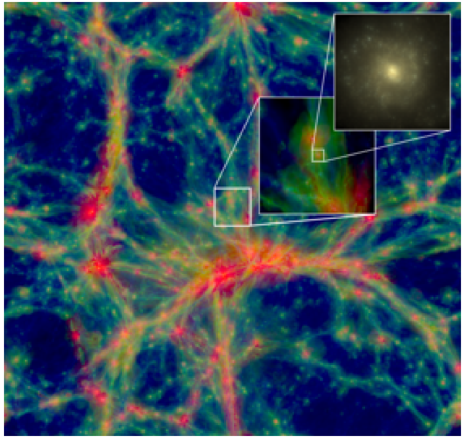
Super simulations help determine the mass of neutrinos

06/23/2020

Felix Spanier from the Center for Astronomy of the University (ZAH) and his collaboration partners Guido Drexlin and Jonas Kellerer from the Karlsruher Institute of Technology (KIT) have achieved great success in the current application round of the Gauss Center for Supercomputing (GCS): 35 million CPU hours can be used for plasma simulations as part of the Karlsruhe Tritium Neutrino Experiment (KATRIN) whose aim is to measure the mass of the neutrino. The result of this measurement is of fundamental importance, among other things, for elementary particle physics or our understanding of the development of structures in the universe.

The KATRIN experiment is a scientific superlative, the construction of which took about 15 years in international cooperation. KATRIN exploits the so-called beta decay of radioactive tritium gas. This decay produces an electron and neutrino at the same time. The neutrino cannot bedetected. But KATRIN can measure a tiny anomaly in the energy distribution of decay electrons and conclude the mass of the neutrino.

However, the tiny anomaly in the energy spectrum is also influenced by the behaviour of the tritium gas. The decay of the tritium frees up high-energy electrons that can ionize the gas itself, so that it becomes a plasma with special electromagnetic properties. The effect on the electrons to be measured is actually minimal, but in order to measure the mass of the neutrino to the required accuracy of 0.000 000 000 000 000 000 000 000 000 000 3 g, the influence of the plasma must be known indeed very precisely.



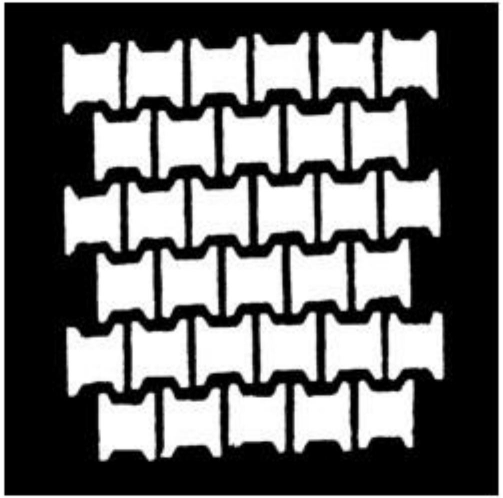
Visualization of a simulation of the formation of cosmic structures. As the most common elementary particle in the universe, the neutrino has a significant impact. Therefore, it is important to measure its mass very accurately. (Copyright: The EAGLE-Project http://icc.dur.ac.uk/Eagle/)

Quality control in concrete production

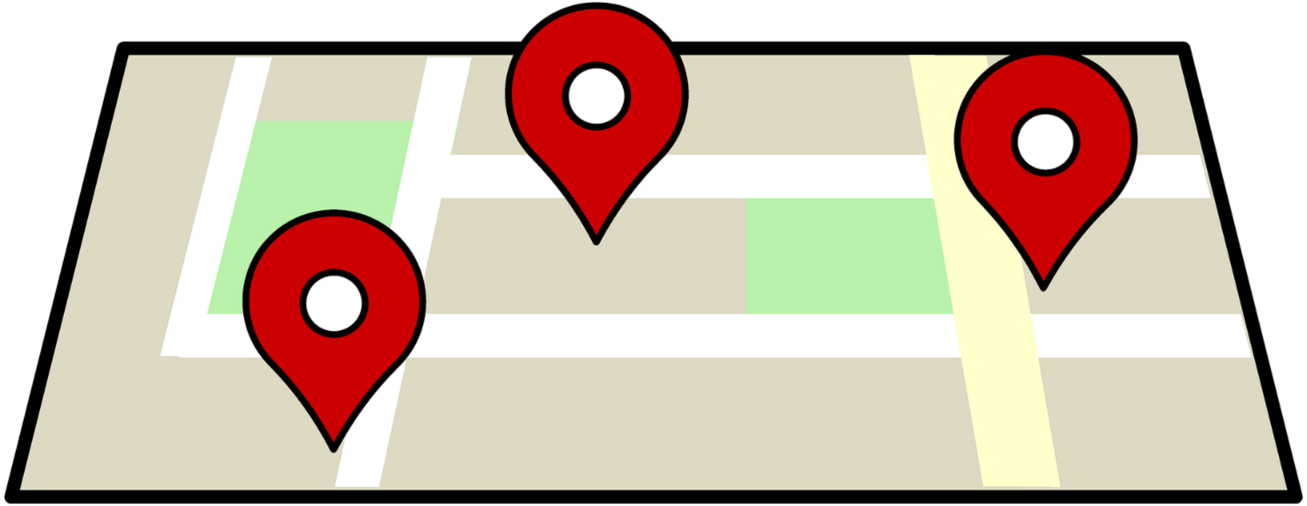
Input image

segmentation

Paving stone mask

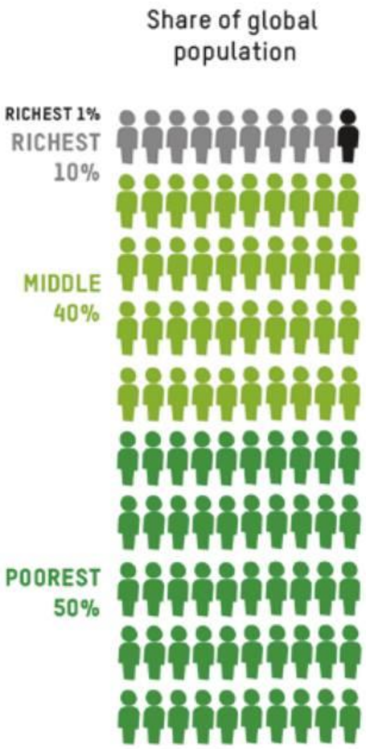


Navigation



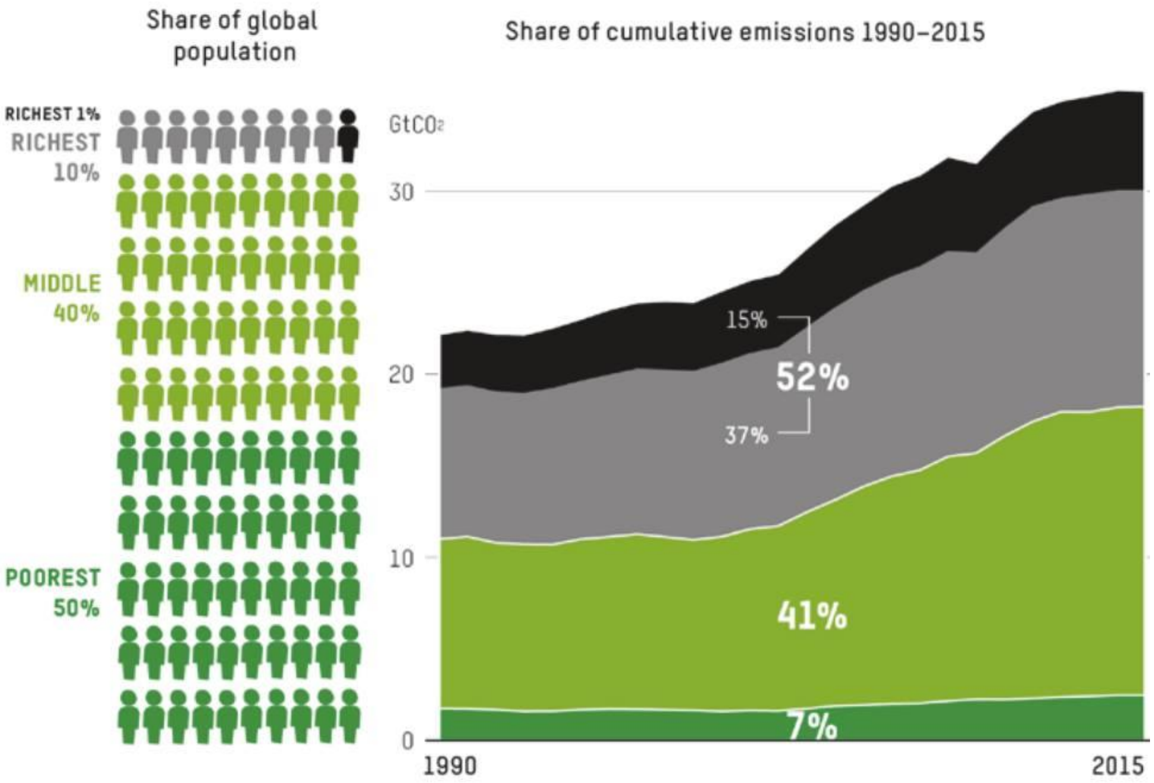
Anthropogenic greenhouse gas emissions are problematic

Introduction



Oxfam

Introduction



Oxfam

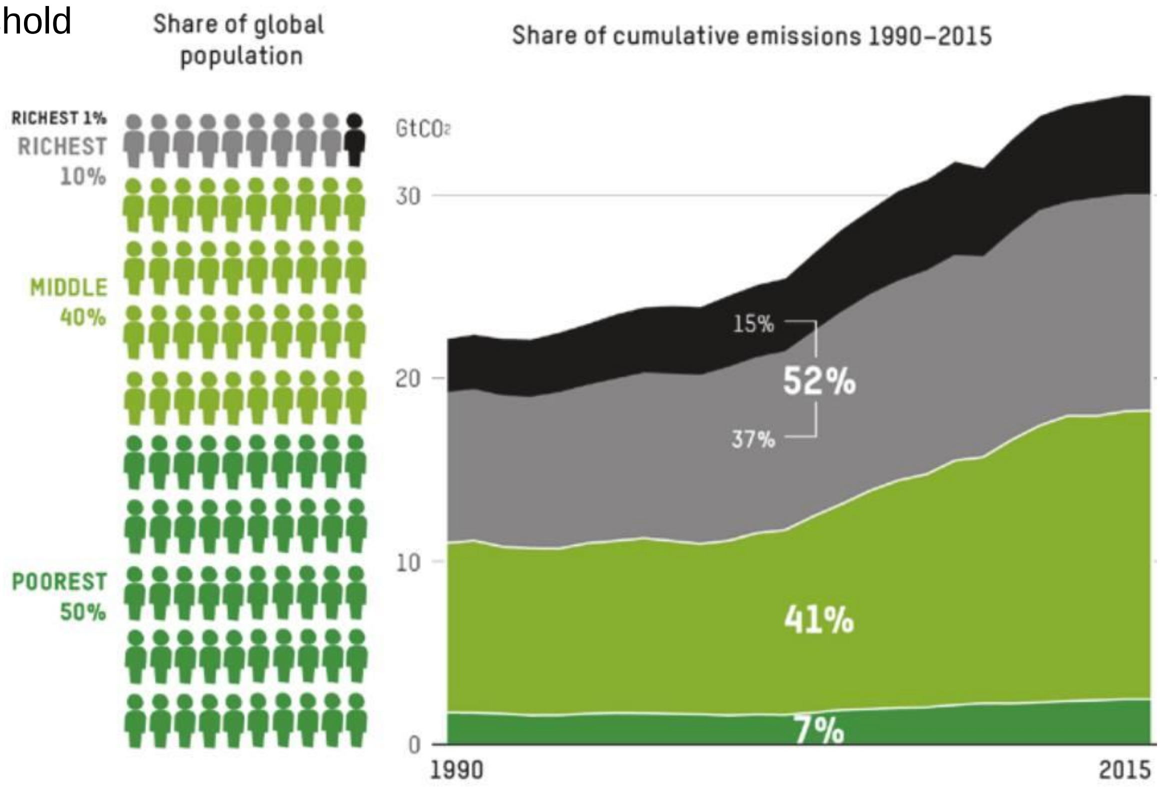
Introduction

income threshold

> 100k € / yr
> 35k € / yr

> 5k € / yr

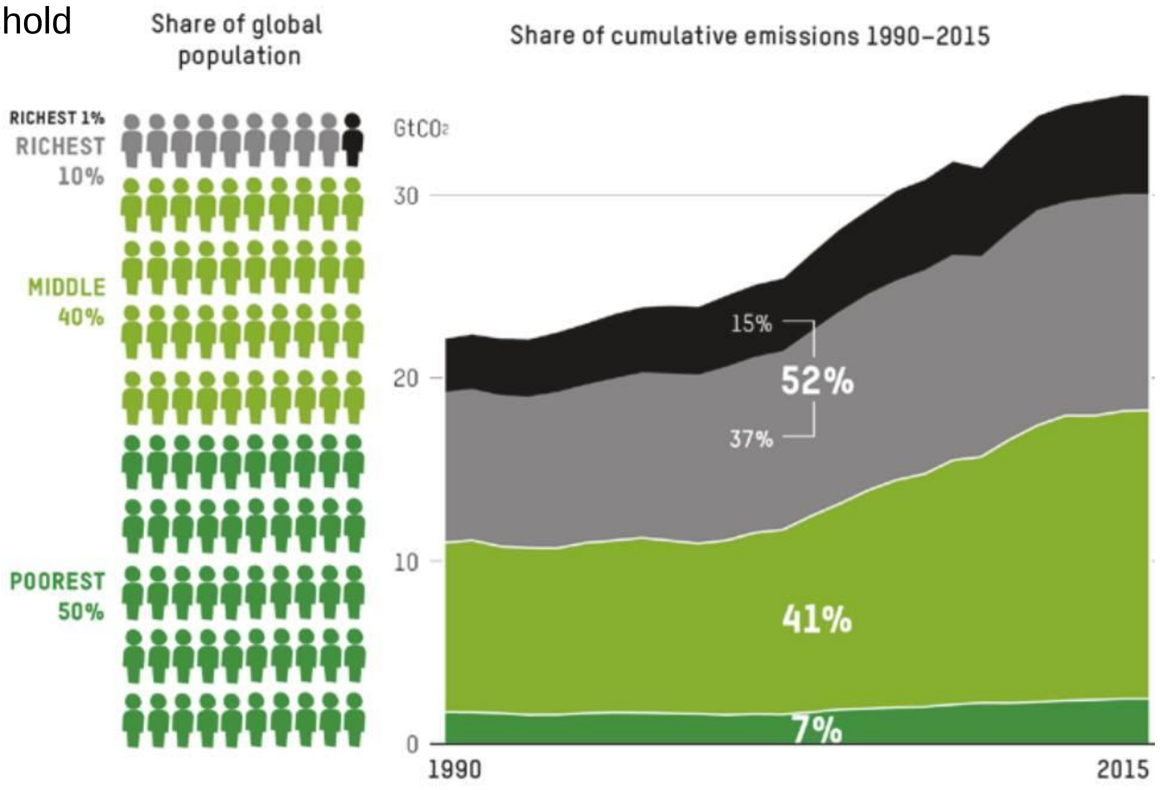
< 5k € / yr



Oxfam

Introduction

average emission	income threshold
75t CO_{2eq}/ yr	> 100k € / yr
23t CO_{2eq}/ yr	> 35k € / yr
5t CO_{2eq}/ yr	> 5k € / yr
0.75t CO_{2eq}/ yr	< 5k € / yr



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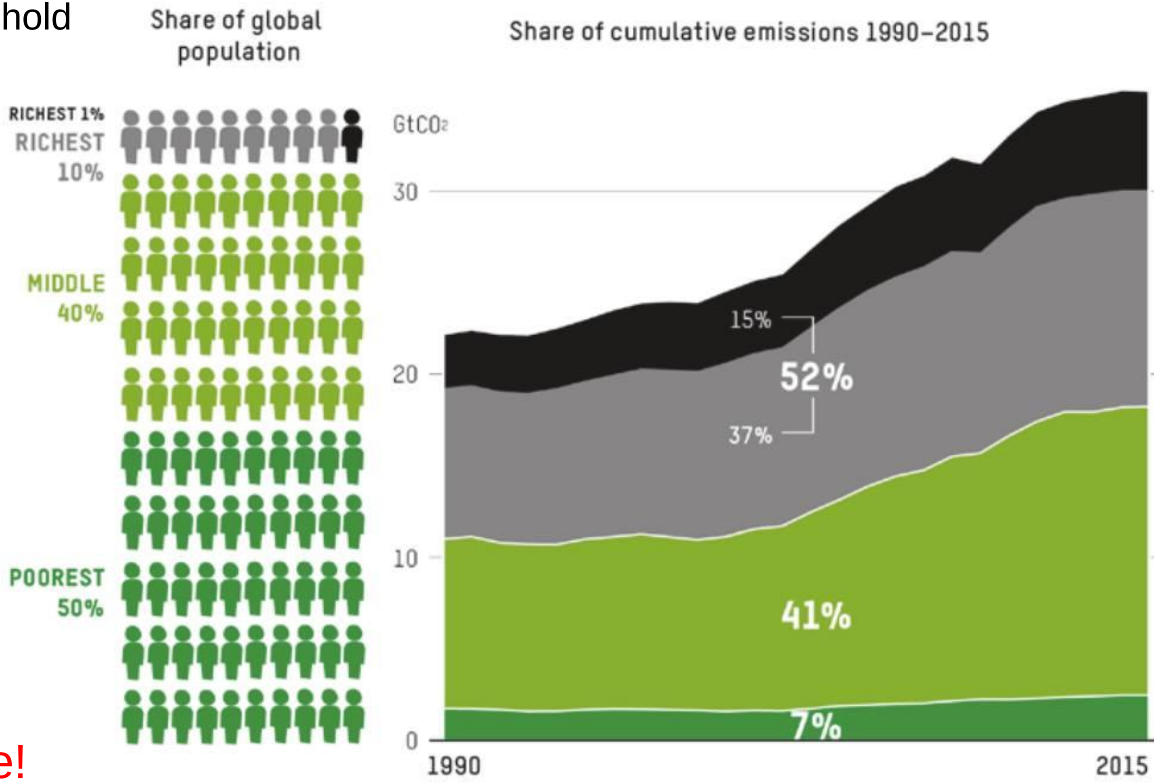

Oxfam

2t CO_{2eq}/ yr is sustainable!

Glad to speak to you!

Overview

- GHG study of MPIA and Australian Astro community
- Background
  - Electricity grid in Germany
  - Computer physical boundaries
  - Data centers energy usage
- Increasing computing efficiency
- Solution ideas

annual tCO_{2eq} per MPIA researcher

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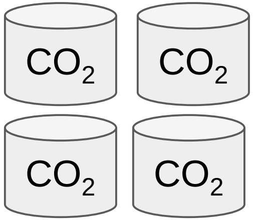
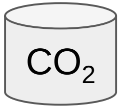
data taken from Jahnke+ 2020 and refined by reanalysis

https://www.nature.com/articles/s41550-020-1202-4

annual tCO_{2eq} per MPIA researcher

Flying





= 1 tCO_{2eq}

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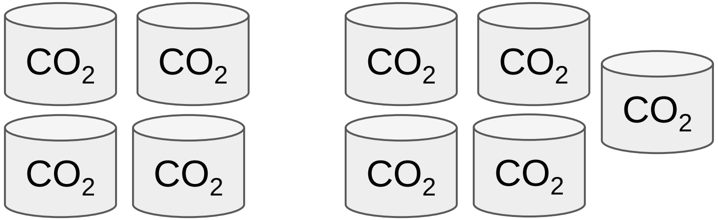
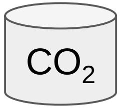
Flying **Electricity**





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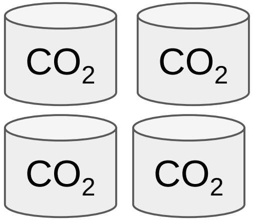
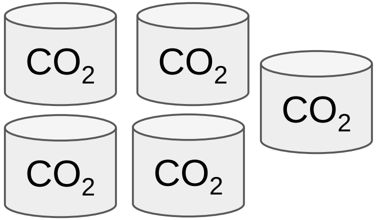
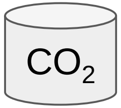


Electricity



Supercomputing facilities make up **~80%** of electricity usage



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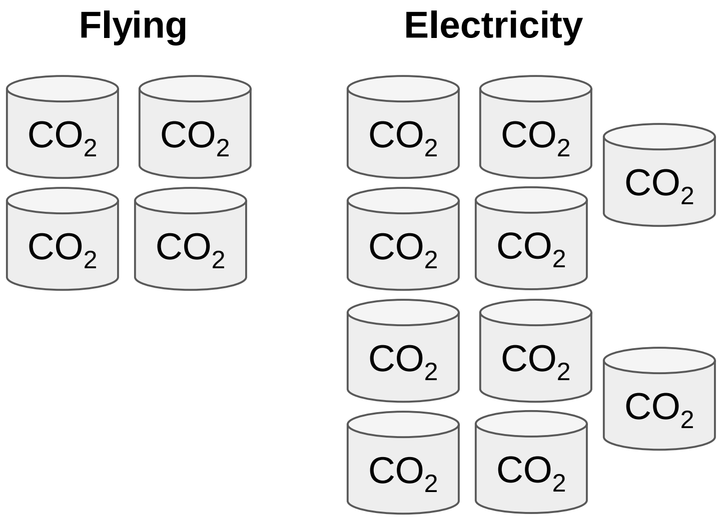
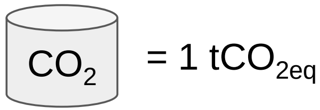


Emissions if we would use the CO_{2eq}-intensity of the German electricity production instead of Heidelberg / Munich city grid



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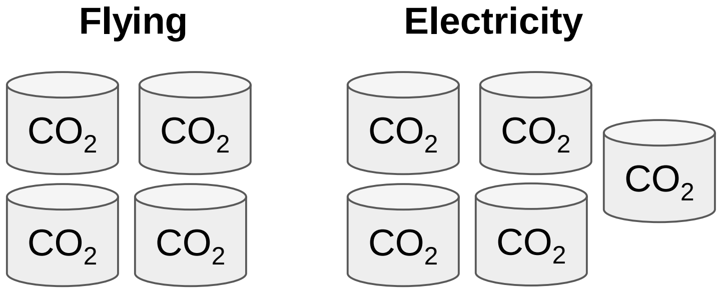

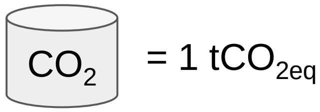

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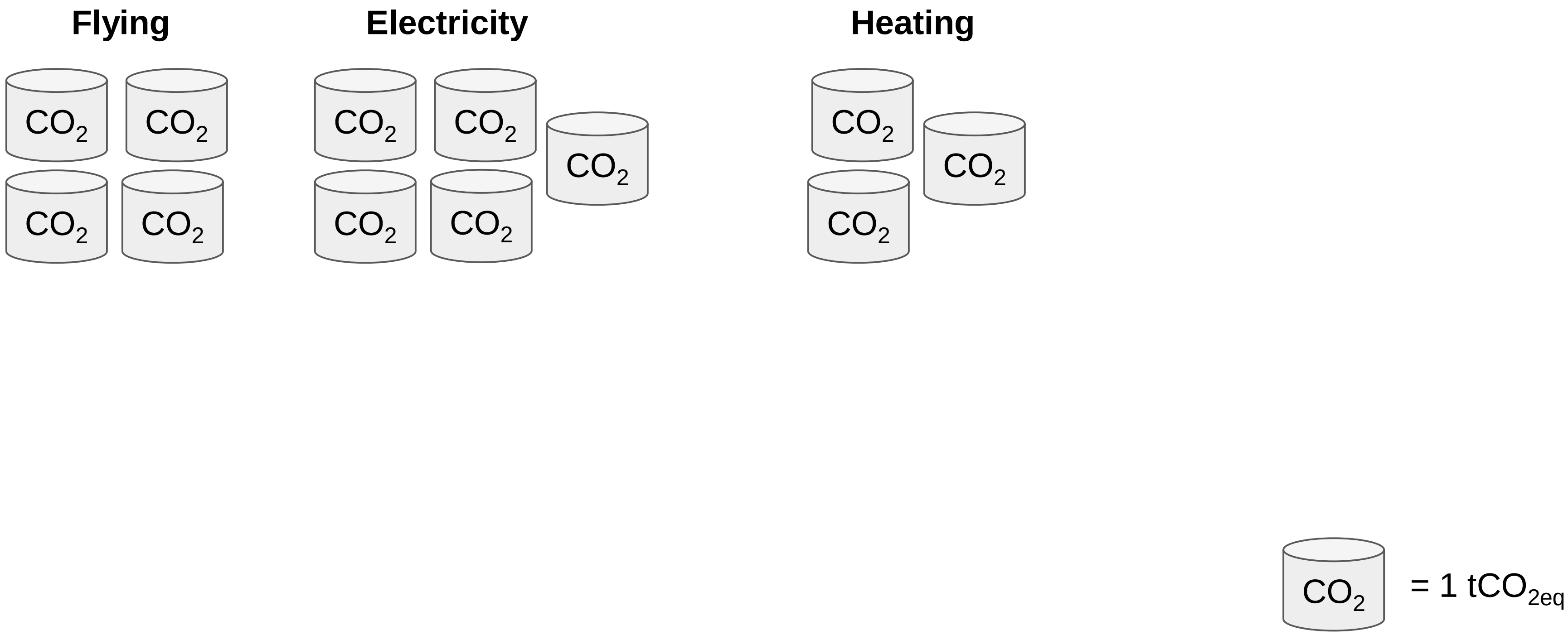


Carolin Liefke, HdA

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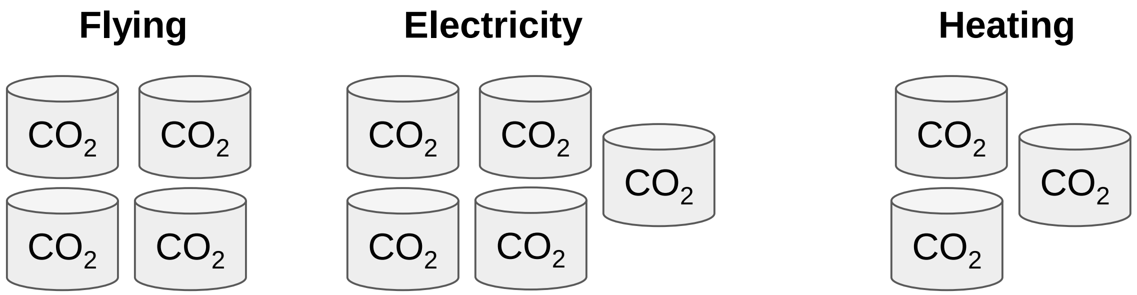

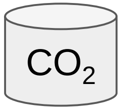

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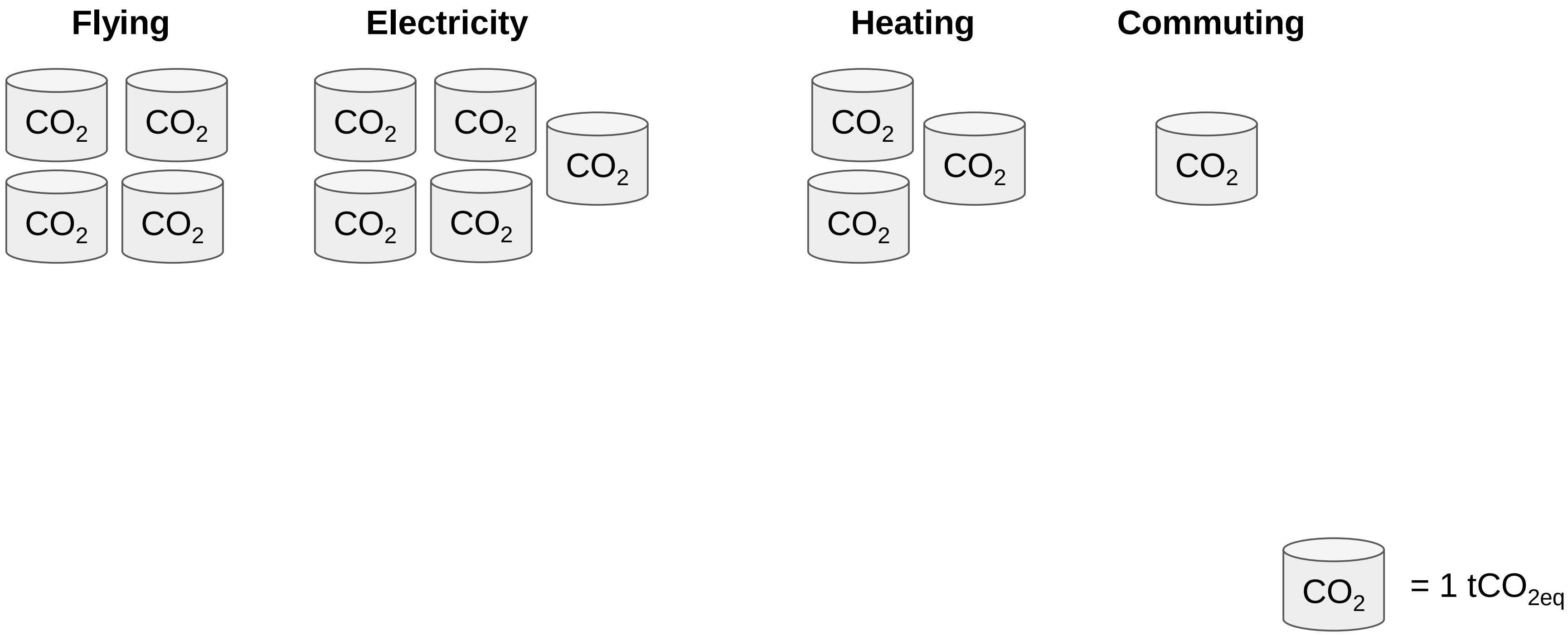

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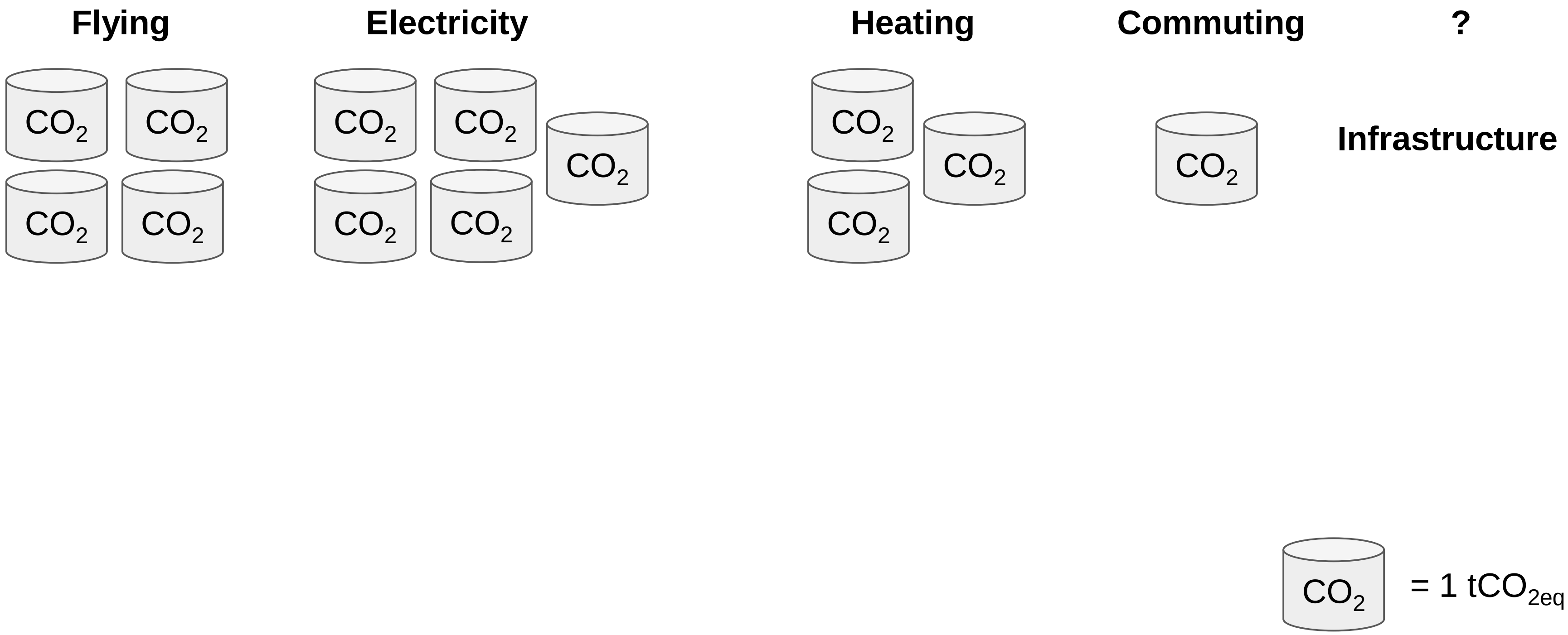

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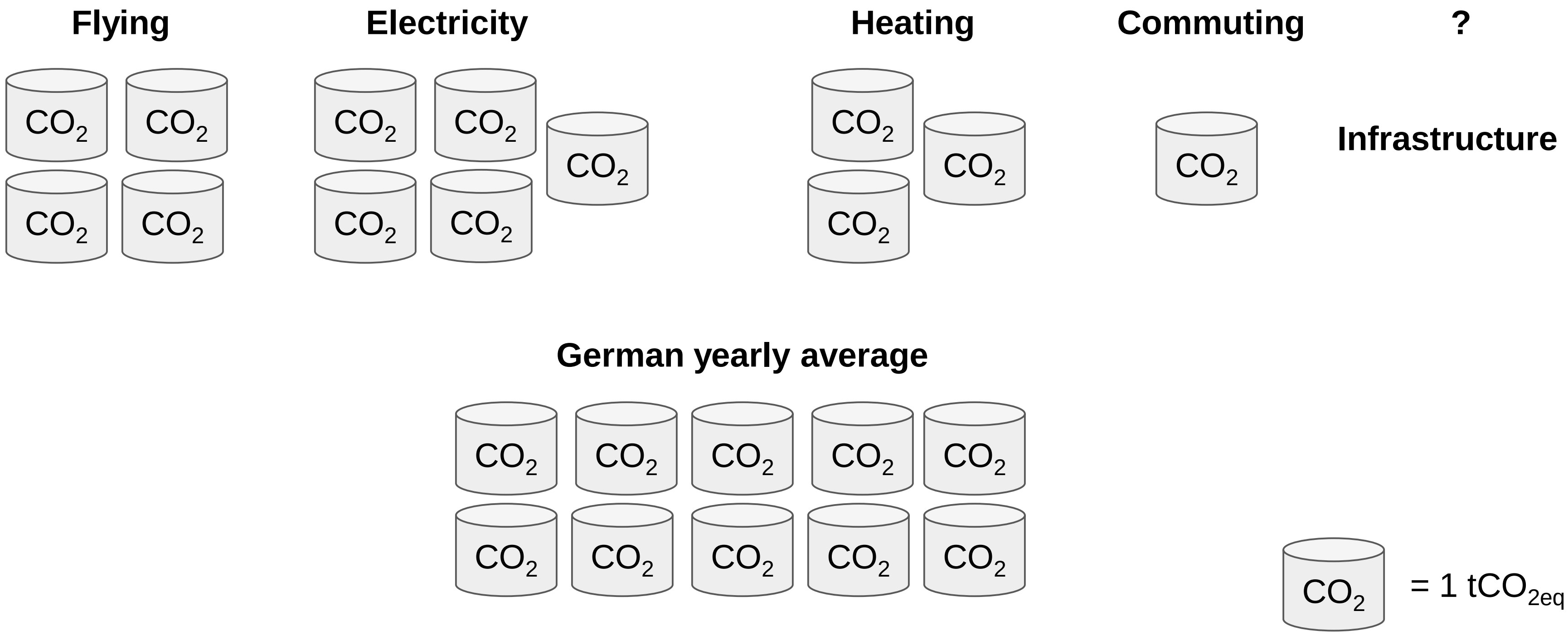

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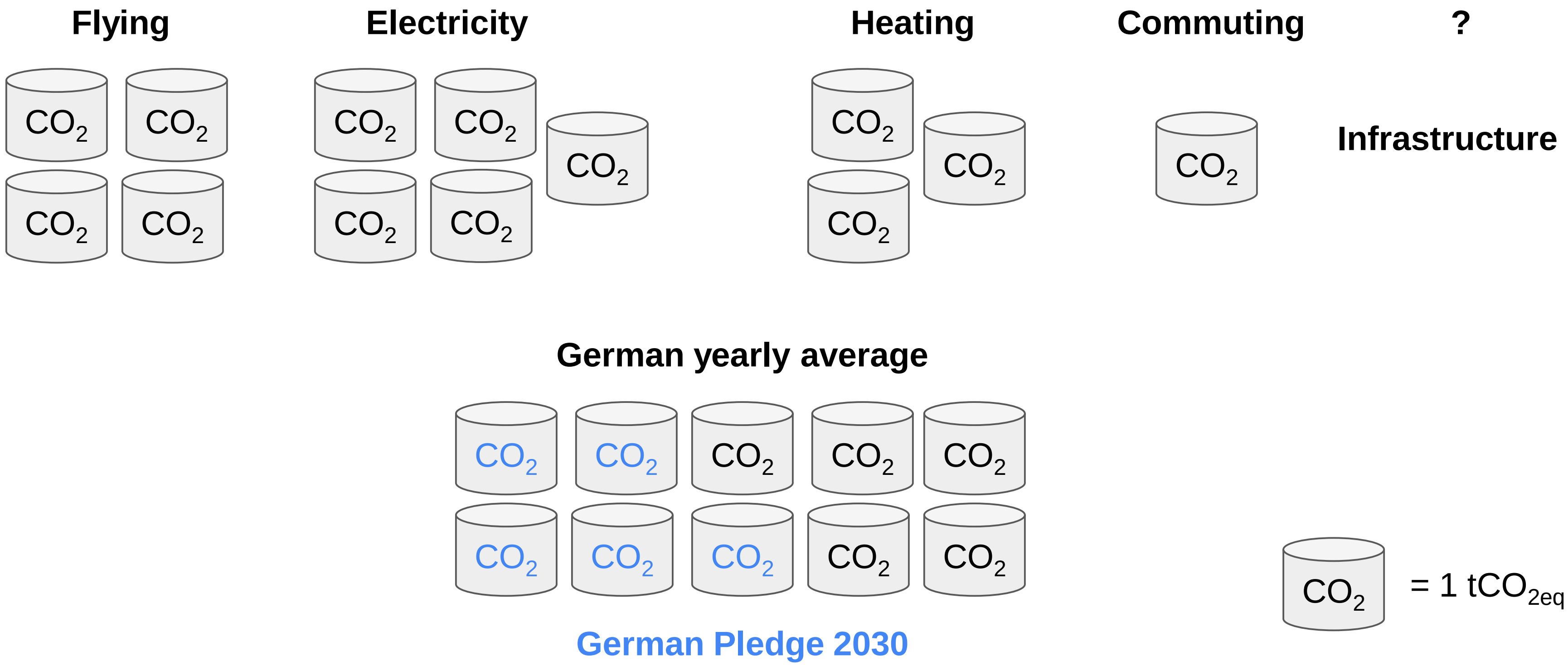

Supercomputing put into perspective

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all year long...

Hardware life-cycle*

*mostly production and shipping vs. consumption

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Check: https://ecoinfo.cnrs.fr/ecodiag-calcul/ to get life-cycle estimates

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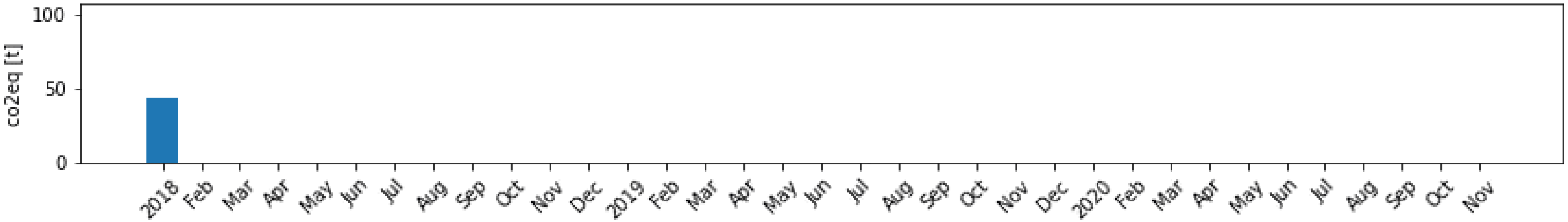
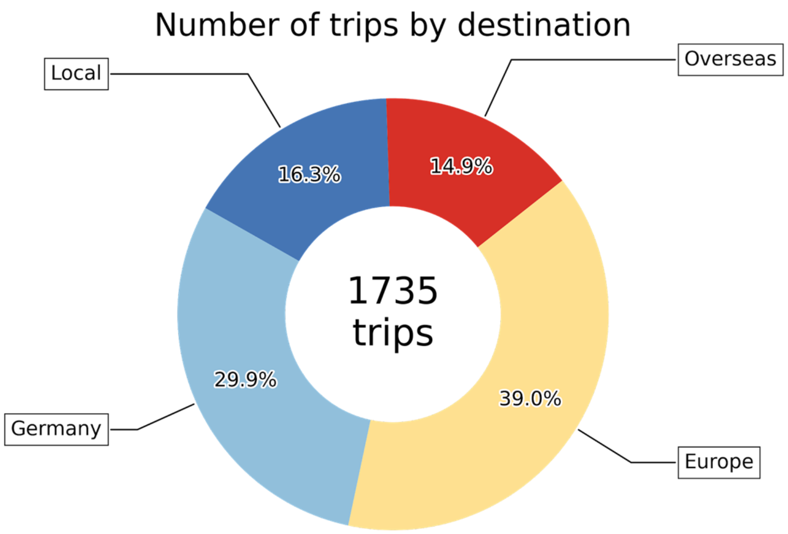
An assessment of MPIA's travel activities

2018-2020

https://github.com/jan-rybizki/Business_trips_carbon_footprint



Number of flights vs. CO_{2eq} emissions by destination



Overseas make up **15%** of trips **by number...**

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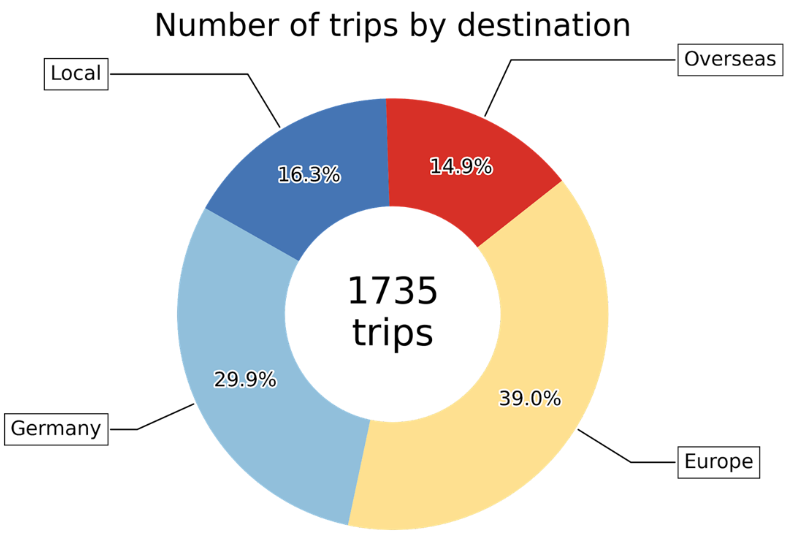

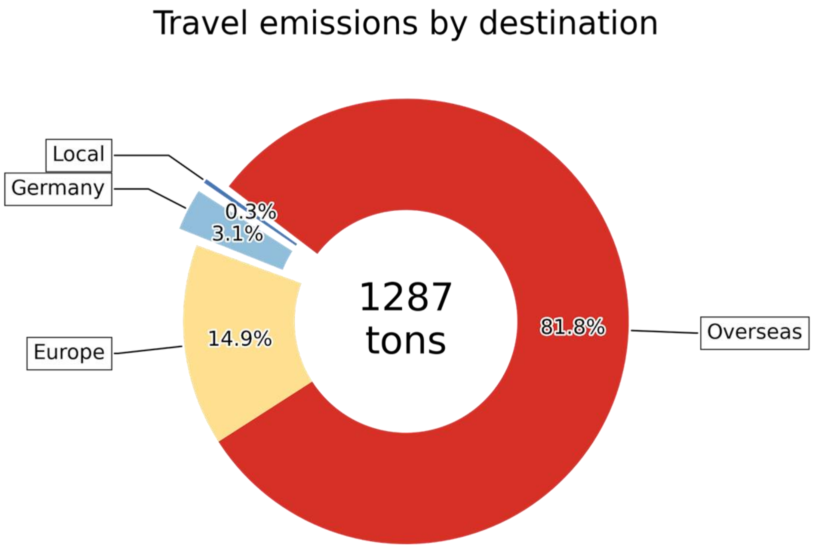

Overseas make up **15%** of trips **by number...**

...but **82%** of trips by **CO_{2eq} emissions**.

Online meetings help!

- Less emissions (a factor of 1000 less)
- More inclusive

Background knowledge

- Electricity grid in Germany
- Computer physical boundaries
- Data centers energy usage

Electric supply - boundary conditions in the near future

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- share of renewables will increase → volatile supply

Germany + electricity consumption

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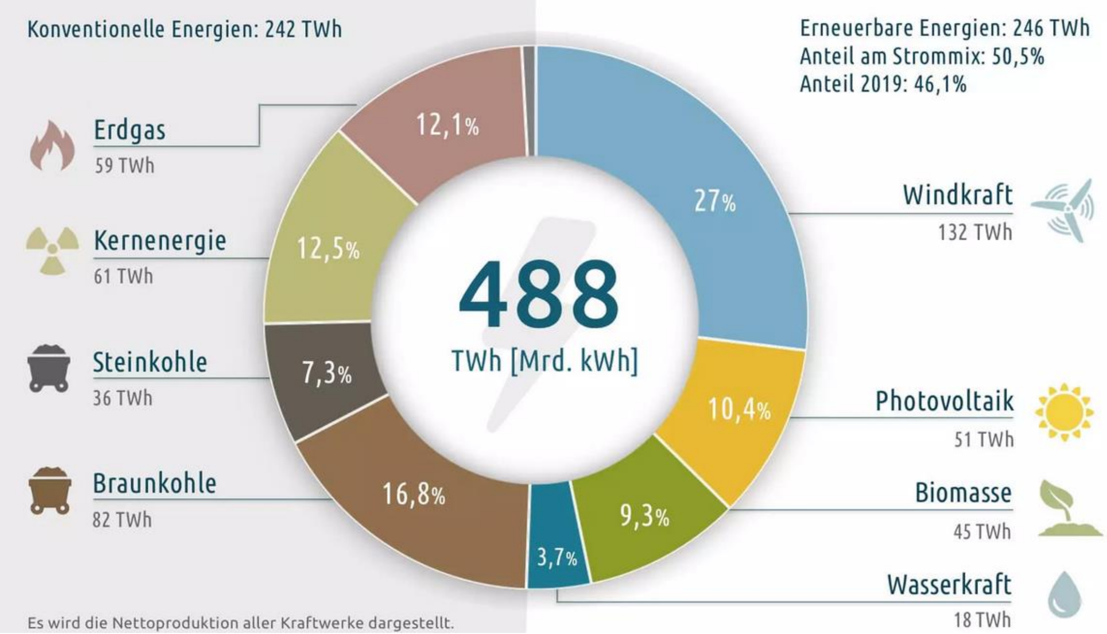
a look into Germany's **electricity mix...**



*each country has a different mix of electricity sources

CO_{2eq}-Emissions German electricity mix [kg / MWh]

Quelle: EUPD Research 2021

	Jan	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Dez
00:00	349	227	297	294	314	362	408	413	450	368	433	396
01:00	346	222	293	287	305	348	399	401	443	362	429	390
02:00	342	217	293	284	301	341	390	393	438	352	425	387
03:00	341	216	290	284	302	340	385	393	437	359	426	385
04:00	343	220	297	290	306	344	386	399	442	368	430	388
05:00	355	232	310	301	319	357	393	414	455	389	441	400
06:00	367	247	322	304	318	360	389	421	464	407	451	414
07:00	373	253	311	288	295	342	360	403	449	407	450	418
08:00	374	253	290	263	268	318	327	373	419	400	440	419
09:00	367	247	273	235	242	294	296	346	393	386	430	416
10:00	359	239	253	203	216	274	273	322	366	372	420	410
11:00	354	232	240	183	200	259	257	302	341	361	412	407
12:00	350	229	235	172	192	250	247	291	324	351	412	409
13:00	353	228	238	167	189	245	242	288	315	349	424	419
14:00	364	233	246	168	189	245	242	292	320	356	444	431
15:00	380	244	263	176	197	251	250	306	340	374	469	437
16:00	389	258	292	198	210	265	269	328	377	398	476	429
17:00	379	264	323	239	240	288	300	360	420	413	460	417
18:00	373	260	335	279	276	320	333	390	454	411	454	418
19:00	372	259	333	301	305	352	364	414	462	404	456	421
20:00	368	254	330	306	324	376	393	427	462	400	460	422
21:00	363	246	326	307	332	388	409	431	468	394	456	418
22:00	359	243	323	305	333	386	413	432	468	386	454	416
23:00	351	235	316	296	326	383	417	432	457	373	448	409

Germany + electricity consumption

Question 1: how much electricity does Germany consume?

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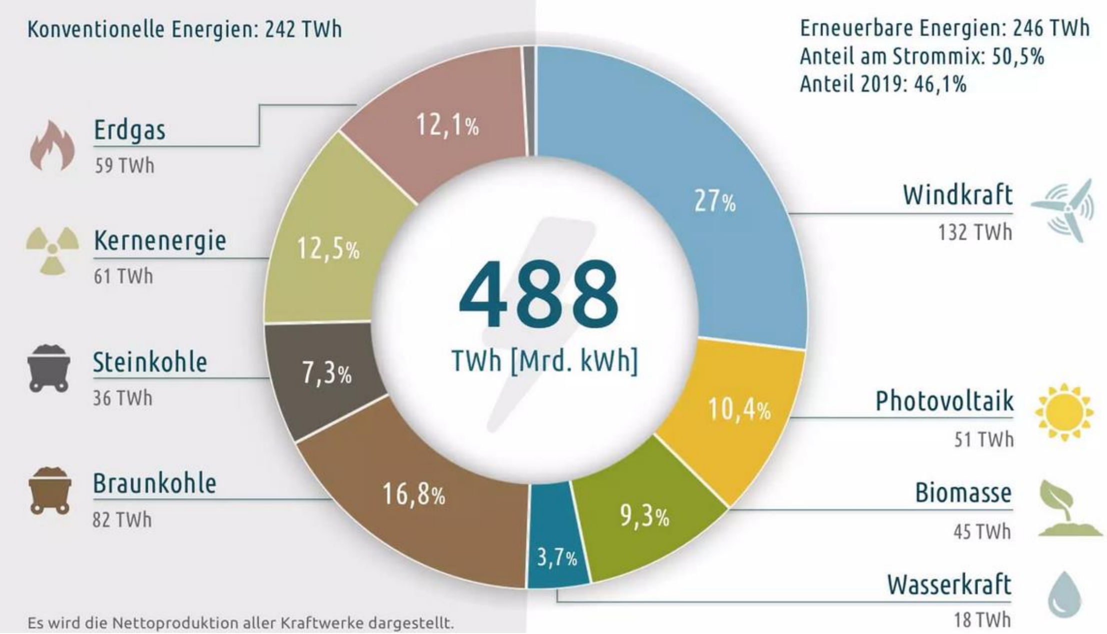
a look into Germany's **electricity mix...**



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→ **2.4 tCO_{2eq}** per person per year

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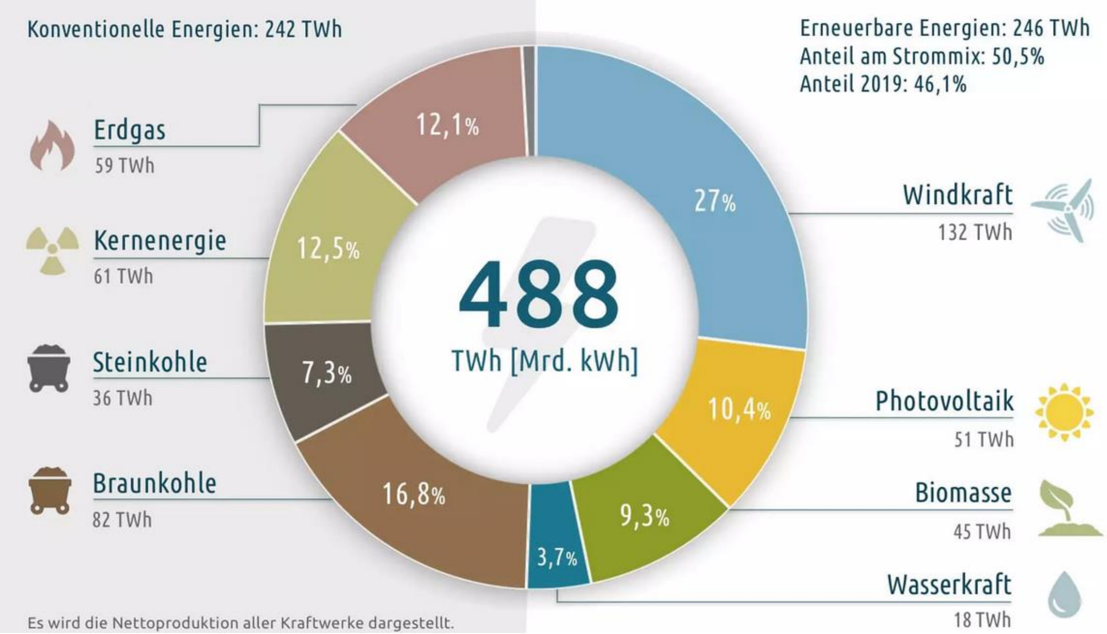

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Computer physical boundaries

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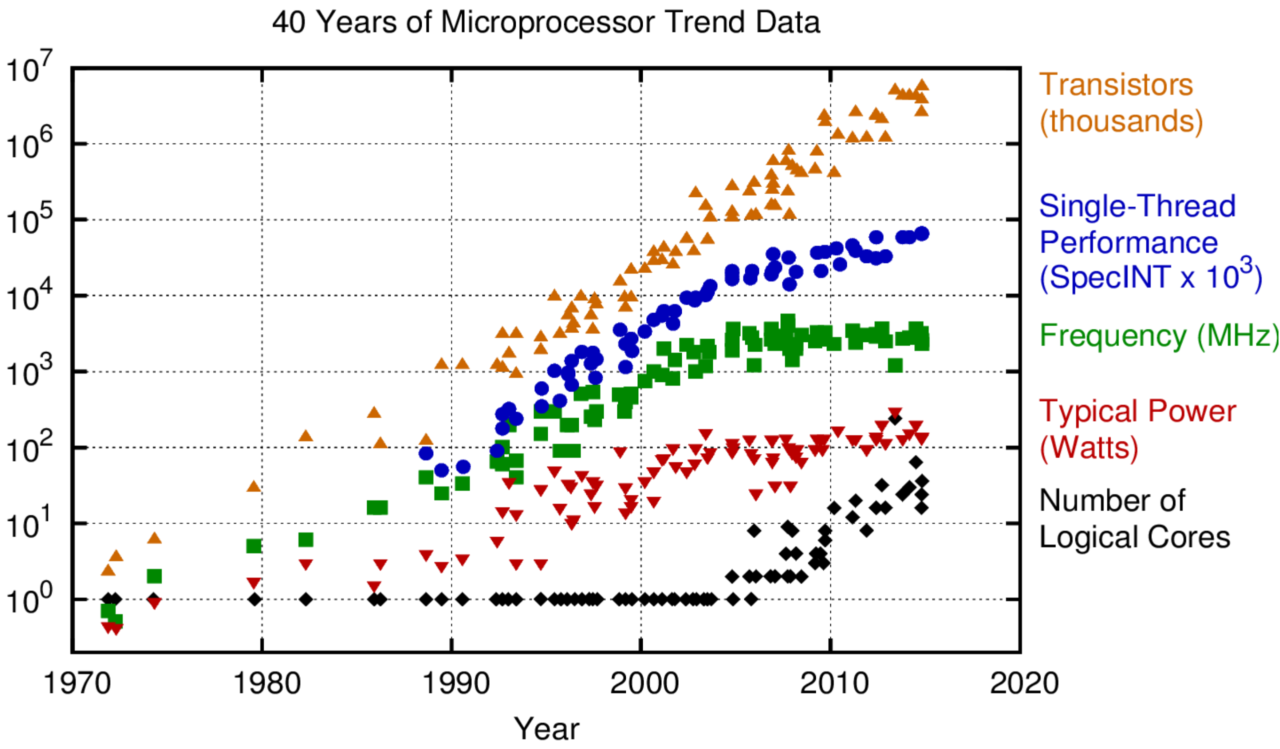
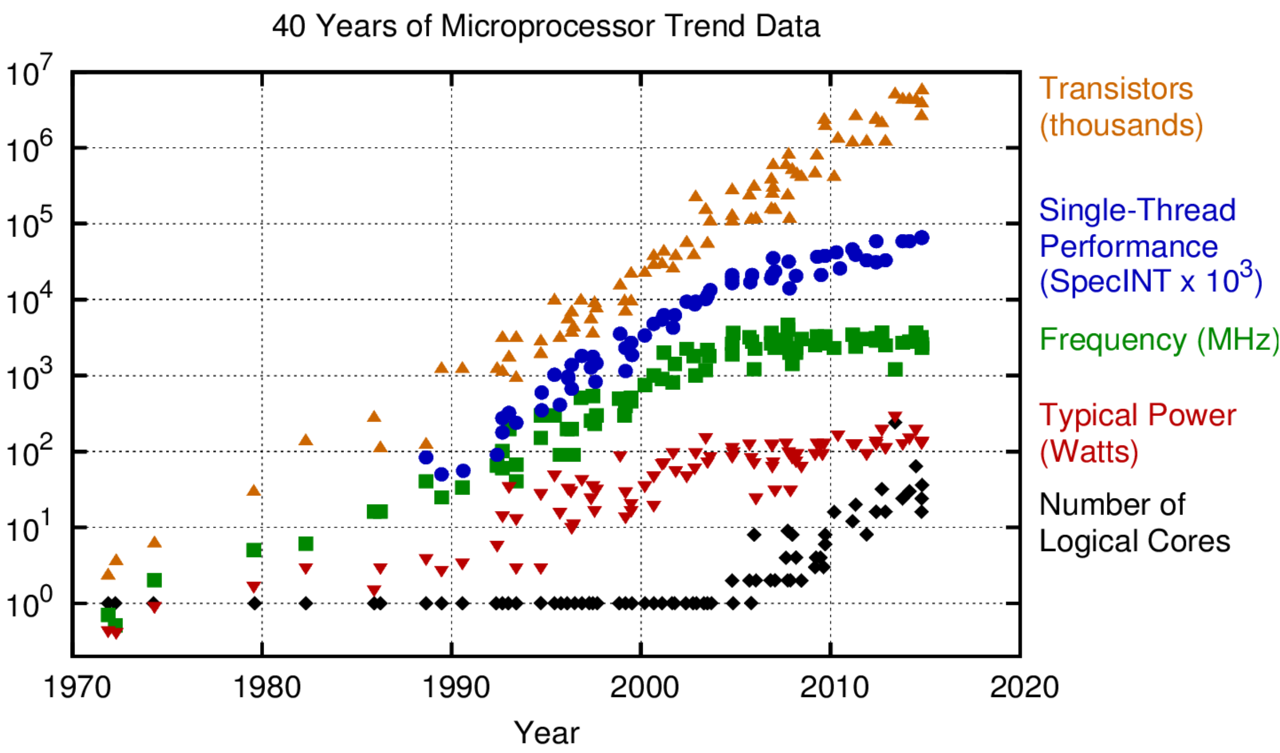


Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2015 by K. Rupp

Computer physical boundaries

- Frequency stalled
  - Heat dissipation
  - Leak current
  - nl power increase



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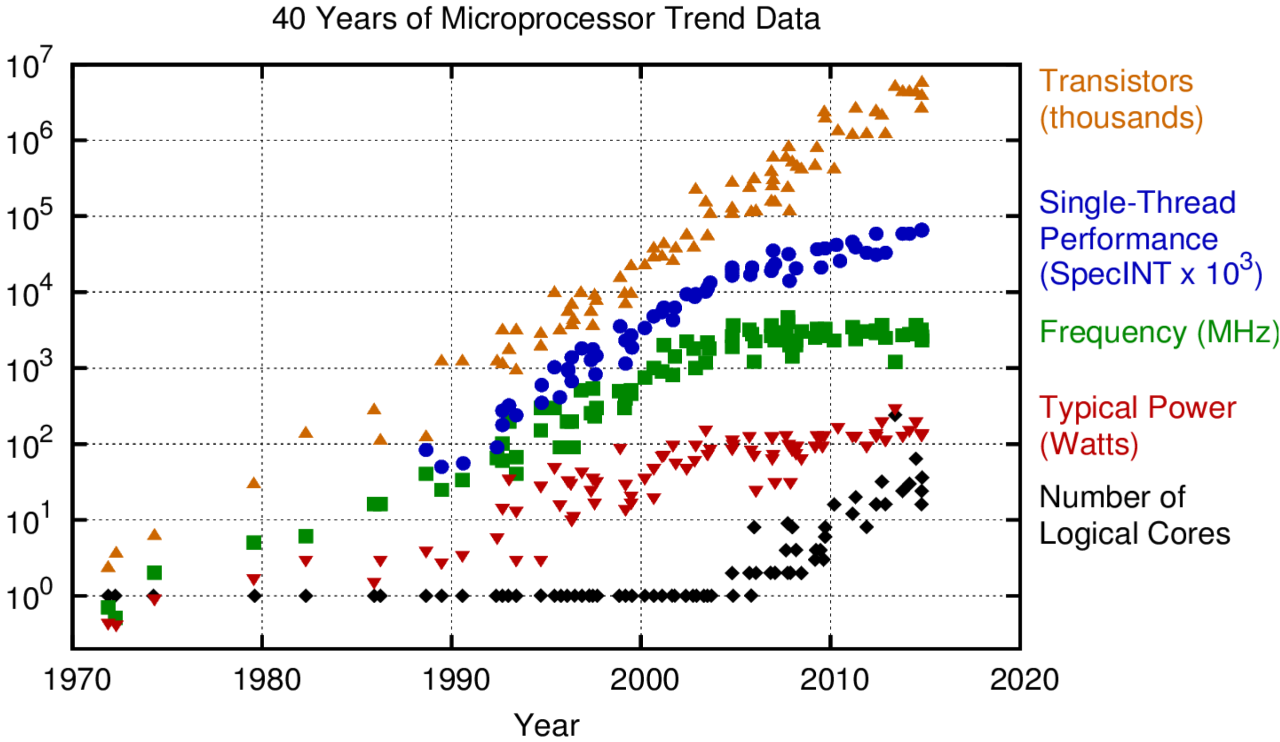

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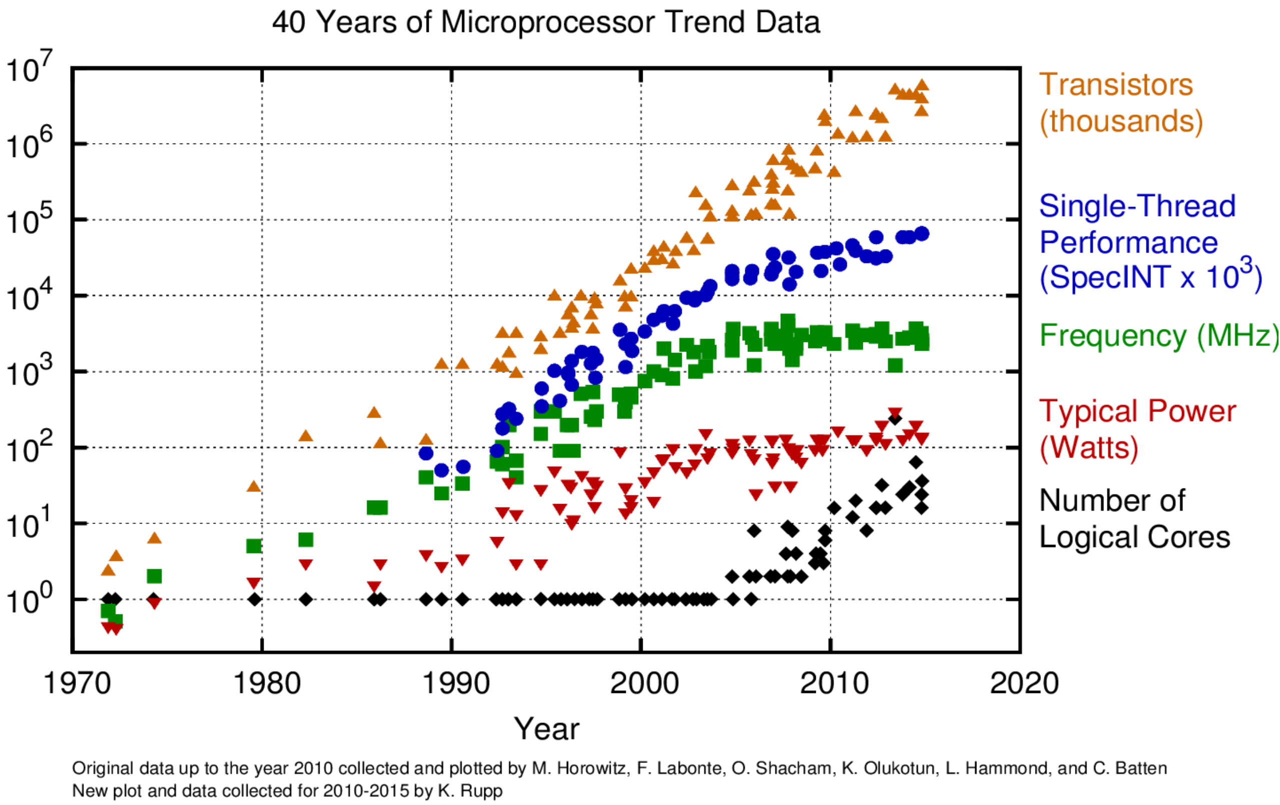

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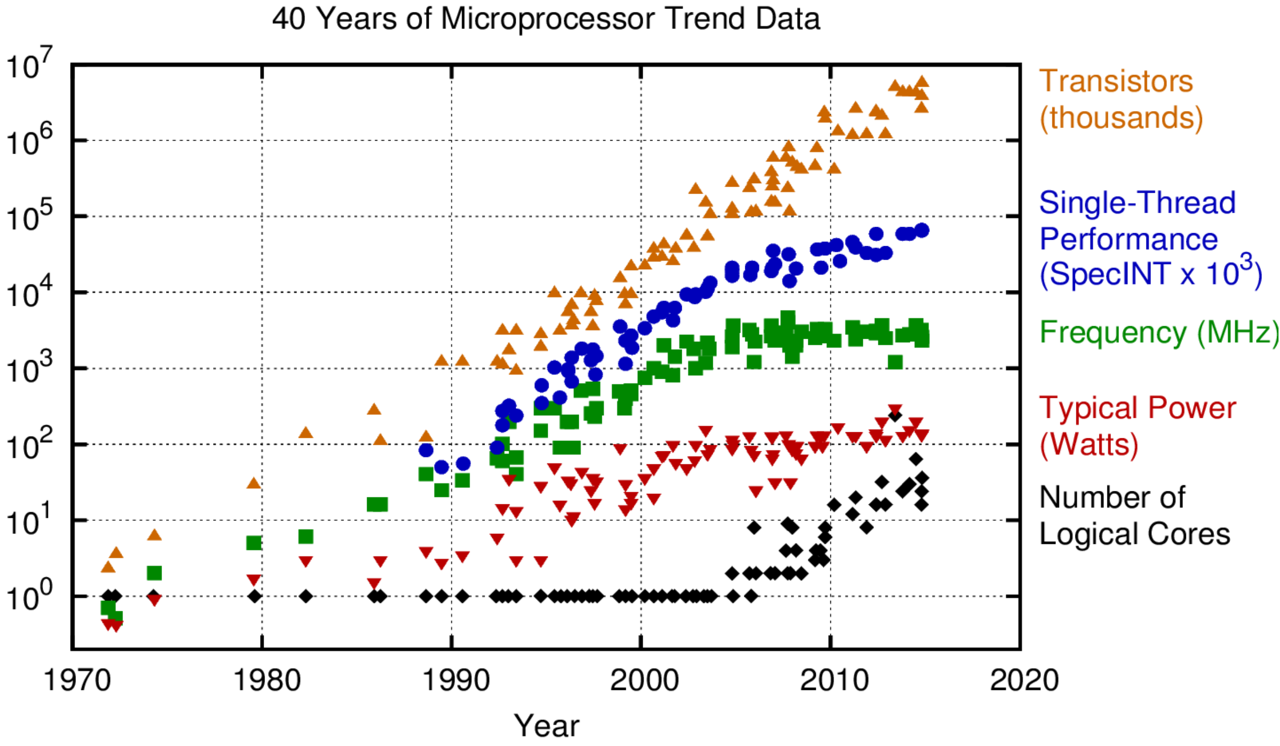
- CPUs more cores
- GPUs



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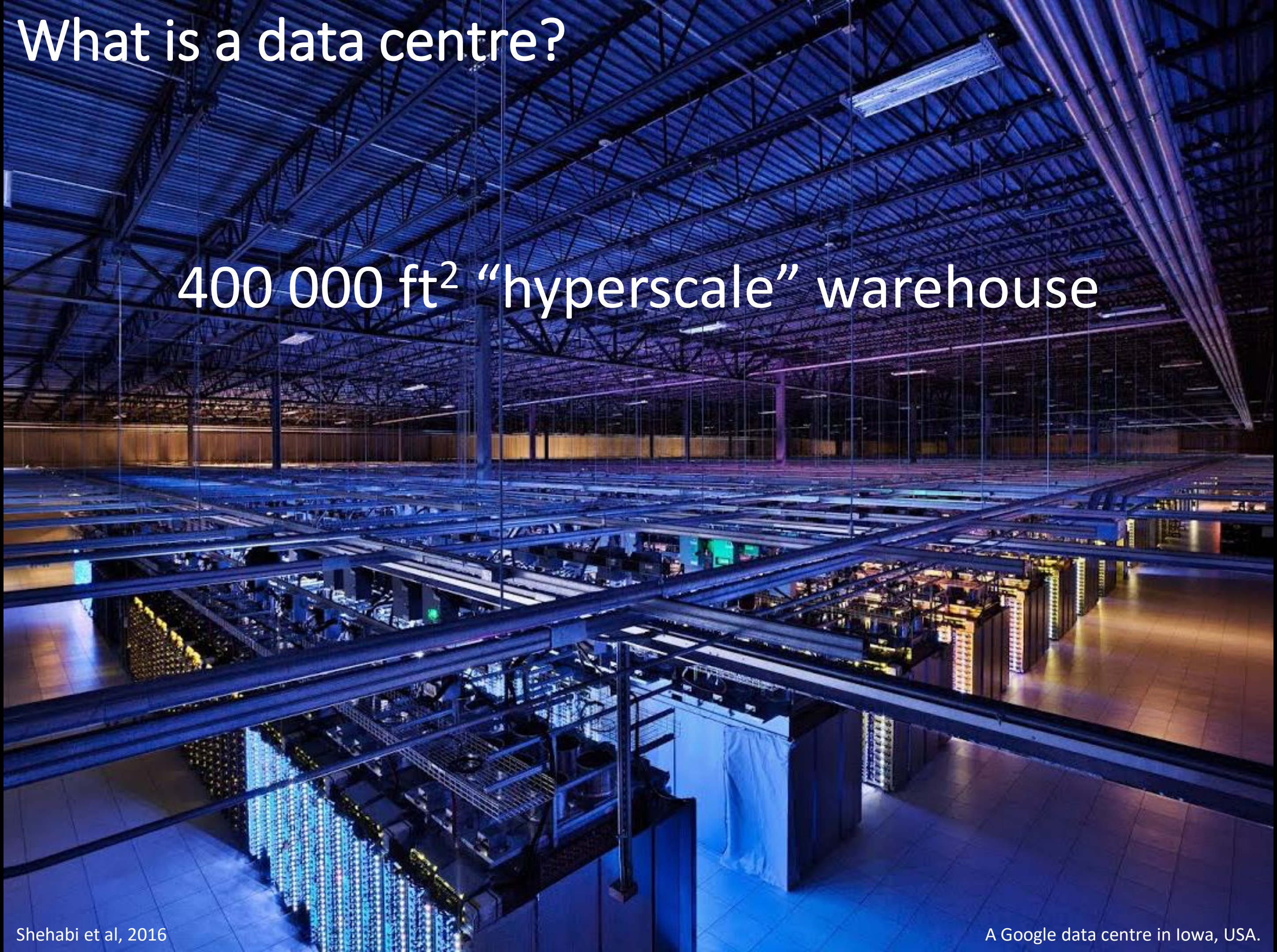
Data Centers energy consumption

copied from David Mytton (@davidmytton on twitter)

Energy (and water) consumption in IT

A Google data centre in Hamina, Finland.

What is a data centre?



Shehabi et al, 2016

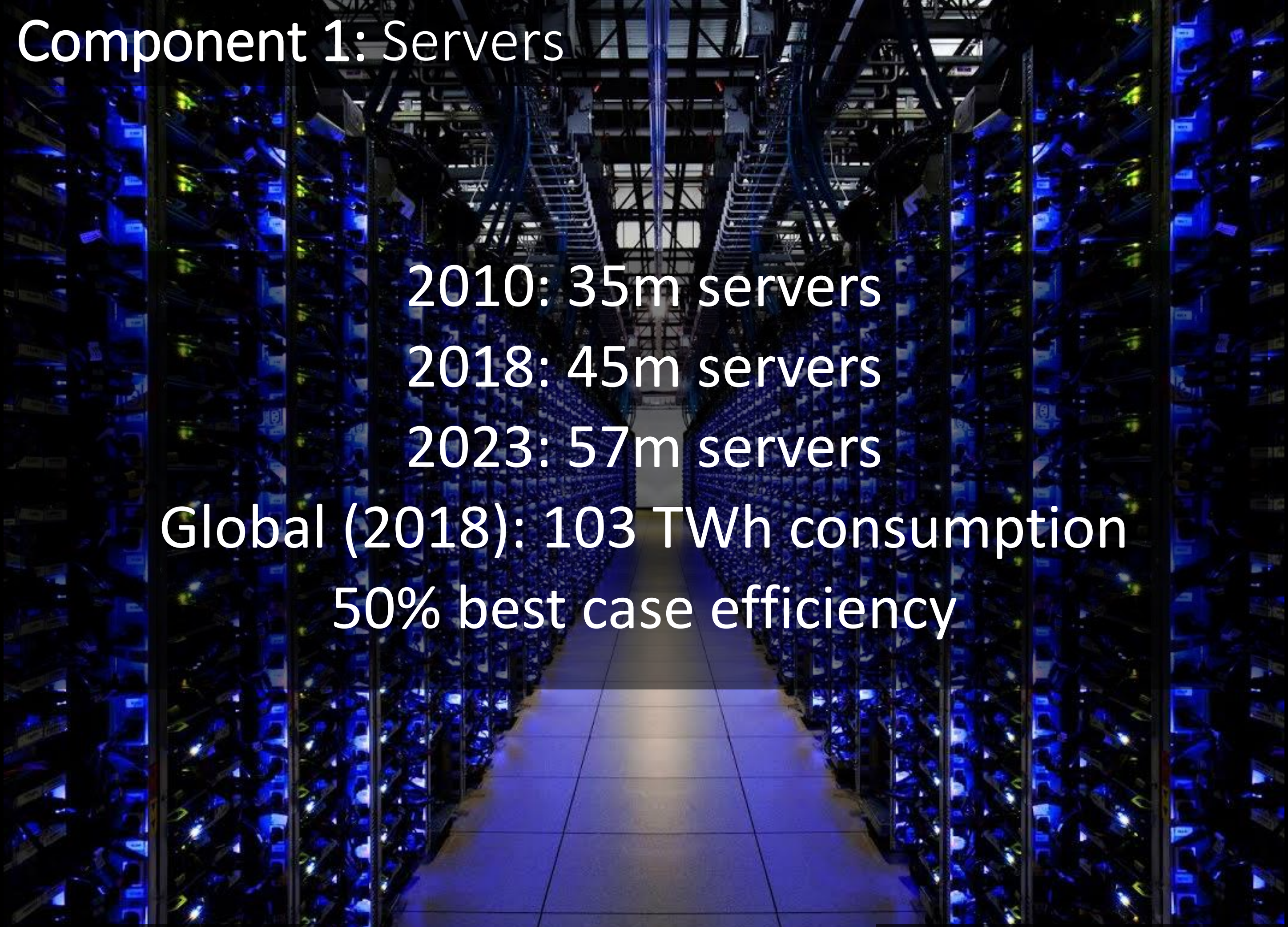
A Google data centre in Iowa, USA.

Data centre components

1. Servers
2. Storage
3. Network
4. Infrastructure

A Google data centre in Oregon, USA.

Component 1: Servers



2010: 35m servers

2018: 45m servers

2023: 57m servers

Global (2018): 103 TWh consumption

50% best case efficiency

Shehabi (2016), Masanet et al (2020)

Google servers in a data centre in Georgia, USA.

Component 2: Storage

Global (2018): 1 043 EB across 227m drives

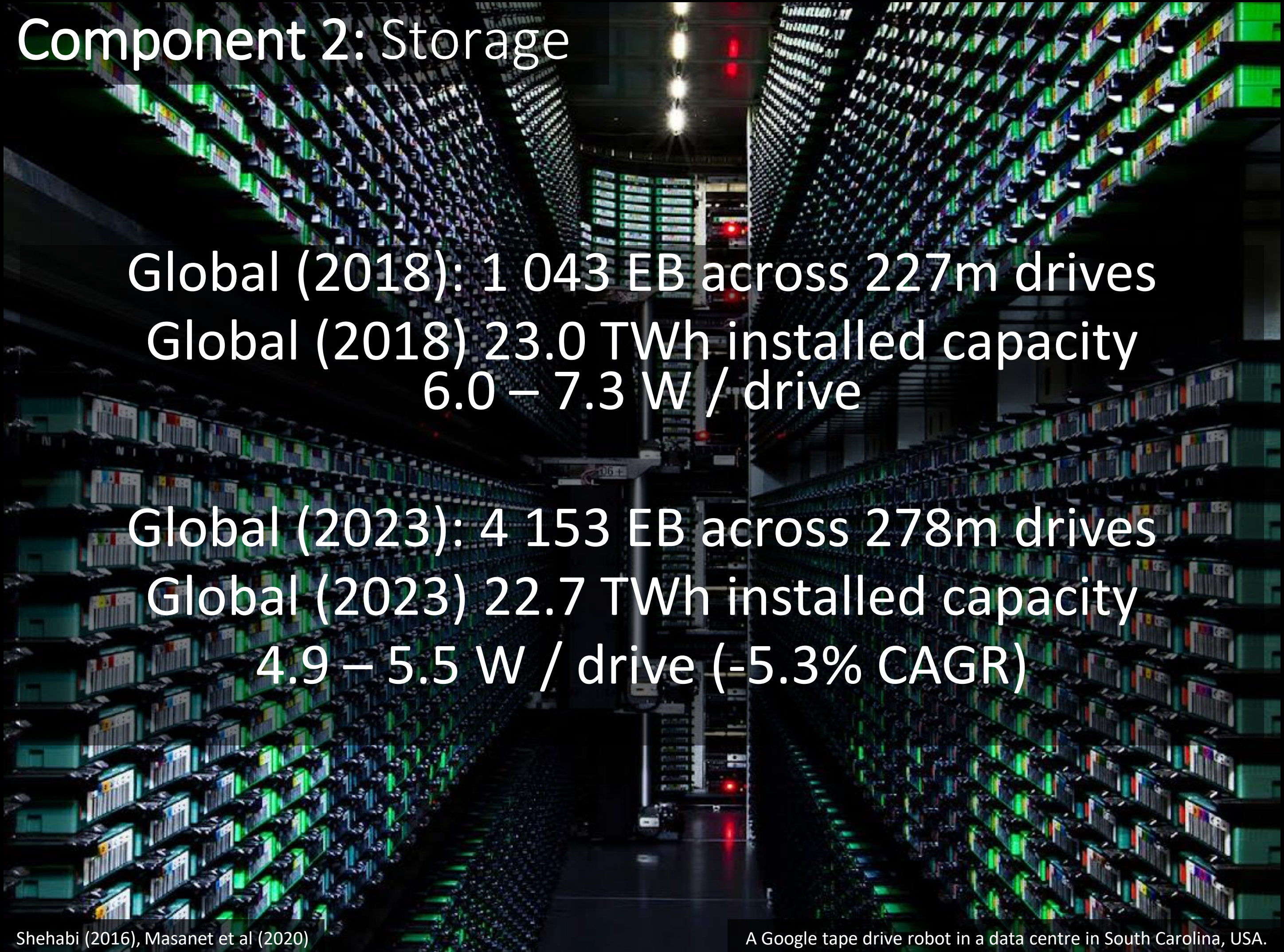
Global (2018) 23.0 TWh installed capacity

6.0 – 7.3 W / drive

Global (2023): 4 153 EB across 278m drives

Global (2023) 22.7 TWh installed capacity

4.9 – 5.5 W / drive (-5.3% CAGR)

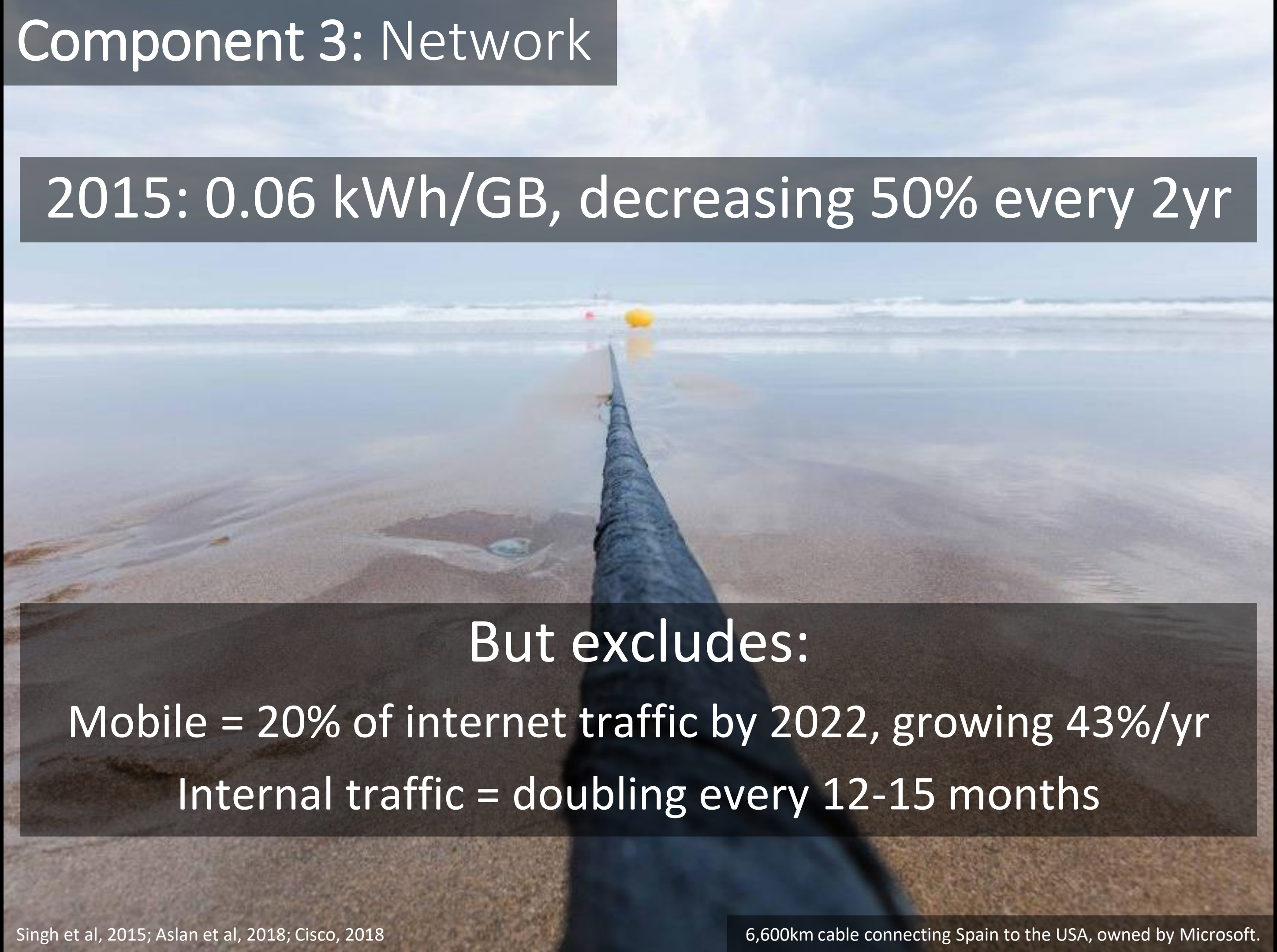


Shehabi (2016), Masanet et al (2020)

A Google tape drive robot in a data centre in South Carolina, USA.

Component 3: Network

2015: 0.06 kWh/GB, decreasing 50% every 2yr



But excludes:

Mobile = 20% of internet traffic by 2022, growing 43%/yr

Internal traffic = doubling every 12-15 months

Singh et al, 2015; Aslan et al, 2018; Cisco, 2018

6,600km cable connecting Spain to the USA, owned by Microsoft.

Component 4: Infrastructure

Power Usage Effectiveness

$$PUE = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy} = 1 + \frac{Non\ Facility\ Energy}{IT\ Equipment\ Energy}$$

A Google data centre in Hamina, Finland.

GHG Protocol, 2017; Uptime Institute, 2019

Component 4: Infrastructure

Power Usage Effectiveness

$$PUE = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy} = 1 + \frac{Non\ Facility\ Energy}{IT\ Equipment\ Energy}$$

1.0 = 100% power to IT equipment

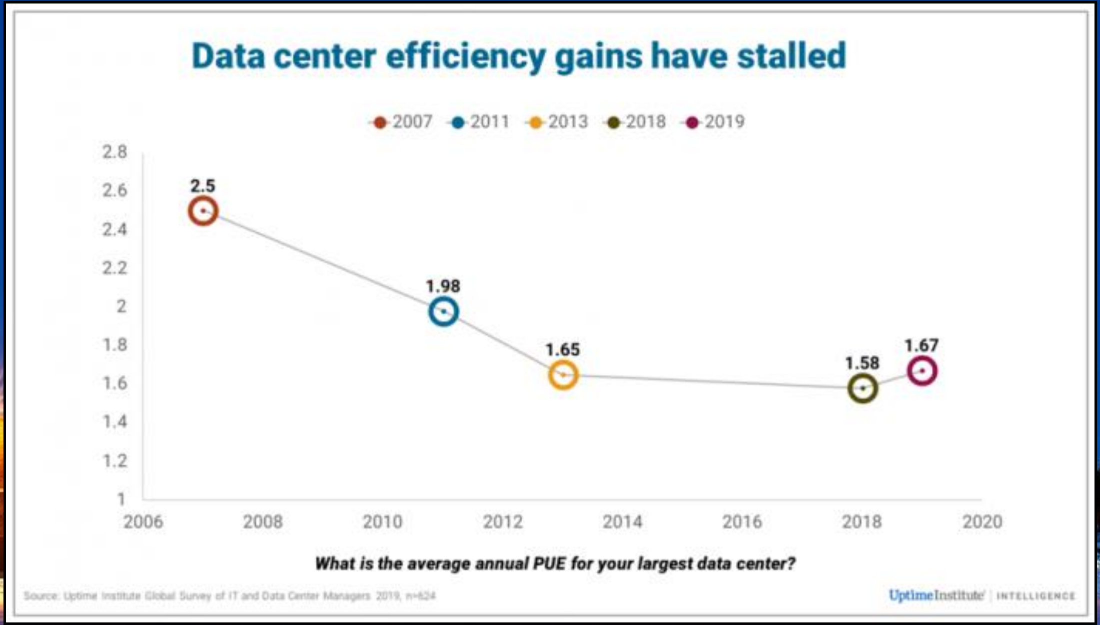
Industry average: 1.67

Brady et al, 2013; Shehabi et al, 2016; Uptime Institute, 2019

A Google data centre in Hamina, Finland.

Component 4: Infrastructure

Power Usage Effectiveness
(Industry wide)

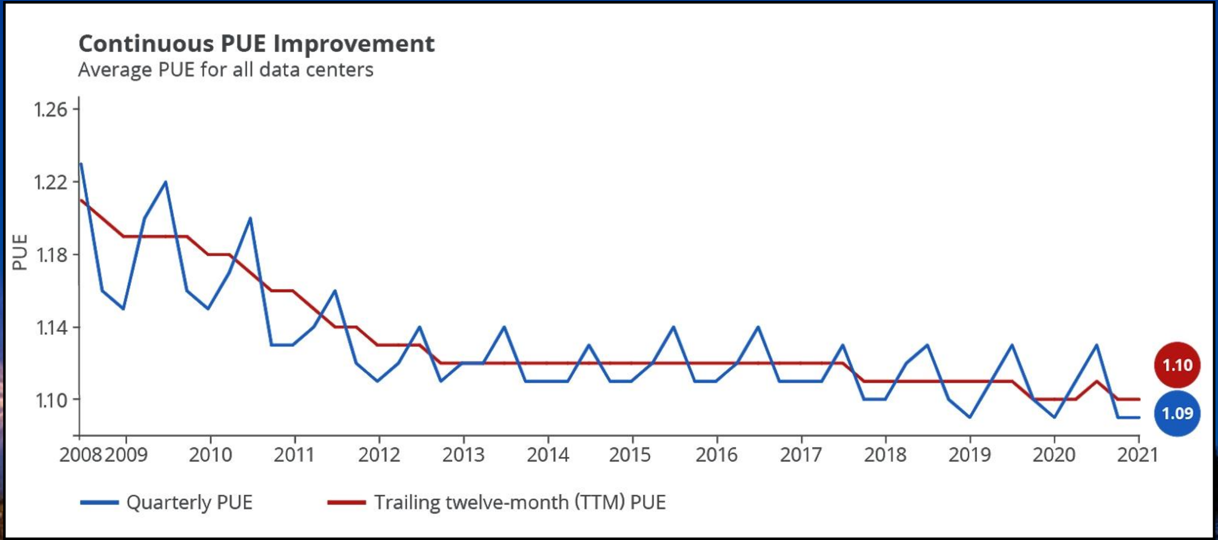


Uptime Institute, 2019

A Google data centre in Hamina, Finland.

Component 4: Infrastructure

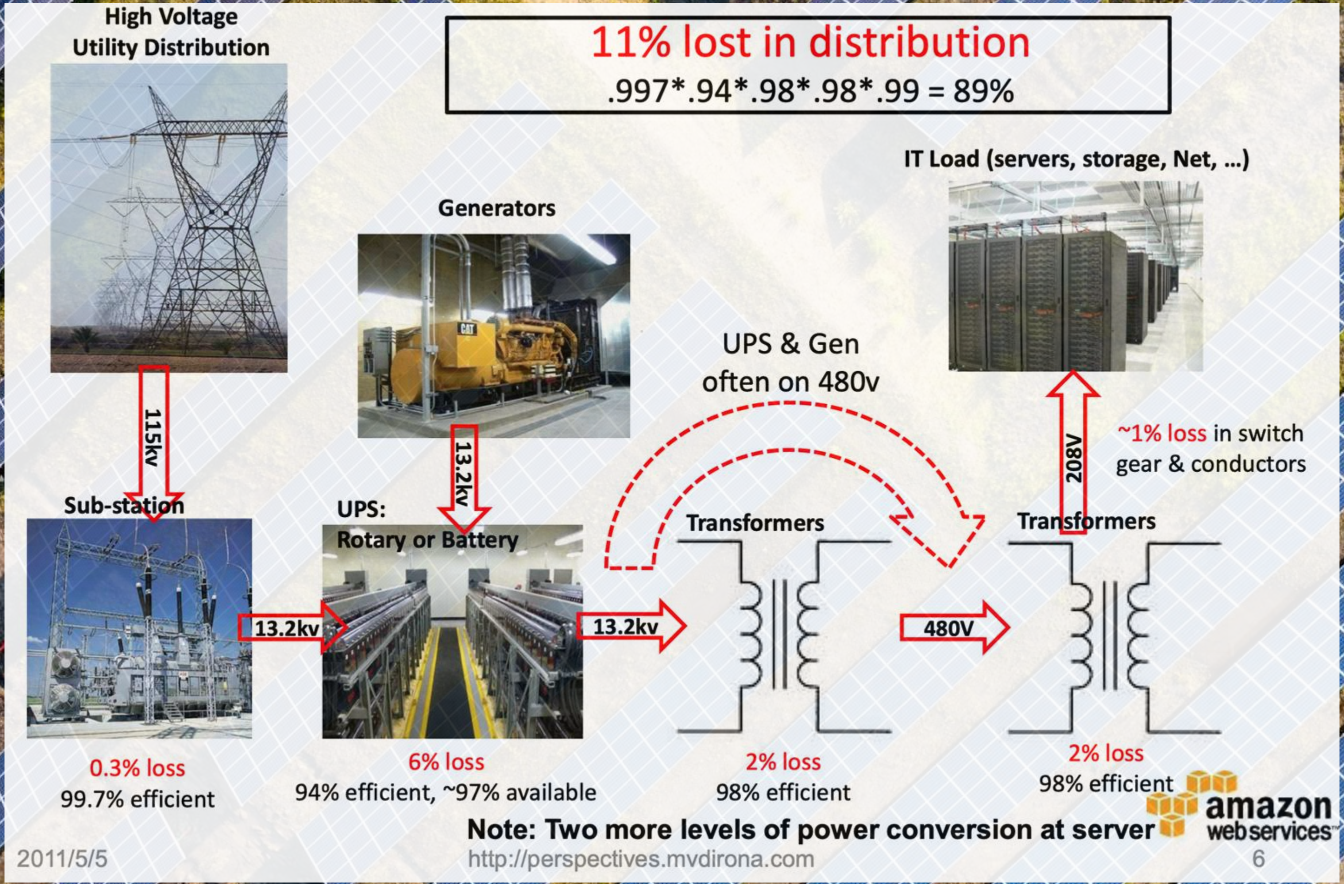
Power Usage Effectiveness
(Google)



Google (2021)

A Google data centre in Hamina, Finland.

Power distribution

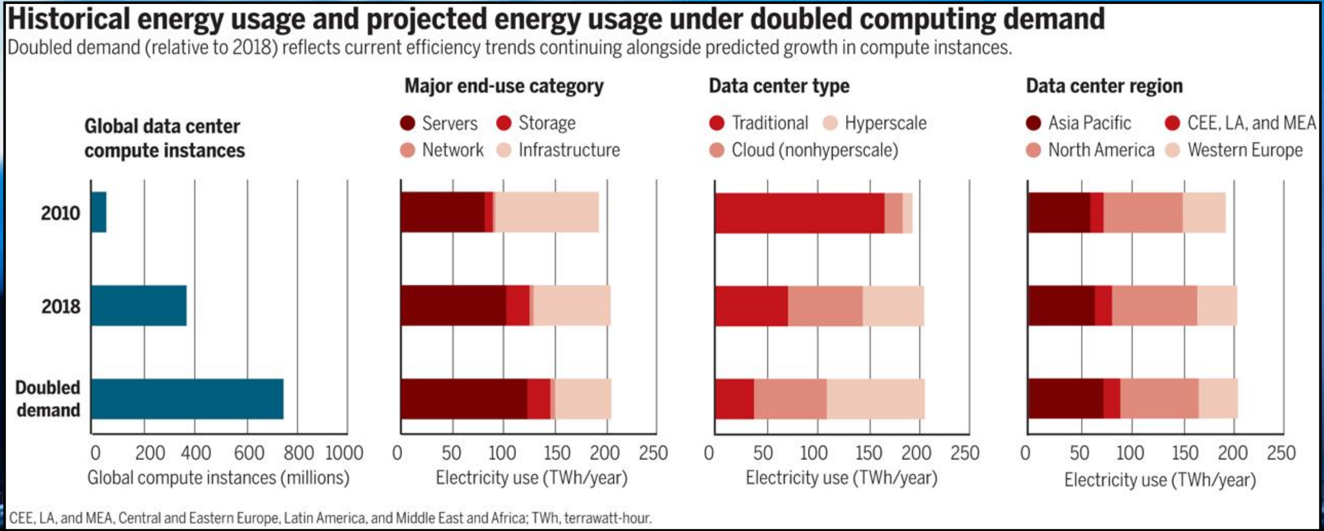


Hamilton, 2011

Solar panels, part of a Google data centre in St. Ghislain, Belgium.

How much energy? Position 1

2018 = 200 TWh/year & growth has plateaued

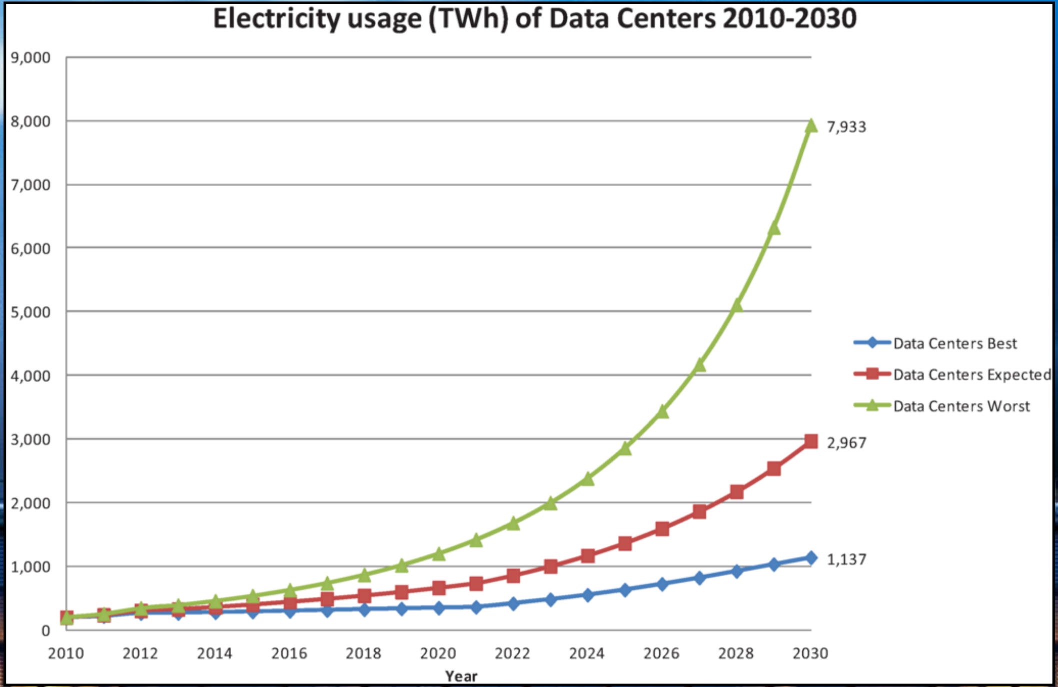


Masanet et al (2020)

A Google data centre in Oregon, USA.

How much energy? Position 2

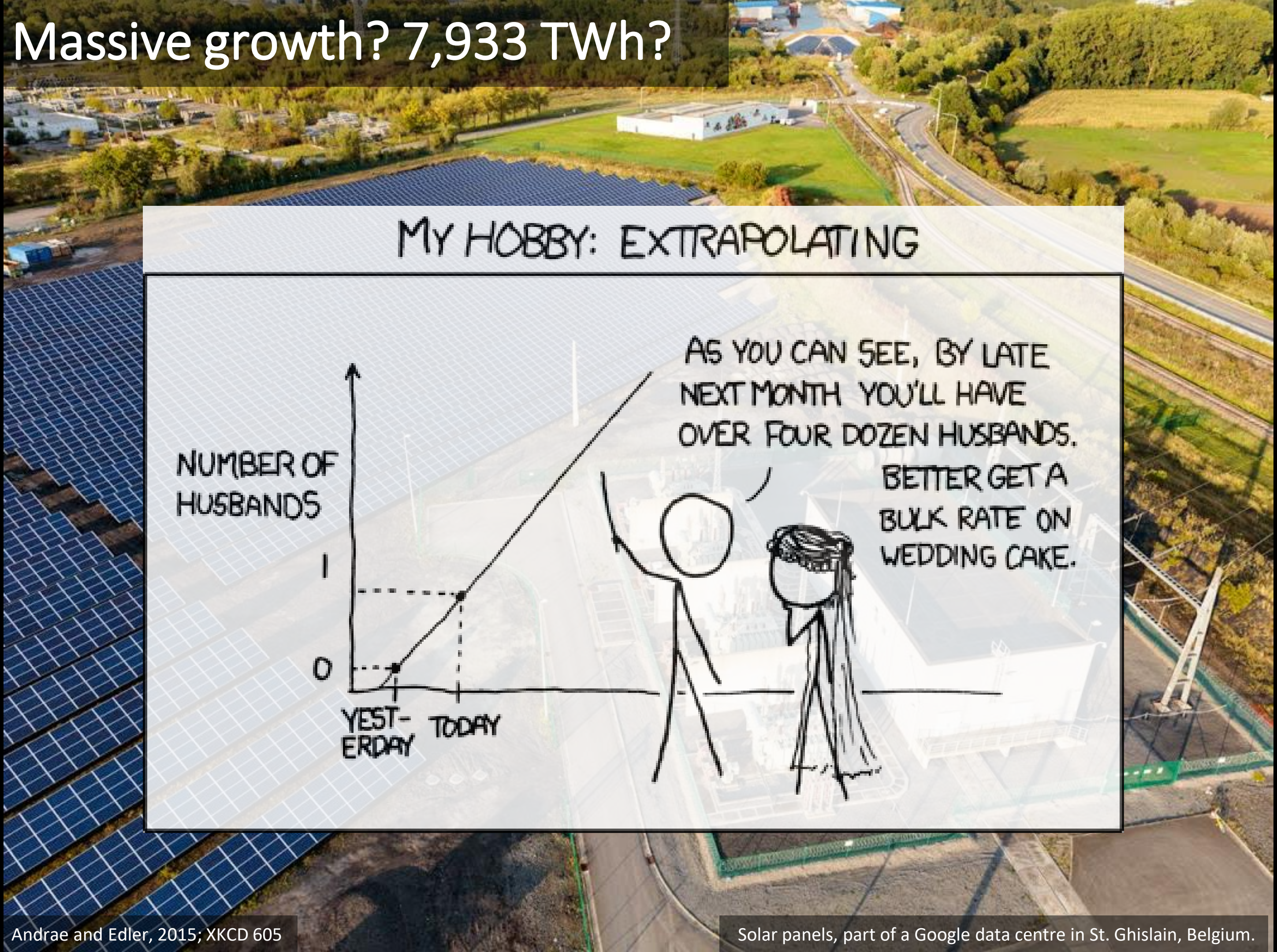
2018 = 600 TWh/year & growth is massive



Andrae & Edler (2015)

A Google data centre in Oregon, USA.

Massive growth? 7,933 TWh?



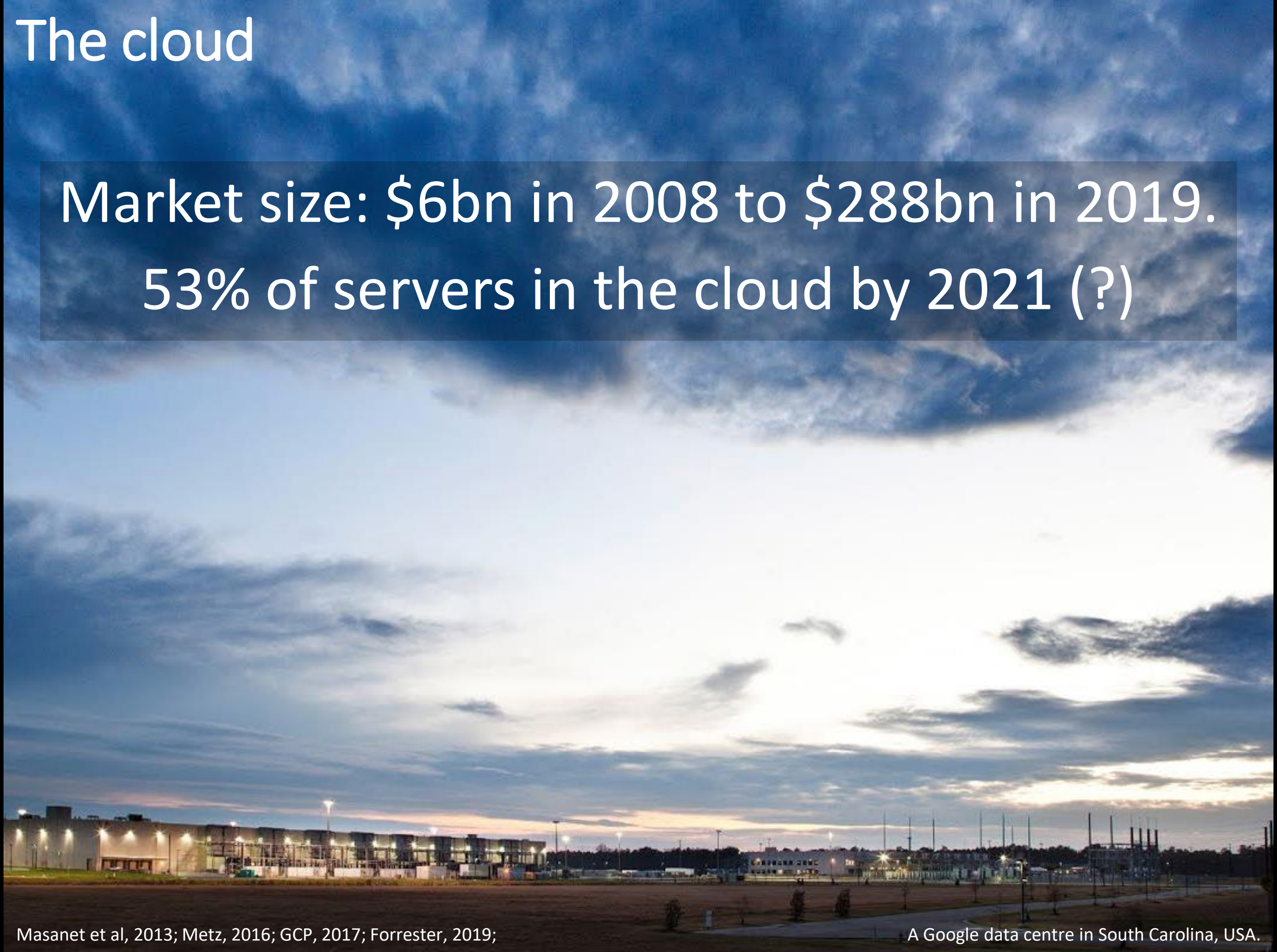
Andrae and Edler, 2015; XKCD 605

Solar panels, part of a Google data centre in St. Ghislain, Belgium.

The cloud

Market size: $6bn in 2008 to $288bn in 2019.

53% of servers in the cloud by 2021 (?)



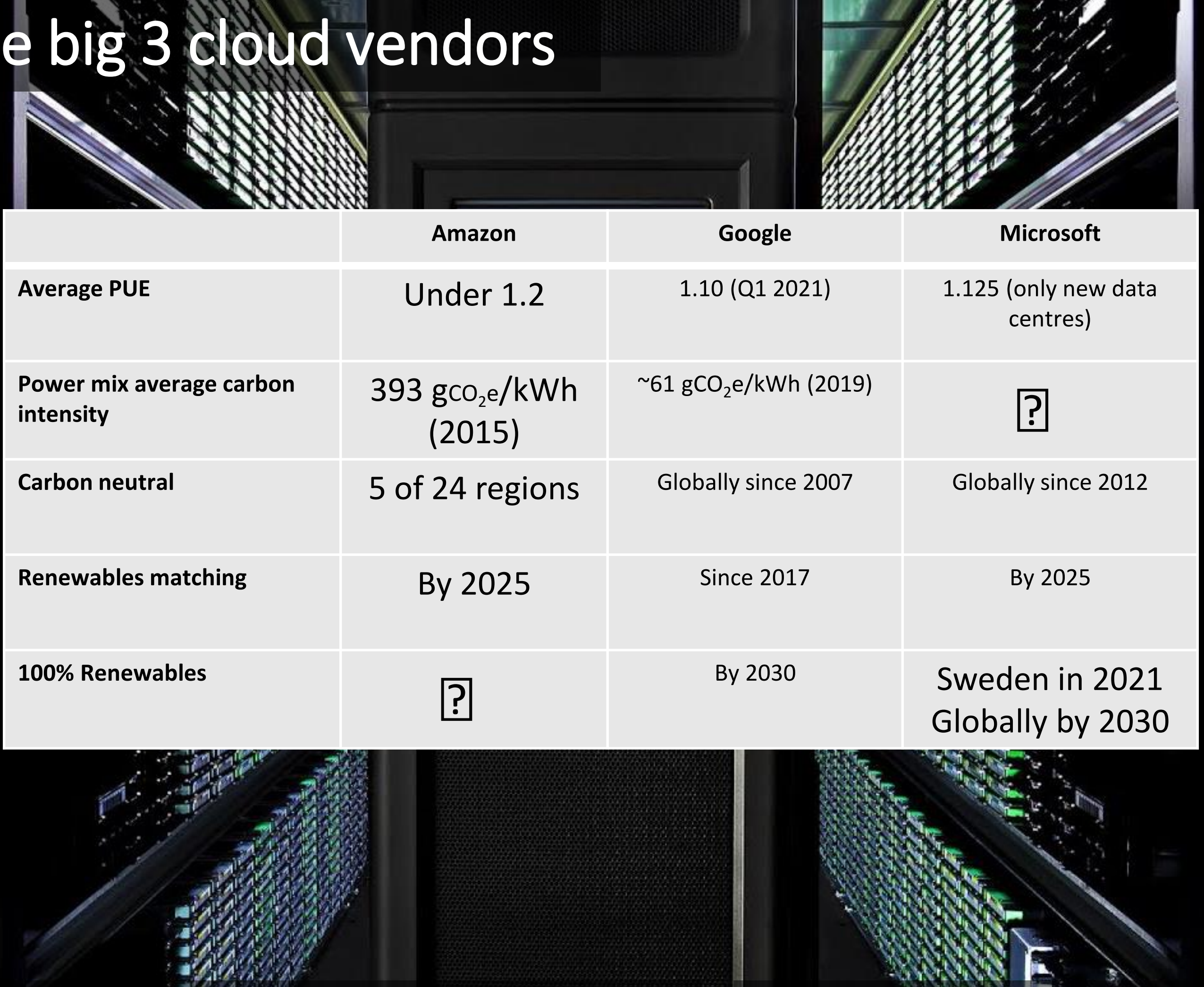
Masanet et al, 2013; Metz, 2016; GCP, 2017; Forrester, 2019;

A Google data centre in South Carolina, USA.

The big 3 cloud vendors

	Amazon	Google	Microsoft
Average PUE	Under 1.2	1.10 (Q1 2021)	1.125 (only new data centres)
Power mix average carbon intensity	393 gCO_2e/kWh (2015)	~61 gCO_2e/kWh (2019)	?
Carbon neutral	5 of 24 regions	Globally since 2007	Globally since 2012
Renewables matching	By 2025	Since 2017	By 2025
100% Renewables	?	By 2030	Sweden in 2021 Globally by 2030

Barr, 2015; Google, 2021; Kamiya and Kvarnström, 2019; Amazon, 2020; Microsoft, 2020

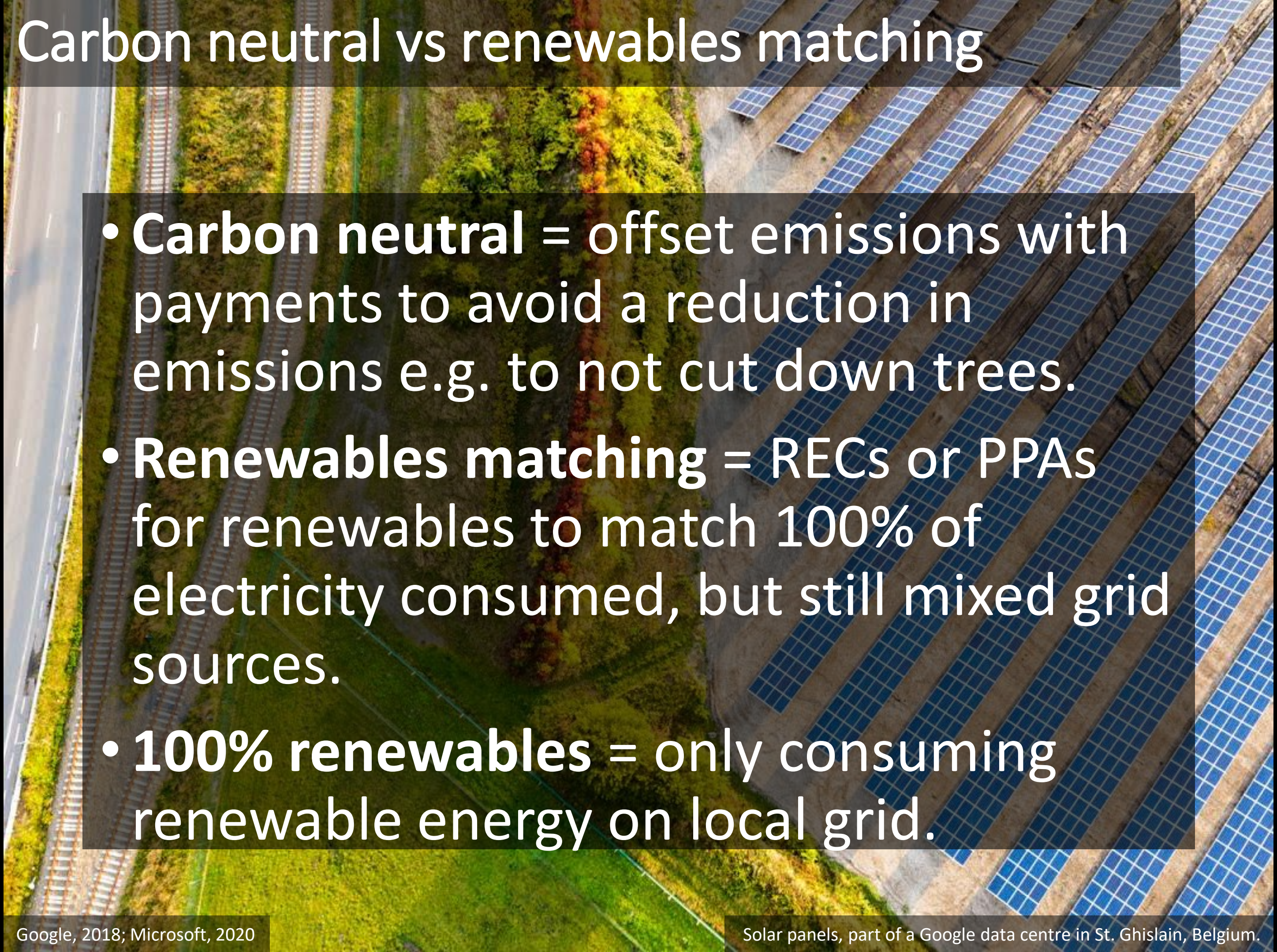


Backup tapes in a Google data centre in South Carolina, USA.

Carbon neutral vs renewables matching

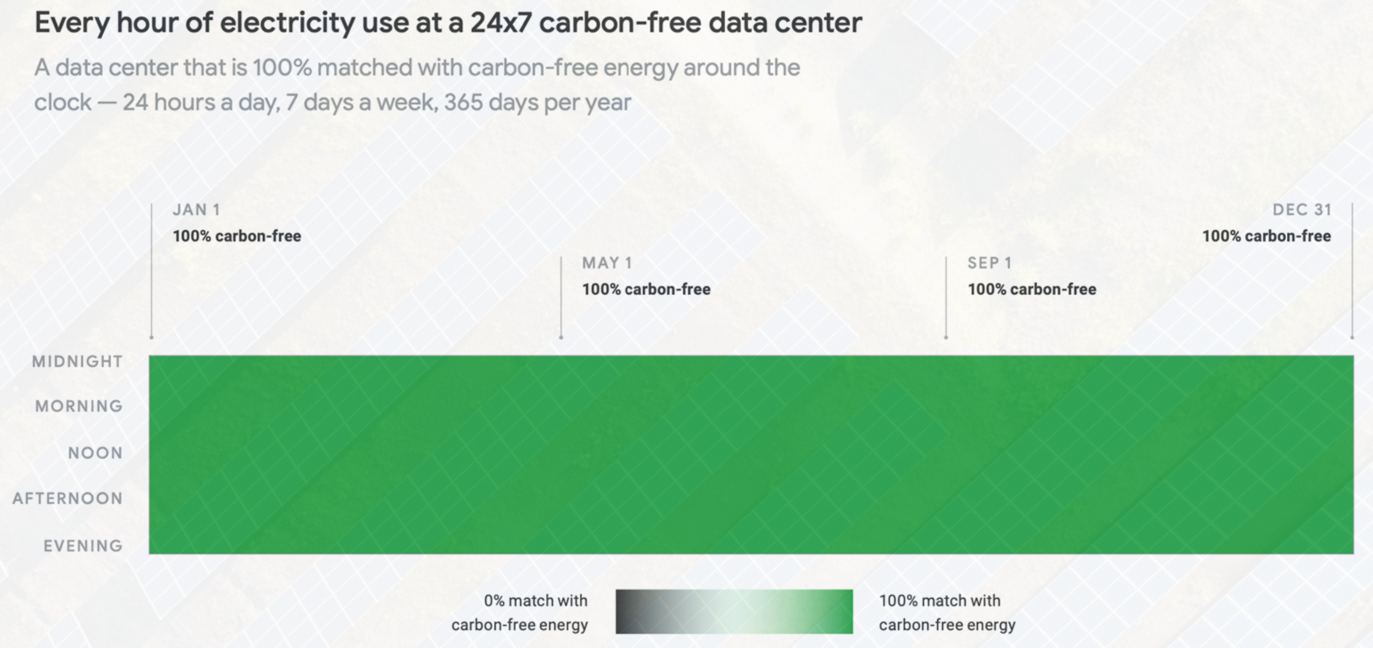
- **Carbon neutral** = offset emissions with payments to avoid a reduction in emissions e.g. to not cut down trees.
- **Renewables matching** = RECs or PPAs for renewables to match 100% of electricity consumed, but still mixed grid sources.
- **100% renewables** = only consuming renewable energy on local grid.

Google, 2018; Microsoft, 2020



Solar panels, part of a Google data centre in St. Ghislain, Belgium.

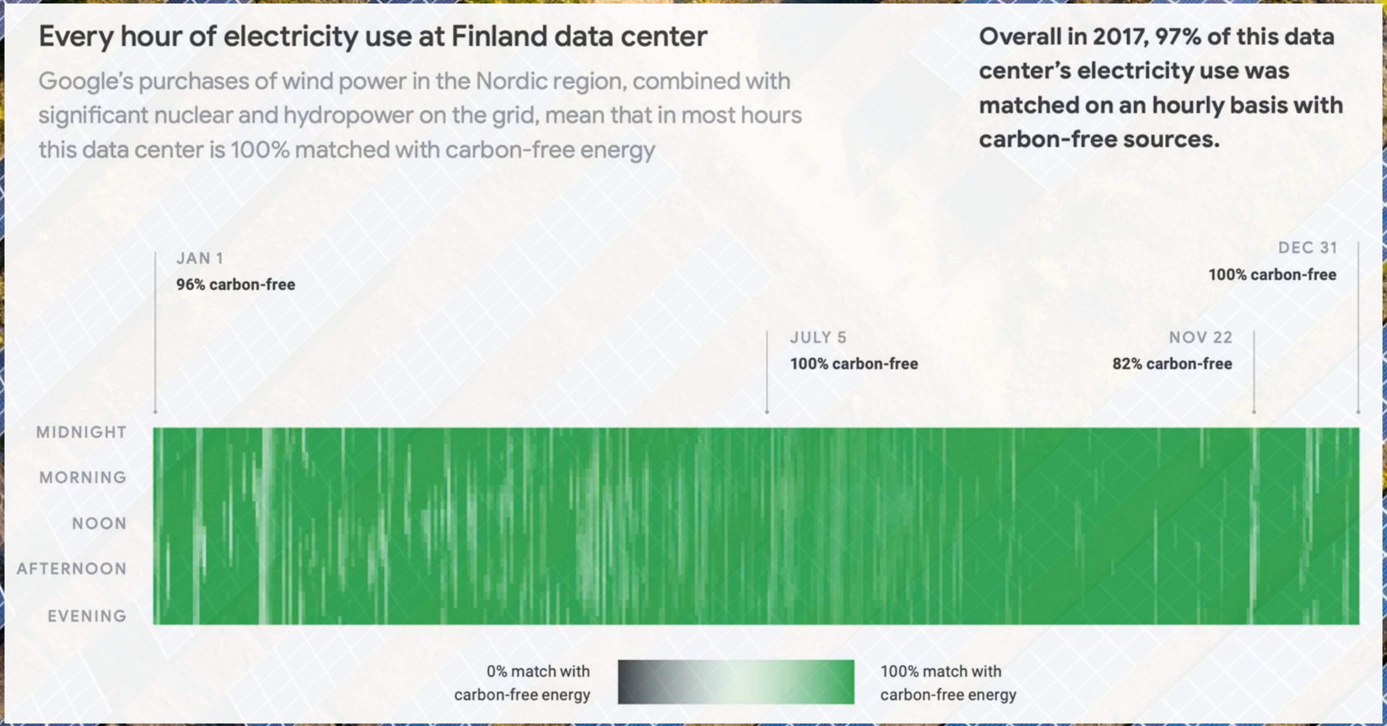
Carbon neutral vs renewables matching



Google, 2018

Solar panels, part of a Google data centre in St. Ghislain, Belgium.

Carbon neutral vs renewables matching



Google, 2018

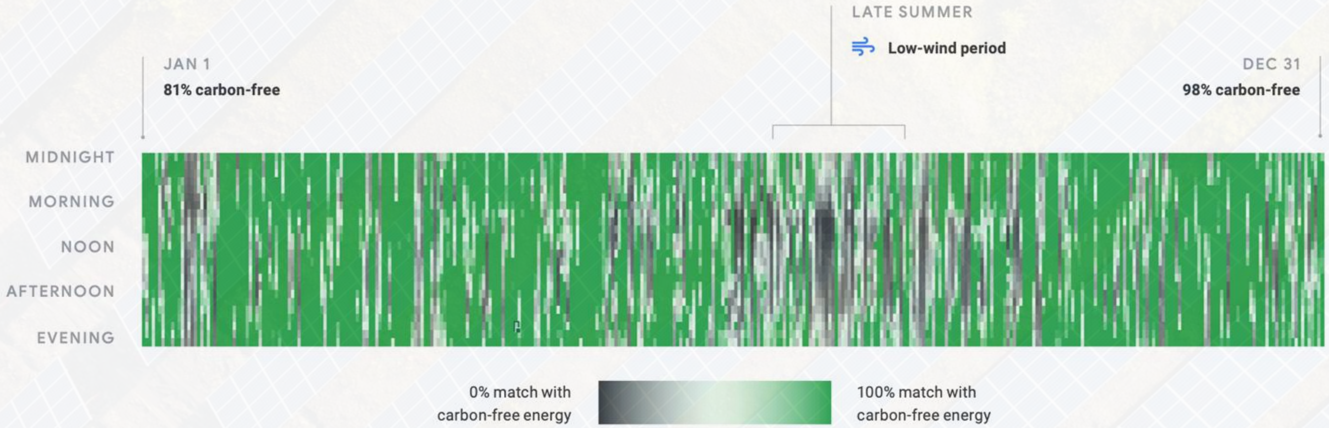
Solar panels, part of a Google data centre in St. Ghislain, Belgium.

Carbon neutral vs renewables matching

Every hour of electricity use at Iowa data center

Although our Iowa data center achieved 100% carbon-free energy during the majority of hours in 2017, there is also a recurring reliance on carbon-based power — most notably in late summer, when wind speeds decline.

Overall in 2017, 74% of this data center's electricity use was matched on an hourly basis with carbon-free sources.

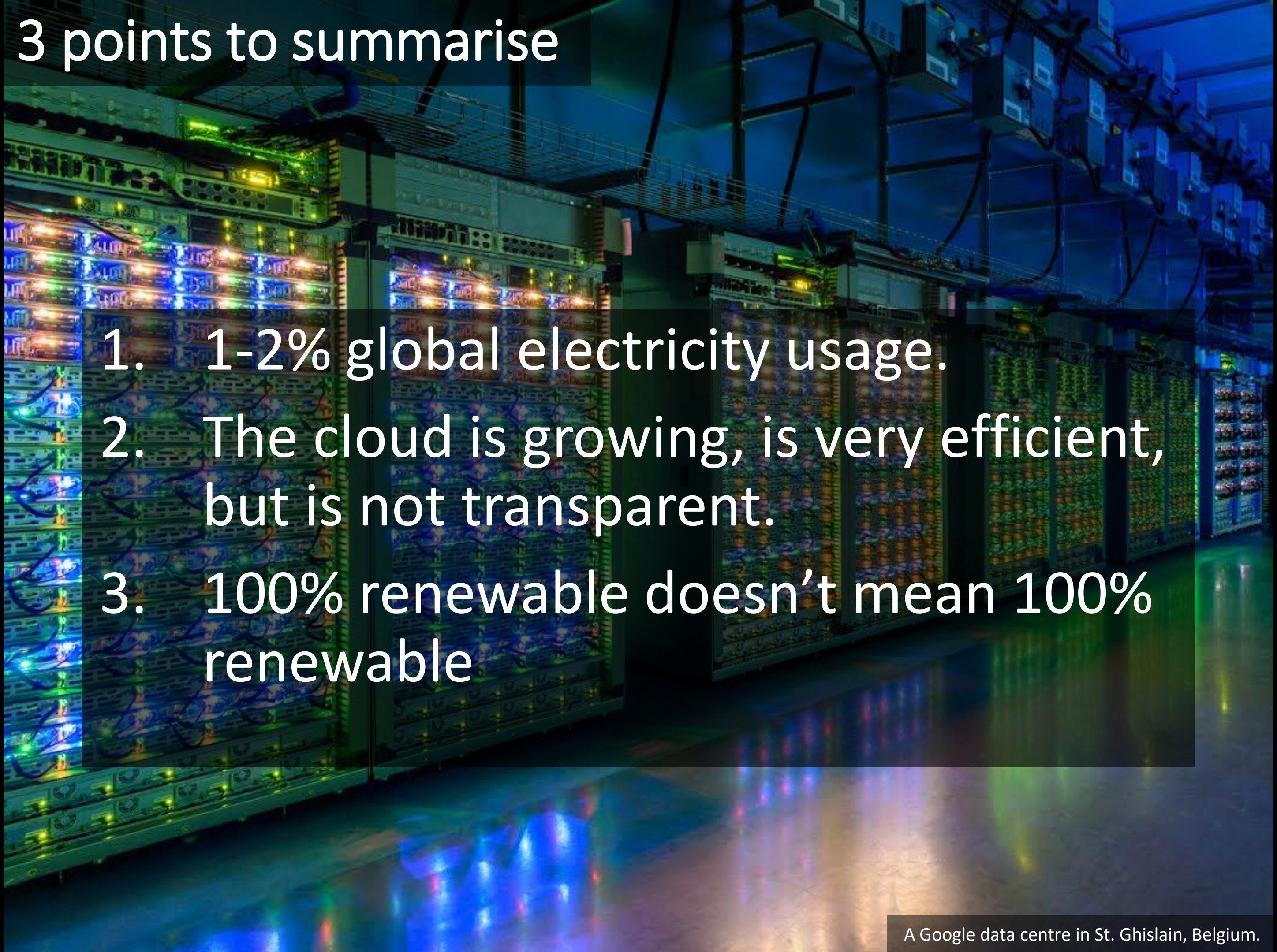


Google, 2018

Solar panels, part of a Google data centre in St. Ghislain, Belgium.

3 points to summarise

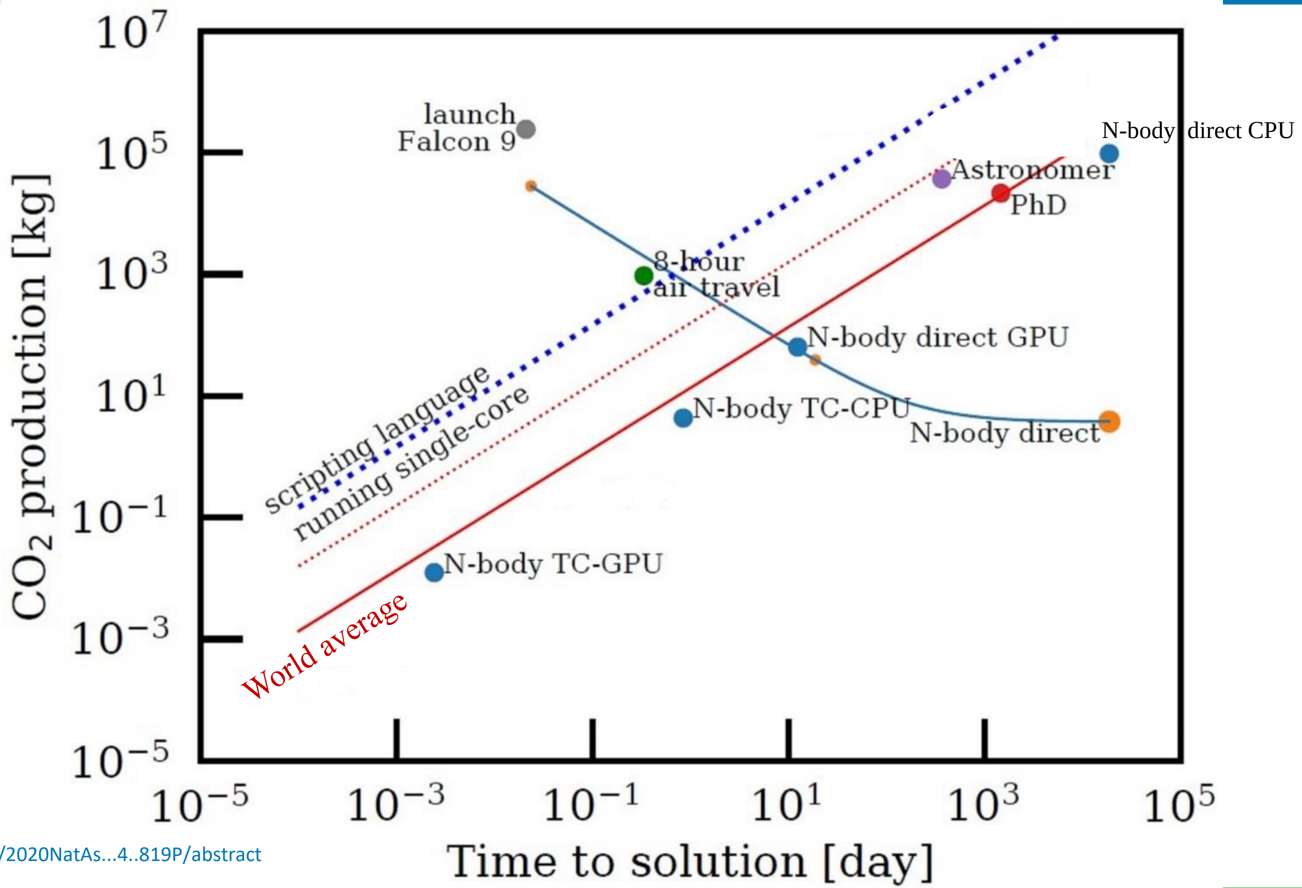
1. 1-2% global electricity usage.
2. The cloud is growing, is very efficient, but is not transparent.
3. 100% renewable doesn't mean 100% renewable



A Google data centre in St. Ghislain, Belgium.

Increasing computing efficiency

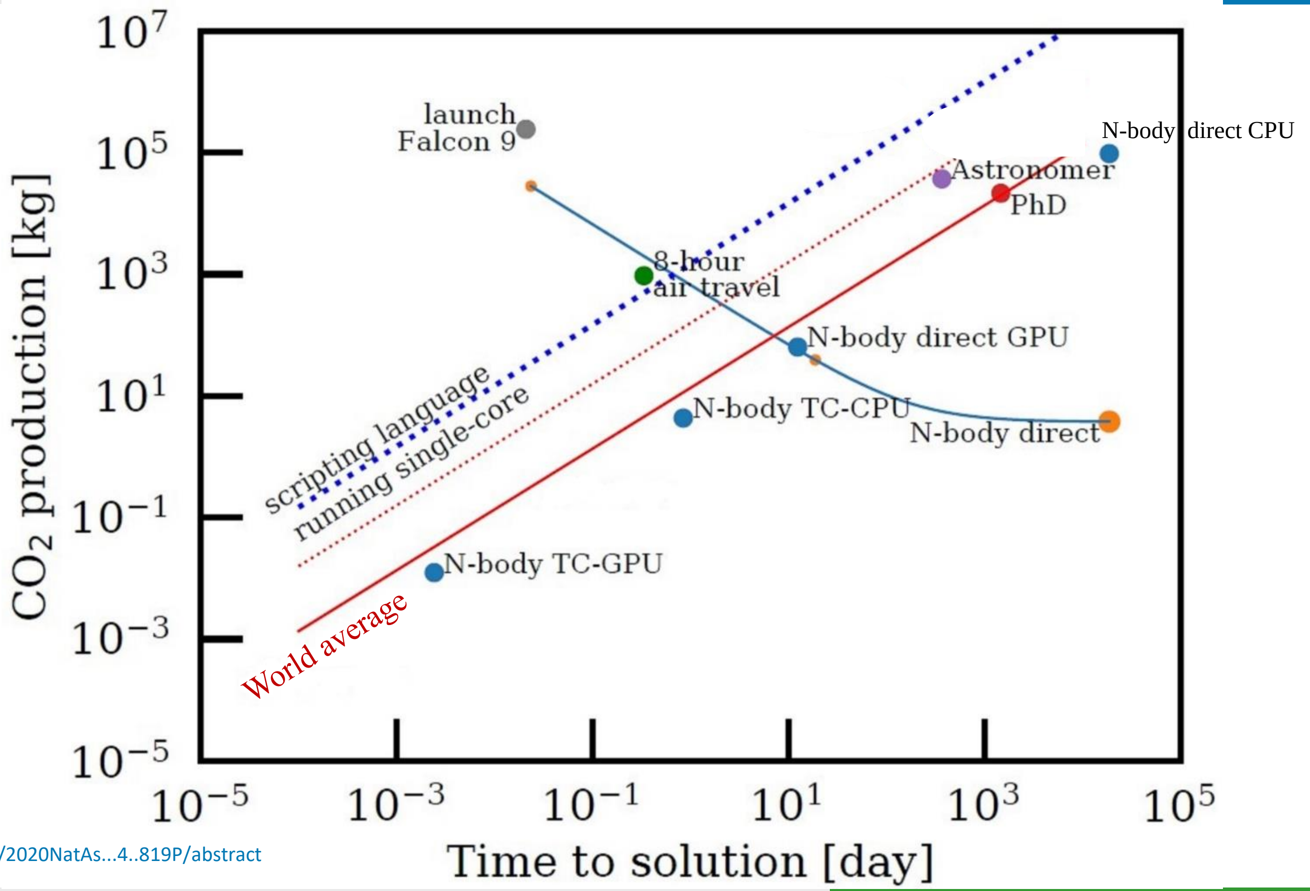
- Calculate wisely



Zwart, P. 2020, Nature Astronomy, https://ui.adsabs.harvard.edu/abs/2020NatAs...4..819P/abstract

Increasing computing efficiency

- Calculate wisely
- hardware



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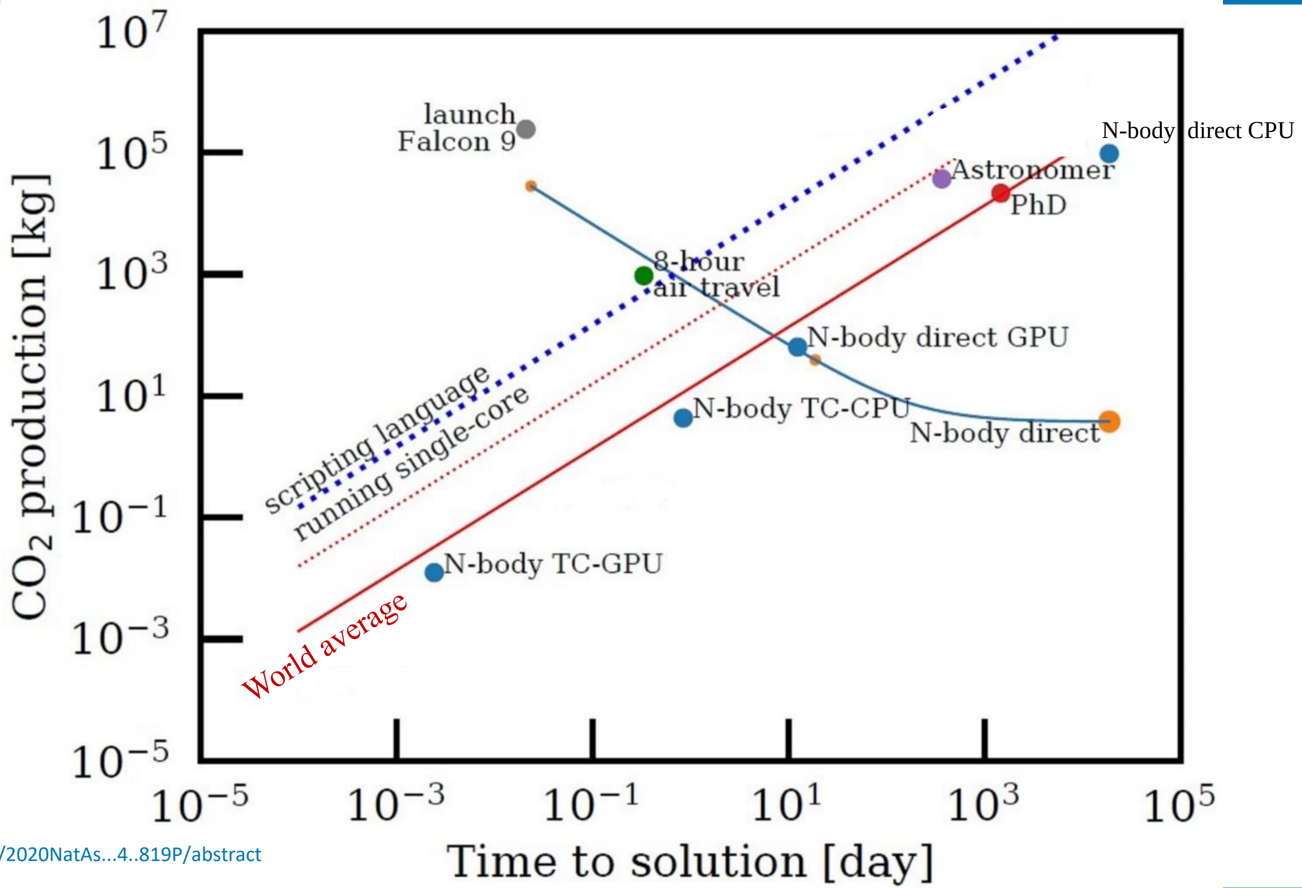
Increasing computing efficiency

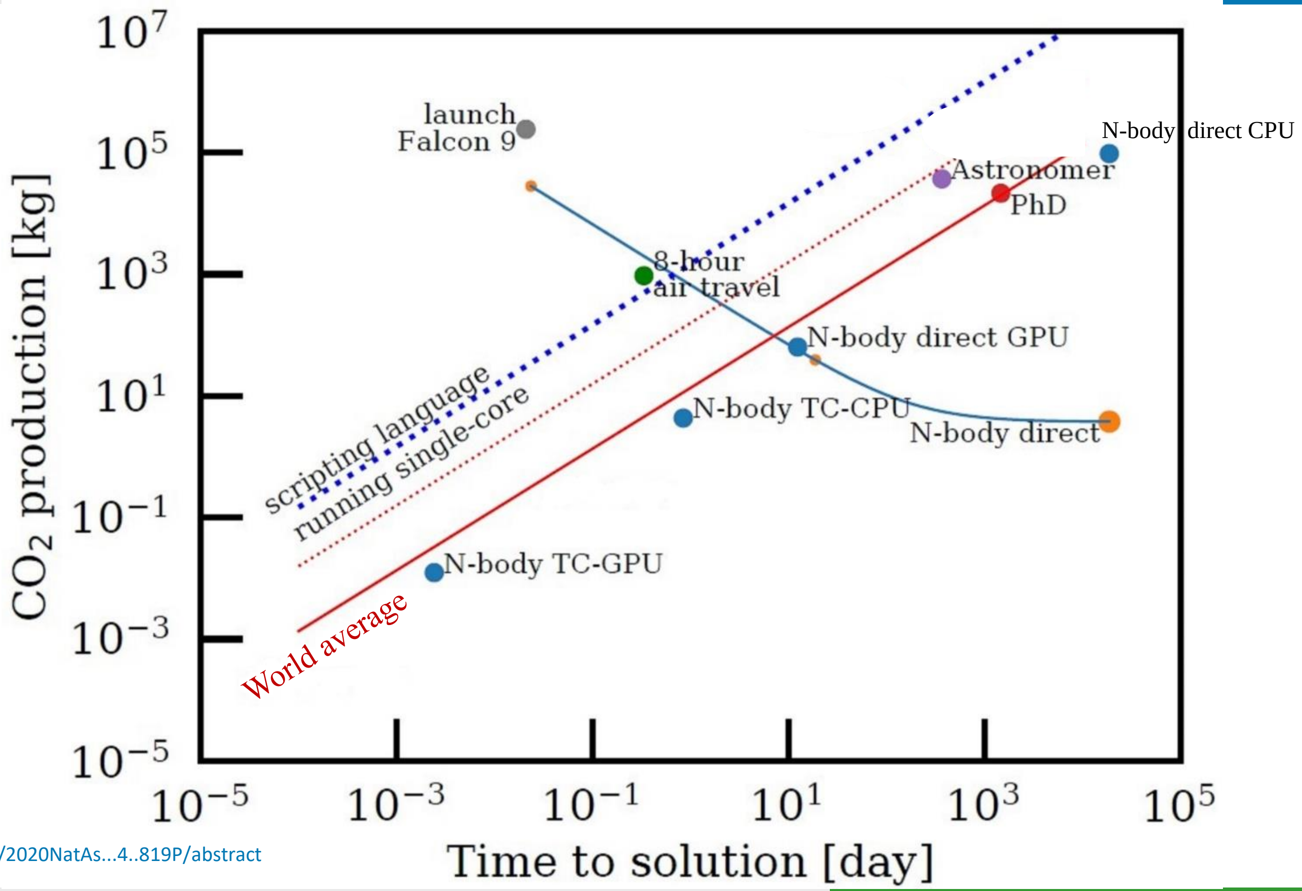
- Calculate wisely
- hardware
- code



Zwart, P. 2020, Nature Astronomy, https://ui.adsabs.harvard.edu/abs/2020NatAs...4..819P/abstract

Increasing computing efficiency

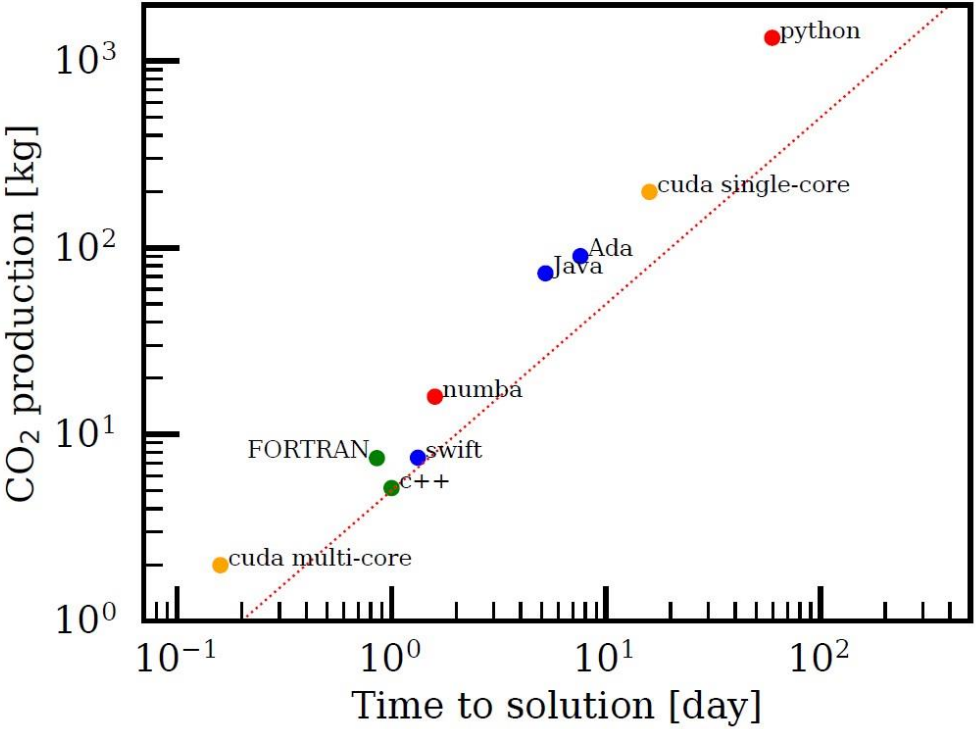
- Calculate wisely
- hardware
- code
- parallelism



Zwart, P. 2020, Nature Astronomy, https://ui.adsabs.harvard.edu/abs/2020NatAs...4..819P/abstract

Increasing computing efficiency

- Python vs. Other languages
- Your own time
  - I had to use JAVA für Gaia
  - With python I would have been able to optimize my code further
- Optimize when using heavily



Zwart, P. 2020, Nature Astronomy, https://ui.adsabs.harvard.edu/abs/2020NatAs...4..819P/abstract

Increasing computing efficiency

- Improve your code

Increasing computing efficiency

- Improve your code
  - https://github.com/uschpc/workshop-hpc-python
  - Profiling
  - Parallel IO

Increasing computing efficiency

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- Write important bits in fast languages

Increasing computing efficiency

- Improve your code
  - https://github.com/uschpc/workshop-hpc-python
  - Profiling
  - Parallel IO
- Write important bits in fast languages
- Or make your code portable between hardware
  - https://github.com/kokkos/kokkos

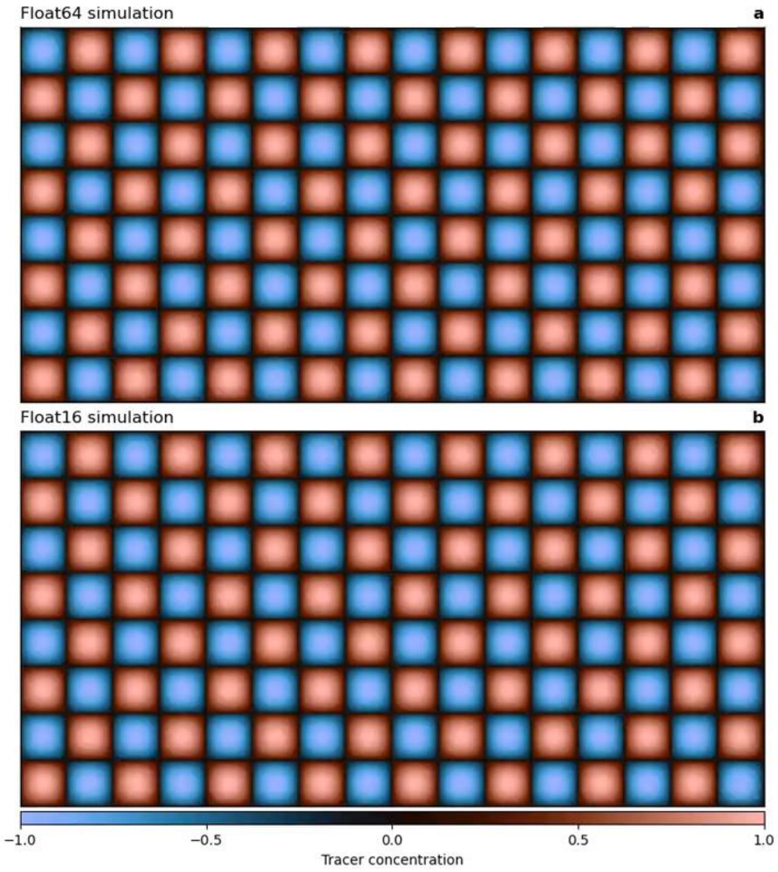
Increasing computing efficiency

- Lower resolution

Increasing computing efficiency

- Lower resolution
- lower accuracy
  - Klöwer+ 2022

(https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021MS002684)



Increasing computing efficiency

- Storing and sending data costs energy

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- Use compression (lossy compression)

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- Sending is approximately 10kWh per TB

Increasing computing efficiency

- Storing and sending data costs energy
- Use compression (lossy compression)
- Only store and send what is needed
- Sending is approximately 10kWh per TB
  - 4kg of CO_2
  - 3€ of electricity cost

Increasing computing efficiency

- Work collectively and reproducibly

Increasing computing efficiency

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  - Share infrastructure and knowledge bases

Increasing computing efficiency

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  - Share infrastructure and knowledge bases
  - Share results, make them reproducible

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  - Plan code development (employ and teach specialists)

Increasing computing efficiency

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  - Share infrastructure and knowledge bases
  - Share results, make them reproducible
  - Share code and improve codes together
  - Plan code development (employ and teach specialists)
  - Make your C++ code available to python ecosystem
    - https://docs.mpcdf.mpg.de/bnb/208.html#python-bindings-for-c-using-pybind11-and-scikit-build

Increasing computing efficiency

- Simplify where possible

Increasing computing efficiency

- Simplify where possible
  - Chempy flexible one-zone chemical evolution code

Rybizki+ 2016 https://ui.adsabs.harvard.edu/abs/2017A%26A...605A..59R/abstract

Increasing computing efficiency

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  - Chempy flexible one-zone chemical evolution code
  - Exploring parameter space via MCMC (1s per call)

Rybizki+ 2016 https://ui.adsabs.harvard.edu/abs/2017A%26A...605A..59R/abstract

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  - Exploring parameter space via MCMC (1s per call)
  - Oliver Philcox made a neural net interpolator of Chempy

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Philcox + 2018 https://ui.adsabs.harvard.edu/abs/2018ApJ...861...40P/abstract

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  →1ms per call and differentiation for free

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Increasing computing efficiency

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  - Chempy flexible one-zone chemical evolution code
  - Exploring parameter space via MCMC (1s per call)
  - Oliver Philcox made a neural net interpolator of Chempy
  - →1ms per call and differentiation for free
  - →Gradient descent method exploring hundreds of one-zones with exclusive and shared variables marginalizing over uncertainties in the model

Rybizki+ 2016 https://ui.adsabs.harvard.edu/abs/2017A%26A...605A..59R/abstract

Philcox + 2018 https://ui.adsabs.harvard.edu/abs/2018ApJ...861...40P/abstract

Philcox & Rybizki 2019 https://ui.adsabs.harvard.edu/abs/2019ApJ...887....9P/abstract

Increasing computing efficiency

- Replace expensive computions where possible
  - By interpolators
  - By approximate models (if accuracy still sufficient for the task)

Solution ideas

- Raise awareness

Solution ideas

- Raise awareness
  - E.g. acknowledge the CO2 footprint of your calculations

butions of all these computing allocations. All simulations performed for this study including test runs and failed simulations used about 2.5M core-hours which under the assumption of 30W per core-hour and a CO2 intensity of electricity of $\sim$ 600 kgCO2/MWh amounts to a carbon footprint of $\sim$ 45t of CO2.

Buck+ 2021

Solution ideas

- Raise awareness
  - Acknowledge the CO_2 footprint of your calculations
  - Measure/estimate your CO_2 footprint
    - E.g. https://mlco2.github.io/impact/

Buck+ 2021

Solution ideas

- Plan ahead in projects

Solution ideas

- Plan ahead in projects
- Example GRAND collaboration

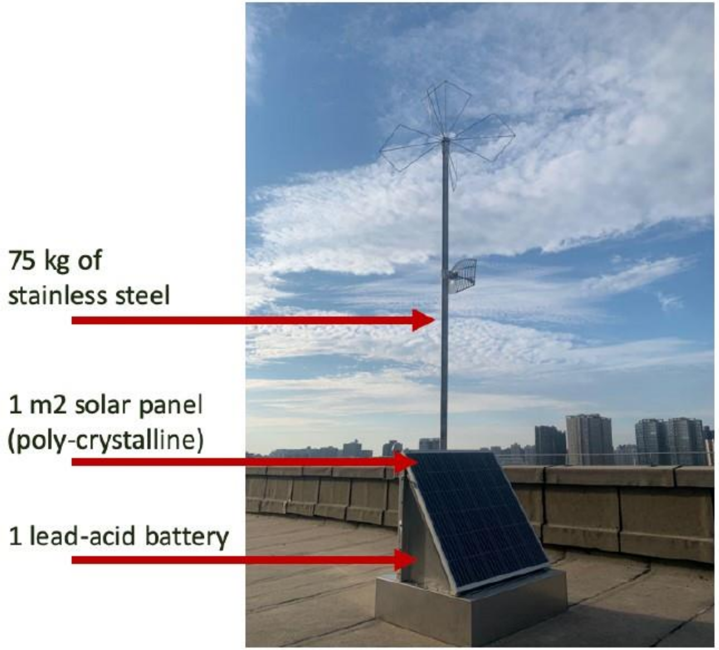


Figure 9: GRANDProto300 prototype antenna.

Aujoux+2021 https://ui.adsabs.harvard.edu/abs/2021APh...13102587A/abstract

Solution ideas

- Plan ahead in projects
- Example GRAND collaboration
  - 300, 10k, 200k antennas

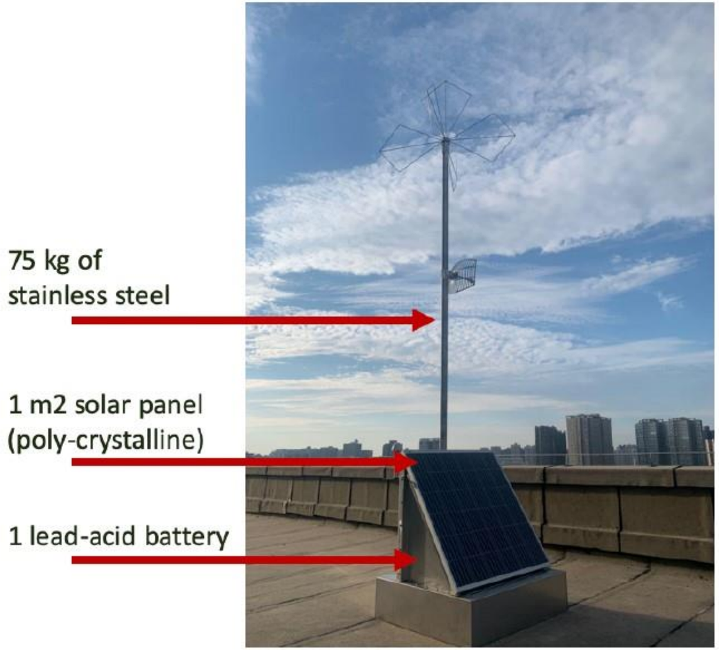


Figure 9: GRANDProto300 prototype antenna.

Aujoux+2021 https://ui.adsabs.harvard.edu/abs/2021APh...13102587A/abstract

Solution ideas

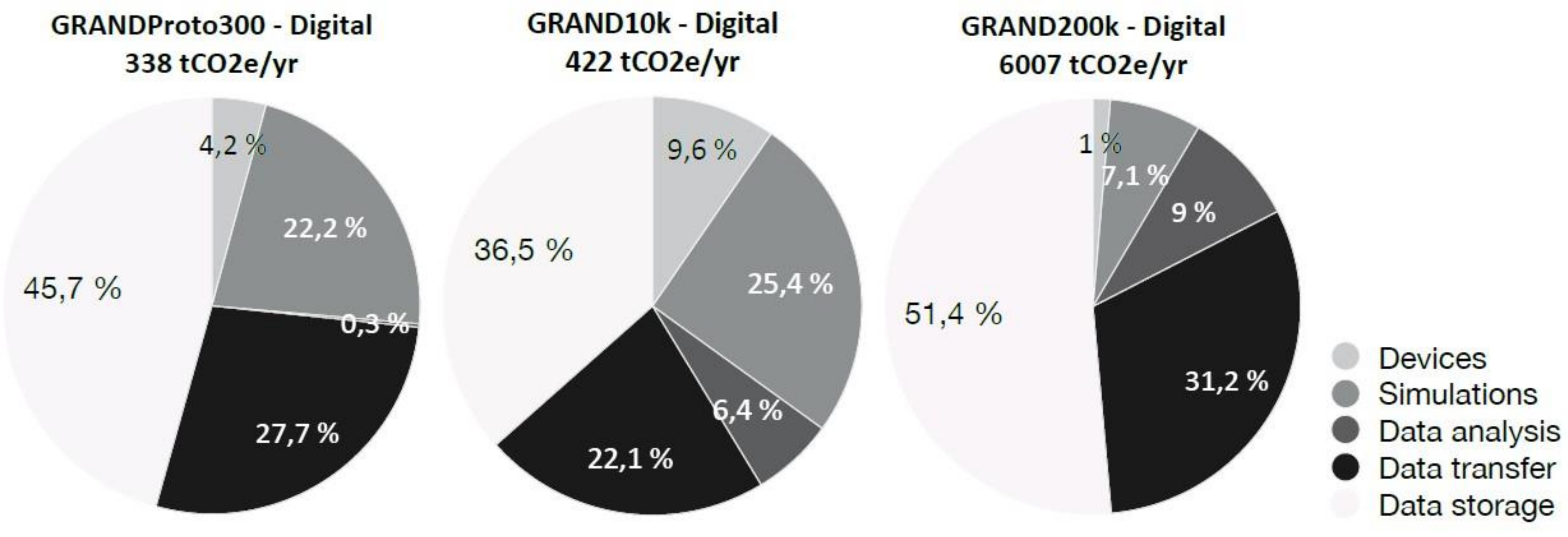
IAB

- Plan ahead in projects

	2021 – 2025	2025 – 203X	203X –
	GRANDProto300	**GRAND10k**	**GRAND200k**
Set-up	300 radio antennas over 200 km² in Western China	10,000 radio antennas over 10,000 km² in China	200,000 radio antennas over 200,000 km² ~20 subarrays of 10,000 antennas
People	~70 members (~30% strong involvement)	~100 members (~30% strong involvement)	~400 - 1000 members
Emission [tCO_2e/yr]	Digital: 338 (69%) Travel: 130 (27%) Hardware: 18 (4%) **Total: 486 tCO_2e/yr**	Digital: 422 (39%) Travel: 328 (31%) Hardware: 322 (30%) **Total: 1072 tCO_2e/yr**	Hardware: 6435 (48%) Digital: 6007 (45%) Travel: 965 (7%) **Total: 13407 tCO_2e/yr**

Solution ideas

- Plan ahead in projects



Solution ideas

- Over- and underclocking with availability of renewables

Solution ideas

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- Queuing system with availability of renewebles

Solution ideas

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- Queuing system with availability of renewebles
- Generate your own electricity with renewables
- Use the waste heat of your computations
- Move computations where:
  - Electricity is greener
  - Computing is more efficient (hyperscale data centers)

The way forward

General ideas **computing**

The way forward

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- evaluate data / processing demands when planning experiments

The way forward

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- reduce CO_{2eq}-intensity of electricity (renewables, location, time)

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- improve utilization rate → reduce/share hardware → cloud

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The way forward

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- reduce data volume (lossy compression?)
- share expensive simulations in scientific community
- use computing waste heat

The way forward

General ideas **computing**

- teach efficient programming

The way forward

General ideas **computing**

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- monitor energy demand

The way forward

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Most importantly:

- Judge which computations make sense

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The way forward

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- adapt codes to GPUs, install GPU systems
- (use IT hardware longer)

Most importantly:

- Judge which computations make sense
- What is the code doing (purpose) that you are investing your time in
- What are you working on, how much infrastructure/energy is needed?

End of lecture

- Thank you for your attention

- Questions / Comments / Discussion

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Twitter: @rybizki