



CNRS - INP - UT3 - UT1 - UT2J

Institut de Recherche en Informatique de Toulouse



Sustainable computing ?

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PROGRAMME
DE RECHERCHE

NUMÉRIQUE
POUR L'EXASCALE





Climate change and energy

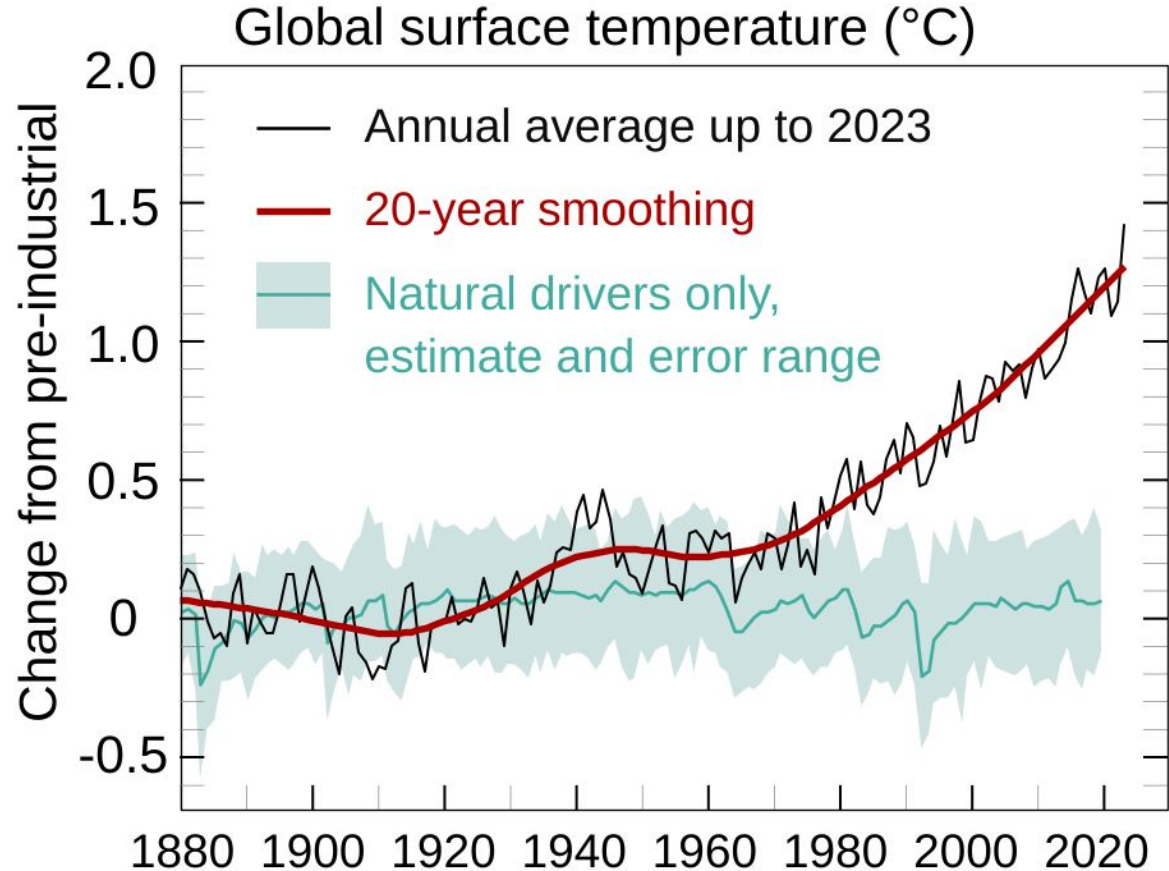




An on-going climate change

Global surface temperatures 1880 to 2023 (relative to 1850 – 1900 average)

Source: [wikimedia](https://www.wikimedia.org/)





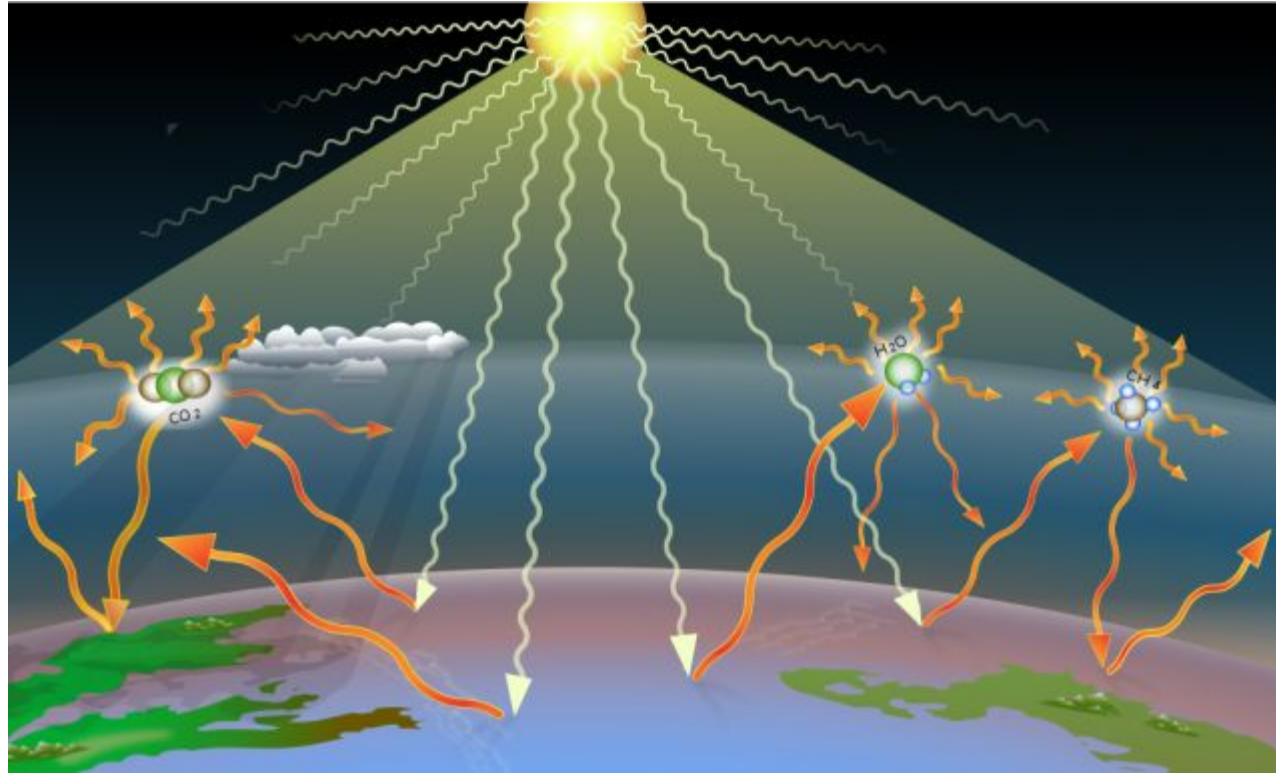
The main source is well known

greenhouse effect

Mostly

- CO_2
- H_2O
- CH_4

A loose necktie on
Wikimedia Commons





A fragile balance

Historically: 750 GT/year emitted and absorbed

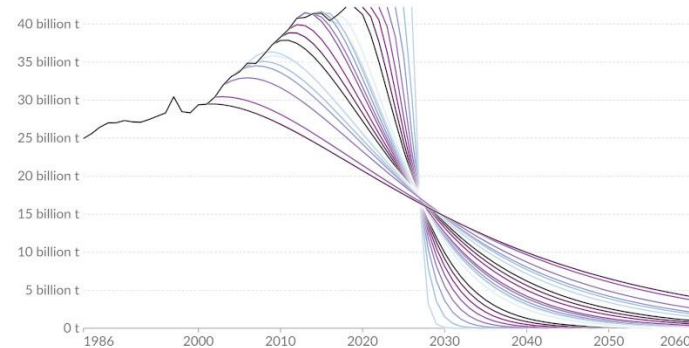
- H_2O and CO_2
- Methane CH_4 , nitrous oxide N_2O and ozone O_3
- CO_2 , CH_4 and N_2O account for 96% of the 7 GHGs covered by the Kyoto Protocol

Long duration

- 100 years for CO_2 , 9 years for methane

CO_2 reductions needed to keep global temperature rise below 1.5°C
Annual emissions of carbon dioxide under various mitigation scenarios to keep global average temperature rise below 1.5°C . Scenarios are based on the CO_2 reductions necessary if mitigation had started - with global emissions peaking and quickly reducing - in the given year.

Our World
in Data

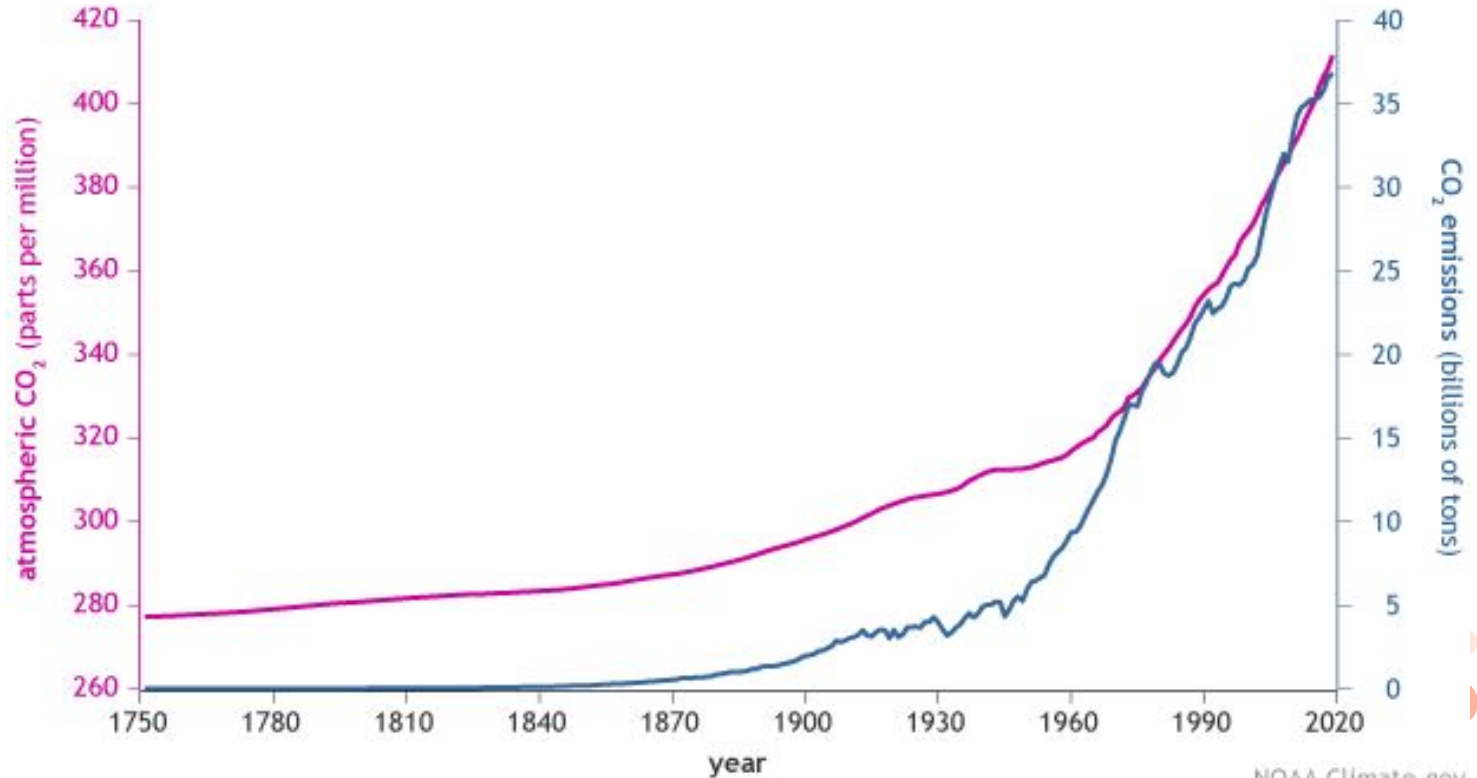


Source: Robbie Andrews (2019); based on Global Carbon Project & IPCC SR15
Note: Carbon budgets are based on a >66% chance of staying below 1.5°C from the IPCC's SR15 Report.
OurWorldinData.org/co2-and-other-greenhouse-gas-emissions • CC BY



CO₂ and industrial revolution

CO₂ in the atmosphere and annual emissions (1750-2019)



NOAA Climate.gov
Data: NOAA, ETHZ, Our World in Data

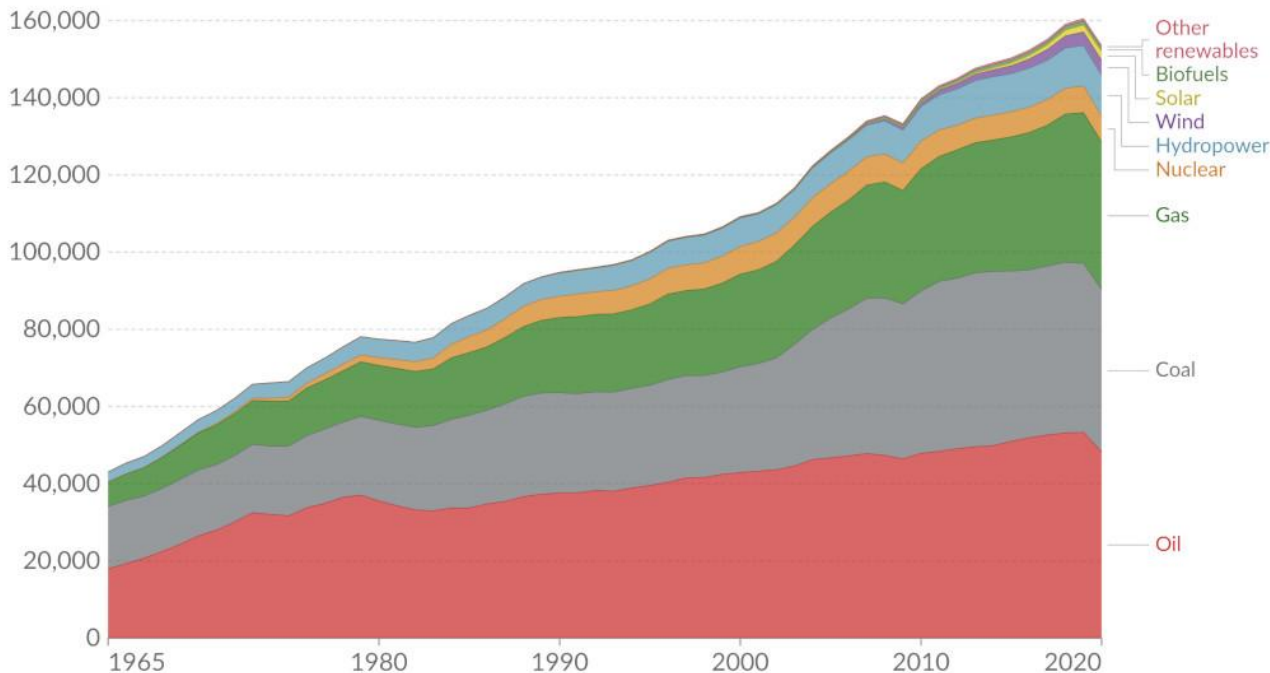


Global energy mix

Energy consumption by source, World

Primary energy consumption is measured in terawatt-hours (TWh). Here an inefficiency factor (the 'substitution' method) has been applied for fossil fuels, meaning the shares by each energy source give a better approximation of final energy consumption.

Our World
in Data



Source: BP Statistical Review of World Energy
Note: 'Other renewables' includes geothermal, biomass and waste energy.

OurWorldInData.org/energy • CC BY

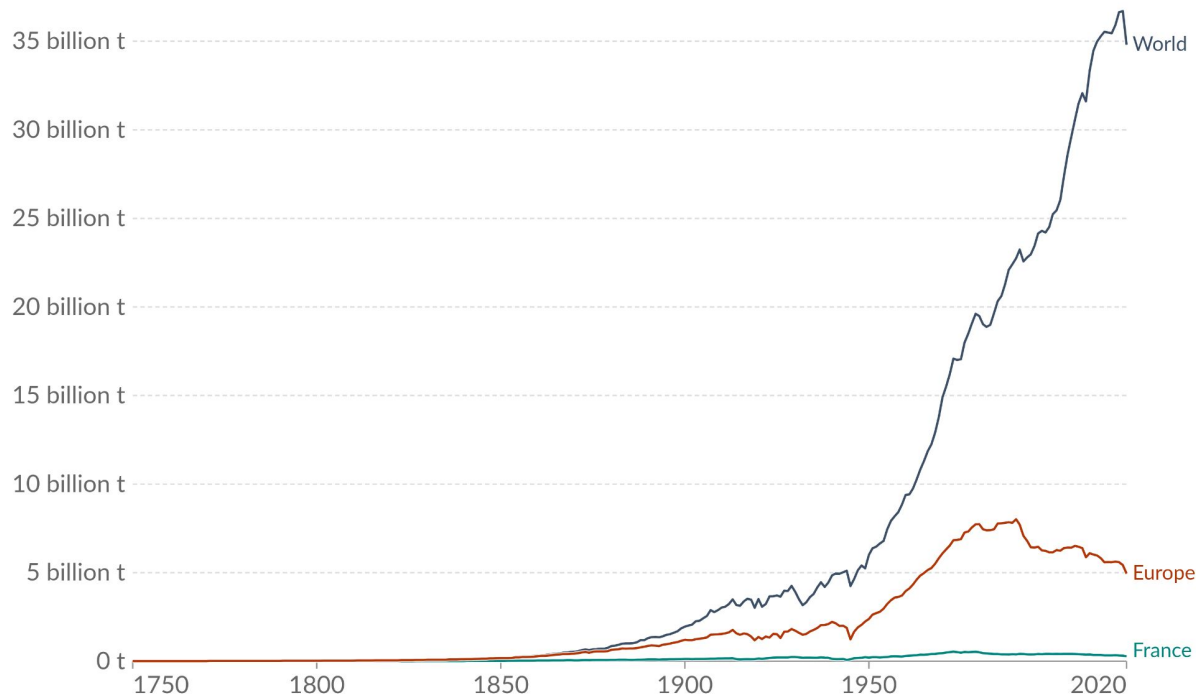


Energy-related CO₂ production

Annual CO₂ emissions

Carbon dioxide (CO₂) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.

Our World
in Data



Source: Global Carbon Project

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY



Zoom in Europe and France

CO₂ per person

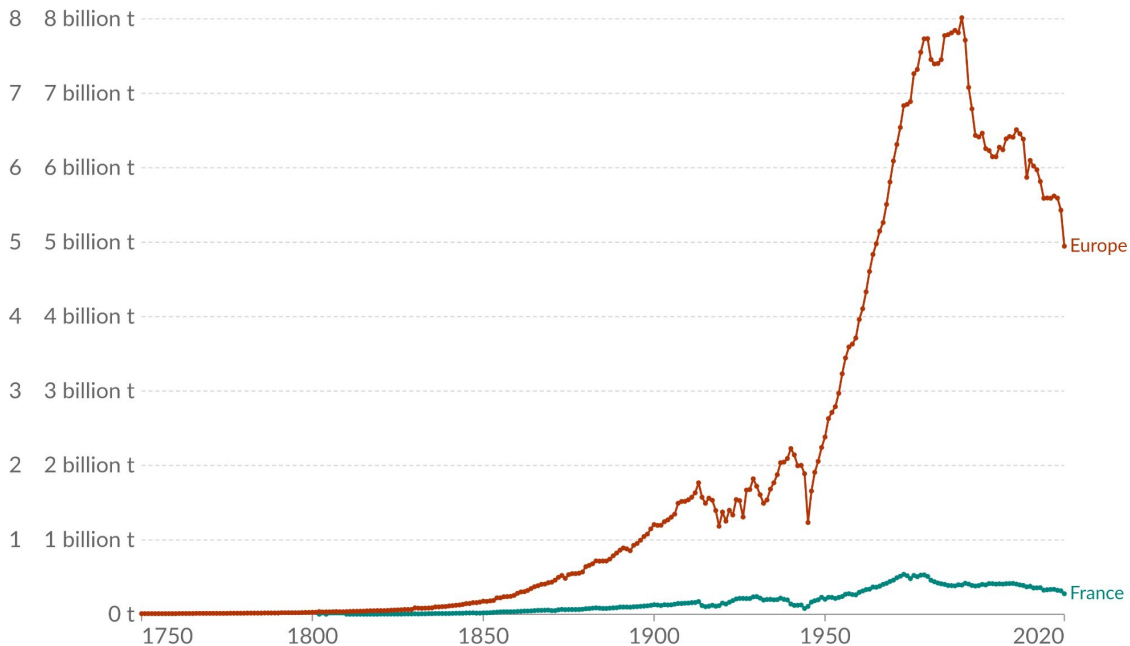
- France : 4.6
- EU : 6.4

WorldBank

A Annual CO₂ emissions

C Carbon dioxide (CO₂) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.

Our World
in Data



Sc Source: Global Carbon Project

OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

The difficulty of 100% renewable energy

Uncontrollable sources

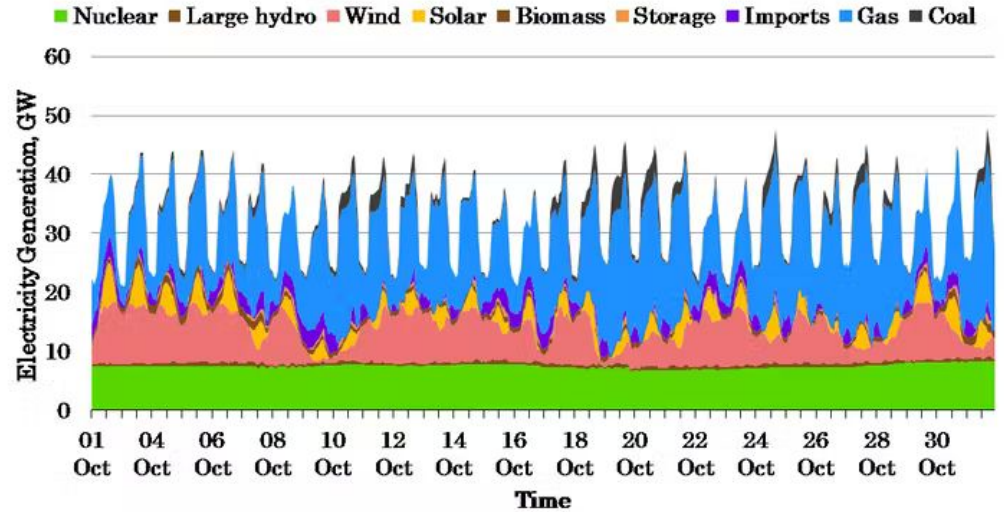
- Renewable

Constant sources

- Nuclear

Auxiliary sources

- Hydraulic, fuel, coal, ...



Carbon Emissions	Electricity from Low Carbon Sources	Electricity from Gas
248 gCO ₂ eq./kWh	52%	41%

British electricity generation in Oct. 2018

Dr Andrew Crossland/MyGridGB



Energy sources

Nothing is carbon-neutral

	Coal	Diesel	Natural gas	Wind turbines	Photovoltaic	Nuclear	Geothermal	Hydraulic
g CO ₂ eq/kWh	1000	780	443	14.5	44	66	38	12

Lifespan, production, transport, installation, maintenance

https://bilans-ges.ademe.fr/documentation/UPLOAD_DOC_FR/index.htm?renouvelable.htm



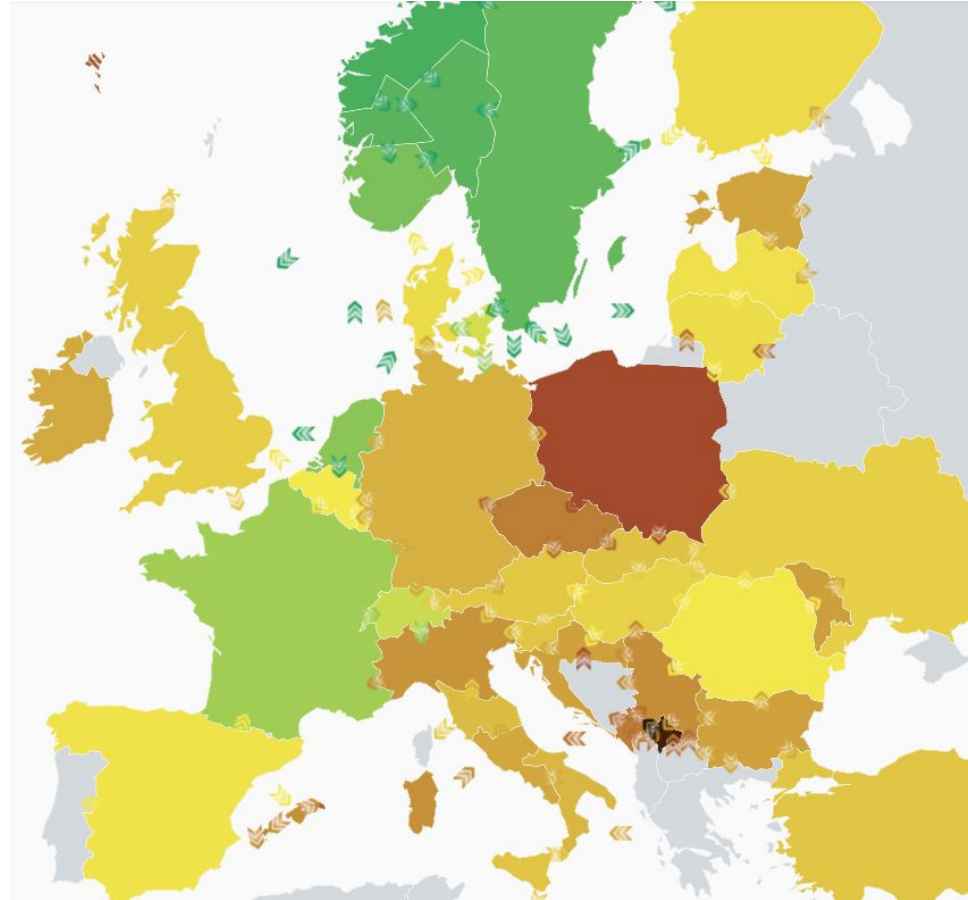


An interconnected system

At multiple levels

- Regional
- European

<https://app.electricitymap.org/map>



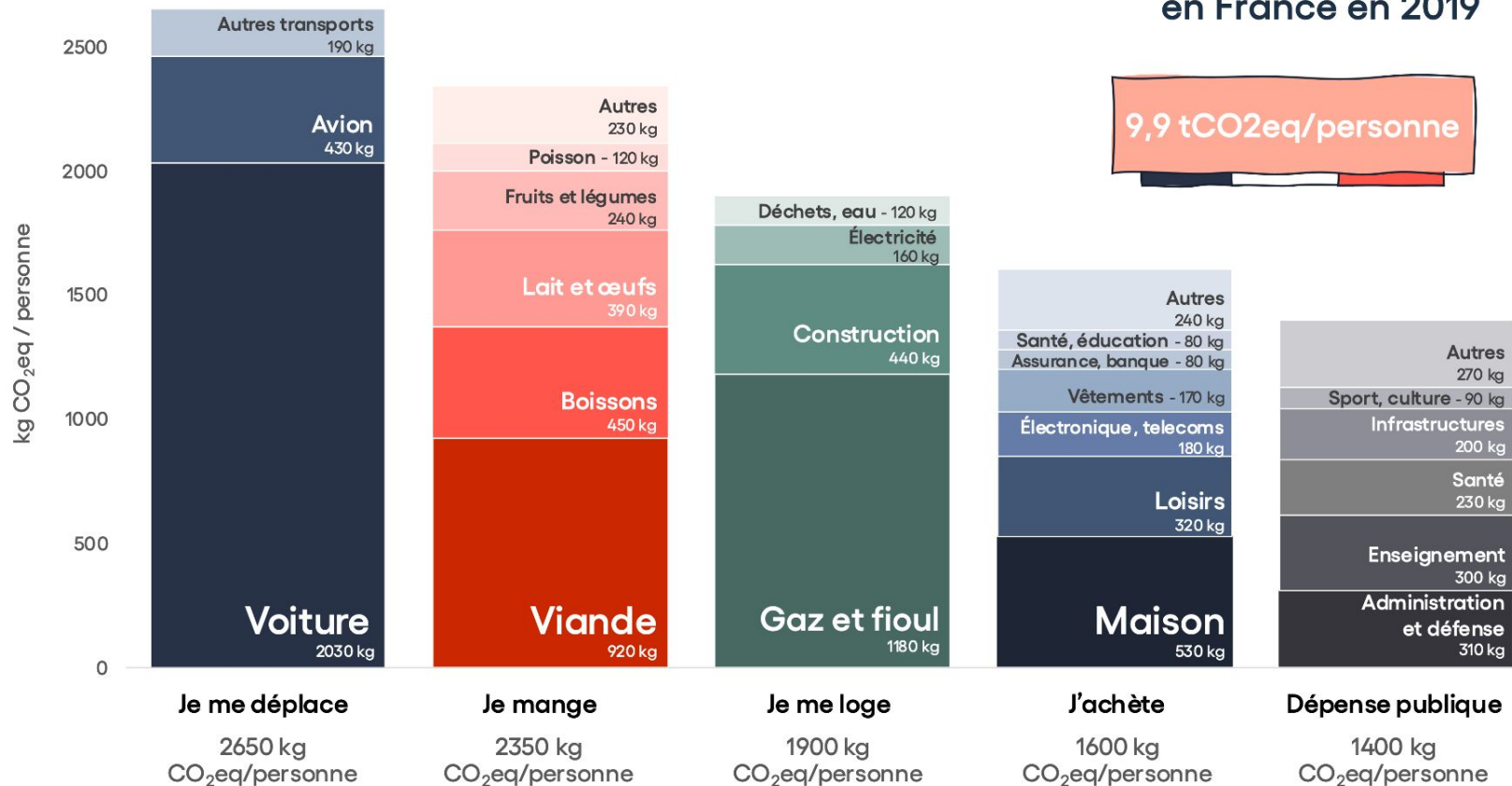


Invisible and visible consumption

Energy Slaves



Empreinte carbone moyenne en France en 2019

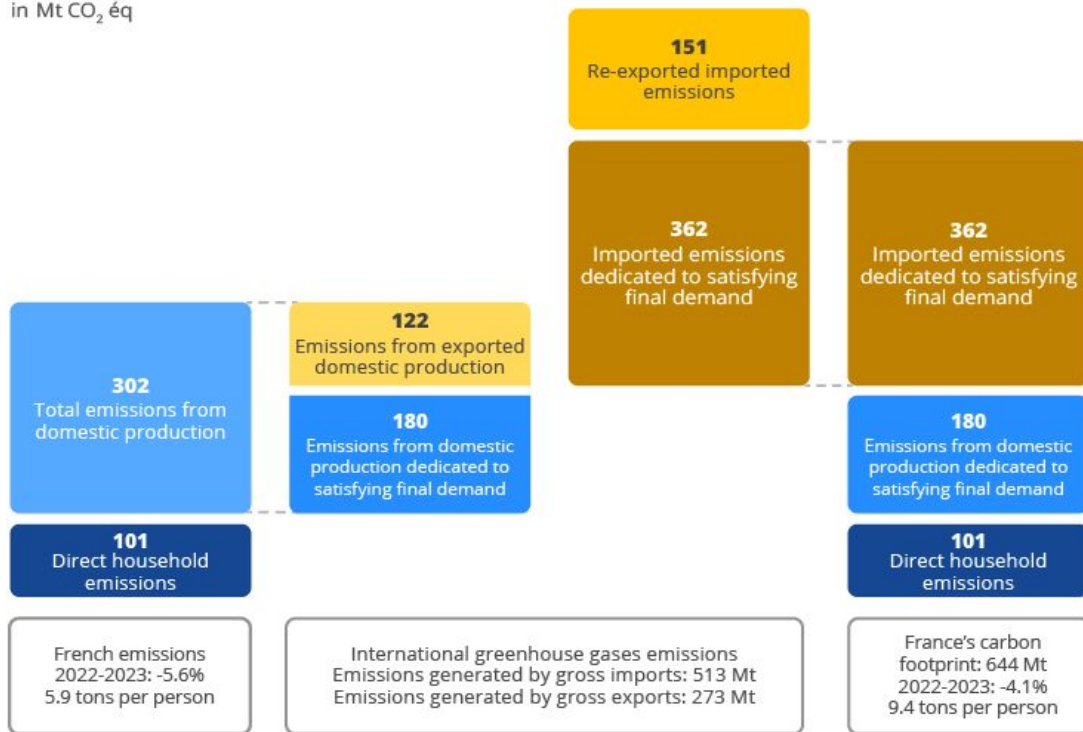




Includes imported emissions

Source [Insee](#)

in Mt CO₂ éq

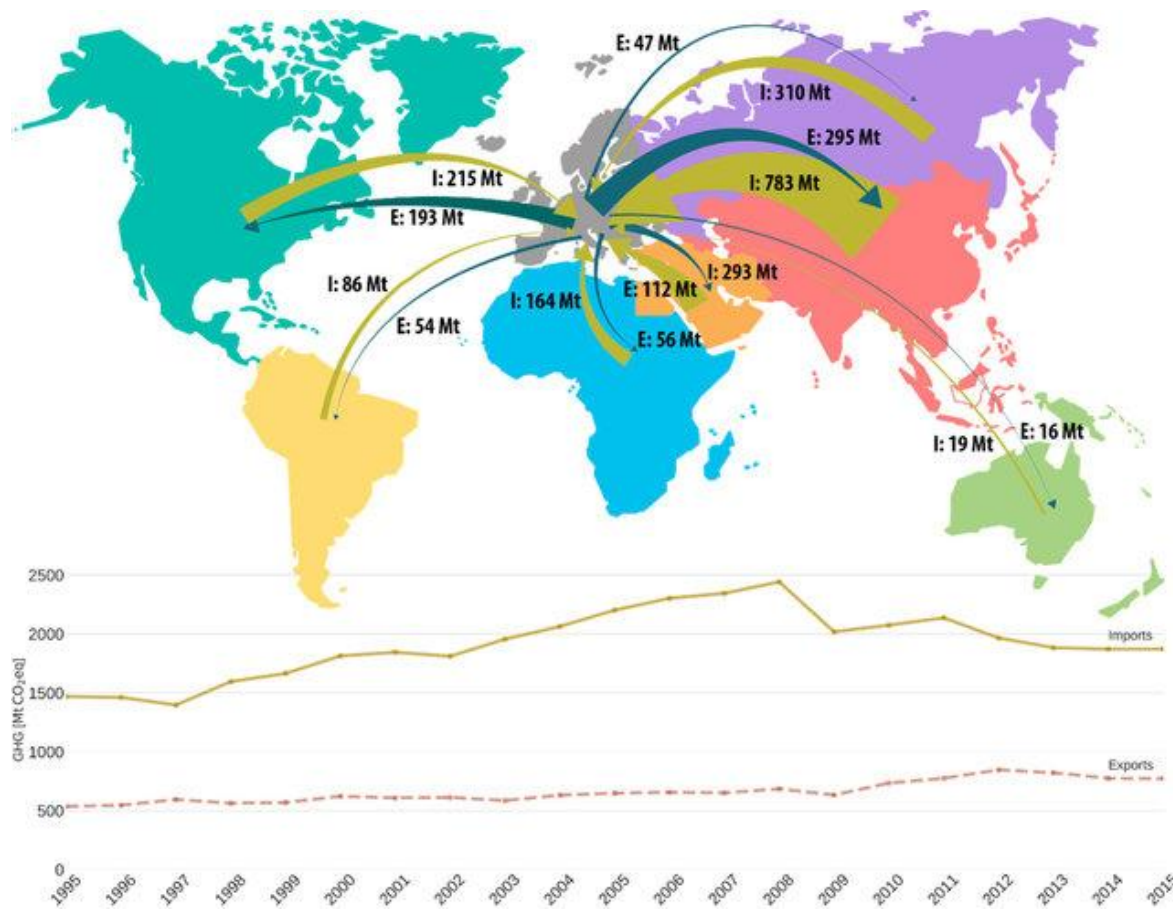




European import/export carbon footprint

A global problem

Richard Wood et al. 2019





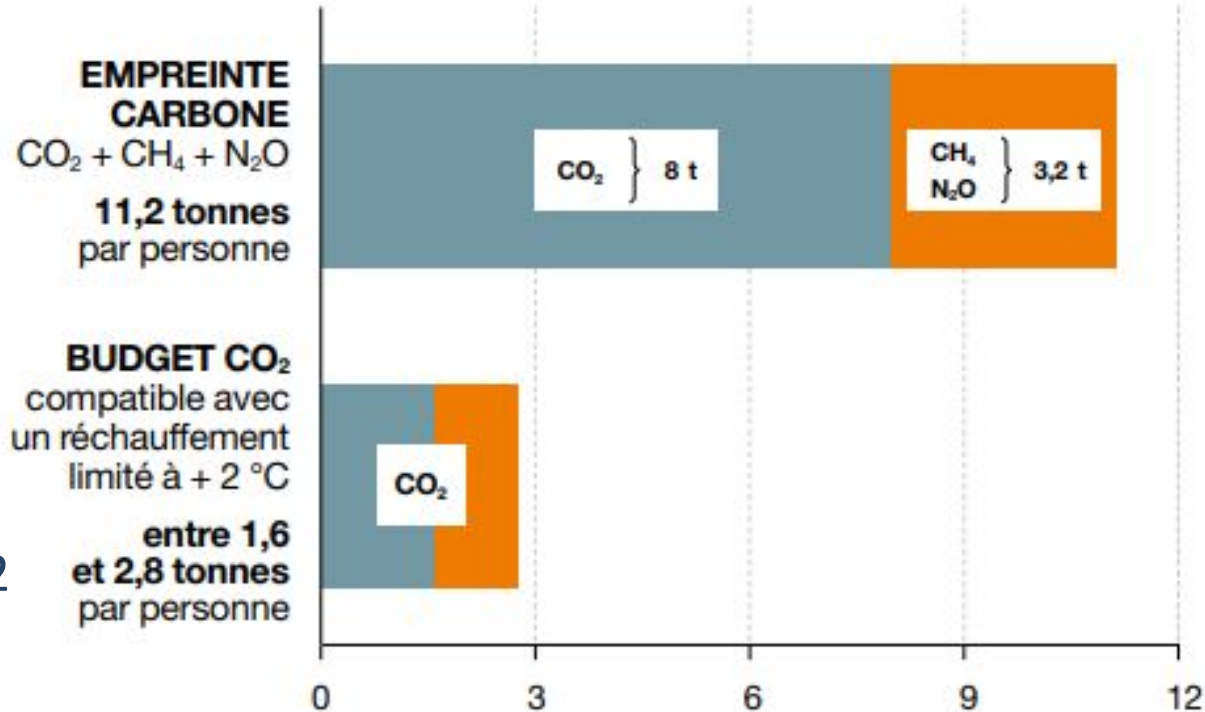
A change of civilization is needed

Objective

- Divide by 6

Current part of the digital sector

- 0.8Teq on the 11.2
GreenIT 2019



Champ : France métropolitaine + Drom (périmètre Kyoto).

Sources : GIEC ; Citepa ; AIE ; FAO ; Douanes ; Eurostat ; Insee.

Traitements : SDES, 2019



Environmental impact of digital technology

Part 1 : The digital world





?

How many digital devices does an European owns?

1. Less than 6
2. 6 to 10
3. More than 10

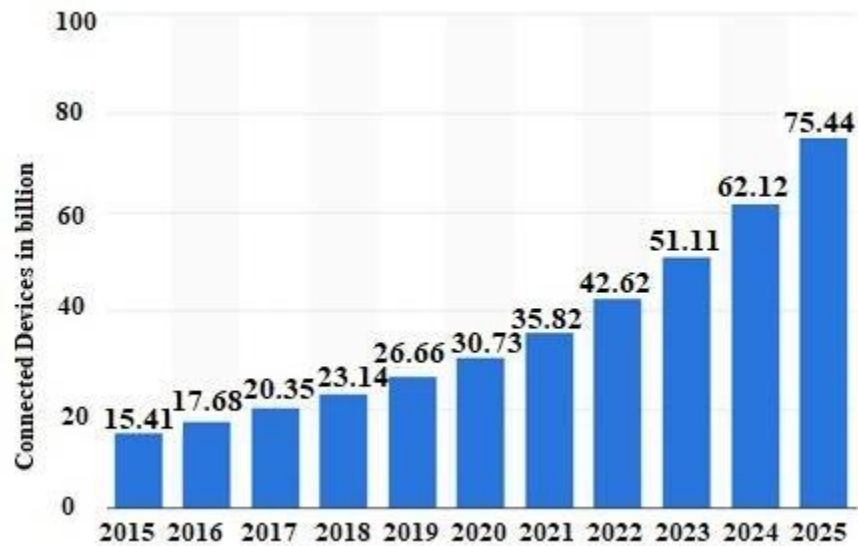




Connected devices

Excluding computers and smartphones

	World	France
Devices	34 billions	651 millions
Users	5 billions	58 millions
Ratio	4	15
Daily usage	6h42	4h38





Cloud services

Web sites, banks, snapchat, amazon, ...

Keyword: virtualization / transparency

Independents :

- From the place
- From the device/hardware

Infinite

? Comparison between video playing

- Online
- Local





Example of a web page

<https://www.enseignementsup-recherche.gouv.fr/fr>

Browsing this webpage needs

- 1 download
- 2 to 9 downloads
- More than 10 downloads

And encompass the usage of

- 1 remote server
- 4 remote servers
- Impossible to know

?





Example of a web page

<https://www.enseignementsup-recherche.gouv.fr/fr>

- 1.50 g of CO2 per visit
- 46 files
- 4.3Mb
- 1.15s of total download

<https://www.websitecarbon.com/>





At the center of Internet: data centers

A physical infrastructure

Farms of servers

Each with multiple services

- Web pages
- Search engine
- Text of new articles
- Authentication
- Domain name service
- Picture database
- ...

wikipedia



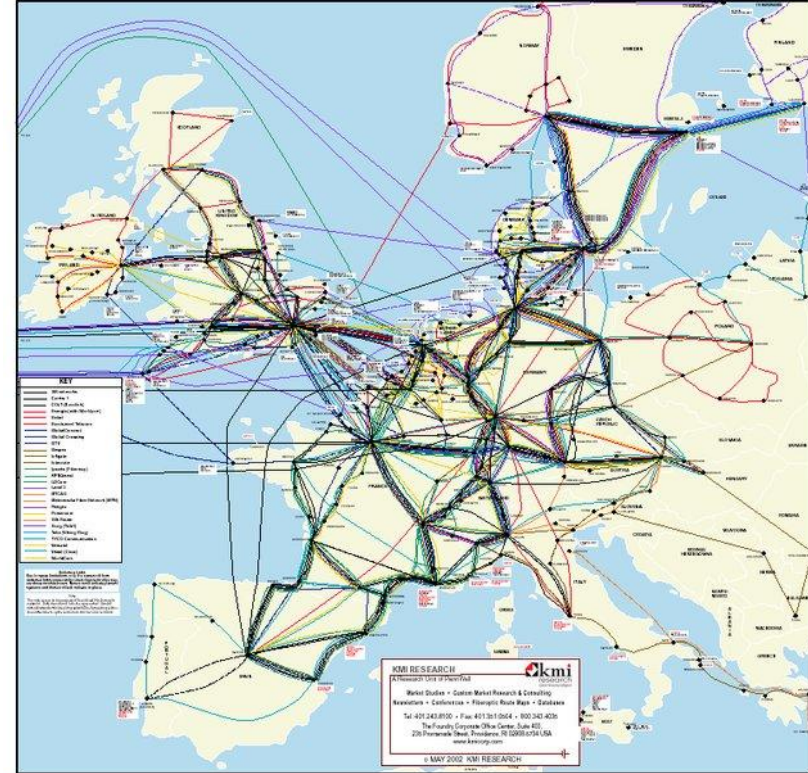
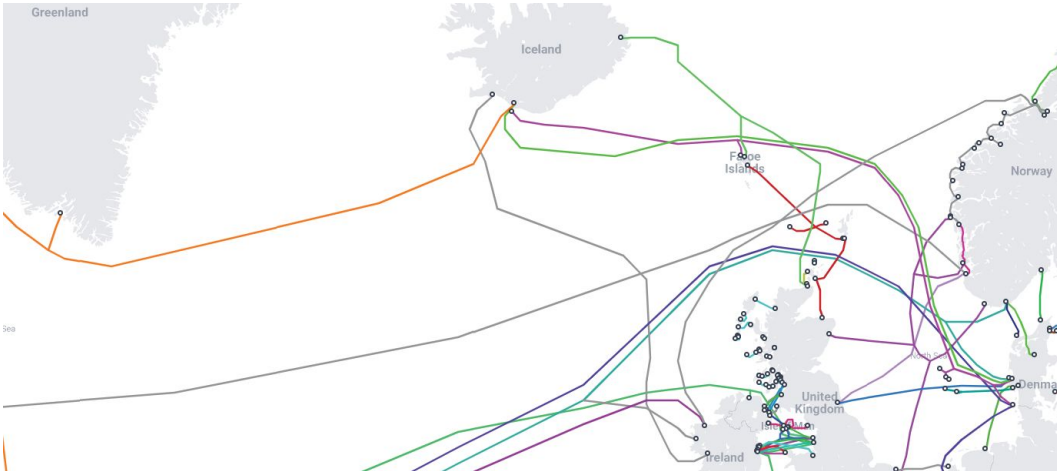


Internet: World-wide cooperation of DCs

A physical infrastructure

Spine of Internet:

- International network of fiber
- Geopolitical importance



Laura A. Schintler et al. 2005

<https://www.submarinecablemap.com/>



Complex softwares

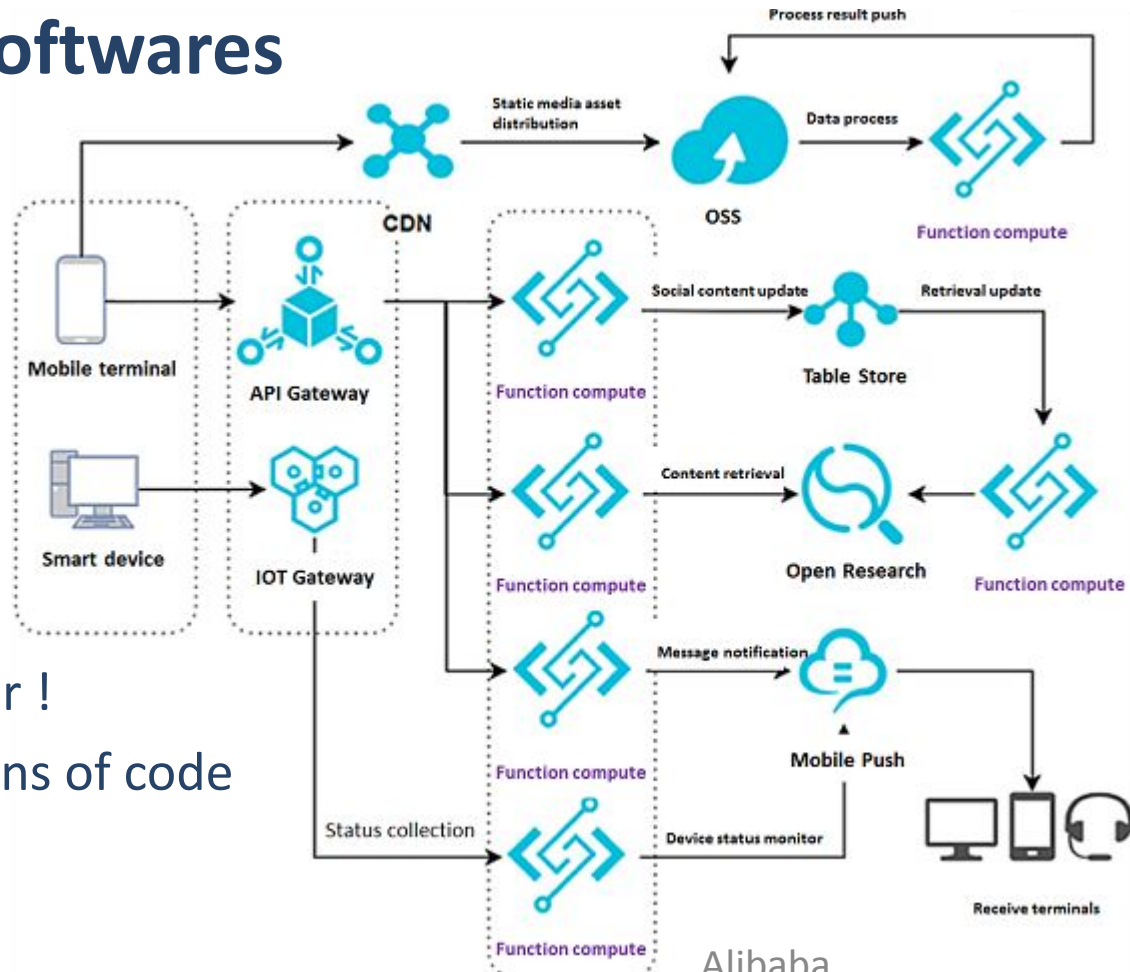
A logic infrastructure

Softwares are split

- In tasks
 - Simplification
 - Delegation
- Duplicated
 - Speed, resilience

Dr. Frankenstein monster !

- Facebook : 50 millions of code lines
- TikTok : 15 millions



Alibaba



Environmental impact of digital technology

Part 2 : Environmental impact





Small-quizz

Is my footprint mainly linked to

1. Data centres and their electricity consumption?
2. The intermediate network (access provider, fibre optics, backbone)?
3. The equipment I own directly?



Does this footprint come from

1. My actual usage?
2. The manufacture of the equipment?
3. Other source(s)?

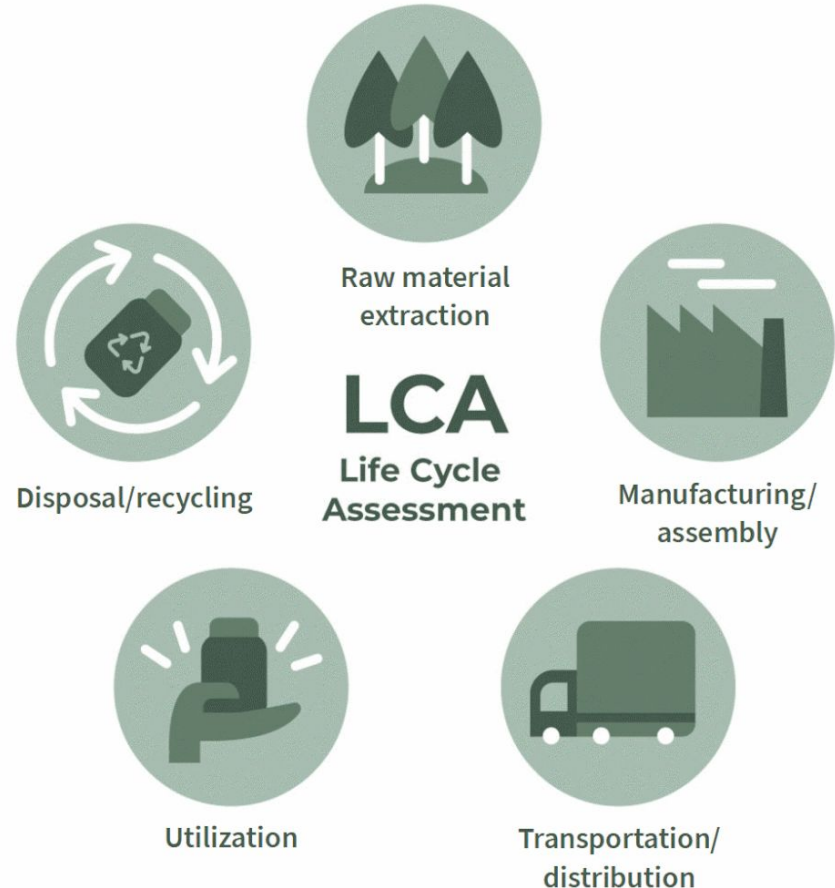




LCA: Life Cycle Assessment

Beyond energy alone

- Abiotic resources
 - kg equivalent antimony
- Climatic impact
 - kg equivalent CO₂
- Water depletion
 - l or m² of water
- Primary energy
 - Wh





Distribution from users to data centers

Datacenter :

- High efficiency
- No screen
- Always on
- High computing per Watt

	Users 34Mds	Networks 1.5Mds	Datacenter .07Mds
Energy	60	23	17
GHG	63	22	15
Water	83	9	7
Electricity	44	32	24
Resources	75	17	8



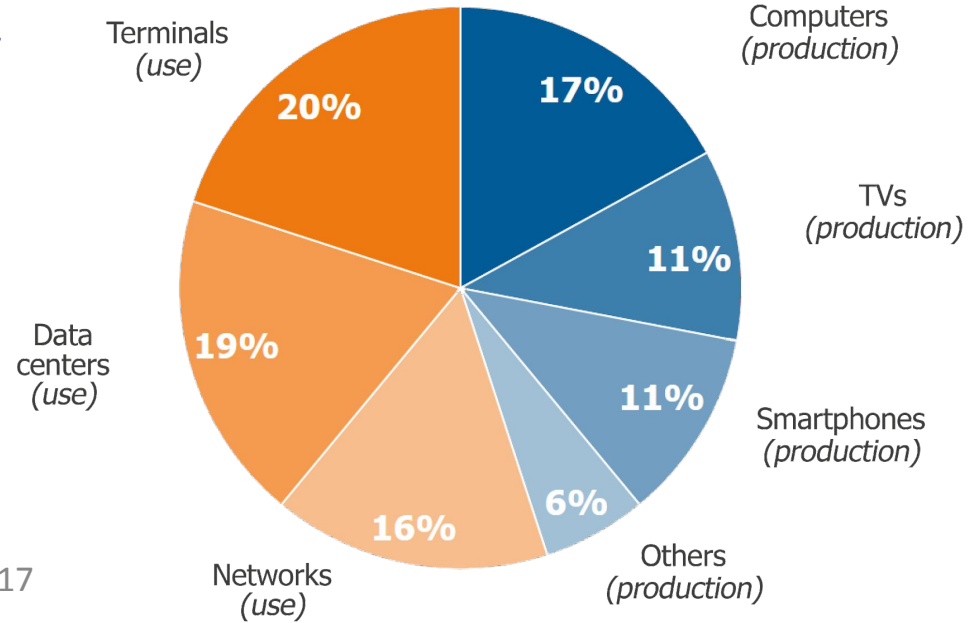


Zoom on Energy

Costly steps:

- Extraction and refining
 - 1 T copper = 100 T to extract
- Component manufacturing
 - Silicon purification
 - 2MW per kg
 - 20l of water per cm²
 - 1% without any defect
 - Toxic substances, arsenic, antimony, phosphorus, hydrogen peroxide, nitric, sulphuric and hydrofluoric acids

ecoInfo 2010



Distribution of the energy consumption of digital technologies for production (45 %) and use (55 %) in 2017

[Source : Lean ICT, The Shift Project 2018]





Trends

Usage only

Different models:

- Calculation method
- Degree of change

Similar conclusions:

- Explosion

Even sufficiency is not sufficient to reach a reduction

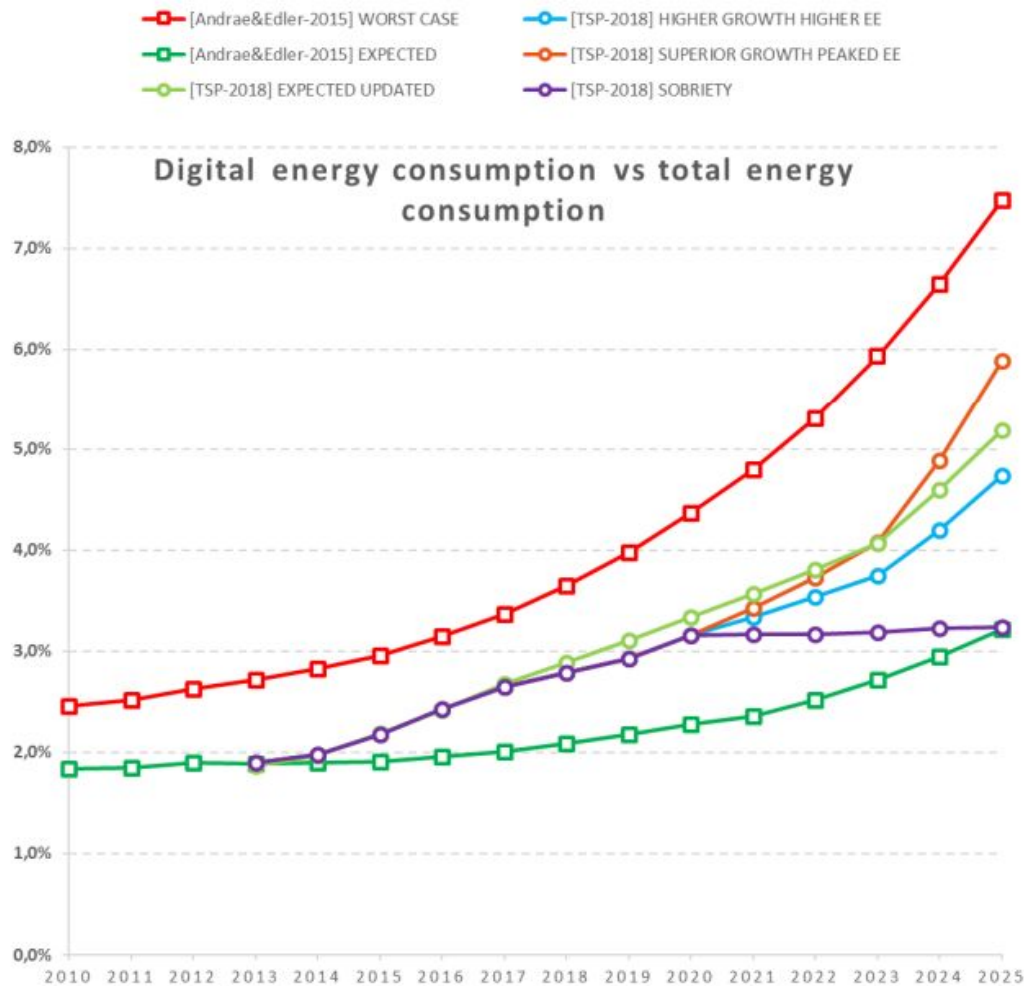
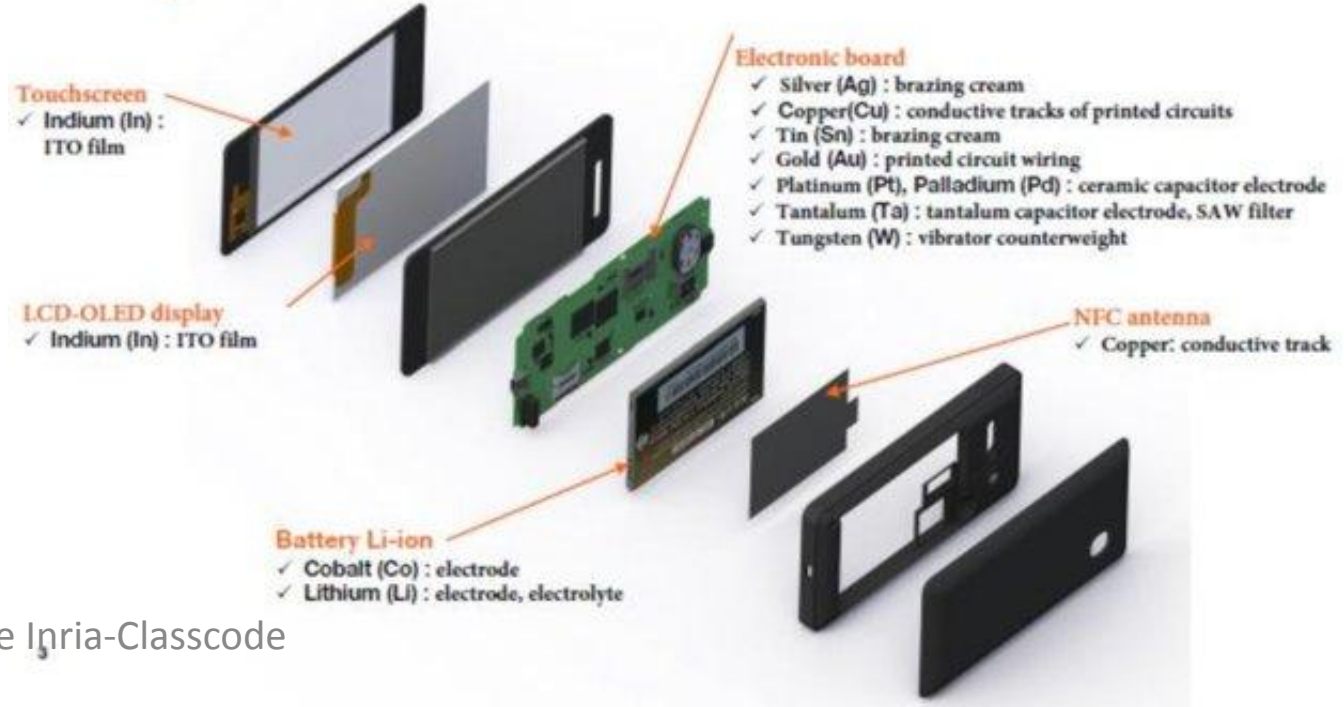


Figure 2: Evolution 2010-2025 of energy consumption of digital technology versus world energy consumption⁹.
[Source: [Lean ICT Materials] Forecast Model. Produced by The Shift Project from data published by (Andrae & Edler, 2015)]

Example: A smartphone

Smartphone: architecture and rare metals



Smartphone Apple 12

- 83% production
- 2% transport
- 14% usage
- 1% end of life

Use of rare materials

Geopolitical tensions

Limited resources

Tensions in usage

The main metals of ICTs.

Bihouix P. , 2015

The main metals of ICTs

Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo		44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi			
7			**															
	*Lanthanides (Rare earths)			57 La	58 Ce	59 Pr	60 Nd		62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
	**Actinides				90 Th		92 U											

Conductors, contactors, switches

Batteries

Flame retardant

Welds

Capacitors

Misc (precious)

Optoelectronics

Misc (others)

Multiple



A difficult recycling

Profitable reserves
depleted in 30 years
(greenIT)

Challenges in Metal Recycling
2012

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	(117) (Uus)	118 Uuo

* Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

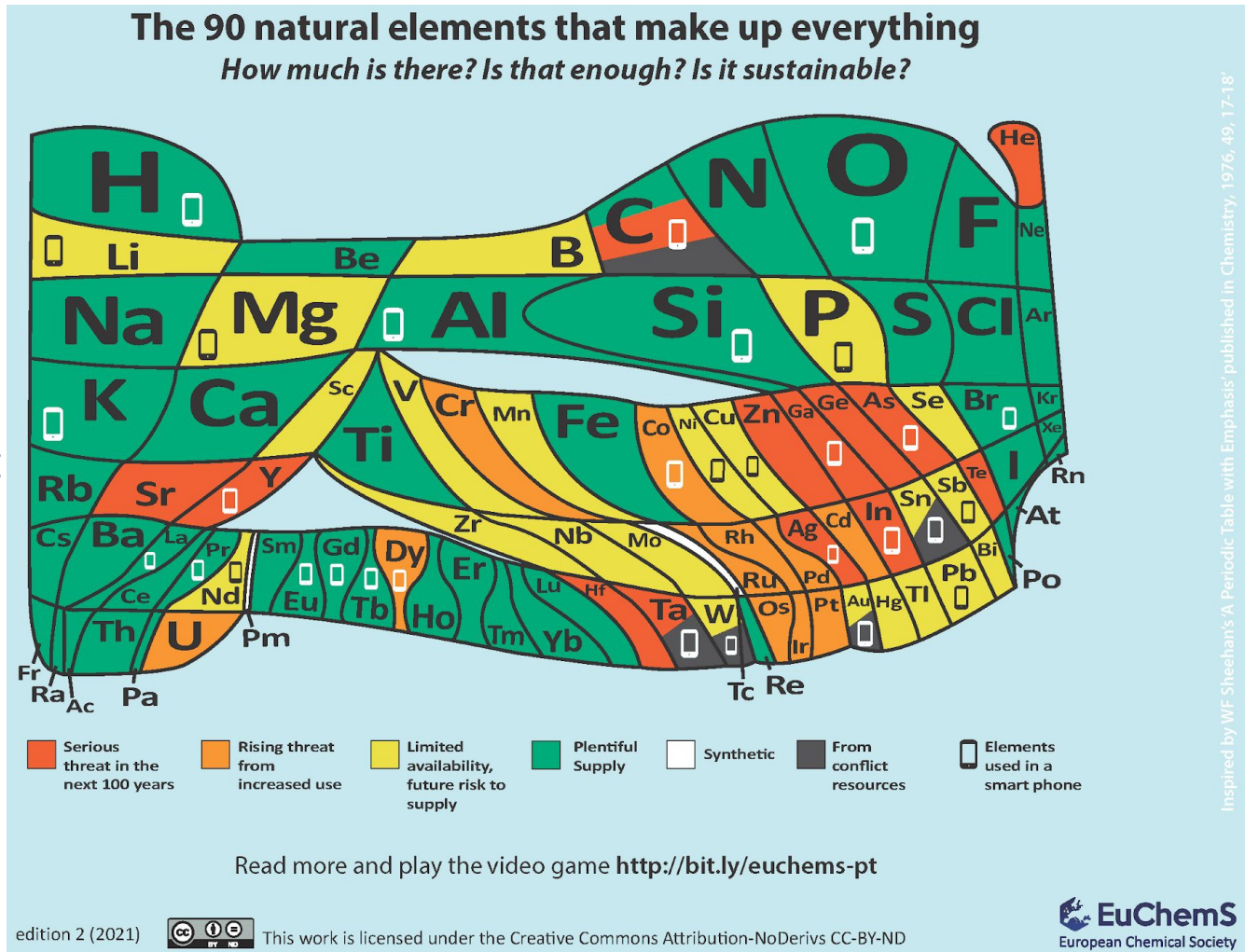
 <1%  1-10%  >10-25%  >25-50%  >50%



Size : Availability

- Atmosphere
- Earth's crust

[Link](#)





Service LCA

- Manufacture of the user terminal

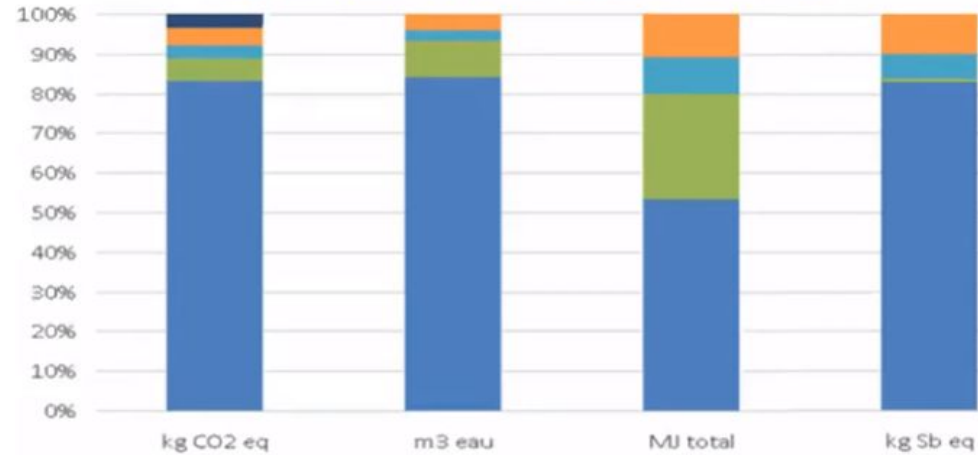
Most cost are before

- Usage
- Even switching-on

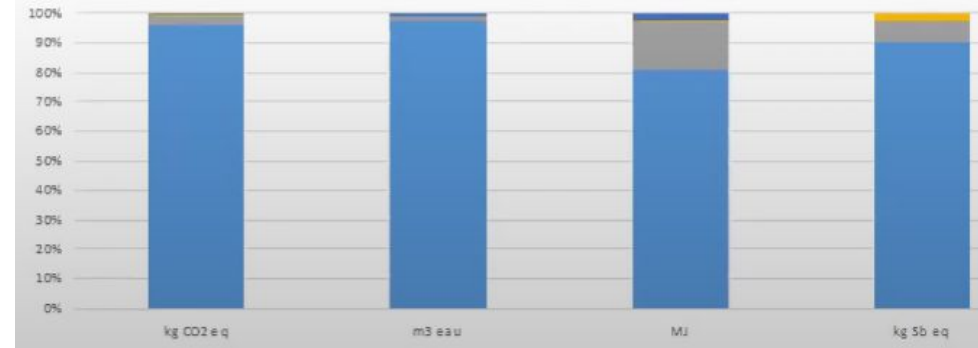
Important to remember

- Reduce obsolescence
 - Of personal devices
 - Of Internet

Trouver l'horaire d'un train depuis un site web



Regarder un film en streaming





Environmental impact of digital technology

Part 3 : Take action





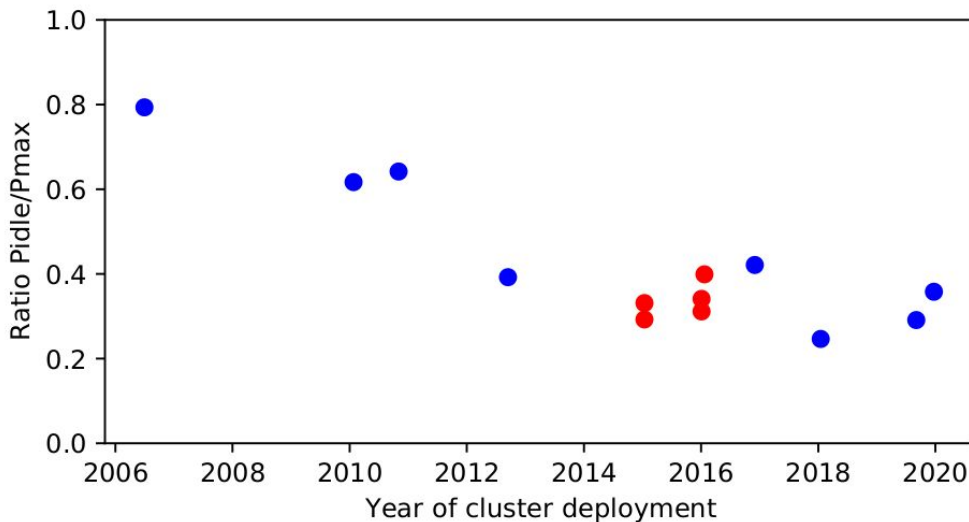
Improve the hardware

Even idle a computer consumes electricity

In 2000 a server was consuming 80% of its maximum just for being switched on

Now 20 to 30%

Recycling issues, obsolescence



Koomey's Law : Performance per Joules : double every 2 years



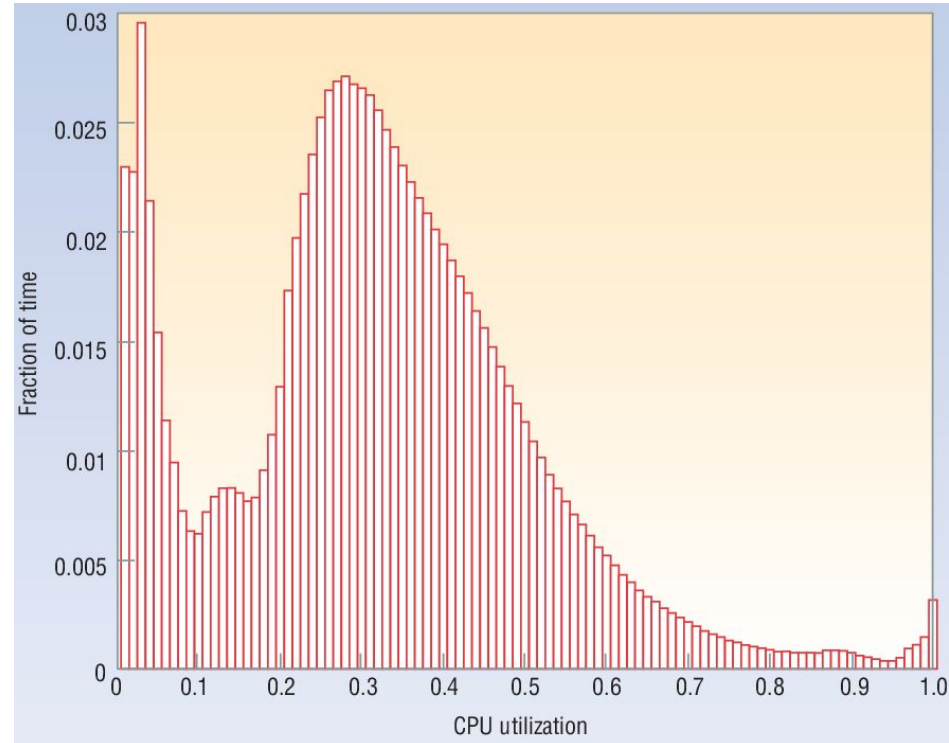
Improve the management

At the infrastructure level

Servers often underutilized

A mean usage of

- 30% in data centers (now more toward 70%)
- Even less for personal computers



The Case for Energy-Proportional Computing

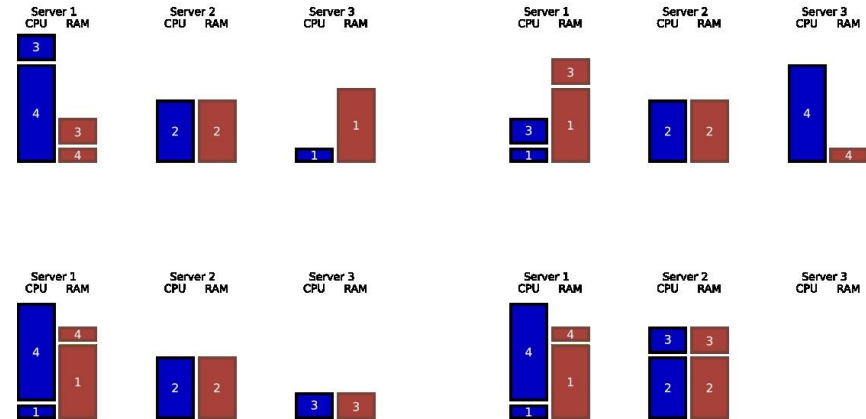
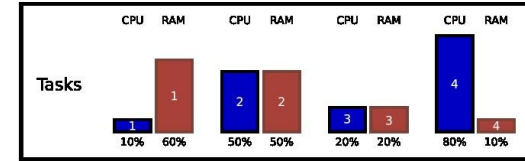


Improve the management : Consolidation

Virtualization techniques in data centers

Algorithms for

- Sharing the resources
- Move the applications where they impact less
- Switch off idle servers



Energy-aware service allocation



Improve the softwares: Eco-design

- I understand the number of software features
 - Avoiding bloatware
 - Data volume and digital sobriety
- I understand what I am doing
 - Detailed analysis of initial requirements
 - Behaviour measurement
- I favour open source: reusing and contributing to the commons
- I plan software management
 - Increasing lifespan
 - Continuous improvement

Je code : les bonnes pratiques en éco-conception de service numérique à destination des développeurs de logiciels





Decentralising the internet

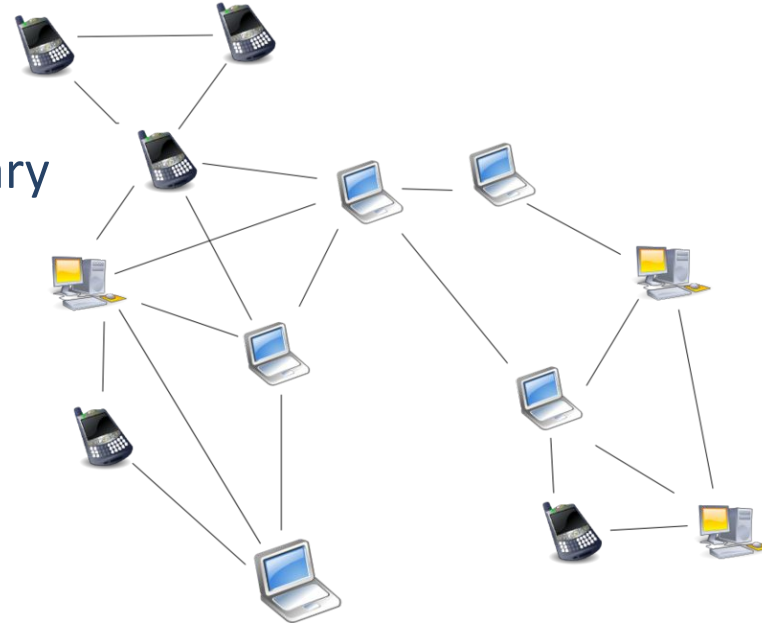
Web 3.0 but the real one

Direct communications without intermediary

- Less infrastructure
- More resilience
- Wifi-direct / Wi-Fi ad hoc

Blockchain

- Yes but in 5 years





Improve usage

Moderation in consumption does not mean renunciation.

Only use useful features.

- HD video on your phone?
- Back up all your photos for eternity?

Use appropriate means.

- 5G on the train?
- Cloud-only services?
- Photo transfer: Cloud or phone to phone?

Word processing, Presentation, Spreadsheet

Local	0.2 → 0.5W
Online	1.7 → 7.8W
Offline with saves	.8 → 2.9W





Taking action

At the personal level

- Do not increase the rate of equipment ownership.
 - Mutualise (smartphone = Swiss Army knife) and sharing.
- Extend the lifespan.
 - Reuse, repair.
 - Second-hand.
 - Consider when purchasing.
- Turn off unused devices.
 - Internet box (7 to 10W, equivalent to an energy-efficient refrigerator).
- Moderate usage
 - 4G consumes 23 times more than WiFi (especially on aeroplanes)
- Collect waste
 - Reused, repaired, recycled and decontaminated

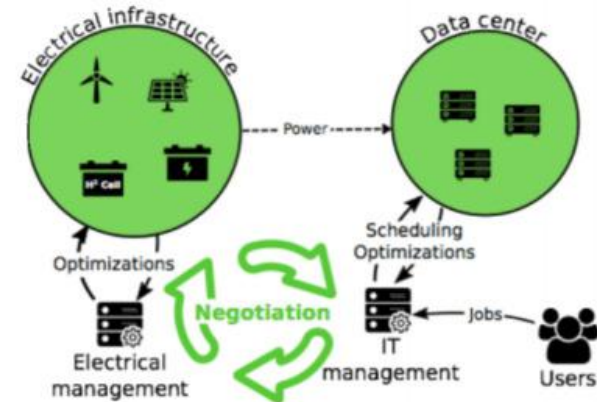




Scaling

At the institutional level (professional, academic, ...)

- Reduce equipment levels
 - One desktop or laptop computer is sufficient, as is one monitor
 - Reuse at end of life
- Manage travel
 - Carpooling, public transport, fleet of vehicles
- Aim for eco-design
 - Take it into account in your activity
 - Aim to reduce it as part of your activity
- Manage consumables.
 - Recycled paper, green electricity.
- Measure/evaluate.
 - LCA of an activity (not of software).





Some openings

A.I.

?





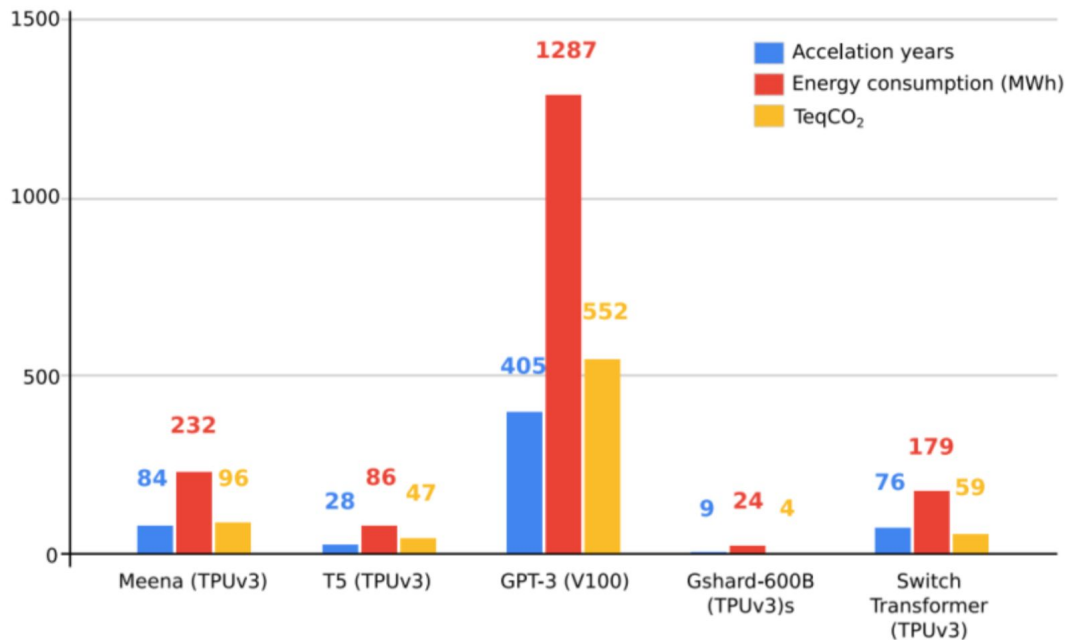
Artificial intelligence

Deep Learning

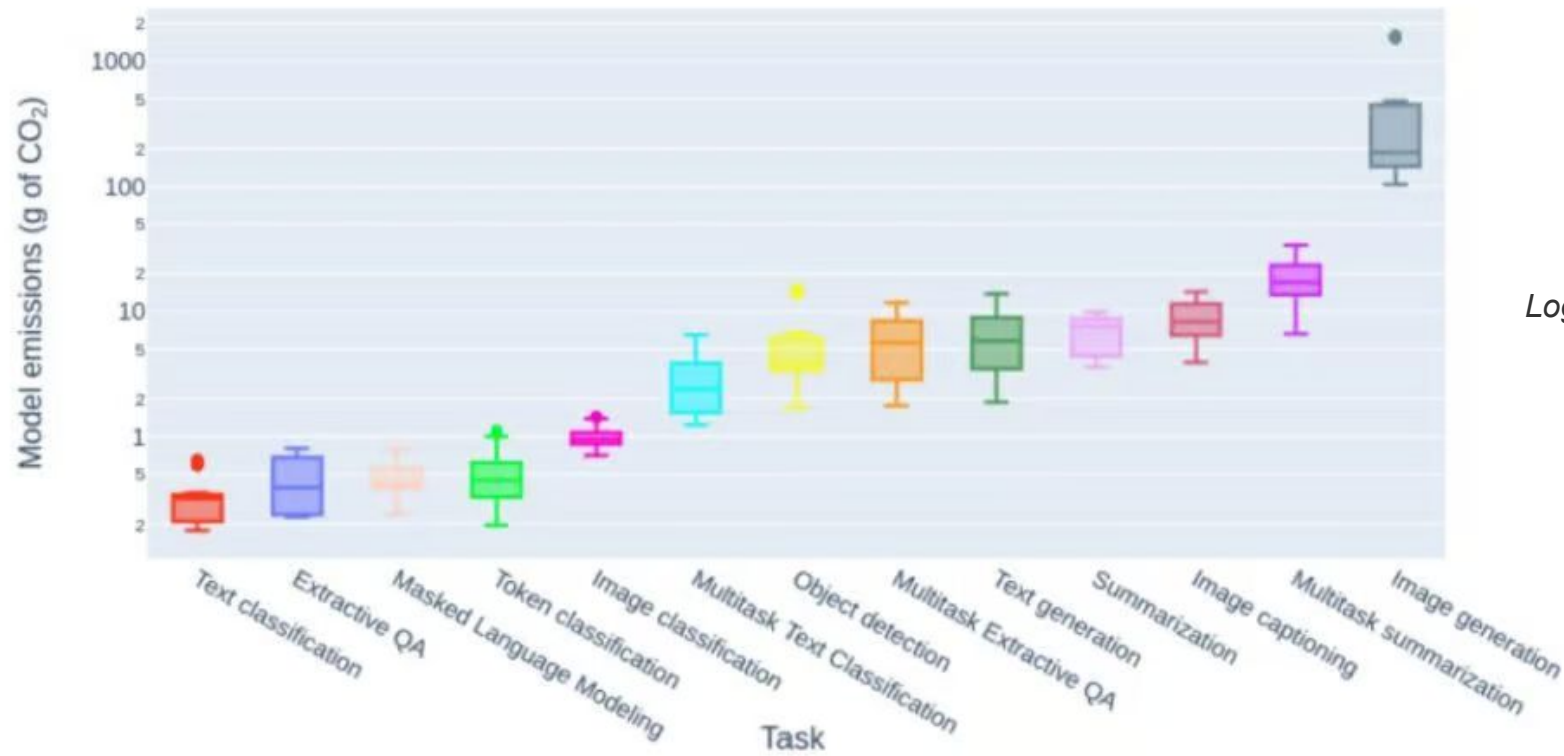
GPT-3

- Creation and synthesis of documents
- $1\text{TeqCO}_2 = 1$ return trip Paris-New York
- 100k€ of electricity

But “free” usage



More details on A.I. phases





Some openings

Low Tech Internet

?





Keep It Simple Stupid

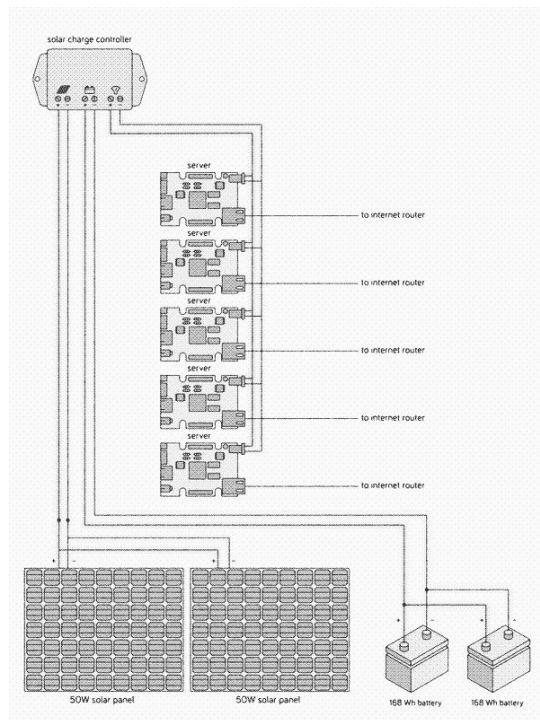
Low tech magazine

Optimization

- Software
- Hardware

Simplification

- Capacity
- Expectation



LOW ← TECH MAGAZINE

Ce site fonctionne à l'énergie solaire, et se retrouve parfois hors-ligne *
MENU



Le site imprimé : premier volume en français

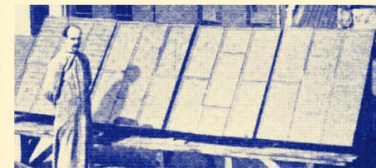
Lisez Low-tech Magazine sans avoir besoin d'un ordinateur, d'internet ou d'une alimentation électrique – ou quand le site internet solaire est hors service à cause d'une mauvaise météo.

March 2022



Les Matelas-Fascines : la Vannerie se Déchaîne

Taille de la page: 620 884 D



Comment fabriquer un panneau solaire low-tech

<https://solar.lowtechmagazine.com/>



Keep It Simple Stupid

Live sports results

Purely software optimization

- 23 matches
- 300kB transferred from one server
 - Estimation for a mail: 75kB on average
- 3 round-trips
- Simple to display (eq. 0g CO₂)

<https://plaintextsports.com/>

Page loaded: 9:03:47 PM (~5 seconds ago)
Data loaded: 9:03:36 PM (~20 seconds ago)

plaintextsports.com

Dark Mode

< Apr. 2

Sunday, April 3

Apr. 4 >

Leagues: [NBA](#) [NHL](#) [MLS](#) [NWSL](#)

College: [NCAA WB](#) [NCAA MB](#)

NCAA Women's Basketball Tournament

Game links open ncaa.com in a new tab

Fri		Final	Fri		Final
1	S CAR	72	1	STAN	58
1	LOUIS	59	2	UConn	63

Sun 2:00 AM GMT+2	
1	S CAR 34-2
2	UConn 30-5

[See all NCAA Women's Basketball games](#)

National Basketball Association

[Teams](#) [Standings](#)

Q4 08:14		Q4 06:03	
DAL	93	WAS	91
MIL	91	BOS	126

9:30 PM GMT+2		11:00 PM GMT+2	
DEN	46-32	DET	22-56
LAL	31-46	IND	25-53



Some openings

Rebound effect

?





Rebound effect (Jevons paradox)

improved coal efficiency → increased consumption

Type of effect	Level of influence	ICT as a solution	ICT as a problem
1st order (direct)	ICT itself	Producing more with less	ICT life cycle: Production, Use, End of life
2nd order (indirect)	ICT applications in other sectors	Optimisation effects, substitution effects	Induced effects
3rd order (systemic)	Social change	Profound structural change towards a dematerialised economy	Rebound effects, new critical information infrastructures



What rebound effects have you experienced in your use?





Some openings

Bitcoin, blockchain, NFT

?

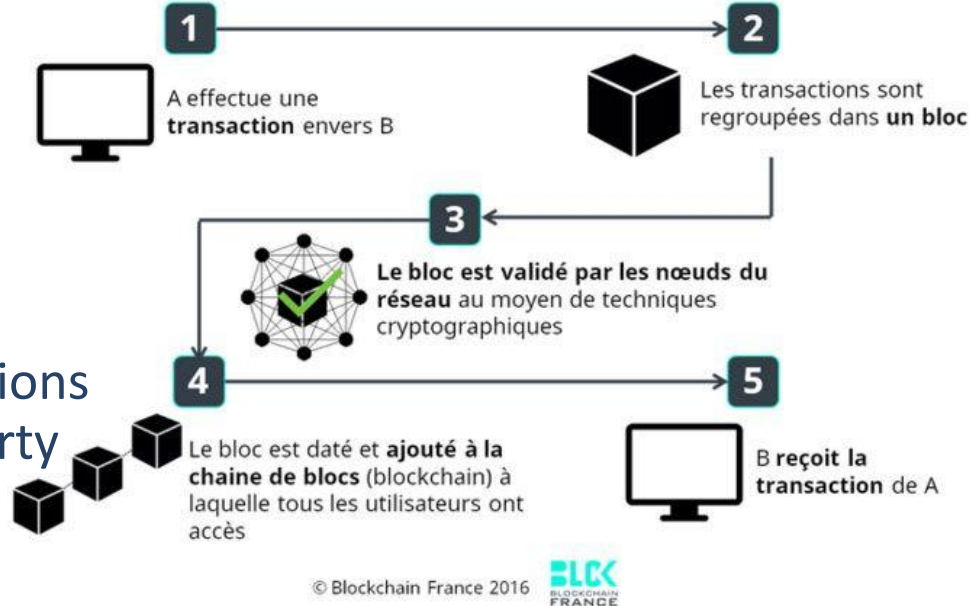




Bitcoin / NFT

BlockChain principe

- Information storage/transactions
- Replaces the trusted third party
- All participants
 - Record all transactions
 - Verify all transactions
 - Often, 'verifying' provides a benefit
- Bitcoin:
 - Transactions: transfer internal value (divisible)
- NFT:
 - Transaction: transfer an internet address



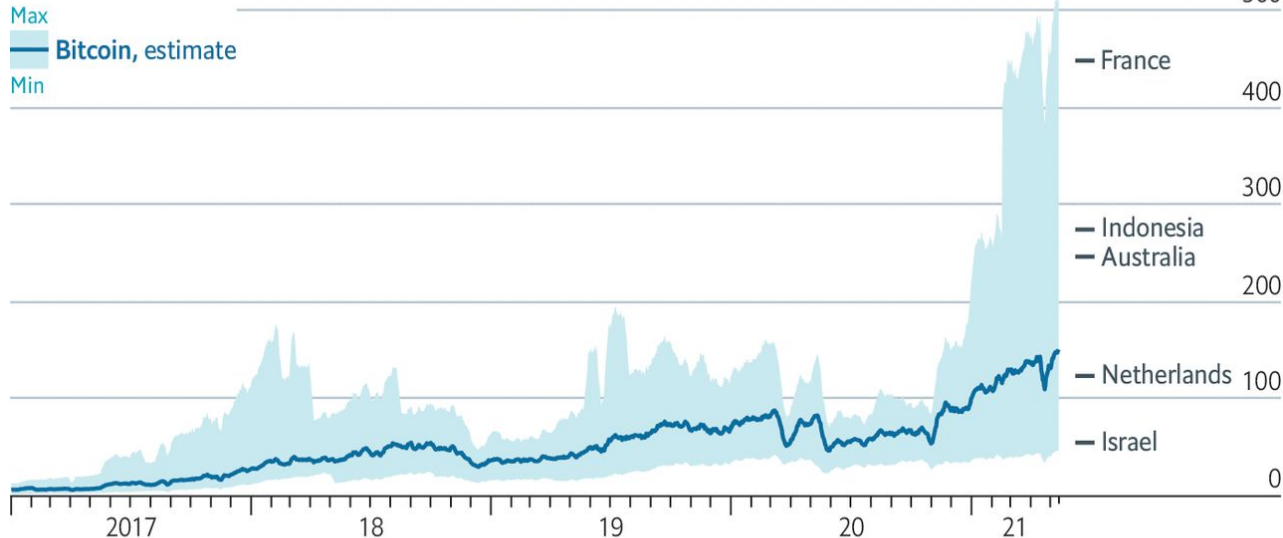


Bitcoin / NFT

Bitcoin : 1,000,000 bitcoin miners

Power hungry

Electricity consumption, terawatt-hours, annualised



Source: Cambridge bitcoin electricity consumption index

The Economist



Intrinsic value

Creating uniqueness

Value of a

- BitCoin
- NFT





Bitcoin / NFT

Adding value to what can be copied for free

Affluent society, zero marginal cost

Culture: Ian M. Banks

- Virtually infinite resources and colonialism

The Diamond Age: Neal Stephenson

- Hierarchical (noble) control of resources

Star Trek

- Replicator and altruistic vision and colonialism

In the real world: Promise of fusion





Some openings

Video Games

?





The rise of mobile

A new category, new usages

Overall market stability

- PC, Console

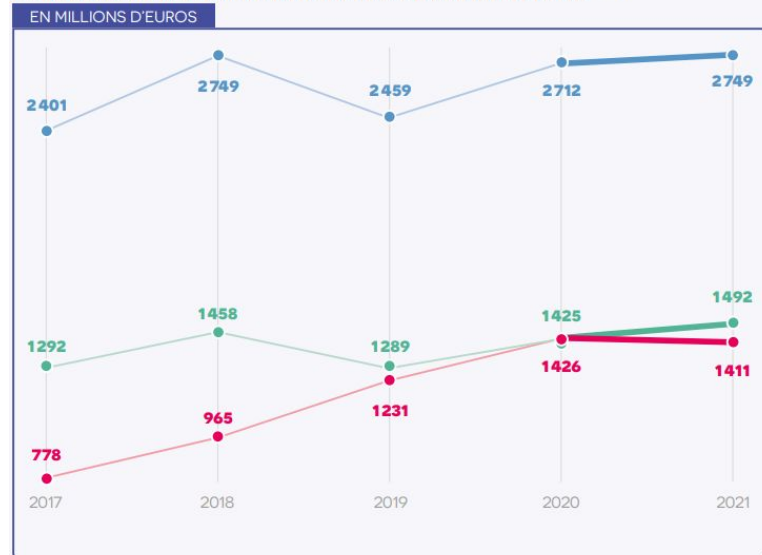
Strong growth in the mobile market

- x2 in 5 years

SELL 2021



ÉVOLUTION DU CHIFFRE D'AFFAIRES PAR ÉCOSYSTÈME****





Cloud gaming

Everything is done in a data centre; only the display and interaction are local.

Complex subject matter

Positive

- Servers 100% utilised
- Modular vision

Negative

- Hidden costs
- Additional network costs
- Rebound effect

2020: 36 million players

2022: £3.2 billion market





Augmented reality / Virtual reality

Still as complex as ever

Positive

- Fewer materials than a large television

Negative

- Double the processing (resolution, latency)





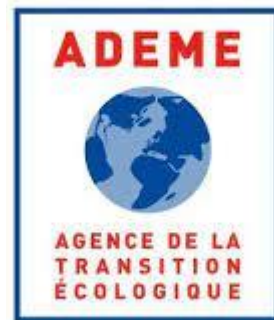
Thanks



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Super thanks to Denis Trystram