



Digital technologies : Environmental issues, rebound effects

Bruno Gayral

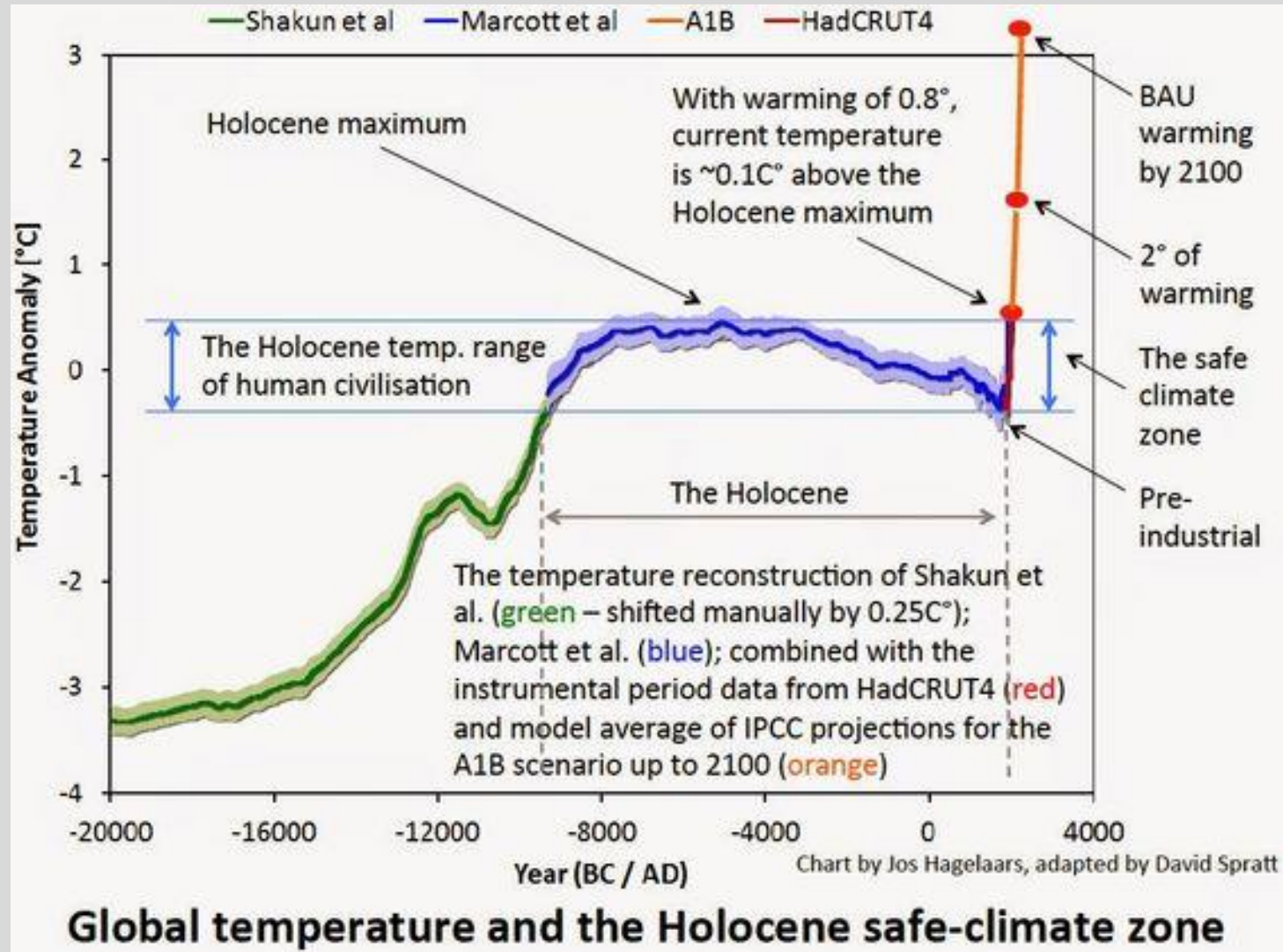
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Becoming resilient in a world exposed to unprecedented systemic risk

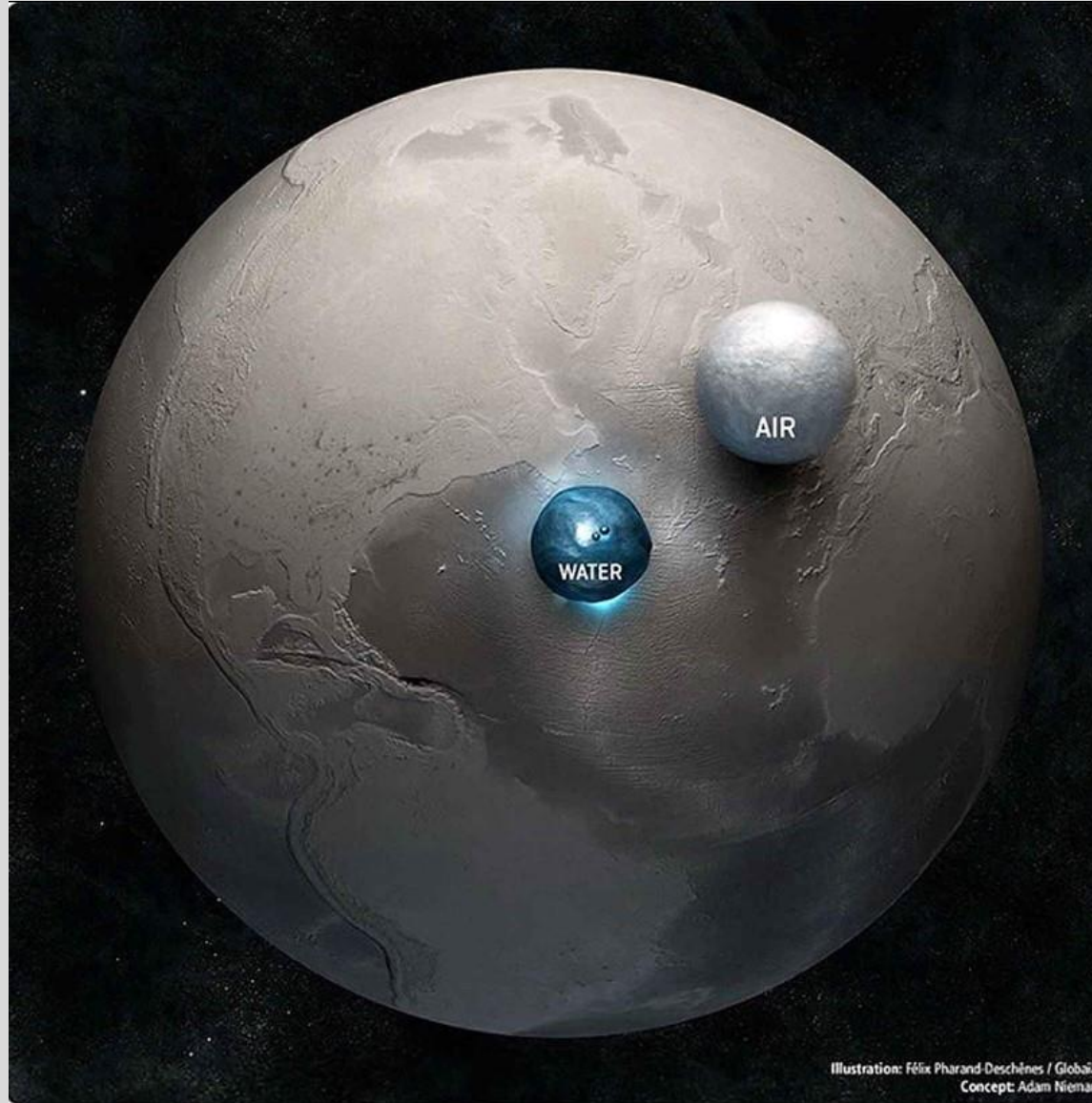
Arthur Keller

The context



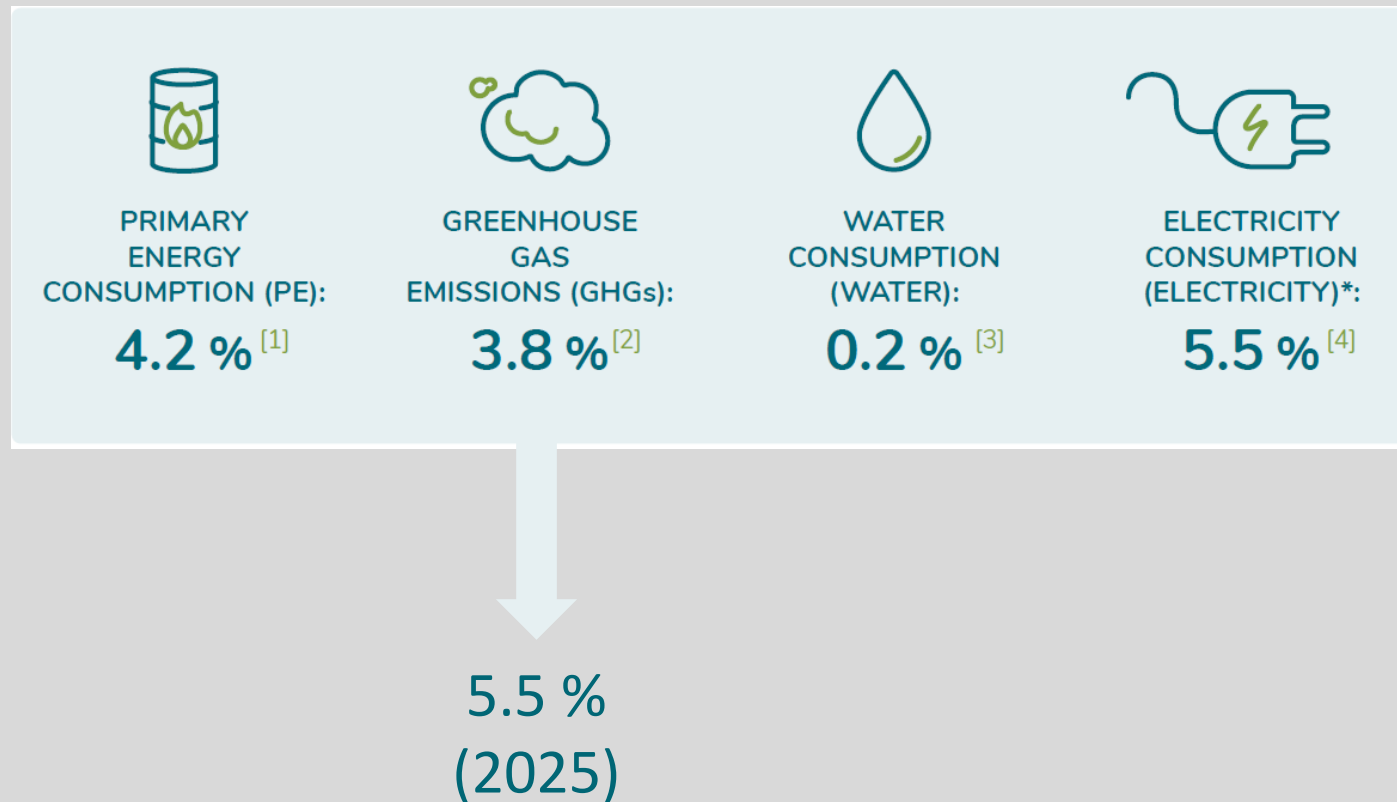
Adapted from Jos Hagelaars, David Spratt

The context








ICT and environmental issues

Environmental footprint of digital technologies



ICT and environmental issues

Environmental footprint of digital technologies

%	 Energy	 GHG	 Water	 Elec.	 ADP
User equipment	60%	63%	83%	44%	75%
Network	23%	22%	9%	32%	16%
Data centres	17%	15%	7%	24%	8%

Abiotic Depletion Potential

Mostly manufacturing

Decreasing impact

1. Manufacturing of user equipment;
2. Power consumption of user equipment;
3. Power consumption of the network;
4. Power consumption of data centres;
5. Manufacturing of network equipment;
6. Manufacturing of equipment hosted by data centres (servers, etc.).

Use devices as long as possible !!!
...obsolescence (technical, technological, cultural...)

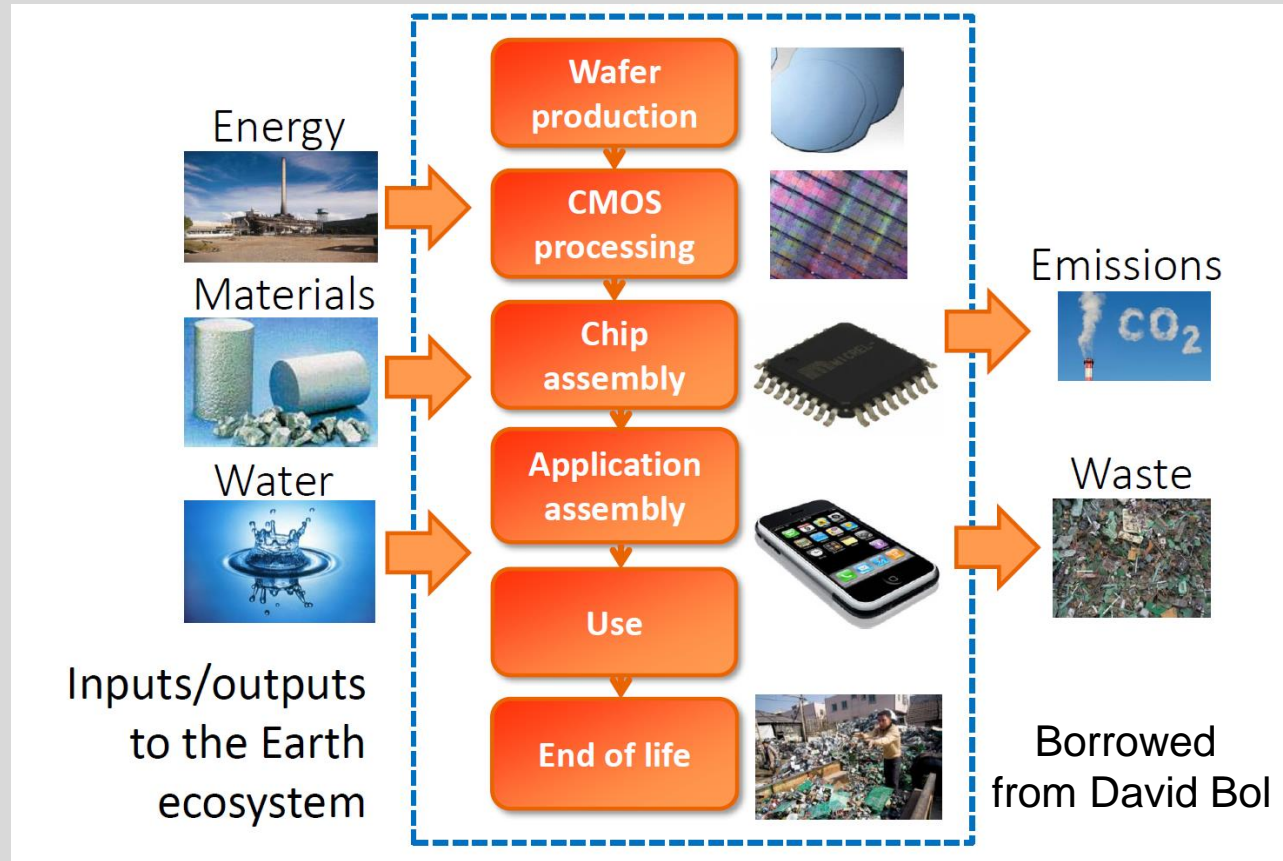


Before Gen-AI !!!

GreenIT, « Environmental footprint of the digital world » 2019

ICT and environmental issues

Environmental impact not restricted to CO₂ emissions !!!



Environmental impact not restricted to CO₂ emissions !!!

EDITORS' PICK

No Water No Microchips: What Is Happening In Taiwan?

Emanuela Barbiroglio Senior Contributor 
I write about sustainability

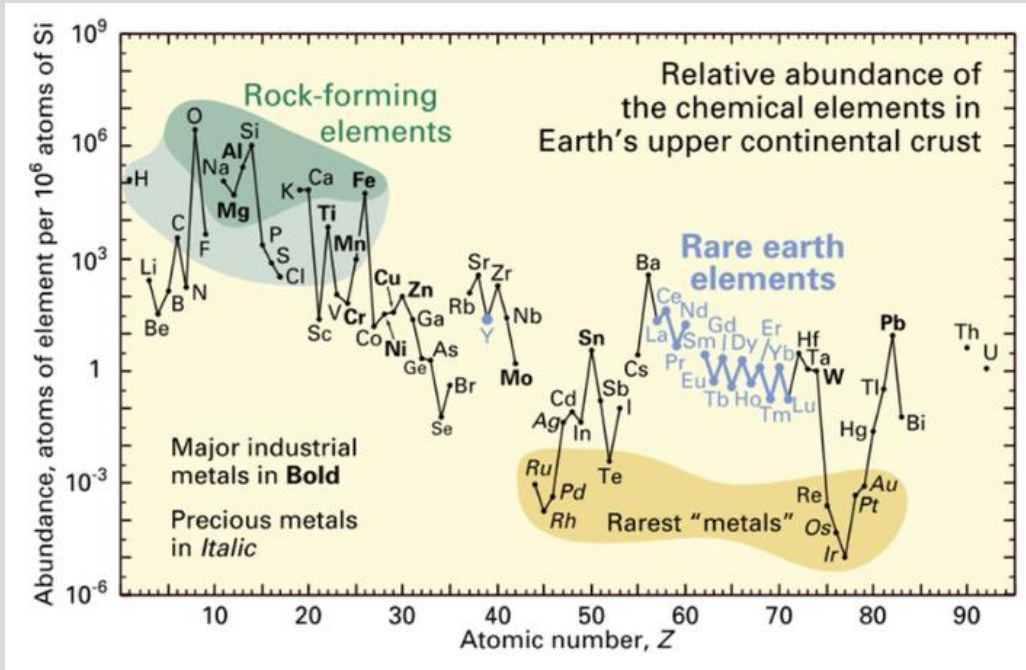
May 31, 2021, 05:09pm EDT

FROM DAVID BOI

Follow

TSMC needs 150 000 m³ water each day, up by 70 % between 2015 and 2019
2021 : water restrictions due to 20 % decrease in rainfall

ICT and environmental issues : metals



16 PERIODIC TABLE OF MOBILE PHONE ELEMENTS

KEY

- Screen: Includes touch screen, glass, and colour sources
- Battery: Includes battery electrodes, electrolyte and casing
- Processor, electronics & components: Includes wiring, silicon chip, microphones and speakers
- Casing: Includes materials in the phone's external casing

1 H Hydrogen	2 He Helium	3 Li Lithium	4 Be Beryllium	5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium	13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon	19 K Potassium	20 Ca Calcium
21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc
31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton	37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium
41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin
51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon	55 Cs Cesium	56 Ba Barium	57 La-Lu Lanthanum-Lutetium	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium
61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium
71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury
81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon	87 Fr Francium	88 Ra Radium	89 Ac Actinium	90 Th Thorium
91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium
101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium
111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson		



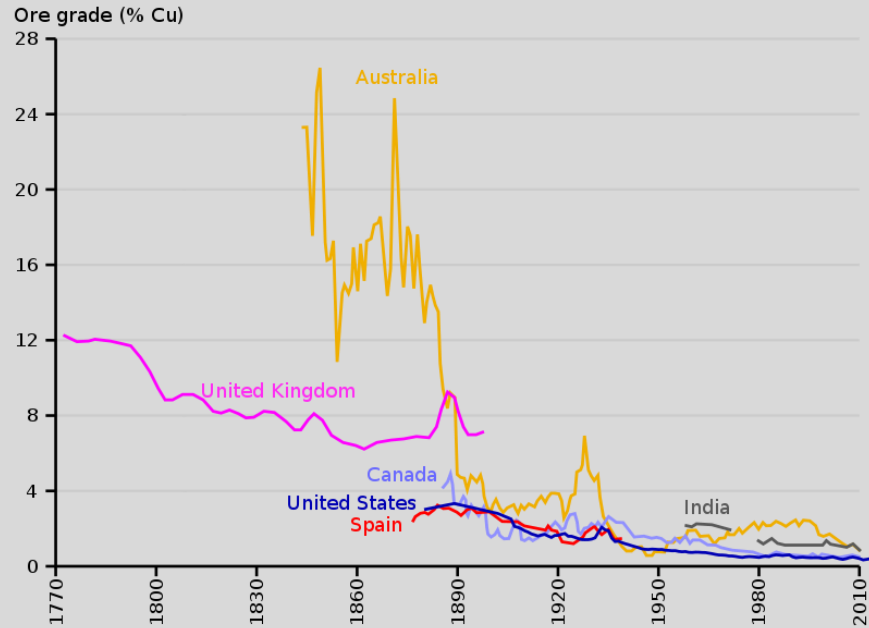
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#IYPT2019

56 elements !!!

ICT and environmental issues : metals



8 kg/capita.year



ICT and environmental issues : metals

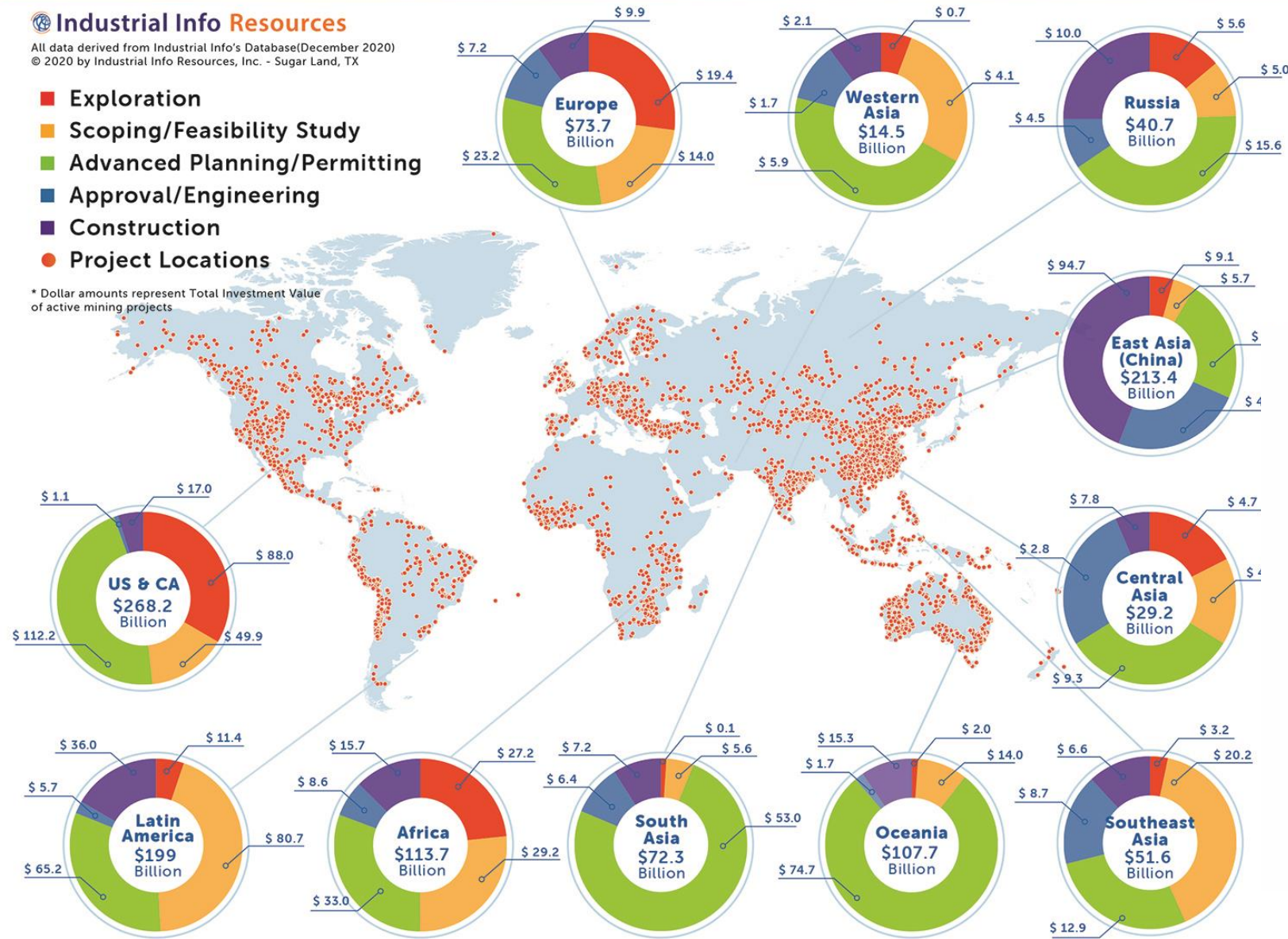
GLOBAL MINING PROJECT DEVELOPMENT

Industrial Info Resources

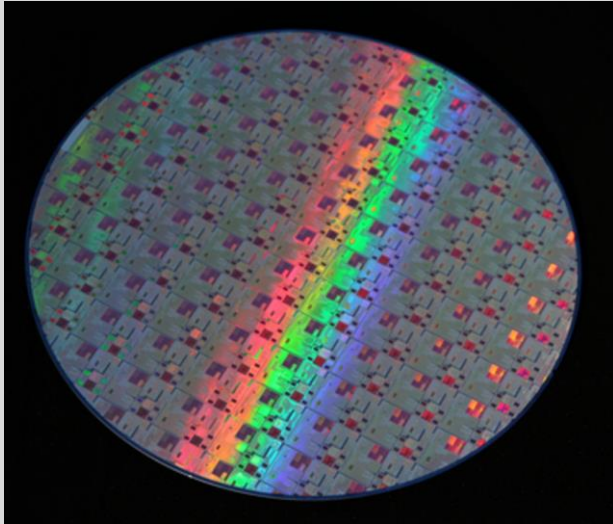
All data derived from Industrial Info's Database(December 2020)
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- Exploration
- Scoping/Feasibility Study
- Advanced Planning/Permitting
- Approval/Engineering
- Construction
- Project Locations

* Dollar amounts represent Total Investment Value of active mining projects



The "miracle" of microelectronics



© ST Microelectronics

Moore's Law: The number of transistors on microchips doubles every two years Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

Transistor count

50,000,000,000

10,000,000,000

5,000,000,000

1,000,000,000

500,000,000

100,000,000

50,000,000

10,000,000

5,000,000

1,000,000

500,000

100,000

50,000

10,000

5,000

1,000

Year in which the microchip was first introduced

Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world's largest problems. Licensed under CC-BY by the authors Hannah Ritchie and Max Roser.

Fair enough, what about energy consumption ???

Microelectronics and energy efficiency

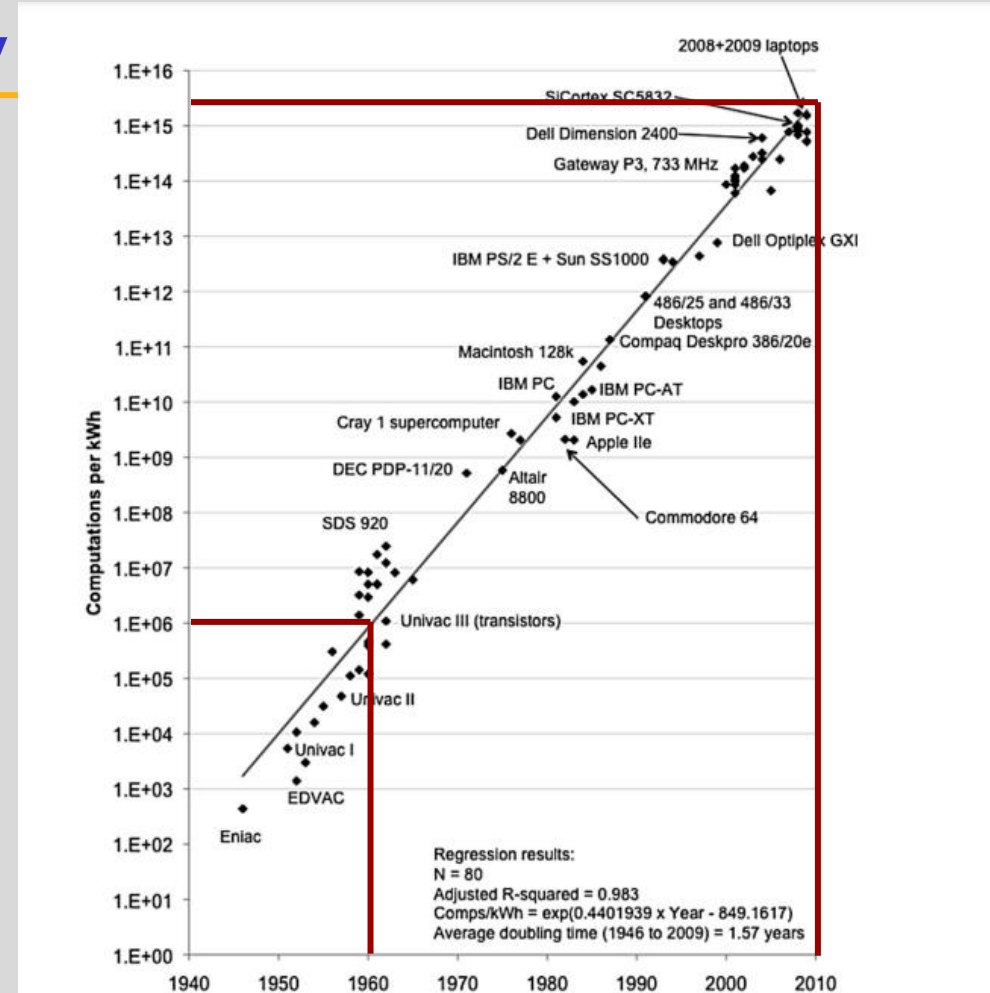
Koomey's law

⇒ Energetic efficiency doubling every 1.6 yrs
⇒ **10^9 increase** 1960 - 2010

⇒ Yet the GHG (Green House Gas) emissions linked to ICT increase (~ 4 % in 2019, ~ 5.5 % in 2025....)

Energy efficiency => Energy savings

???

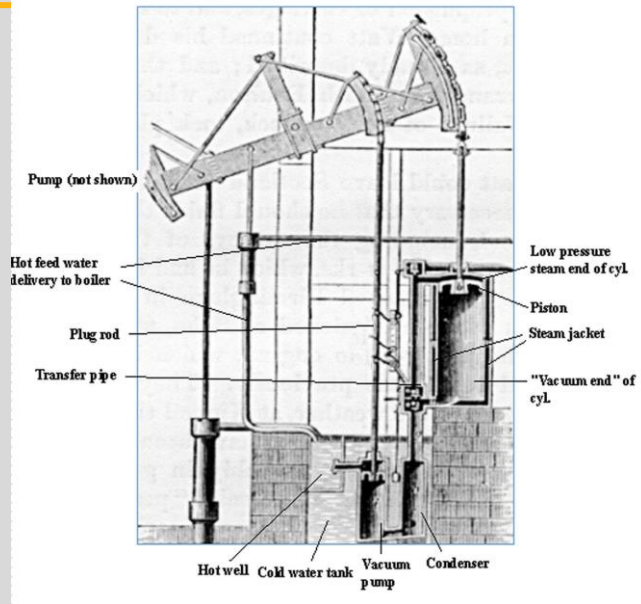


J. G. Koomey et al.,
IEEE Annals of the History of Computing, **33**, 46 (2011)

=> **Rebound effects** (cf *Jevons paradox*)

S.W. Jevons "The Coal Question: an Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-mines." 1865

Jevons paradox



1776

Watt steam engine => more efficient

More and more
efficient machines



Less coal for
a given work



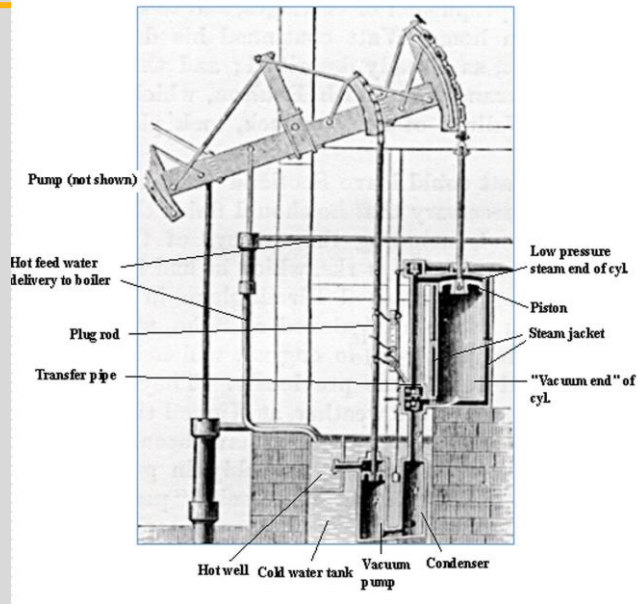
Will our coal reserves
last longer ?

S. W. Jevons : « The coal question, : an Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-mines. » (1865)

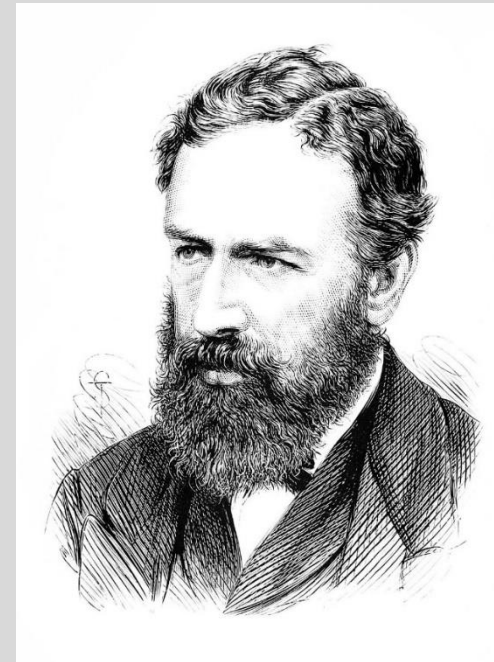
Jevons paradox

1776

Watt steam engine => more efficient

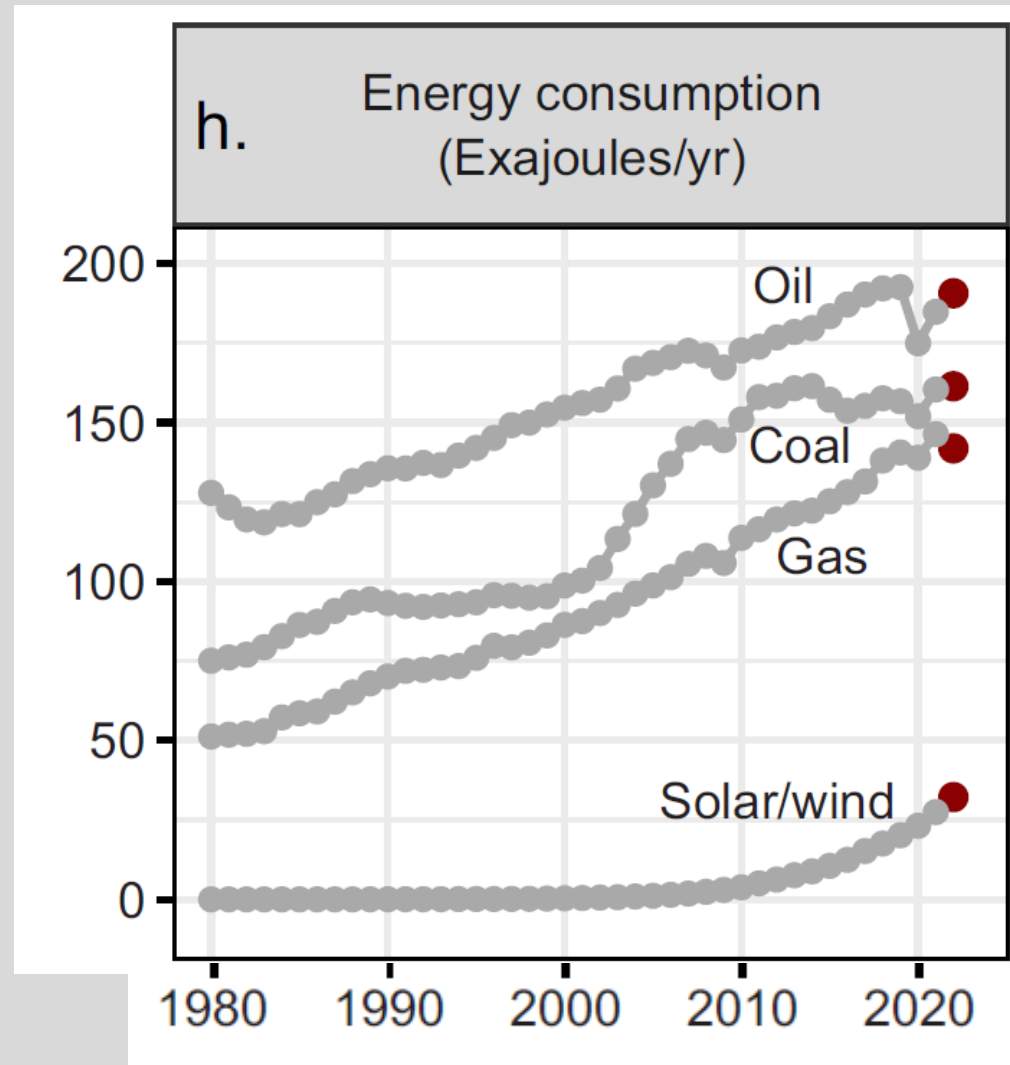


“It is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption.
The very contrary is the truth.”



S. W. Jevons : « The coal question, : an Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-mines. » (1865)

Coal consumption...



W.J. Ripple *et al.* "The 2023 state of the climate report: Entering uncharted territory", Bioscience **0** p 1 (2023)

Rebound effect : a short introduction

Defining the rebound effect :

- *Improvements in the technical efficiency of energy use that has a smaller energy-saving effect than predicted by engineers*

D.J. Khazoom "Economic implications of mandated efficiency standards for household appliances" , Energy J. 1 21 (1980)

Energy consumption

Energy per unit

$$C = \mu N$$

Units consumed

Technological innovation

$$C = (g\mu)(aN)$$

Technological efficiency gain

"Behavioral" consumption change

Rebound effect

$$R = \frac{g(a - 1)}{1 - g}$$

Jevons paradox

$R=0$: full technological gain

$0 < R < 1$: usual case

$1 < R$: back-fire

Rebound effect : a short introduction

Typical example : car consumption

8 l/100 km \Rightarrow 6 l/100 km

Direct rebound effect : - more driving (can even backfire !)

Indirect rebound effect : - less fuel consumption but transfer to other energy intensive consumption
- overall increase in car sales

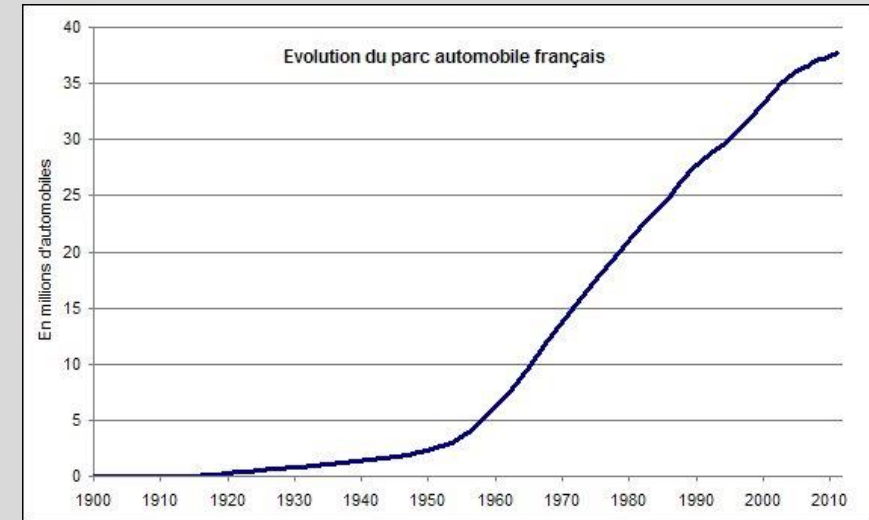
Frontier effect : - more cars/distance \Rightarrow more roads, more malls etc...



570 kg, 8.2 l/100 km
1963



1300 kg, 5.2 l/100 km
2019



Rebound effects and semiconductor technologies

Energy efficiency gains come with other benefits :

Microelectronics : faster clock rates

Datacom : faster bit-rate

LEDs : - Much more flexibility for lighting
- Display back-lighting
- Micro-displays for AR/VR

Large R&D & equipment investments + low marginal cost

Production volume is an economical necessity, *so are the various rebound effects*

Pervasive technologies => large frontier/induction effects

=> Consumption enablers + Socio-economical transformations

The power and curse of the roadmaps

Why are roadmaps needed ?

- Complex supply chains => coordination needed between actors (+ standardization)
- Large investments => visibility (also on regulation side) + market forecast

Who decides ?

- Industrial stakeholders, sometimes governmental institutions
- Profoundly affects our economies and societies, hardly democratically debated (internet, smartphone, 5G, AI...)

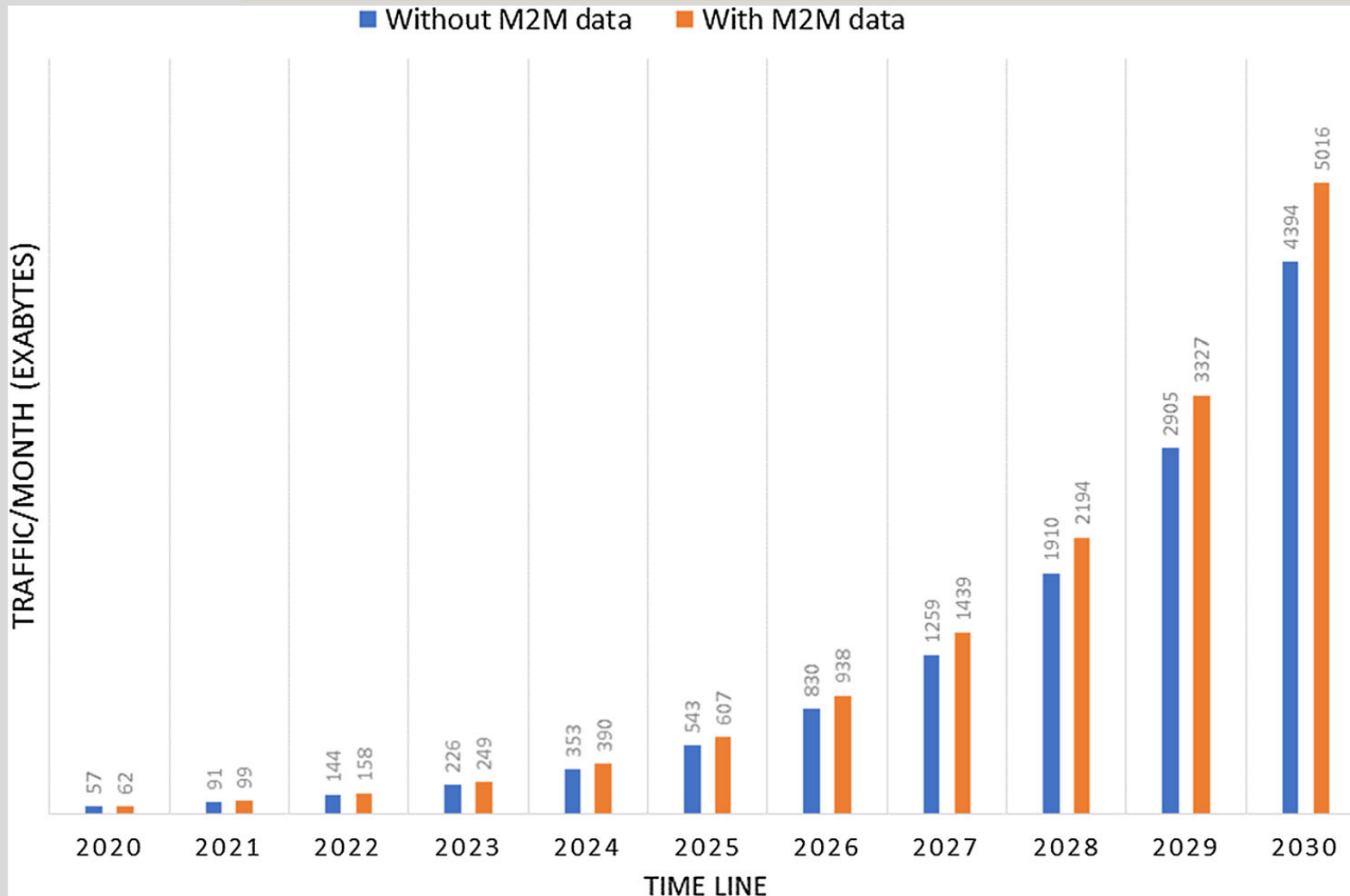
From the viewpoint of research

- Take the deployment roadmap as a « given » => any technological efficiency gain considered as an energy saving

OR

- Question the roadmap ? Anticipate ? Regulate ?

The power and curse of the roadmaps



Exponential increase
(doubles every 1.7 years)

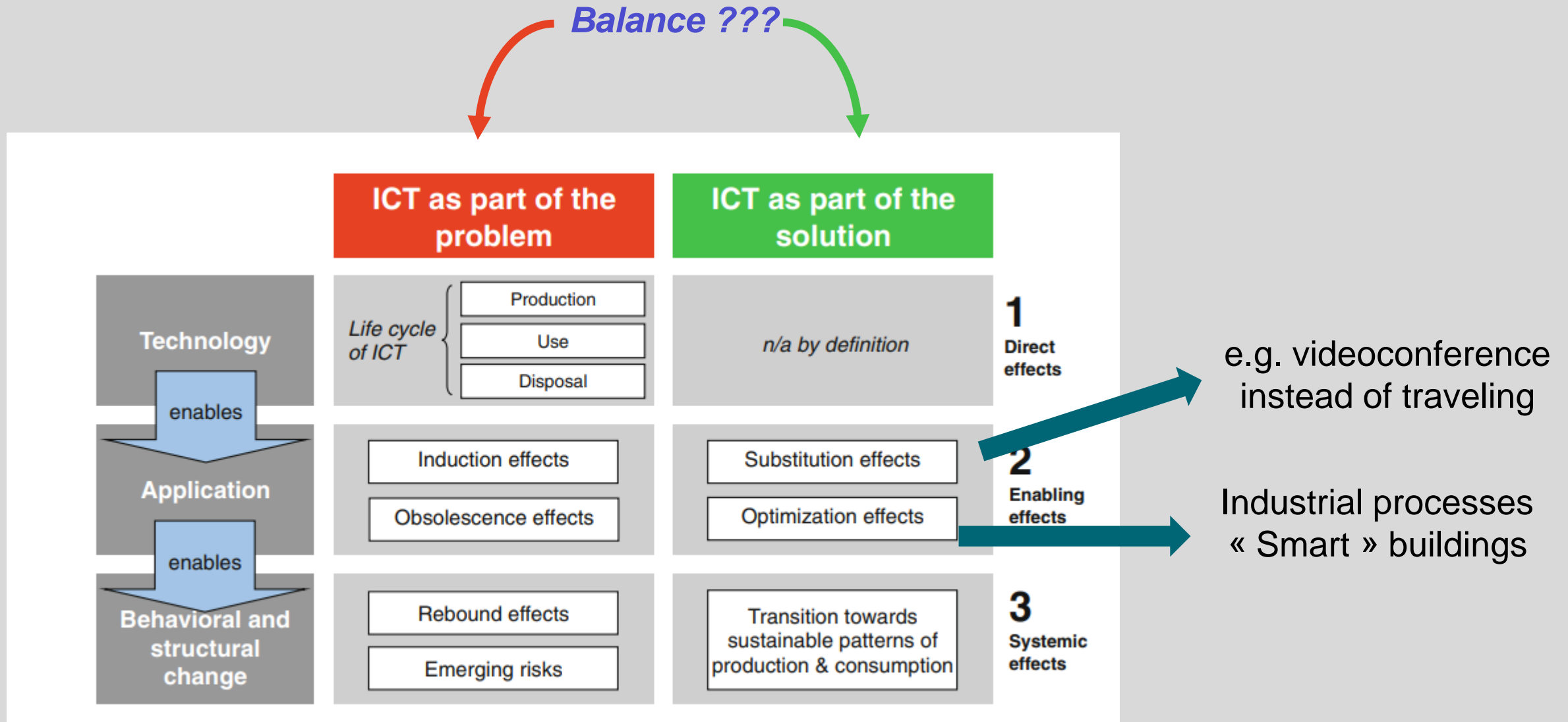
A linear efficiency improvement
yields an exponential energy saving !

S. Rajoria and K. Mishra "A brief survey on 6G communications"

Wireless Networks **28** 2901 (2022)

Report ITU-R "IMT traffic estimates for the years 2020 to 2030" 2015

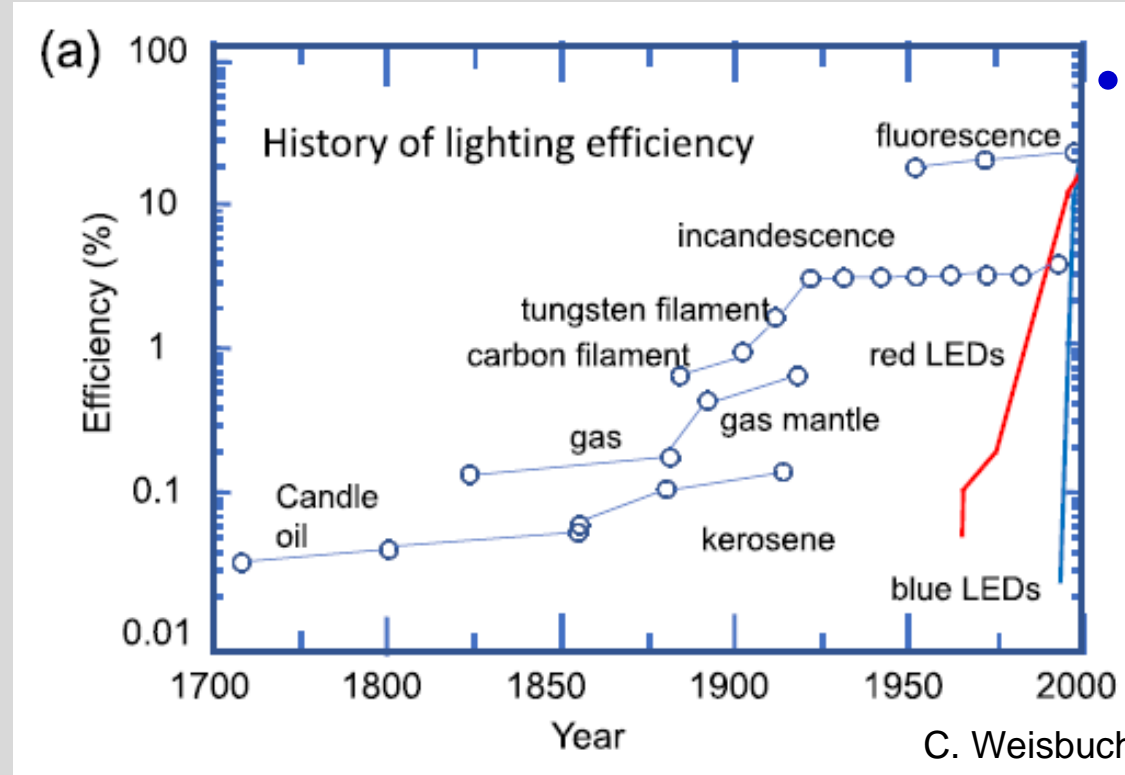
ICT and environmental issues



L. M. Hilty *et al.* in *ICT Innovations for Sustainability*, Springer, 2015

The issue of visible / white LEDs

- The LED is a technology with various use cases
- The most sought application is general lighting
- Lighting is "essential" for mankind (400 000 yrs of usage !)
- LEDs are the most energy efficient lighting devices



2014 : Nobel prize for for the invention of efficient blue light-emitting diodes which has enabled bright and **energy-saving** white light sources

Rebound effects and LED lighting : ex-post studies

Surprisingly few articles !!!

Possible LED lighting rebound effects :

- Lights less switched off

- More lighting fixtures overall

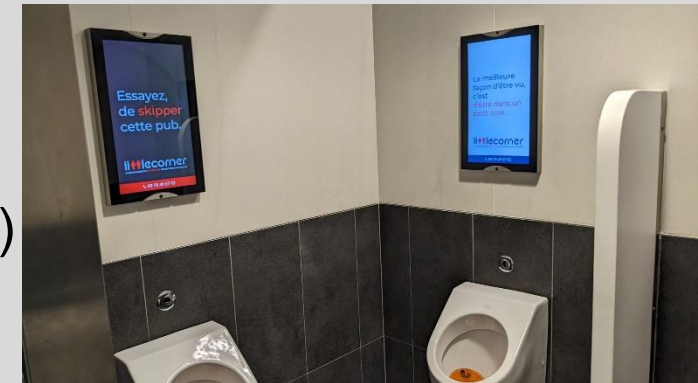
- More lighting due to expanded technological possibilities (colored lighting, architectural lighting...)



LEDs as a global technology

- Replacement + increased sales of various displays (TVs, PC screens....)

- LEDs for the automotive industry



LEDs for lighting

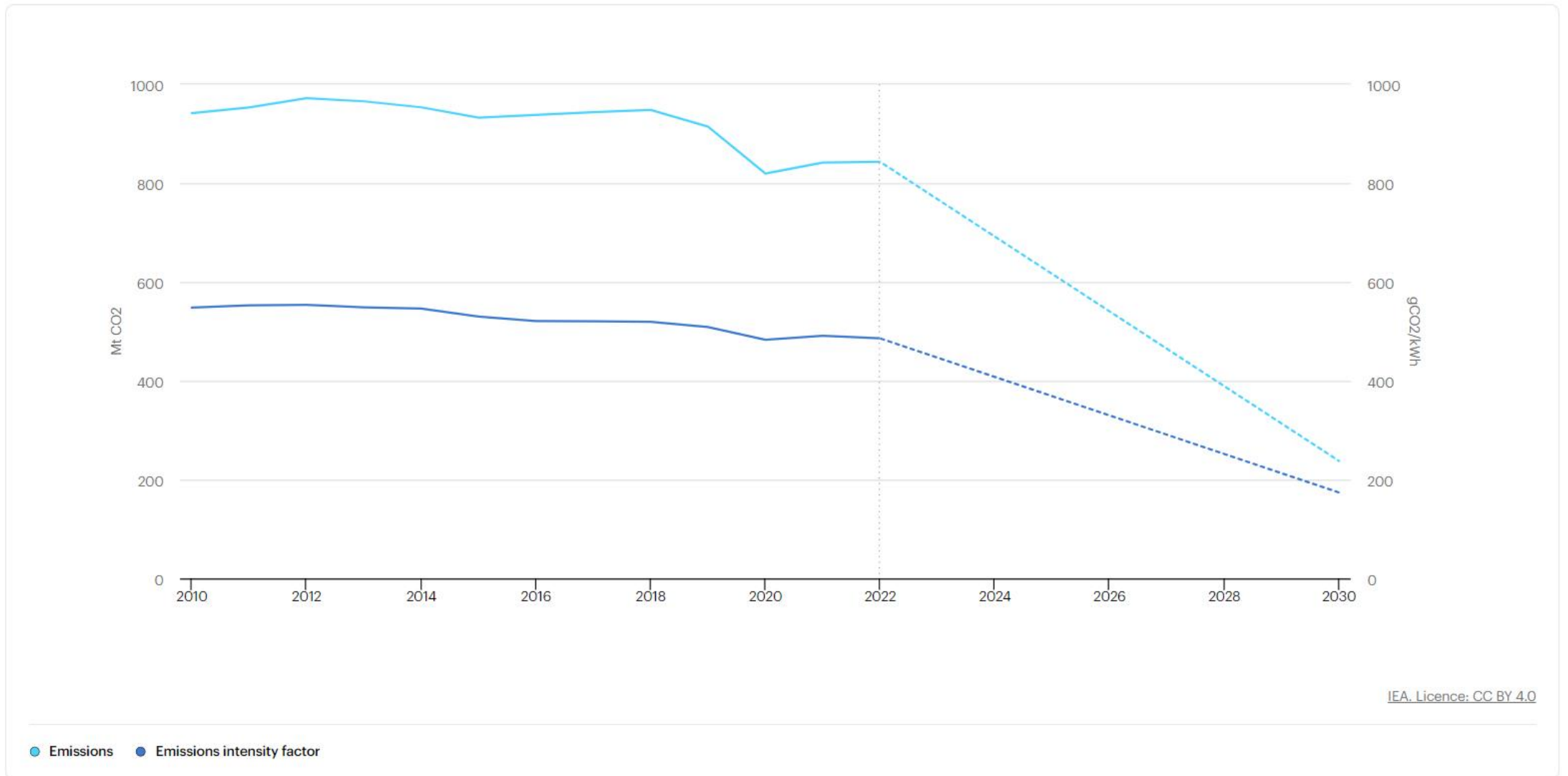
Has the LED technology for lighting resulted in energy savings ?

- ⇒ **Probably yes**, how much : ???? We have no idea !!!
- ⇒ Developing countries : *increase in lighting fixtures* for general lighting
- ⇒ Developed countries : *new lighting behaviors* due to LED peculiarities
 - ⇒ Decorative/architectural lighting, colored lighting...

Note : since the IL ban and switch to CFLs and then LEDs, no measurable inflexion in electricity consumption in Europe / USA

Conclusion : do we have an answer ?

Has the LED technology for lighting resulted in energy savings ?



Conclusion : visible LED technology and energy

Other applications of visible LEDs contributing to the rebound effect

Present

- *LEDs for large displays => more displays in public areas + TV replacement
=> Most carbon impact at manufacturing stage*

Future

- *Microdisplays for AR / VR
=> All ingredients for **major rebound effects**
=> Totally new use-cases
=> Very large diffusion expected
=> Rapid technological upgrades leading to frequent replacements
=> Very large frontier effects : will require more data transmission and storage*



Apple Vision Pro
3500 US\$ (2024)
3 screens
12 cameras



Conclusion : what do I make out of that ?

- *Go beyond simple ideas on the real-world impact of technology*

Energy efficiency does not imply energy savings !!!

"Dematerialization", "cloud", "virtual" => misleading

=> ICT is quite "material" (terminals, data centers, telecom infrastructures...)

Environmental impacts of ICT are diverse (CO₂, pollution, abiotic depletion...)

=> Beware of impact transfer !

More systemic (vs silo) thinking + culture

Humbly accept that the "energetic transition" *is not mainly a technical issue to be solved*

- *Be cautious concerning claims about the environmental impact of technology*

It is largely a question of usage => difficult to assess !

Green technology

At most : state that a new technology has a **potential** for energy savings

Questions worth asking

On a topic supposed to be important (LEDs and energy savings), why don't we have more ex-post studies ?

=> We don't know how to measure ?

=> We don't care ?

=> We don't want to know ?

Would the business model of replacing every lamp in OECD countries by 25 000 hours lifetime LEDs make sense ?



~20 years, 3 hours a day

Neutrality and impartiality

Impartiality : grounds to accept a result / hypothesis

=> « pure science », the way it is done in a particular context

Neutrality : related to the implications, consequences of a choice/decision

=> You expect judges to be impartial, but their decisions are not neutral !

By definition, research, teaching should ideally be impartial

Are science, research, teaching etc... neutral ???

Credit : S. Ruphy, "S'engager par le choix de ses sujets de recherche : enjeux épistémologiques et politiques« Séminaire d'Alembert 2023

The neutrality paradoxical injunction

- Researchers have a strong incentive to brag about the socio-economical implications and potential use-cases of their research
=> *Responsibility* for the possible outcomes of their research
- Fundamental research is often justified by unexpected applications of « blue sky science » (iconical example : the laser)
=> *Irresponsibility* for the possible outcomes of their research

Examples of non-neutrality

In public research

- Funding particular fields of science (corollary : not funding particular fields of science)
- Making (or not) a partnership with an industrial
- Making (optimistic) statements about potential applications and socio-economical consequences
- Teaching a lecture on « Technology and society » at a summer school !

More generally in technology

- The build-up of industrial roadmaps and corresponding investments

The paradox of fundamental research

- Strong incentive to brag about positive socio-economical consequences and vertuous usage cases of our research
⇒ *Responsibility* concerning the consequences of the research
- Fundamental research is often justified by the possibility of unexpected applications (iconic example : the laser)
⇒ *Irresponsibility* concerning the consequences of the research

The technological promise

"Creating a horizon of expectation where the new technology appears as a necessity"

"Promoters strive to demonstrate that the new technology is the solution of important societal problems, thus translating it into an obligatory passage point."

P.-B. Joly and C. Le Renard "The past futures of techno-scientific promises", *Sci. Public Policy* **48** 900 (2021)

The global context : Social control of technology/Governance of science

Collingridge dilemma :

"Attempting to control a technology is difficult...because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development; but by the time these consequences are apparent, control has become costly and slow" ("The social control of technology", 1980)

=> How does this question the discourses about potential impacts of our research ?

Claims about the impacts of innovation...

It is not in our hands => we have no idea !

The grant system pushes us to make over-optimistic claims about our research's impact

Techno-scientific promises have been around for a long time

=> Who is accountable ?

=> Does it act as a disincentive to socio-economical transformations ?

=> Can it have an impact on the credibility of the scientific community ?

We tend to be rigorous in the practice of our research (integrity) but quite biased and sloppy when discussing its impacts (ethics issue ?)