Université Paris Cité

Dézombifier les technologies numériques

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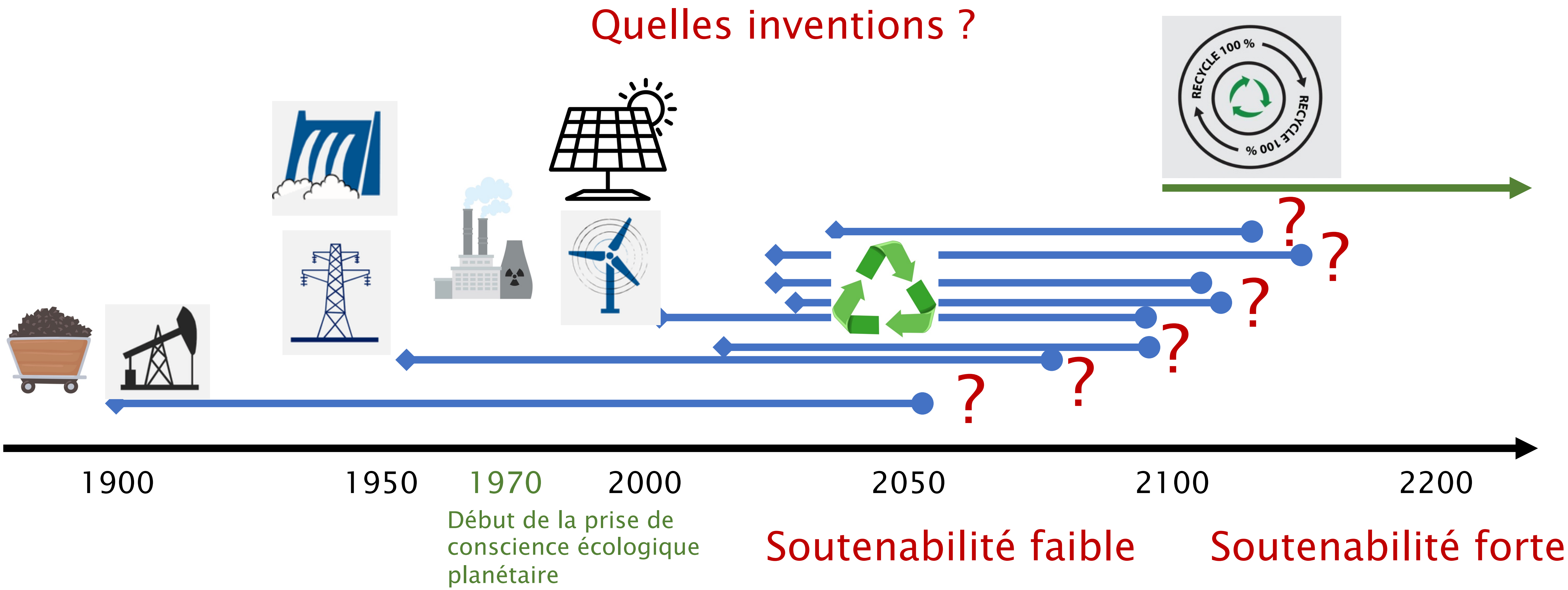
La soutenabilité des technologies planétaires?

- Soutenable: (a) Qu'on peut défendre au moyen de raisons recevables. (b) Qui peut être supporté.
- Durable: Qui présente les conditions requises pour durer longtemps, qui est susceptible de durer longtemps.
- Scénario « business as usual »: faire perdurer le monde actuel le plus longtemps possible.
- Soutenabilité forte: qui peut durer au-delà du 21e siècle et sur plusieurs siècles.
- Soutenabilité faible: qui ne dure que pendant le 21e siècle et pas au-delà des siècles suivants.
- Les technologies modernes sont planétaires.

Successions d'inventions dont la soutenabilité augmente?



Inventer des technologies soutenables selon quels critères?

Les systèmes techniques

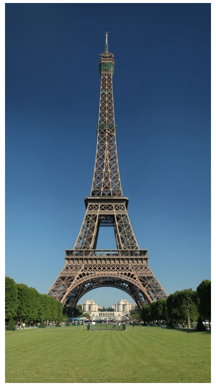
Il existe une **interdépendance** entre les matériaux et les sources d'énergie.

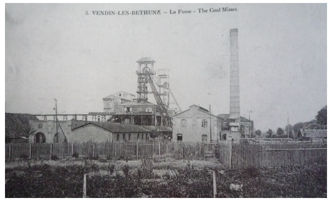
L'utilisation des **combustibles fossiles** modifie la **nature des matériaux et les quantités produites**, en raison des interactions entre les matériaux, la **puissance** (l'énergie concentrée), les techniques et les nouvelles institutions.

Un système technique est constitué d'un ensemble de techniques et de technologies associées, de matériaux, de sources d'énergie, de savoir-faire, d'institutions, de pratiques et de normes sociales, et de régimes socio-économiques.







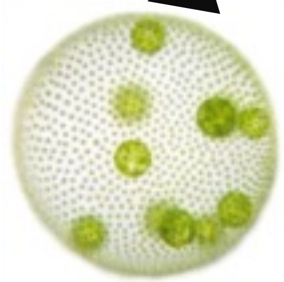






Metabolism

Set of physical-chemical processes that maintain and operate the system

organisms



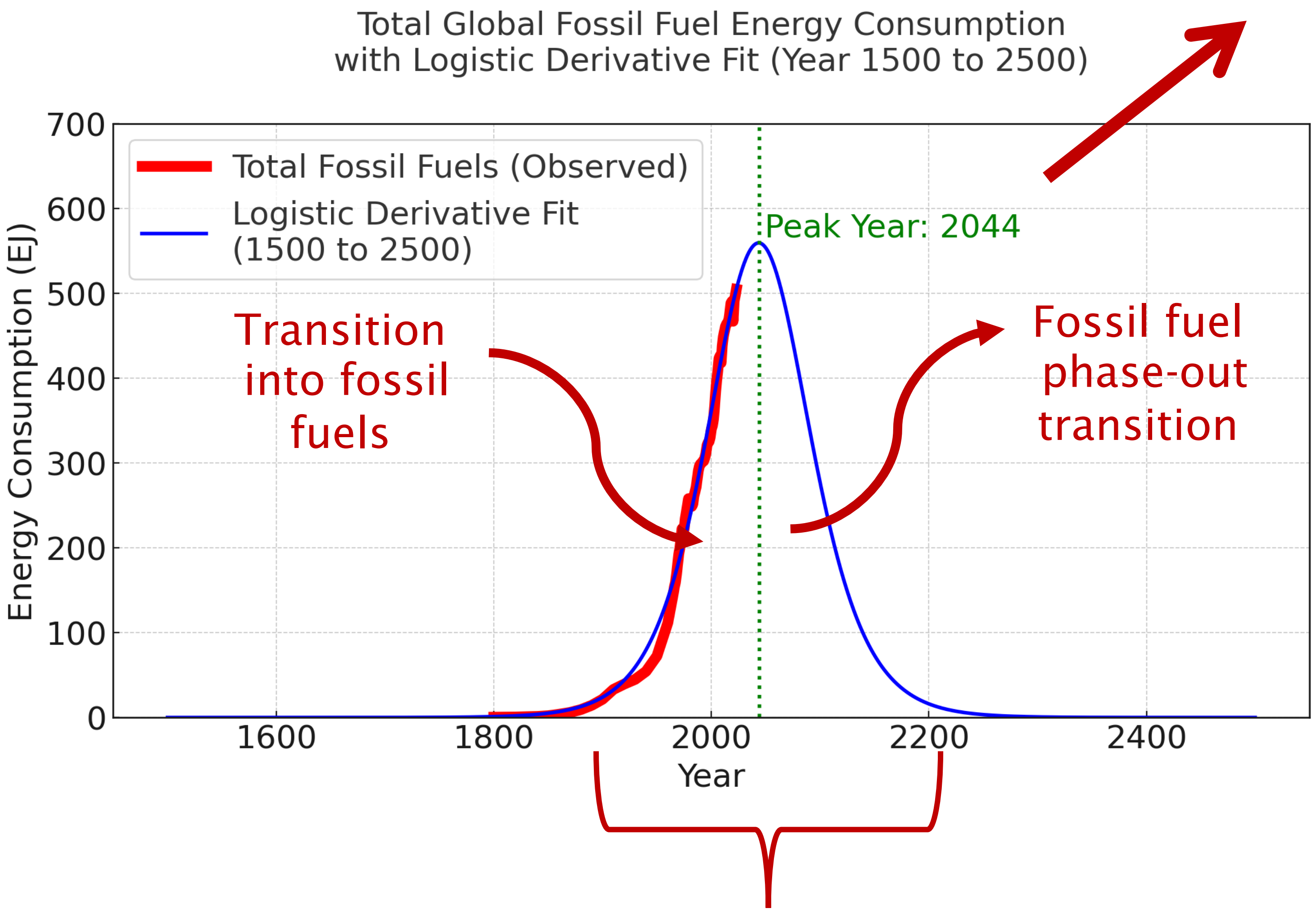
technologies

Planet Earth

Planétarité des technologies

Two major energy transitions: in fossil fuels, out of fossil fuels

Ceci n’est pas une prédiction !

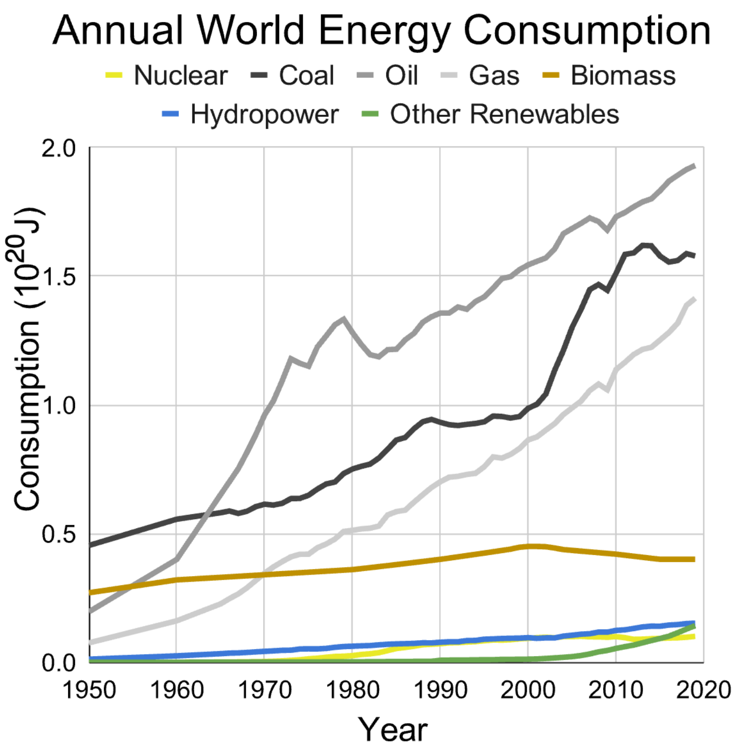


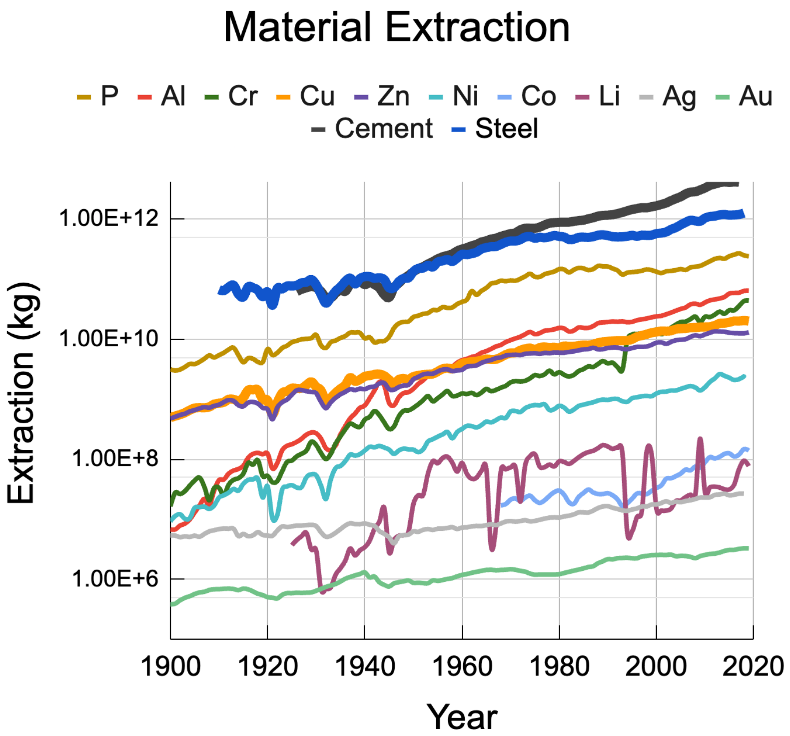
But what is an energy transition in/out fossil fuels?

It's a major power (W) transition.

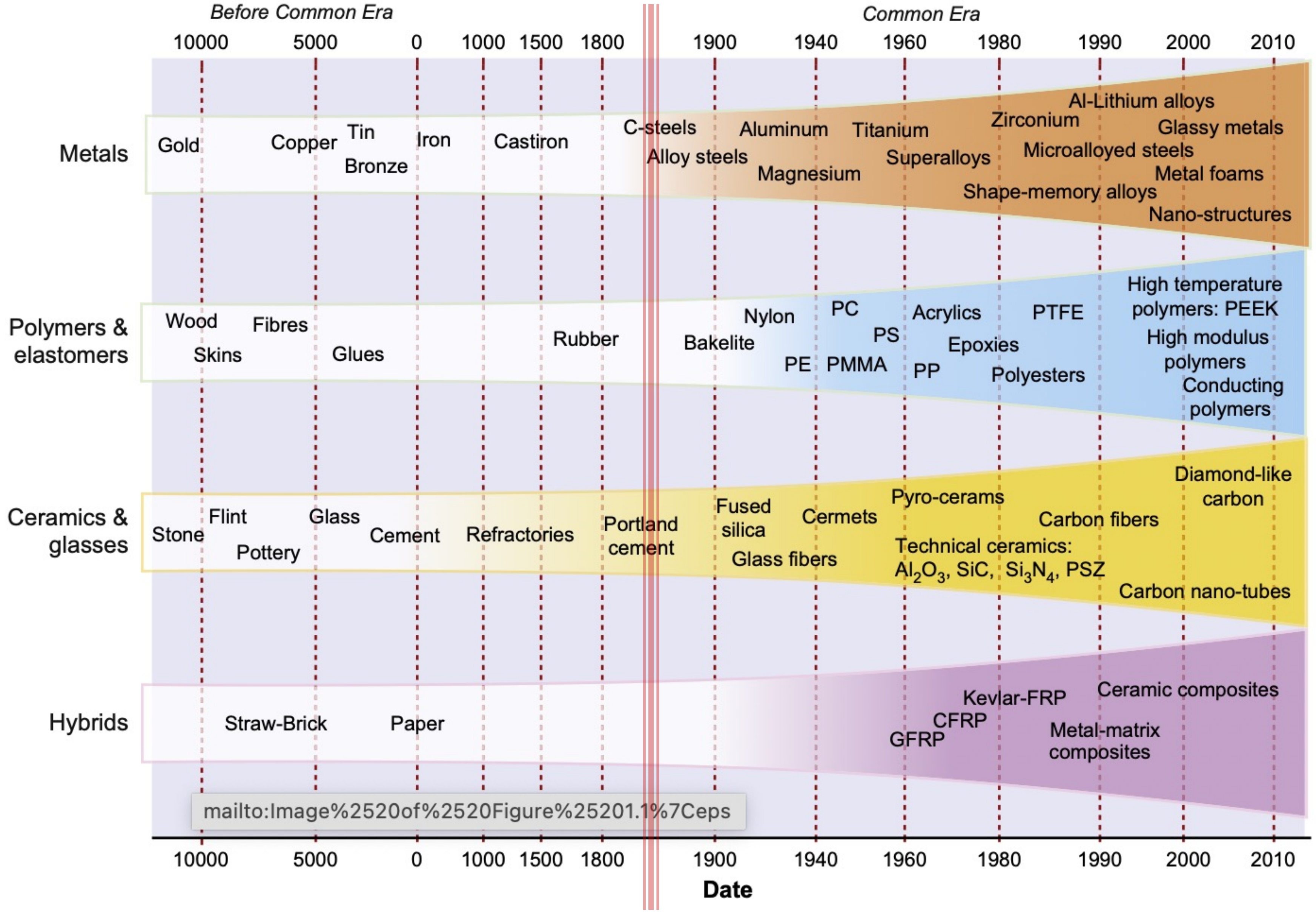
It's a major transition in terms of materials (kg).

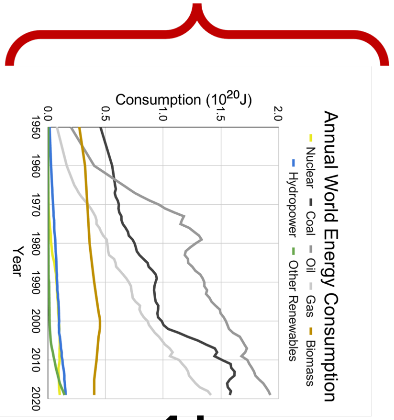
Système technique: combustibles fossiles & minéraux

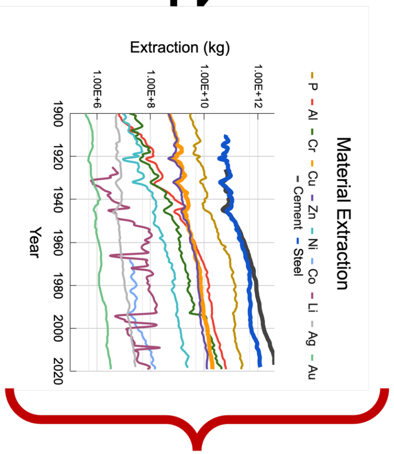


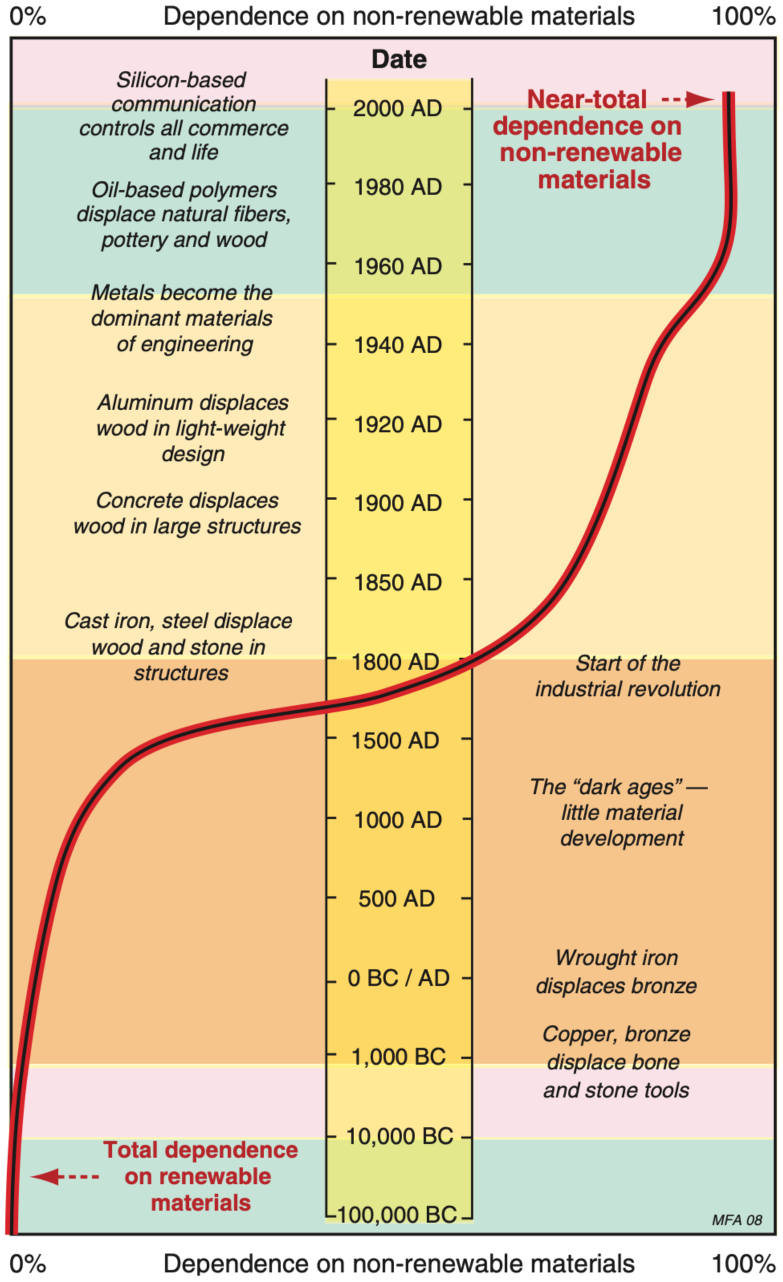


Transition du système technique alimentée
par les combustibles fossiles

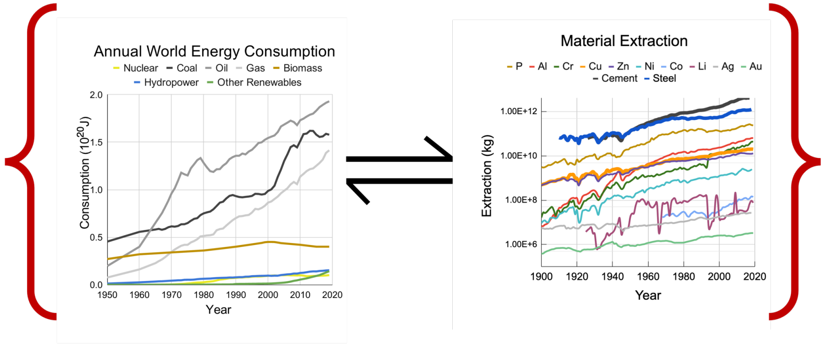




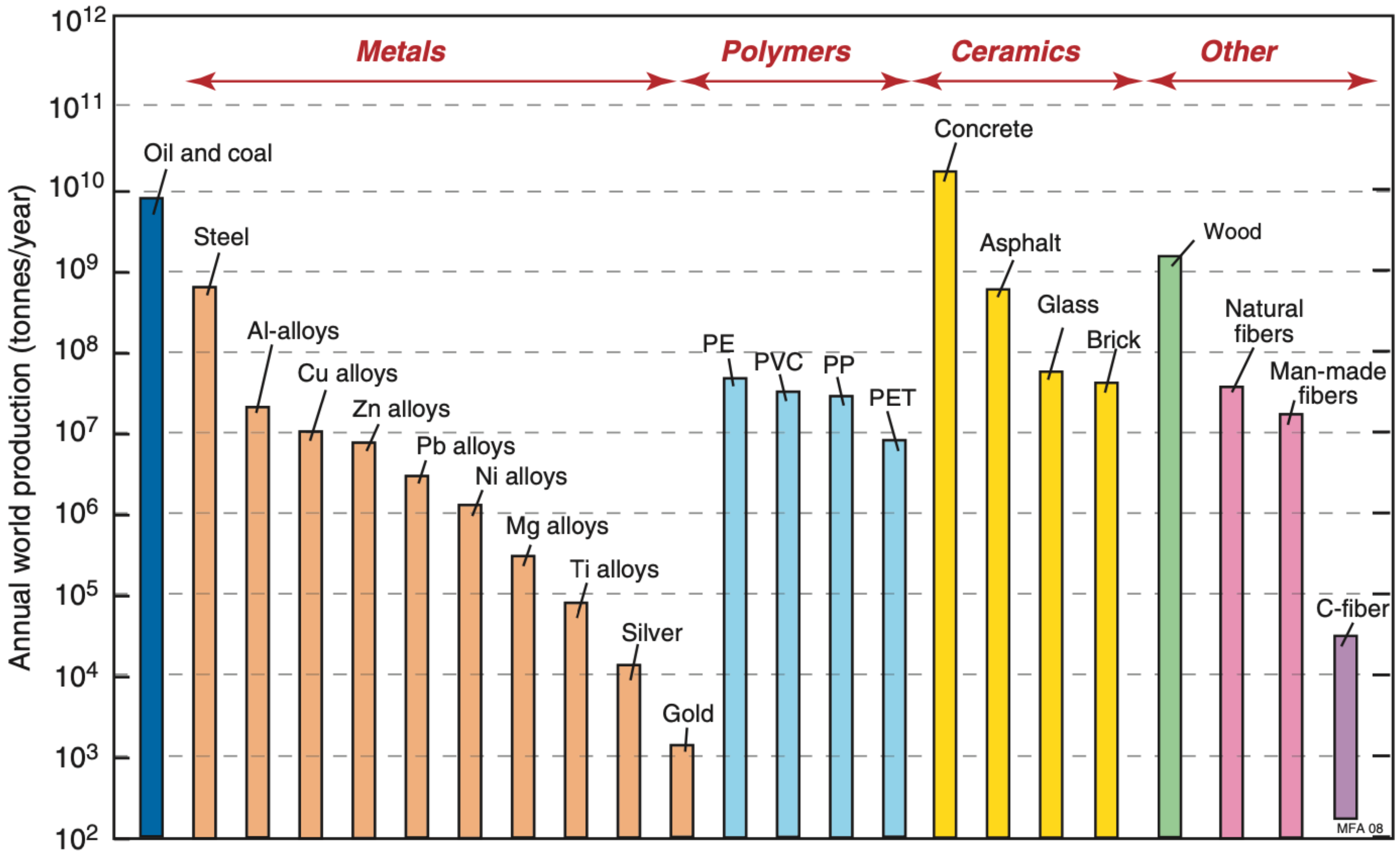




0%
Dependence on non-renewable materials
100%
Date
Silicon-based communication controls all commerce and life
Oil-based polymers displace natural fibers, pottery and wood
Metals become the dominant materials of engineering
Aluminum displaces wood in light-weight design
Concrete displaces wood in large structures
Cast iron, steel displace wood and stone in structures
2000 AD
1980 AD
1960 AD
1940 AD
1920 AD
1900 AD
1850 AD
1800 AD
1500 AD
1000 AD
500 AD
0 BC / AD
1,000 BC
10,000 BC
100,000 BC
Near-total dependence on non-renewable materials
Start of the industrial revolution
The "dark ages" — little material development
Wrought iron displaces bronze
Copper, bronze displace bone and stone tools
Total dependence on renewable materials
MFA 08
0%
Dependence on non-renewable materials
100%



Annual World Energy Consumption
Nuclear
Coal
Oil
Gas
Biomass
Hydropower
Other Renewables
Consumption (10^{20} J)
Year
Material Extraction
P
Al
Cr
Cu
Zn
Ni
Co
Li
Ag
Au
Cement
Steel
Extraction (kg)
Year



Metals
Polymers
Ceramics
Other
Annual world production (tonnes/year)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
Oil and coal
Steel
Al-alloys
Cu alloys
Zn alloys
Pb alloys
Ni alloys
Mg alloys
Ti alloys
Silver
Gold
PE
PVC
PP
PET
Concrete
Asphalt
Glass
Brick
Wood
Natural fibers
Man-made fibers
C-fiber
MFA 08

La fin des combustibles fossiles ?

Causes physiques

- Épuisement des ressources géologiques.
- Technique: extraction de plus en plus complexe.
- Technique: augmentation de l'énergie nécessaire à l'extraction.
- Impacts systémiques : réchauffement climatique et catastrophes écologiques

Causes anthropiques

- Réductions rationnelles des émissions à gaz à effet de serre pour des raisons écologiques.
- Invention d'un nouveau métabolisme industriel.

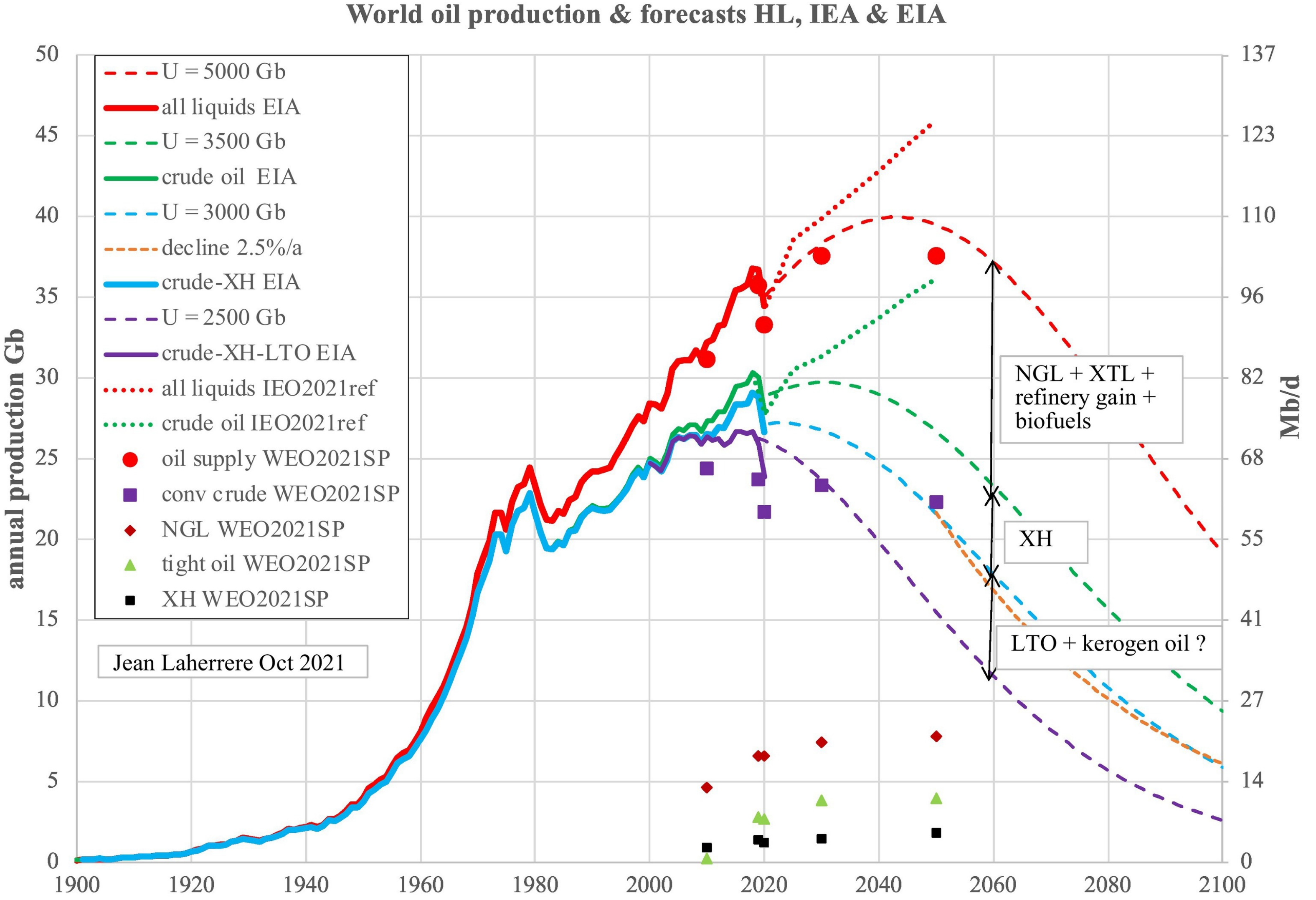
La fin du pétrole ?

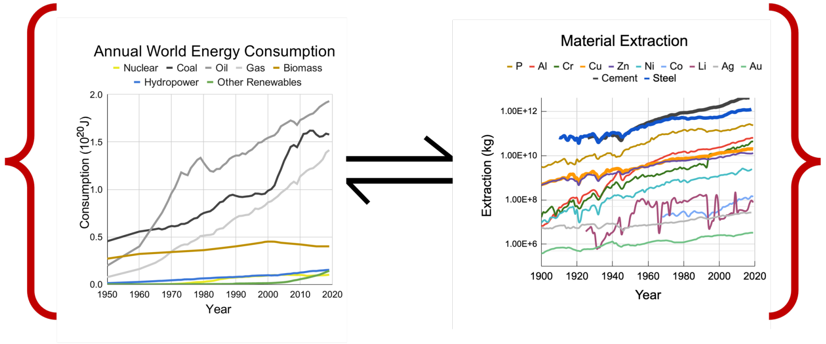
How much oil remains for the world to produce? Comparing assessment methods, and separating fact from fiction

Jean Laherrère [a,d], Charles A.S. Hall [b,*], Roger Bentley [c,e]

[a] Exploration Techniques, Total, France
[b] College of Environmental Science and Forestry, State University of New York, Syracuse, NY, USA
[c] The Oil Age, Petroleum Analysis Centre, Ballydehob, Ireland
[d] President ASPO, France
[e] Former Dept. Cybernetics, University of Reading, UK

Current Research in Environmental Sustainability 4 (2022)
https://doi.org/10.1016/j.crsust.2022.100174

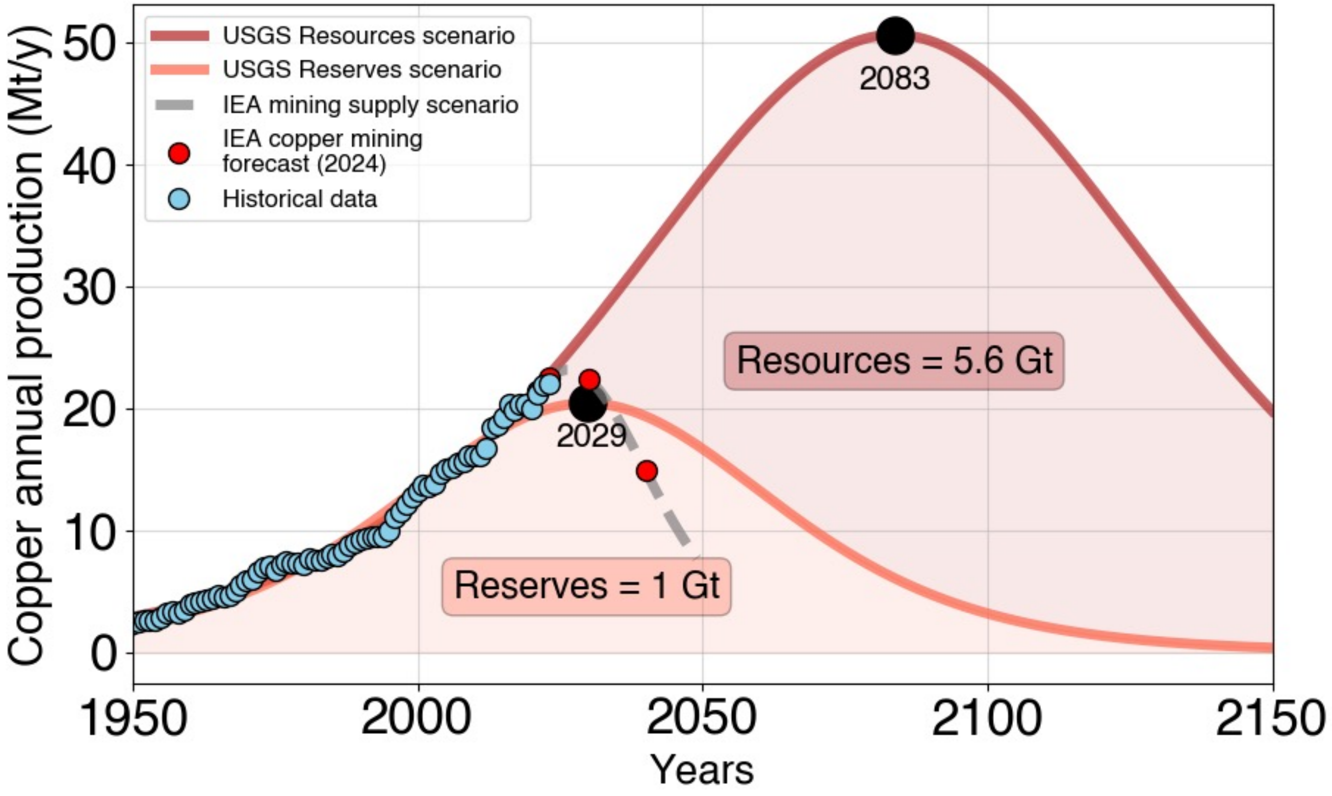




RESEARCH ARTICLE

Applicability of Hubbert model to global mining industry: Interpretations and insights

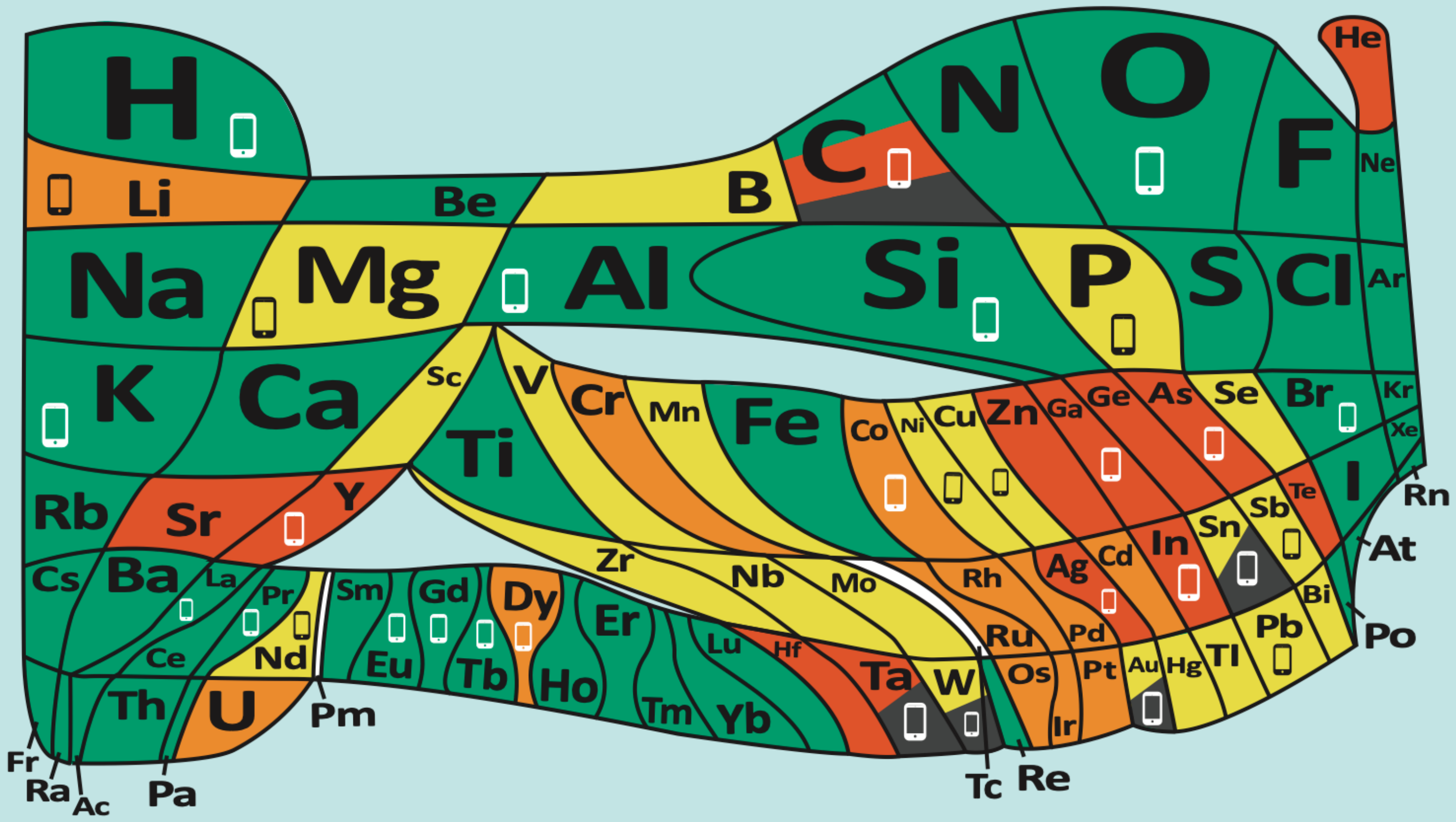
Lucas Riondet[1,2,3]*, Daniel Suchet[4], Olivier Vidal[5], José Halloy[3]*



Thèse, déploiement du PV,
Joseph Le Bihan, 2024

The 90 natural elements that make up everything.

How much is there? Is that enough? Is it sustainable?



Serious threat in the next 100 years.

Rising threat from increased use.

Limited availability, future risk to supply.

Plentiful supply.

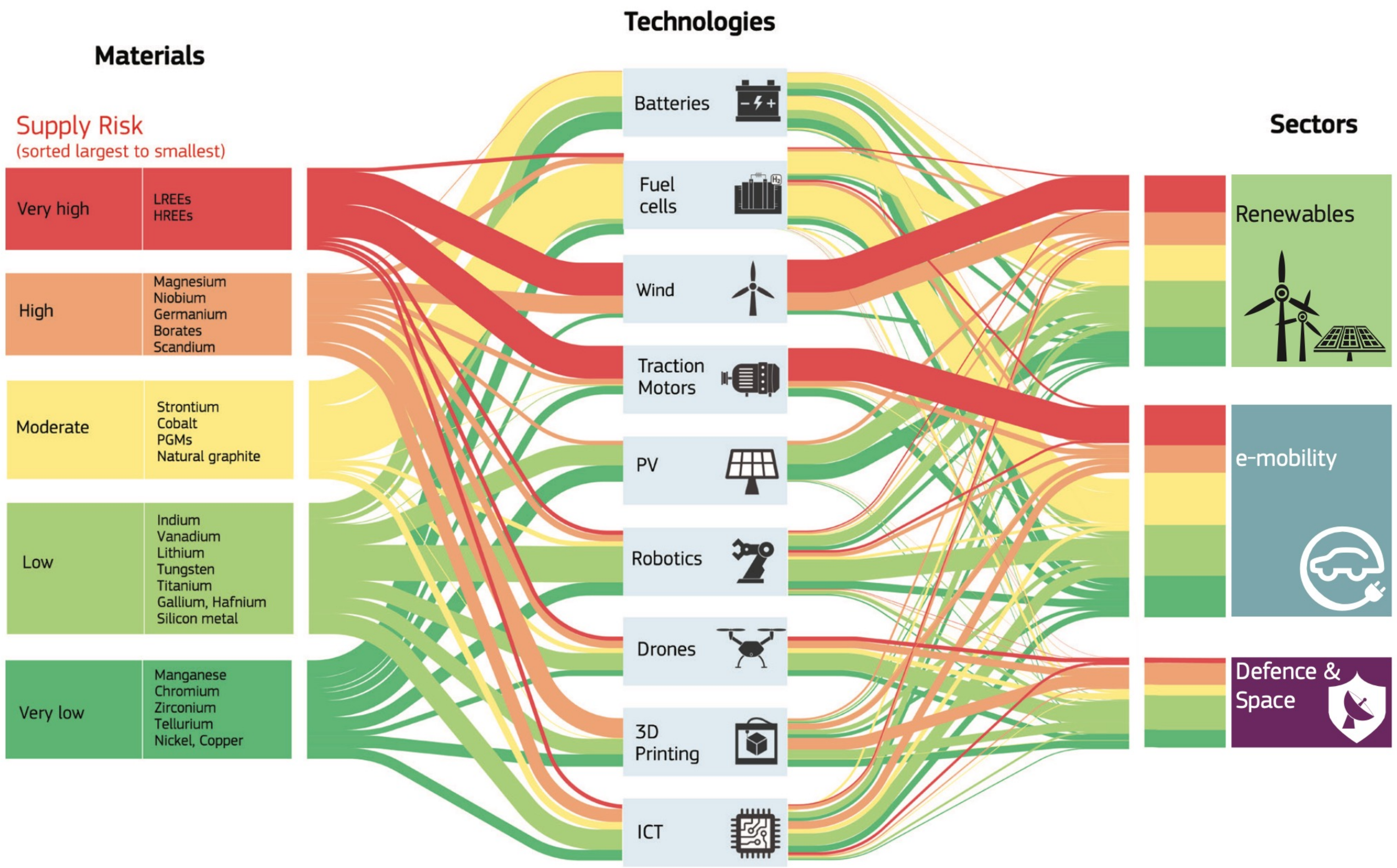
Synthetic

From conflict resources

Elements used in a smartphone.

Inspired by WF Sheehan's 'A Periodic Table with Emphasis' published in Chemistry, 1976, 49, 17-18'

Read more and play the video game http://bit.ly/euchems-pt.



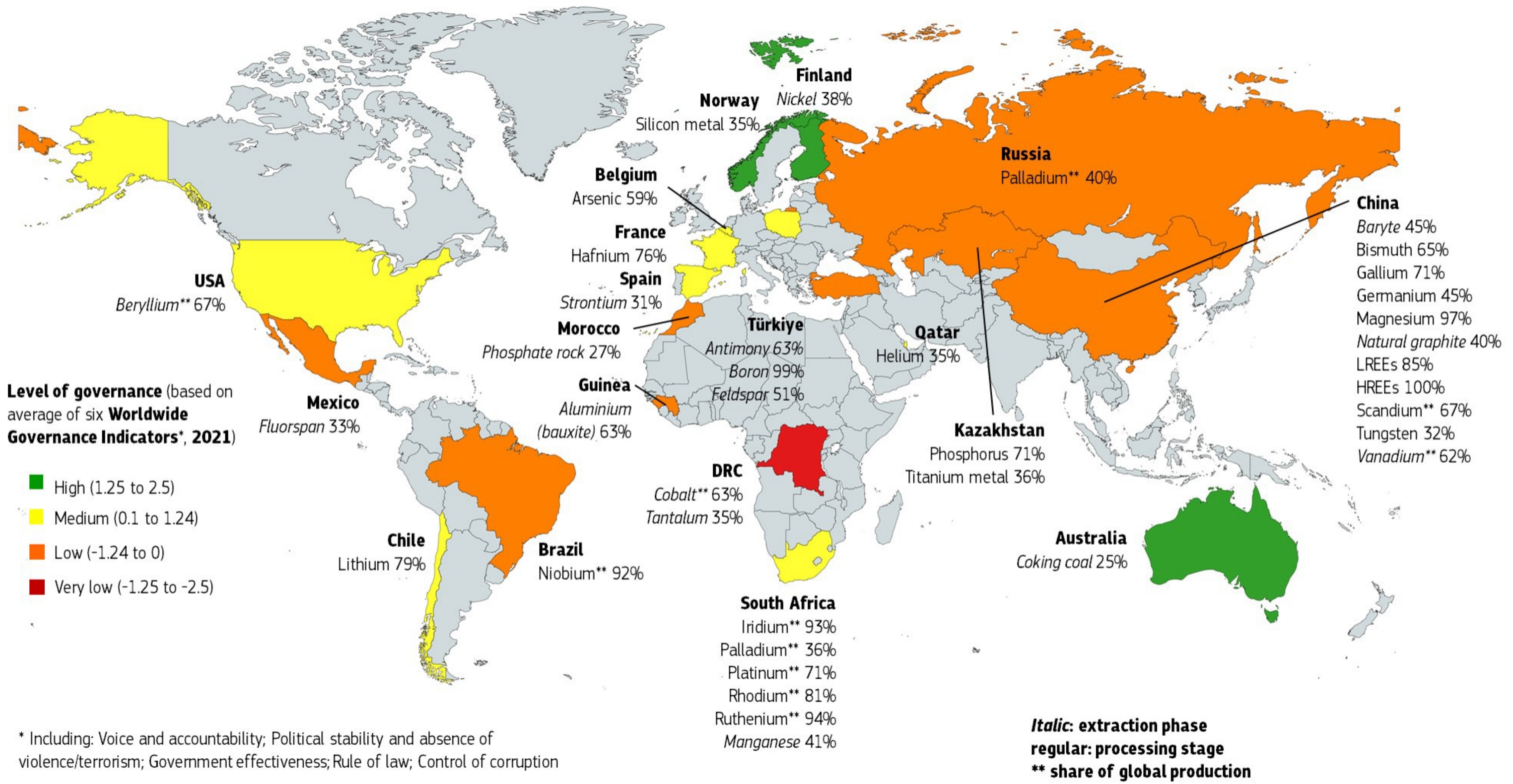
Materials
Technologies
Sectors
Supply Risk
(sorted largest to smallest)
Very high
LREEs
HREEs
High
Magnesium
Niobium
Germanium
Borates
Scandium
Moderate
Strontium
Cobalt
PGMs
Natural graphite
Low
Indium
Vanadium
Lithium
Tungsten
Titanium
Gallium, Hafnium
Silicon metal
Very low
Manganese
Chromium
Zirconium
Tellurium
Nickel, Copper
Batteries
Fuel cells
Wind
Traction Motors
PV
Robotics
Drones
3D Printing
ICT
Renewables
e-mobility
Defence & Space

European Commission
Critical Raw Materials for Strategic Technologies and Sectors in the EU
A Foresight Study

Des questions géopolitiques cruciales et compliquées
Matières premières

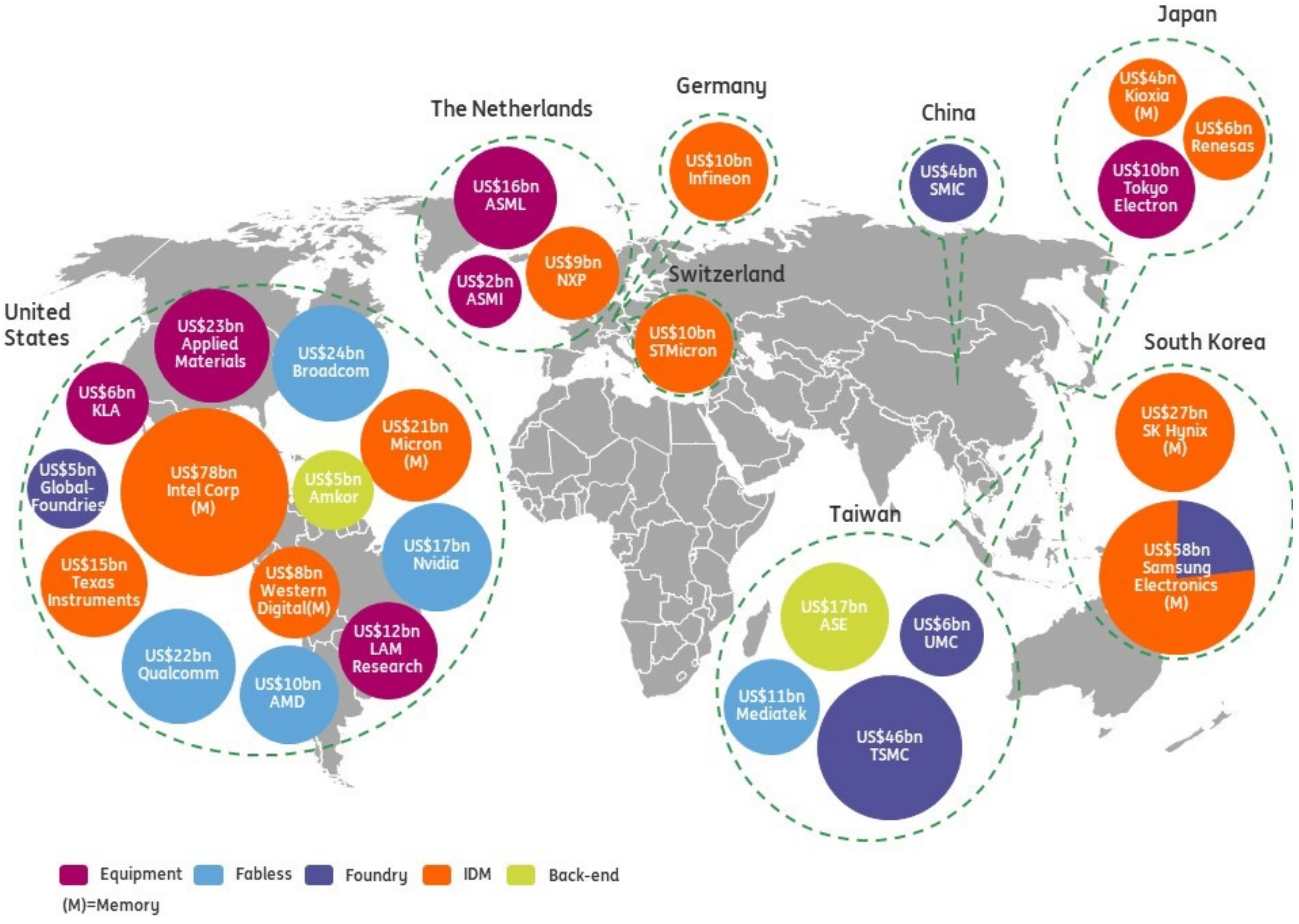
Planétarité des technologies

Planétarité des matières premières



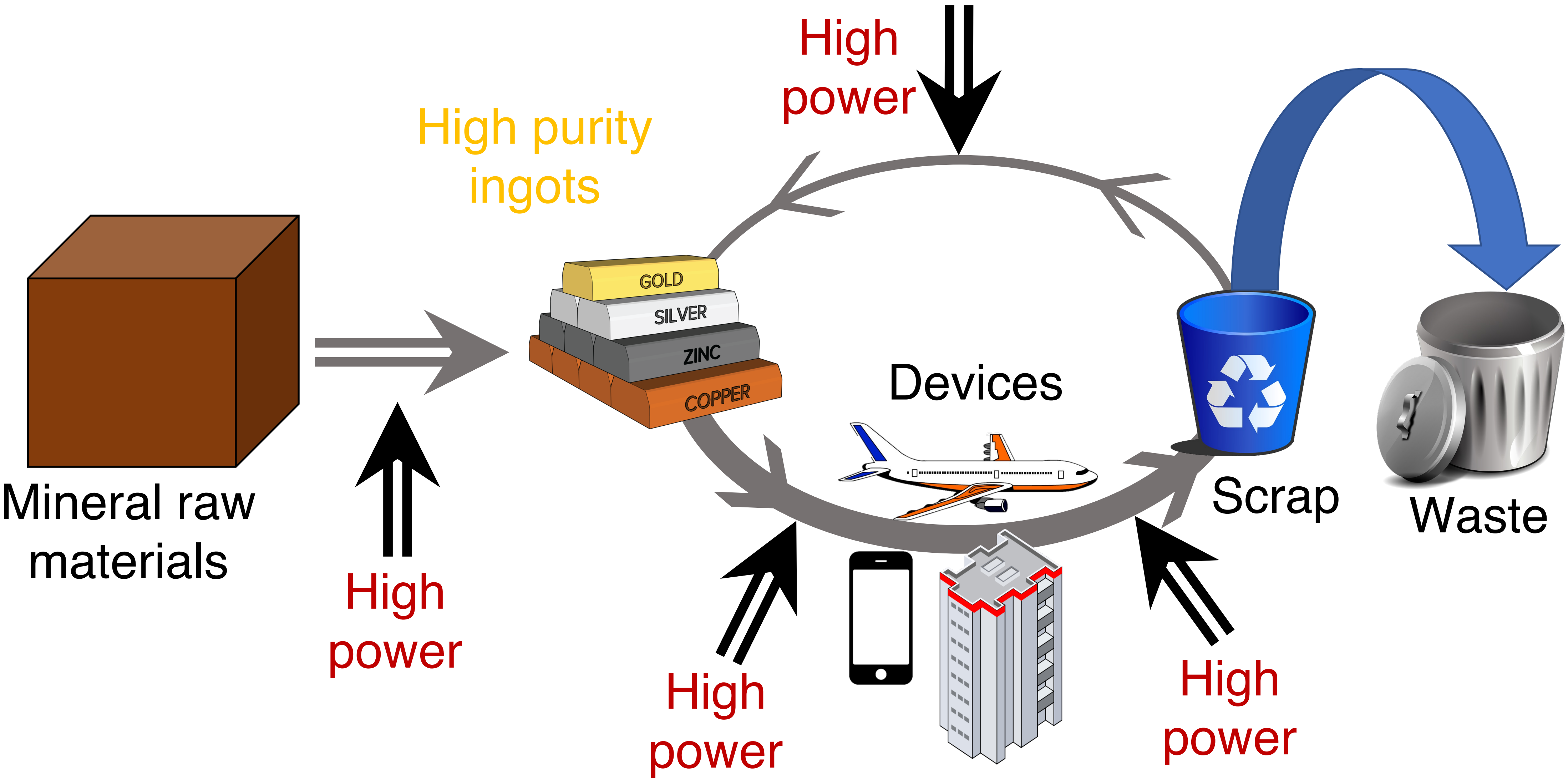
Des questions géopolitiques cruciales et compliquées
Fabrication des semiconducteurs

Planétarité des technologies



Planétarité de l'économie

Technological systems: from mines to trash



Je considère les technologies actuelles comme mortes à l'aune d'une soutenabilité forte, mais elles continuent à envahir le monde au détriment de l'humanité et d'une partie du vivant, je les appelle "technologies zombies".

Elles sont des zombies pour trois raisons principales :

- ✓ elles dépendent des stocks de combustibles fossiles pour être fabriquées et pour fonctionner ;
- ✓ elles sont basées sur des matériaux qui ne sont pas conçus pour être recyclés et créent une pénurie par l'épuisement des ressources ;
- ✓ elles produisent des catastrophes écologiques au détriment de l'humanité et des êtres vivants.

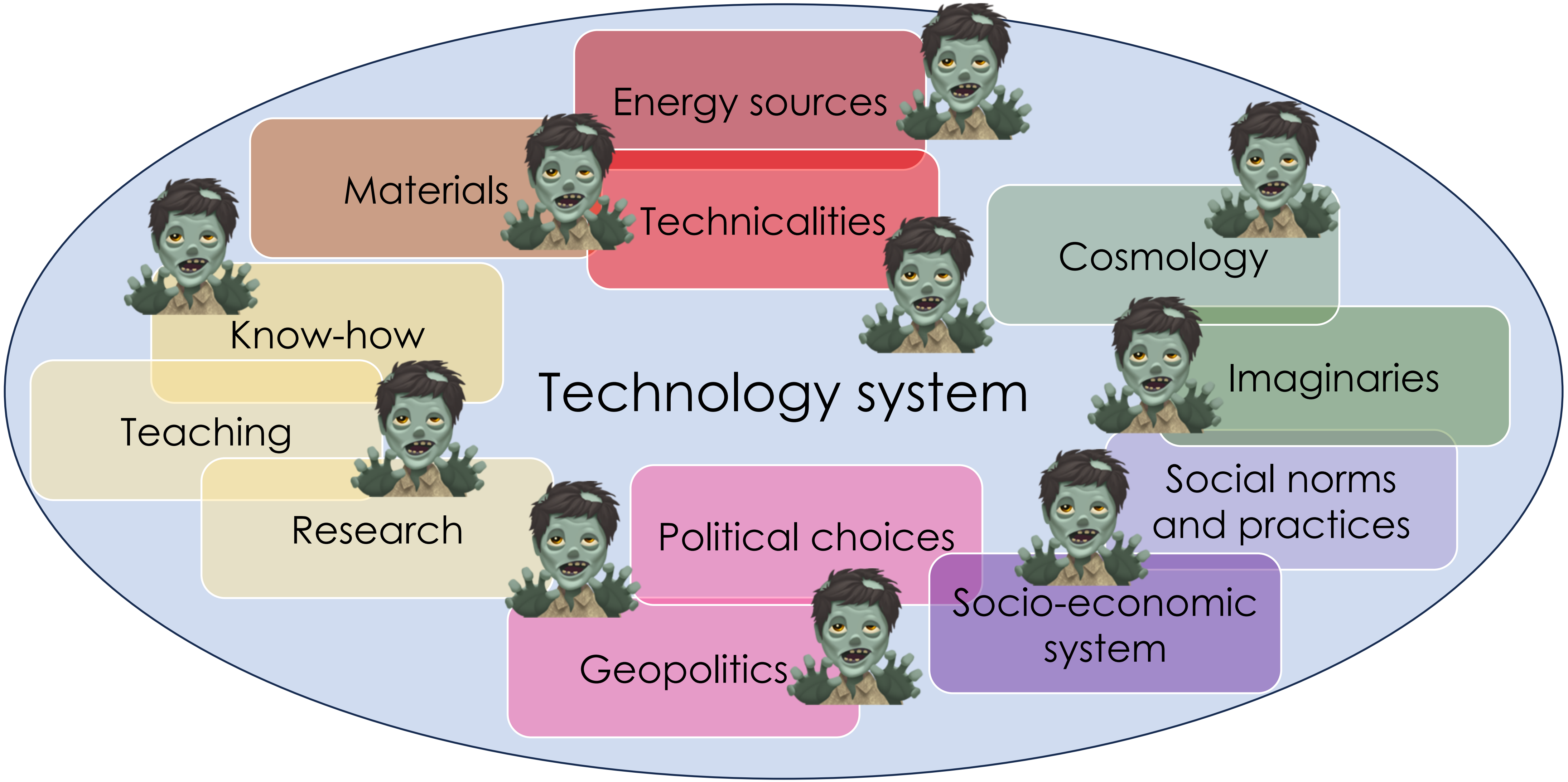
Trois critères favorisent la zombification :

(i) l'utilisation de stocks finis qui par définition imposent une limite à l'activité ;

(ii) l'utilisation d'une puissance dépassant les capacités du milieu dans lequel s'insère cette technique ;

(iii) la généralisation de ces caractéristiques à grande échelle..

It is not only climate change, it is everything change



AlphaGo defeated Lee Sedol

Published: 19 October 2017

Mastering the game of Go without human knowledge

David Silver, Julian Schrittwieser, Karen Simonyan, Ioannis Antonoglou, Aja Huang, Arthur Guez, Thomas Hubert, Lucas Baker, Matthew Lai, Adrian Bolton, Yutian Chen, Timothy Lillicrap, Fan Hui, Laurent Sifre, George van den Driessche, Thore Graepel & Demis Hassabis

Nature **550**, 354–359 (2017) | Cite this article

~100 W per CPU
~200 W per GPU

AlphaGo	Search threads	CPUs	GPUs
Asynchronous	1	48	8
Asynchronous	2	48	8
Asynchronous	4	48	8
Asynchronous	8	48	8
Asynchronous	16	48	8
Asynchronous	32	48	8
Asynchronous	40	48	8
Asynchronous	40	48	1
Asynchronous	40	48	2
Asynchronous	40	48	4
Distributed	12	428	64
Distributed	24	764	112
Distributed	40	1202	176
Distributed	64	1920	280

AlphaGo defeated Lee Sedol

Mineral
& Dry
chemistry

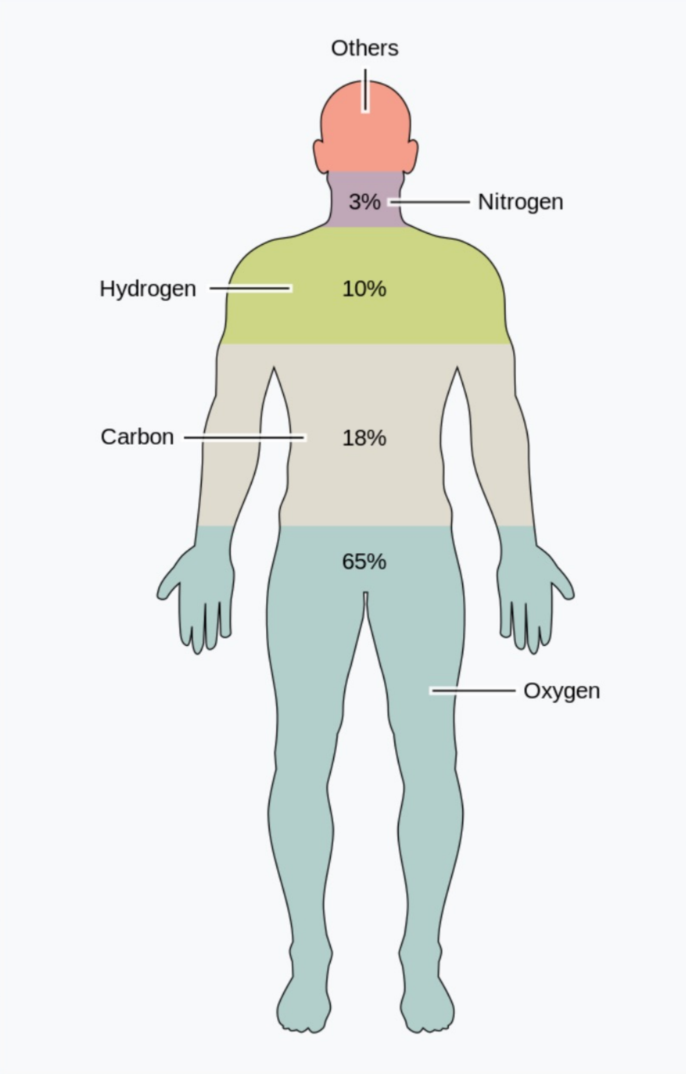
Organic
& wet
chemistry

~ 155 kW
(600 kW)

Brain ~ 20 W
2500 kCal/day ~ 120 W

130 GJ = 9.7 days

34 years = 130 GJ



Element	Symbol	percent mass	percent atoms
Oxygen	O	65.0	24.0
Carbon	C	18.5	12.0
Hydrogen	H	9.5	62.0
Nitrogen	N	2.6	1.1
Calcium	Ca	1.3	0.22
Phosphorus	P	0.6	0.22
Potassium	K	0.2	0.03
Sulfur	S	0.3	0.038
Sodium	Na	0.2	0.037
Chlorine	Cl	0.2	0.024
Magnesium	Mg	0.1	0.015
All others		< 0.1	< 0.3

The main elements that comprise the human body (including water) can be summarized as CHNOPS.

CHNOPS : one organic chemistry

One (nearly) universal genetic code

The metabolism of living systems differs completely from that of the technosphere.

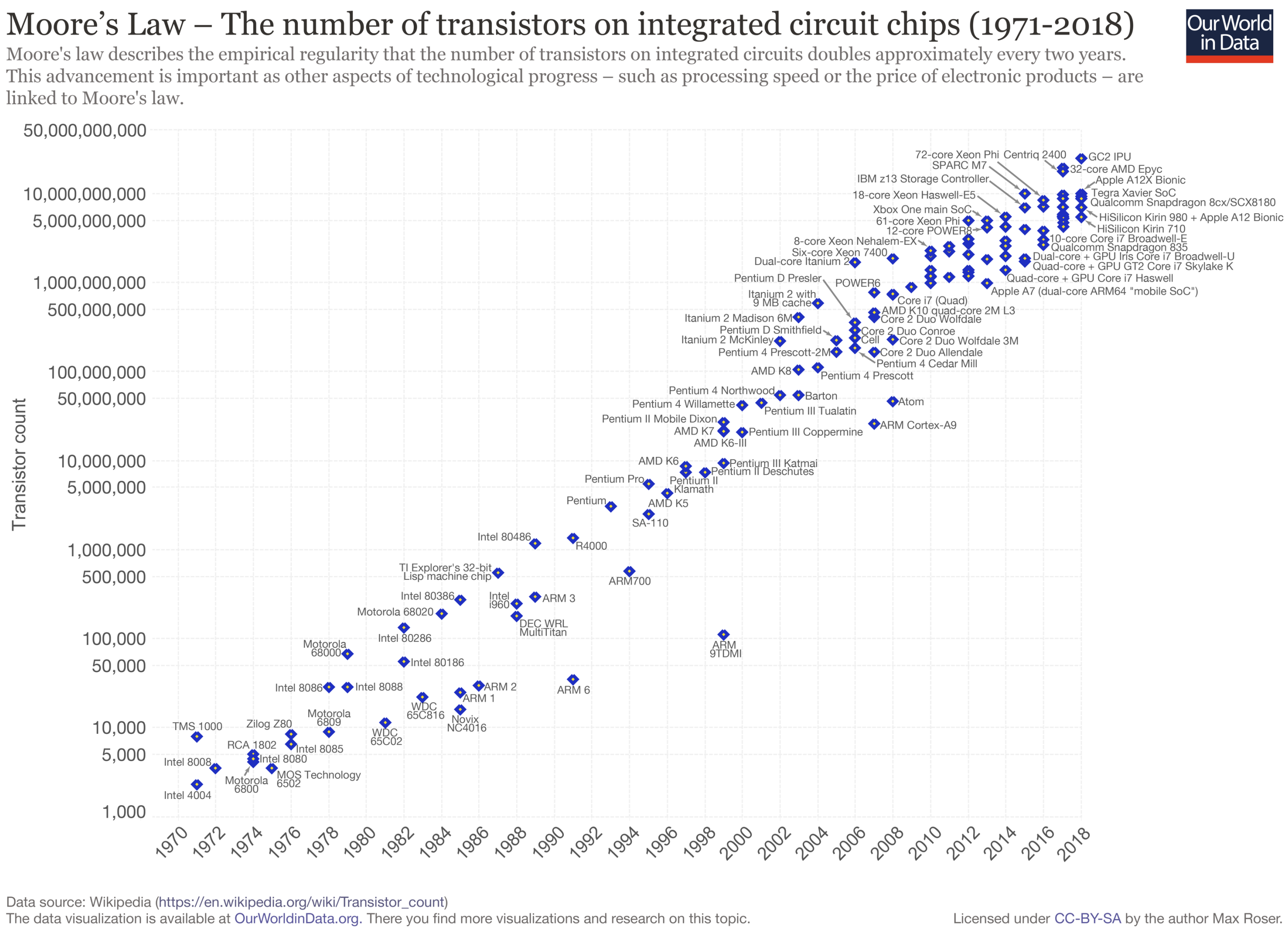
Attention à la question de l'efficacité énergétique et des matériaux

La technologie des semiconducteurs est la plus efficace que je connaisse !

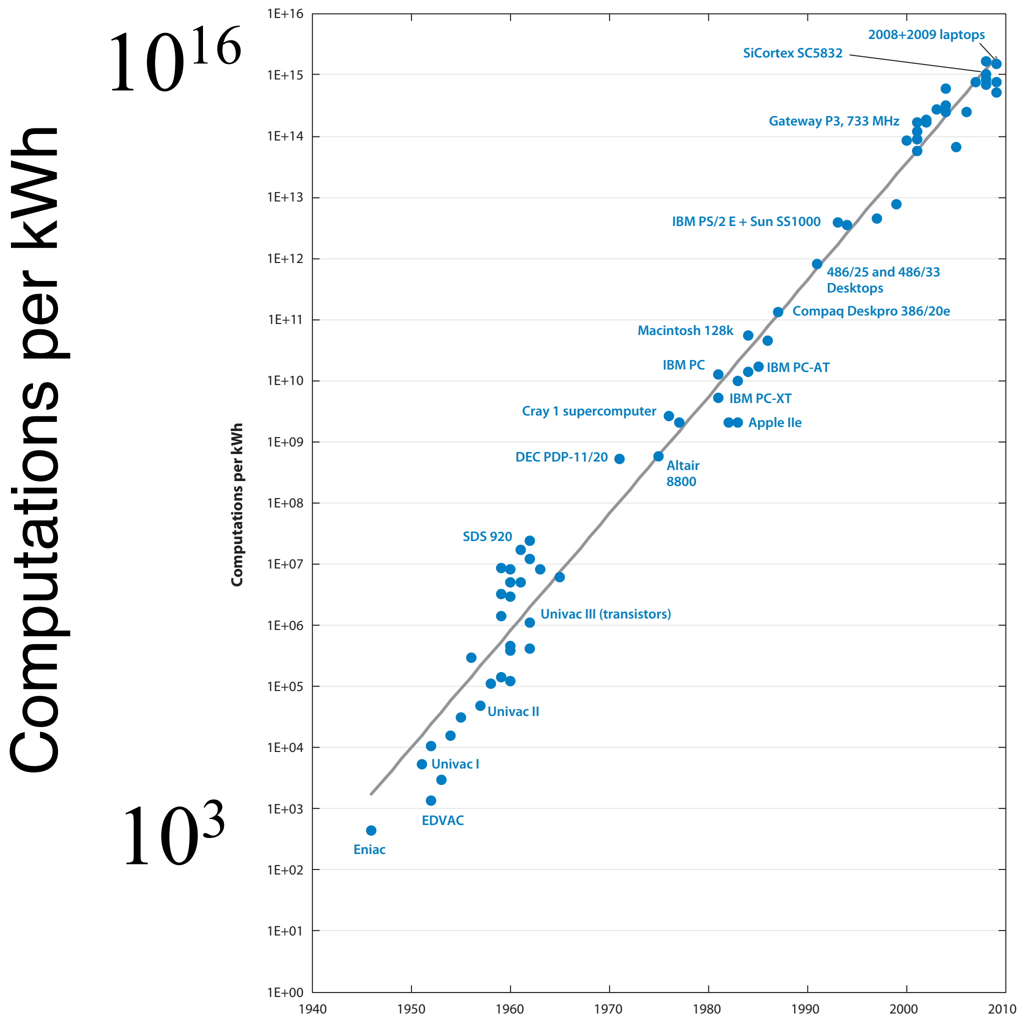
1945: 150 kW 30 tonnes

2024: 1-2 W ~200 g

Extremely material efficient: “Moore’s law”



Extremely energy efficient: “Koomey’s law”



Koomey, Jonathan G., H. Scott Matthews, and Eric Williams. "Smart everything: Will intelligent systems reduce resource use?." *Annual Review of Environment and Resources* 38 (2013): 311-343.

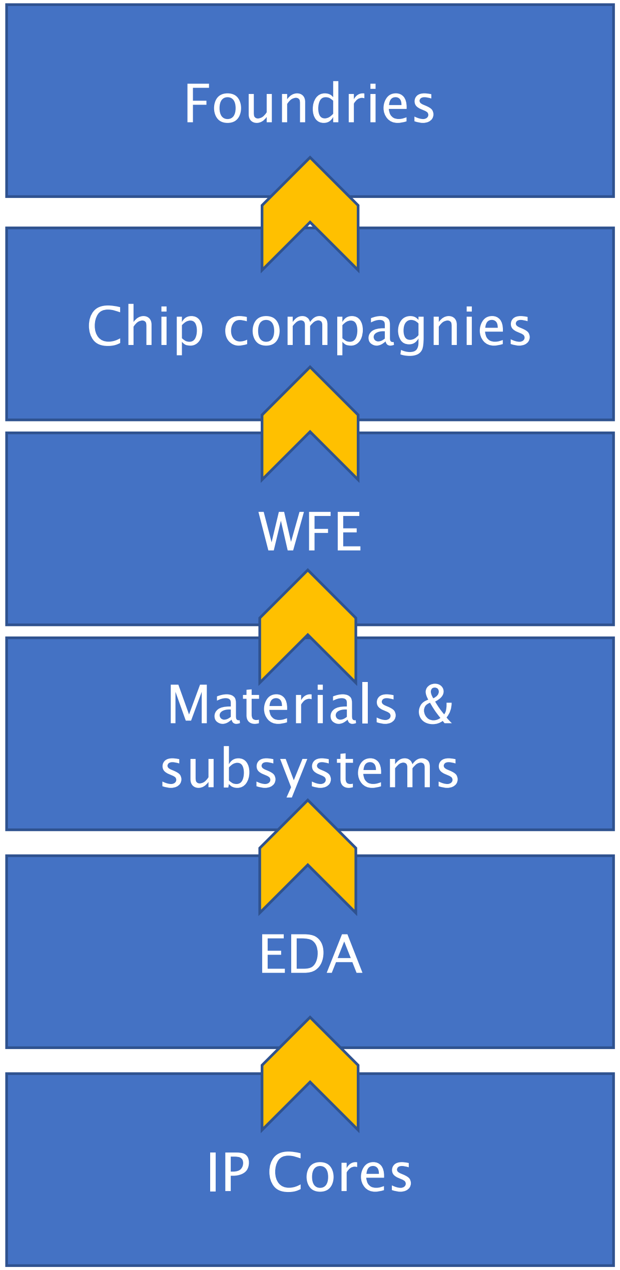
Top 10 of the Green500

In the Green500 the systems of the TOP500 are ranked by how much computational performance they deliver on the HPL benchmark per Watt of electrical power consumed. This electrical power efficiency is measured in Gigaflops/Watt.

Green500 Rank	MFLOPS/W	Site*	Computer*	Total Power (kW)
1	5,271.81	GSI Helmholtz Center	L-CSC - ASUS ESC4000 FDR/G2S, Intel Xeon E5-2690v2 10C 3GHz, Infiniband FDR, AMD FirePro S9150 Level 1 measurement data available	57.15
2	4,945.63	High Energy Accelerator Research Organization /KEK	Suiren - ExaScaler 32U256SC Cluster, Intel Xeon E5-2660v2 10C 2.2GHz, Infiniband FDR, PEZY-SC	37.83
3	4,447.58	GSIC Center, Tokyo Institute of Technology	TSUBAME-KFC - LX 1U-4GPU/104Re-1G Cluster, Intel Xeon E5-2620v2 6C 2.100GHz, Infiniband FDR, NVIDIA K20x	35.39
4	3,962.73	Cray Inc.	Storm1 - Cray CS-Storm, Intel Xeon E5-2660v2 10C 2.2GHz, Infiniband FDR, Nvidia K40m Level 3 measurement data available	44.54
5	3,631.70	Cambridge University	Wilkes - Dell T620 Cluster, Intel Xeon E5-2630v2 6C 2.600GHz, Infiniband FDR, NVIDIA K20	52.62
6	3,543.32	Financial Institution	iDataPlex DX360M4, Intel Xeon E5-2680v2 10C 2.800GHz, Infiniband, NVIDIA K20x	54.60
7	3,517.84	Center for Computational Sciences, University of Tsukuba	HA-PACS TCA - Cray CS300 Cluster, Intel Xeon E5-2680v2 10C 2.800GHz, Infiniband QDR, NVIDIA K20x	78.77
8	3,459.46	SURFsara	Cartesius Accelerator Island - Bullx B515 cluster, Intel Xeon E5-2450v2 8C 2.5GHz, InfiniBand 4× FDR, Nvidia K40m	44.40
9	3,185.91	Swiss National Supercomputing Centre (CSCS)	Piz Daint - Cray XC30, Xeon E5-2670 8C 2.600GHz, Aries interconnect , NVIDIA K20x Level 3 measurement data available	1,753.66
10	3,131.06	ROMEO HPC Center - Champagne-Ardenne	romeo - Bull R421-E3 Cluster, Intel Xeon E5-2650v2 8C 2.600GHz, Infiniband FDR, NVIDIA K20x	81.41

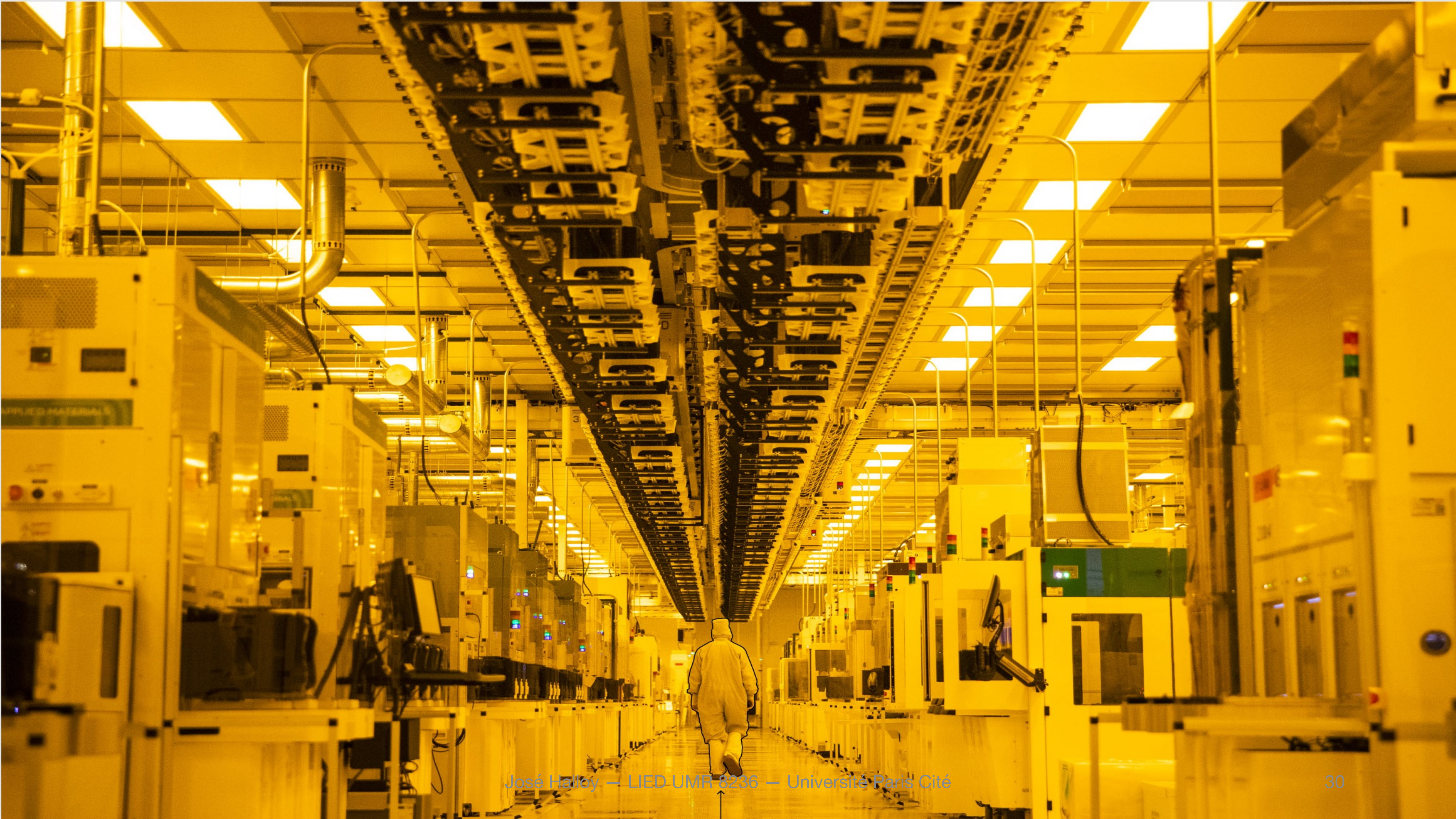
Semiconductor technological system

1. Chip Intellectual Property (IP) Cores
2. Electronic Design Automation (EDA) Tools
3. Specialized Materials and subsystems
4. Wafer Fab Equipment (WFE)
5. "Fabless" Chip Companies
6. Integrated Device Manufacturers (IDMs)
7. Chip Foundries
8. Outsourced Semiconductor Assembly and Test (OSAT)



The $150 Million Machine Keeping Moore’s Law Alive

It contains 100,000 parts and 2 kilometers of cabling.


APPLIED MATERIALS

Non-exhaustive list of gases and their use in microprocessor manufacturing

1. Inert and Carrier Gases	2. Oxidation and Oxide Formation Gases	3. Reducing and Annealing Gases
Used as inert atmospheres, purging, and carrier gases in various processes. •Nitrogen (N_2) •Argon (Ar) •Helium (He) •Neon (Ne) •Krypton (Kr) •Xenon (Xe)	Employed in oxidation processes to grow oxide layers on silicon wafers. •Oxygen (O_2) •Nitrous Oxide (N_2O) •Nitric Oxide (NO) •Ozone (O_3) •Nitrogen Dioxide (NO_2) •Nitrogen Monoxide (NO) •Chlorine Monoxide (ClO) •Chlorine Dioxide (ClO_2)	Used in annealing processes and to create reducing environments. •Hydrogen (H_2) •Forming Gas (H_2/N_2 Mixture) •Deuterium (D_2)

4. Doping Gases

Introduce impurities into silicon to modify its electrical properties.

- Phosphine (PH_3) (n-type doping)
- Arsine (AsH_3) (n-type doping)
- Diborane (B_2H_6) (p-type doping)
- Boron Trichloride (BCl_3)
- Boron Trifluoride (BF_3)
- Phosphorus Pentafluoride (PF_5)
- Phosphorus Oxychloride ($POCl_3$)
- Boron Tribromide (BBr_3)
- Trimethylantimony (TMSb)
- Tris(Dimethylamino)Antimony (TDMASb)
- Trimethylphosphine (TMP)
- Tertiarybutylarsine (TBAs)
- Tertiarybutylphosphine (TBP)
- Hydrogen Selenide (H_2Se)
- Hydrogen Telluride (H_2Te)
- Hydrogen Sulfide (H_2S)

5. Deposition Gases (Chemical Vapor Deposition - CVD)

Used to deposit thin films of various materials on the wafer surface.

- Silane (SiH_4)
- Disilane (Si_2H_6)
- Dichlorosilane (SiH_2Cl_2)
- Trichlorosilane ($SiHCl_3$)
- Tetrachlorosilane ($SiCl_4$)
- Germane (GeH_4)
- Tungsten Hexafluoride (WF_6)
- Titanium Tetrachloride ($TiCl_4$)
- Tetrakis(Dimethylamido)Titanium (TDMAT)
- Trimethylaluminum (TMA)
- Trimethylgallium (TMG)
- Tetraethyl Orthosilicate (TEOS)
- Methylsilane (CH_3SiH_3)
- Dimethylsilane ($(CH_3)_2SiH_2$)
- Ethyl Silicate ($Si(OC_2H_5)_4$)
- Trimethylindium (TMI)
- Tungsten Hexacarbonyl ($W(CO)_6$)

6. Etching Gases

Used in plasma etching to remove specific materials from the wafer.

- Chlorine (Cl_2)
- Fluorine (F_2)
- Sulfur Hexafluoride (SF_6)
- Nitrogen Trifluoride (NF_3)
- Carbon Tetrafluoride (CF_4)
- Hexafluoroethane (C_2F_6)
- Octafluoropropane (C_3F_8)
- Perfluorocyclobutane (C_4F_8)
- Trifluoromethane (CHF_3)
- Hydrogen Bromide (HBr)
- Chlorine Trifluoride (ClF_3)
- Boron Trichloride (BCl_3)
- Hydrogen Chloride (HCl)
- Hydrogen Fluoride (HF)
- Silicon Tetrachloride ($SiCl_4$)
- Silicon Tetrafluoride (SiF_4)
- Hydrogen Iodide (HI)
- Fluoromethane (CH_3F)
- Hexafluoro-1,3-Butadiene (C_4F_6)
- Chlorine Pentafluoride (ClF_5)
- Xenon Difluoride (XeF_2)
- Carbon Tetrachloride (CCl_4)
- Dichlorodifluoromethane (CCl_2F_2)
- Carbonyl Sulfide (OCS)
- Oxygen Difluoride (OF_2)
- Nitrosyl Chloride (NOCl)
- Hydrogen Cyanide (HCN)

7. Chamber Cleaning Gases

Used to clean deposition and etching equipment by removing residues.

- Nitrogen Trifluoride (NF_3)
- Fluorine (F_2)
- Hexafluoroethane (C_2F_6)
- Sulfur Hexafluoride (SF_6)
- Chlorine Trifluoride (ClF_3)
- Perfluorocyclobutane (C_4F_8)
- Octafluoropropane (C_3F_8)
- Oxygen Difluoride (OF_2)
- Hydrogen Peroxide Vapor (H_2O_2)

8. Photoresist Processing Gases

Utilized in photolithography for resist application and removal.

- Ammonia (NH_3)
- Hexamethyldisilazane (HMDS)
- Ethylamine ($C_2H_5NH_2$)
- Dimethylamine ($(CH_3)_2NH$)
- Isopropyl Alcohol Vapor (C_3H_7OH)
- Acetone Vapor (C_3H_6O)

9. Cleaning and Surface Preparation Gases

Employed to clean wafers and prepare surfaces for subsequent processes.

- Hydrogen Fluoride (HF)
- Hydrogen Chloride (HCl)
- Ammonium Fluoride (NH_4F)
- Ammonium Chloride (NH_4Cl)
- Carbon Dioxide (CO_2)
- Carbon Monoxide (CO)
- Ozone (O_3)
- Hydrogen Peroxide Vapor (H_2O_2)
- Sulfur Dioxide (SO_2)
- Nitrogen Dioxide (NO_2)
- Ethylene Oxide (C_2H_4O)
- Chlorine Dioxide (ClO_2)

10. Plasma and Sputtering Gases

Used in plasma-enhanced processes and physical vapor deposition.

- Argon (Ar)
- Helium (He)
- Neon (Ne)
- Krypton (Kr)
- Xenon (Xe)
- Nitrogen (N_2)

11. Deposition of Dielectric and Insulating Layers

Gases used to deposit insulating materials like silicon dioxide and silicon nitride.

- Ammonia (NH_3)
- Nitrous Oxide (N_2O)
- Silane (SiH_4)
- Disilane (Si_2H_6)
- Tetraethyl Orthosilicate (TEOS)
- Ethyl Silicate ($Si(OC_2H_5)_4$)
- Dichlorosilane (SiH_2Cl_2)

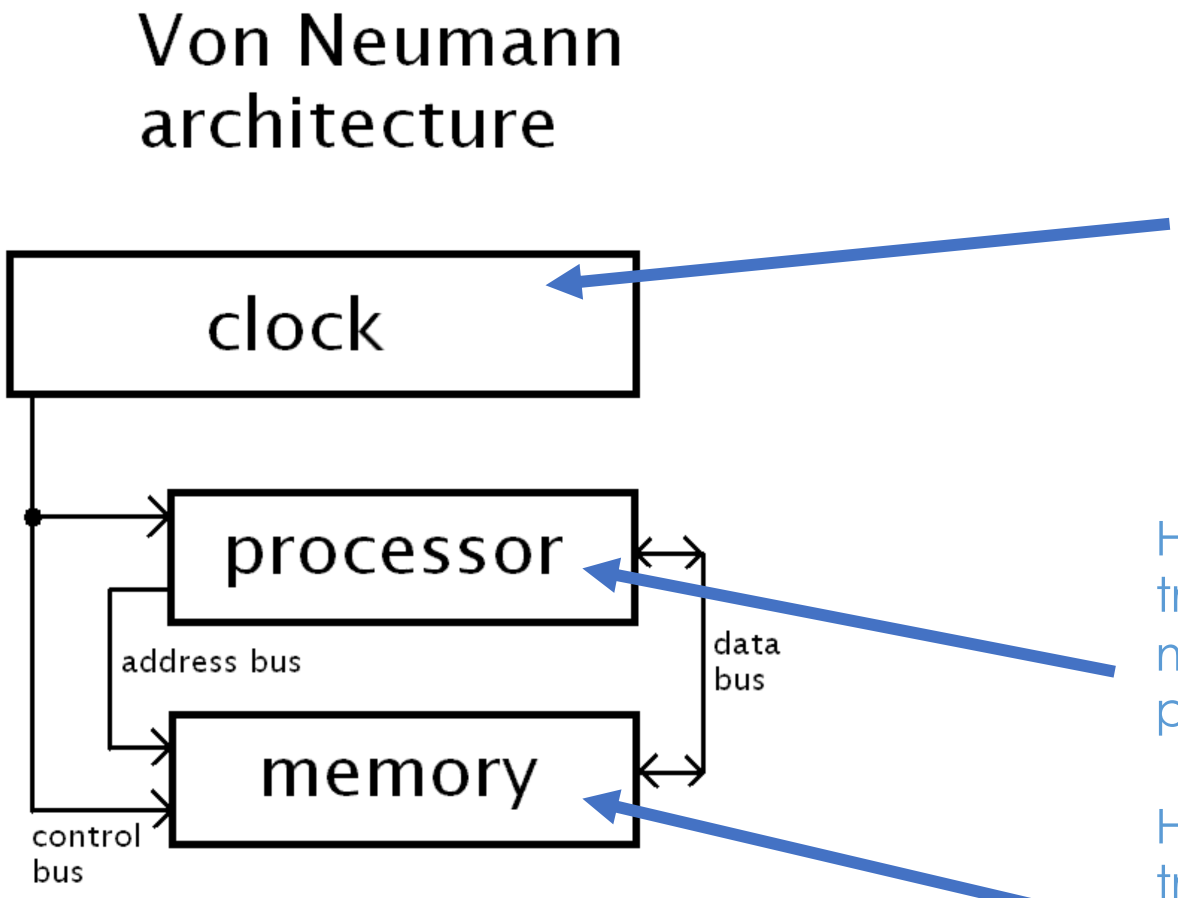
12. Metalization and Barrier Layer Gases

Used to deposit metal films and barrier layers in interconnect structures.

- Tungsten Hexafluoride (WF_6)
- Titanium Tetrachloride ($TiCl_4$)
- Tetrakis(Dimethylamido)Titanium (TDMAT)
- Aluminum Trichloride ($AlCl_3$)
- Trimethylaluminum (TMA)

13. Carbon-Based Film Deposition Gases	14. Miscellaneous and Specialized Gases	
Used to deposit carbon films like diamond-like carbon or graphene. •Methane (CH_4) •Ethane (C_2H_6) •Ethylene (C_2H_4) •Acetylene (C_2H_2) •Carbon Monoxide (CO) •Carbon Dioxide (CO_2) •Tetrafluoroethane ($C_2H_2F_4$)	Used in specialized processes or less common applications. •Hydrogen Sulfide (H_2S) •Hydrogen Selenide (H_2Se) •Hydrogen Telluride (H_2Te) •Hydrogen Peroxide Vapor (H_2O_2) •Hydrogen Cyanide (HCN) •Carbonyl Sulfide (OCS) •Nitrogen Monoxide (NO) •Nitrosyl Chloride (NOCl) •Hydrogen Bromide (HBr) •Sulfur Dioxide (SO_2) •Tellurium Hexafluoride (TeF_6)	Liste non exhaustive d’une centaine de gaz utilisés dans les processus de fabrication d’un microprocesseur

Obsolete architecture ?



Higher frequencies means more instructions per second.

More instructions per seconds means more energy dissipation.

Higher densities of transistors means more instructions per second.

Higher densities of transistors means reaching the physical limits of semiconductors

Advancing Technology for Humanity

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

2024 CHAPTER

ENVIRONMENT, SAFETY, HEALTH & SUSTAINABILITY (ESHS): ENVIRONMENTAL SUSTAINABILITY OF THE SEMICONDUCTOR FACILITIES (ESSF)

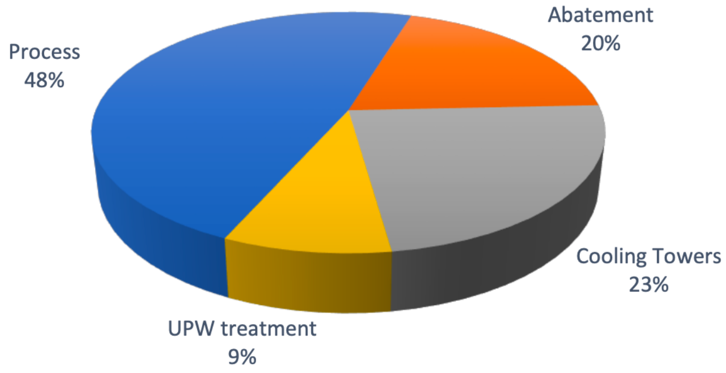


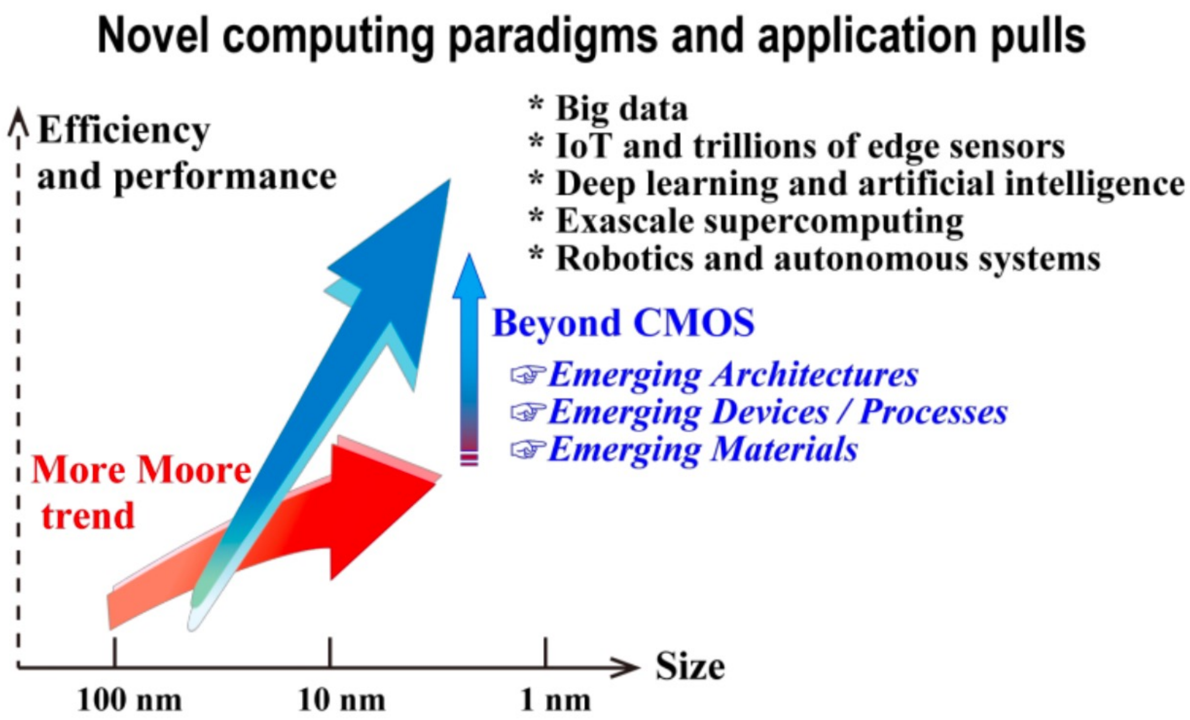
Figure ESHS-3 *Typical Water Usage Distribution for a 300 mm Facility (specific ratio may vary depending on the process and climate conditions)*

International Roadmap for Devices and Systems

International Roadmap for Devices and Systems

2023 Update

Beyond CMOS



Relationship of More Moore, Beyond CMOS, and Novel Computing Paradigms and Applications (Courtesy of Japan beyond-CMOS Group)

IEEE
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International Roadmap for Devices and Systems

International Roadmap for Devices and Systems

2023 Update

Beyond CMOS

6.2.2. Long-term Challenges

Table EMI2 Long-term Difficult Challenges

Long-term Challenges: 2029–2037	*Description*
Materials and processes that achieve 3D monolithic and vertical integration of high mobility and steep subthreshold transistors	Processes for sequential 3D vertical integration of transistors. Methods to lower the synthesis temperature of vertical semiconductor nanowires. Methods to dope and contact vertical semiconductor nanowire transistors. Lithography-free and low-temperature methods to achieve gate stack on vertical transistors.
Materials and processes that replace copper interconnects with improved reliability and electromagnetic performance at the nanoscale	Synthesis or assembly of CNTs in predefined locations and directions with controlled diameters, chirality and site-density. Carbon and collective excitations. Novel interlayer dielectrics: Metal Organic Framework (MOF) and Carbon Organic Framework (COF). Metals with less size effects such as silicides.
Materials and processes for charge-based and non-charge-based beyond CMOS logic that replaces or extends CMOS	Achieving a bandgap and full interfaces control in graphene in FET structures and alternative FETs (TFETs etc). Synthesis of CNTs with tight distribution of bandgap and mobility. Complex metal oxides with low defect density. High mobility transition metal dichalcogenides with low defect density and low resistance ohmic contacts. Spin materials: characterization of spin, magnetic and electrical properties and correlation to nanostructure. Topological materials: large bandgaps much greater that kT at room temperature, ability to modulate bandgap efficiently with electric field. BiSFET heterostructures: achieving exciton condensation at room temperature.
Materials and processes for emerging memory and select devices to replace DRAM/NVM.	Multiferroic with Curie temperature >400K and high remnant magnetization to >400K. Ferromagnetic semiconductor with Curie temperature >400K. Complex Oxides: Control of oxygen vacancy formation at metal interfaces and interactions of electrodes with oxygen and vacancies. Switching mechanism of atomic switch: Improvements in switching speed, cyclic endurance, uniformity of the switching bias voltage and resistances both for the on-state and the off-state.
Materials and processes that enable monolithically 3D integrated complex functionality including thermal and yield challenges	Integration on CMOS Platforms. Integration with flexible electronics. Biocompatible functional materials. Leveraging convergent materials expertise in adjacent sectors, including More than Moore functionalities (photonics, optics/metamaterials, outside connectivity, energy transfer/storage, power circuits).
Green and sustainable fabrication	To realize an integration process that is environmentally friendly and economically viable. Utilizing AI, ML, and informatics to develop production processes that can introduce green new materials.

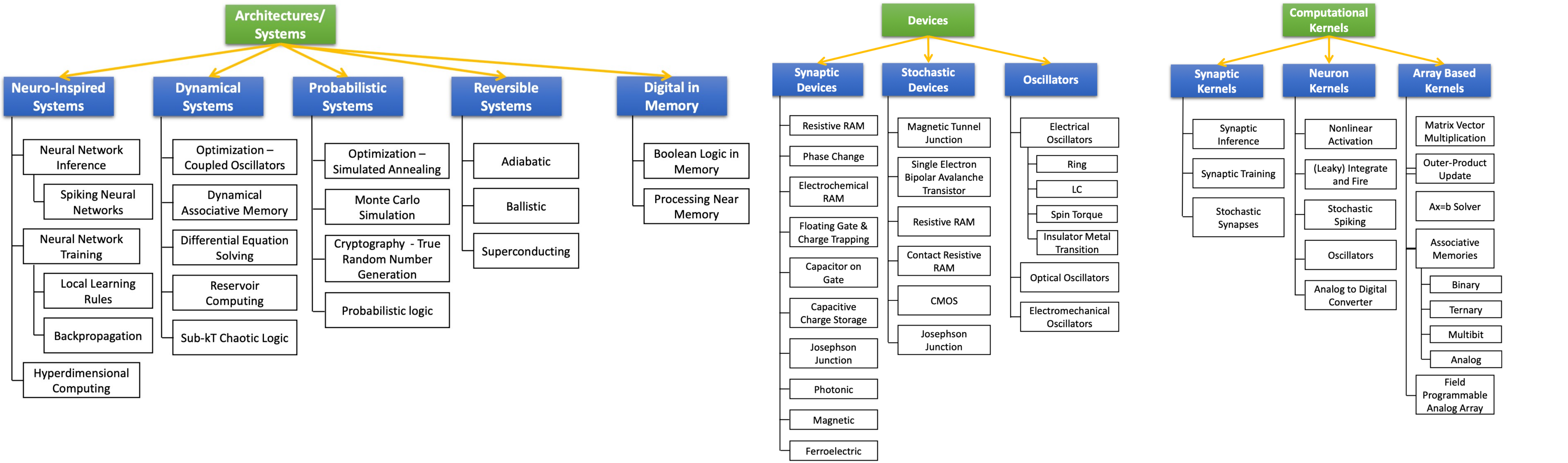

Figure BC4.3. Emerging Devices and Computational Kernels Requiring Codesign between the Device Layer and Higher Layers of the Technology Stack

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IRDS
International Roadmap for Devices and Systems

INTERNATIONAL
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DEVICES AND SYSTEMS

2023 UPDATE

BEYOND CMOS

Nouvelles architectures mais essentiellement les mêmes types de matériaux

Absence de la question fondamentale du recyclage

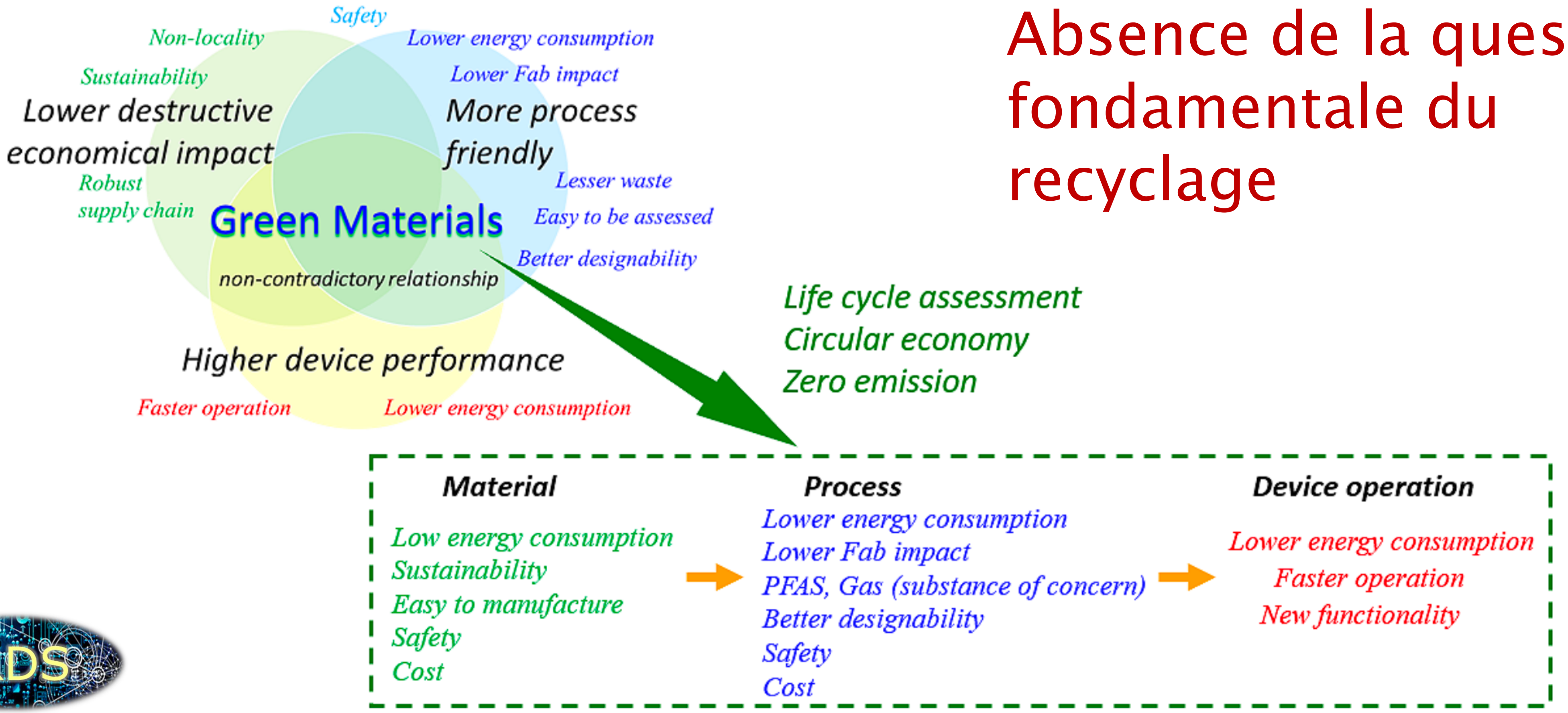

Figure EMI2 Liaison concept of EMI and ESHS

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

INTERNATIONAL
ROADMAP
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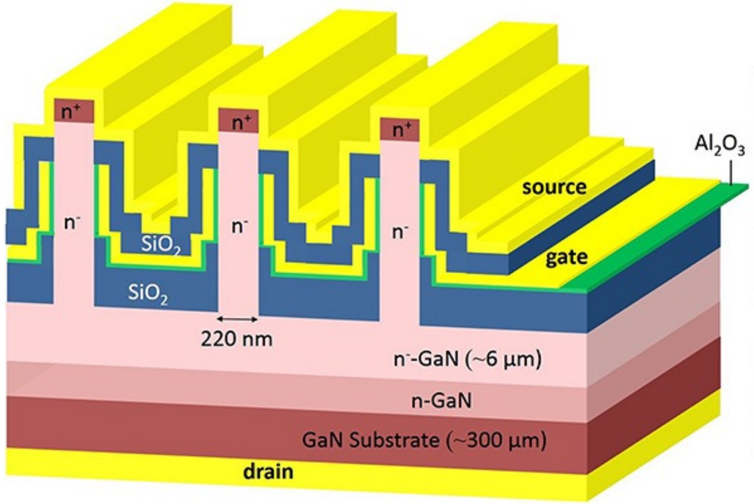
DEVICES AND SYSTEMS

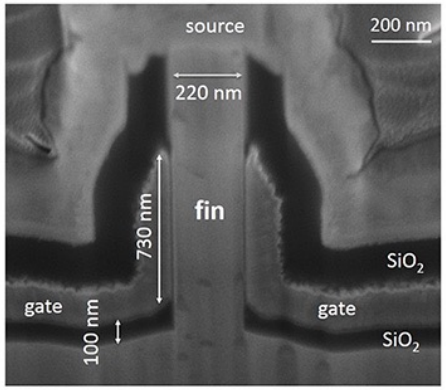
2023 UPDATE

BEYOND CMOS

« New design could dramatically cut energy waste in electric vehicles, data centers, and the power grid. » Tomàs Palacios, MIT

Innovation without sustainability





PHYSICAL REVIEW LETTERS **120,** 097702 (2018)

Editors' Suggestion

Spin-Current-Controlled Modulation of the Magnon Spin Conductance in a Three-Terminal Magnon Transistor

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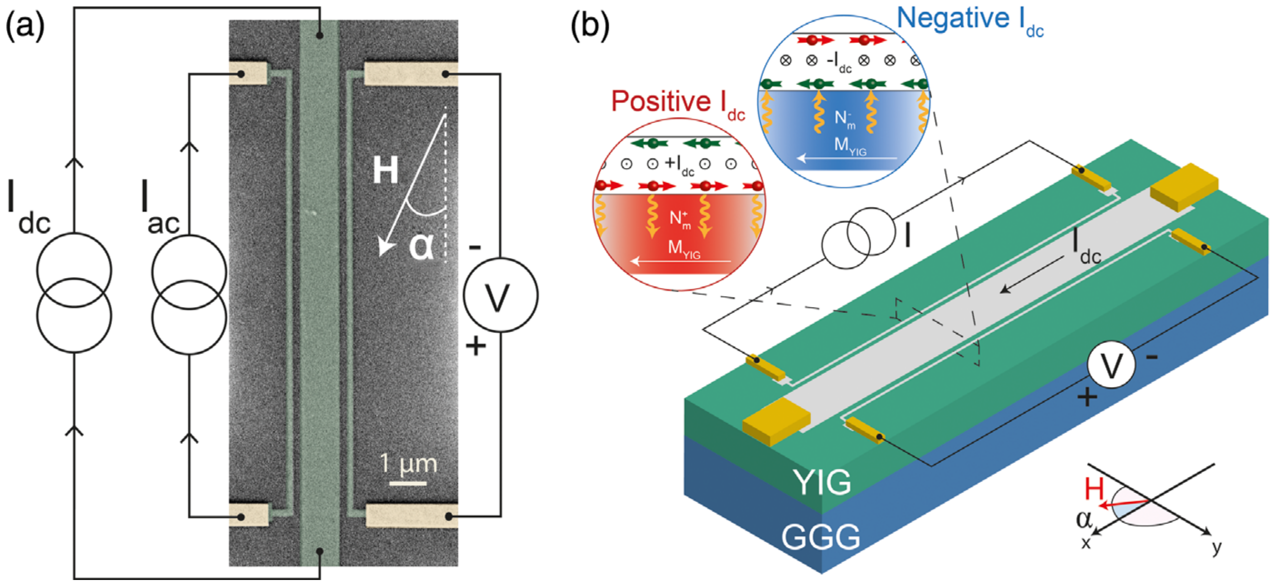
Innovation without sustainability

250K



GGG :Gadolinium Gallium Garnet

$Gd_3Ga_5O_{12}$

$Y_3Fe_2(FeO_4)_3$

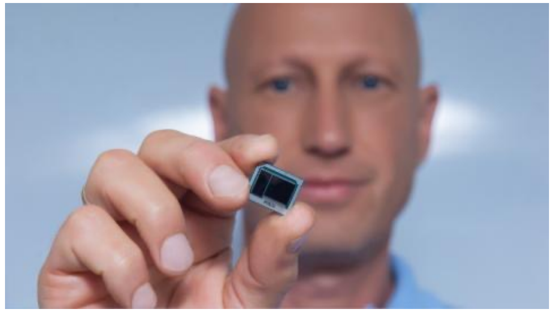
YIG : Yttrium iron garnet

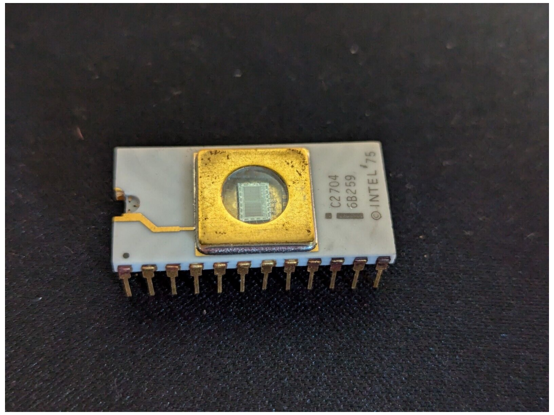
An 8-Bit, 40-Instructions-Per-Second Organic Microprocessor on Plastic Foil

Kris Myny, *Student Member, IEEE*, Erik van Veenendaal, Gerwin H. Gelinck, Jan Genoe, *Member, IEEE*, Wim Dehaene, *Senior Member, IEEE*, and Paul Heremans

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 47, NO. 1, JANUARY 2012

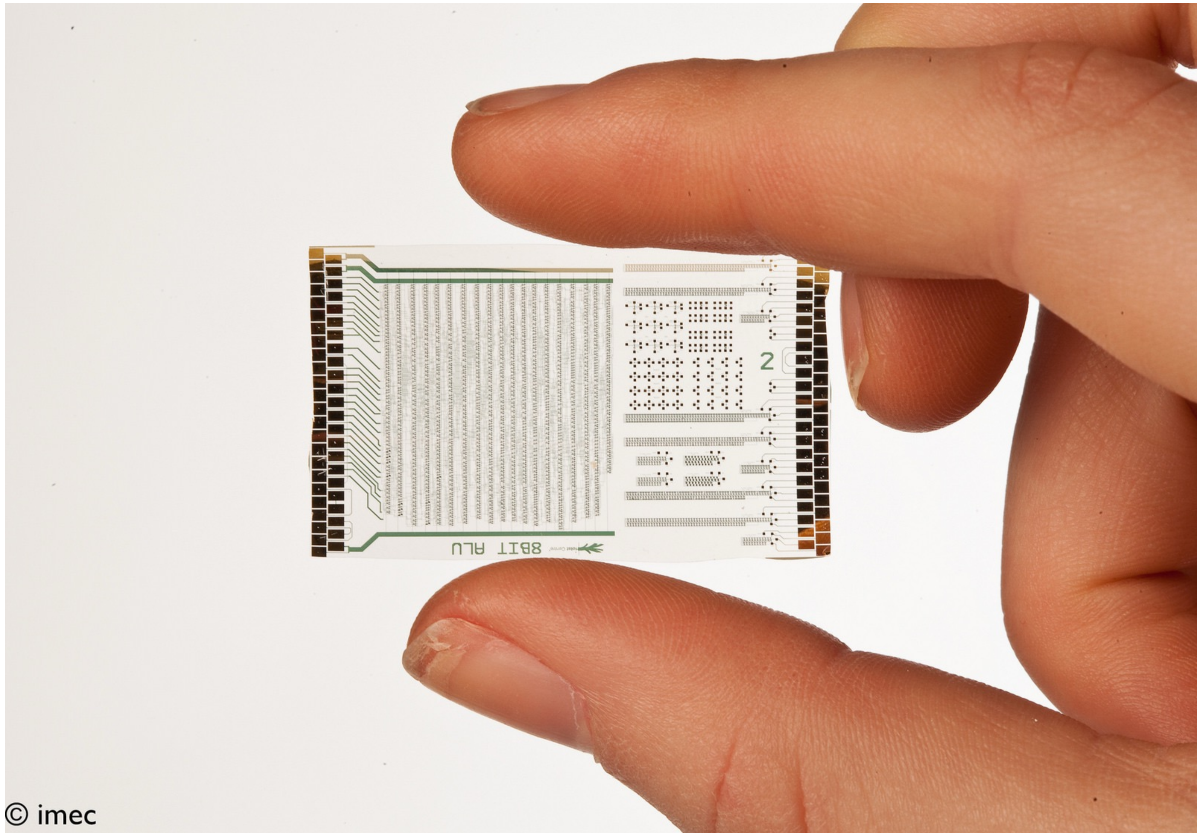
Intel 4004
1971

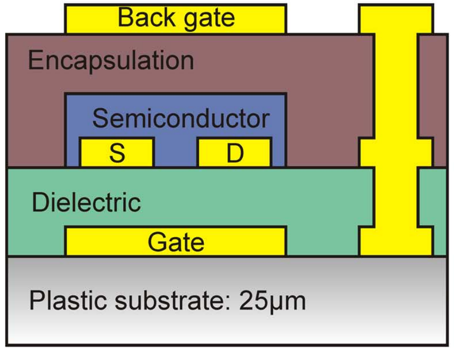




2 300 transistors

Mostly organic materials (carbon based), Au for gates





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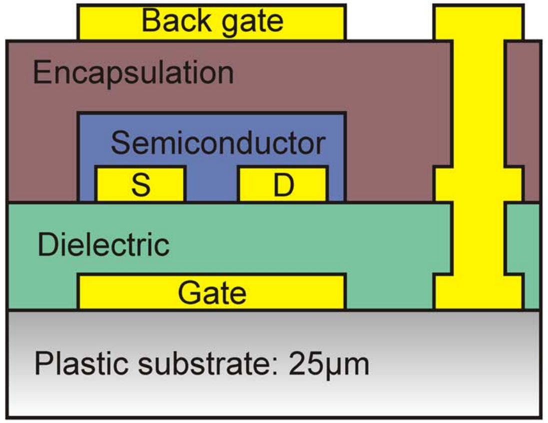
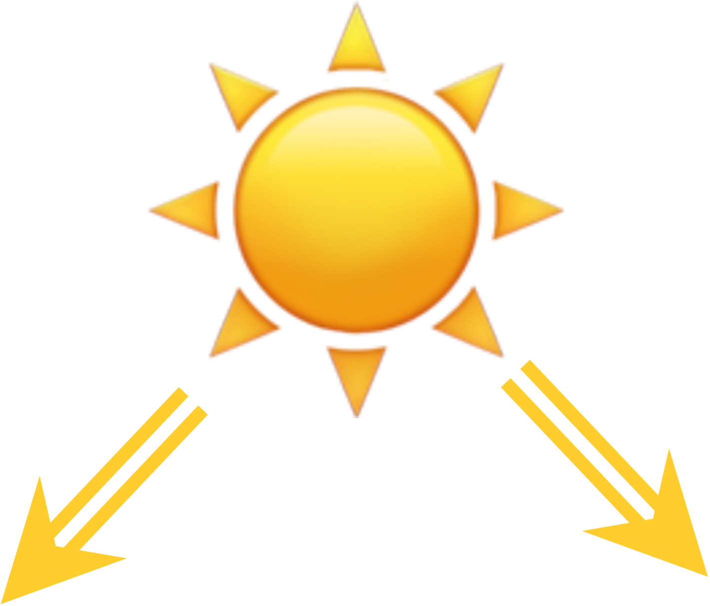


	Plastic microprocessor	Intel 4004
Transistor-count	3381	2300
Area	1.96 x 1.72 cm^2	3 x 4 mm^2
Pin-count	30	16
Power supply voltage	10 V	15 V
Power consumption	92 µW	1 W
Operation speed	40 operations/second	92000 operations/second
Semiconductor	Pentacene	Silicon
P-type mobility	~0.15 cm^2/Vs	~450 cm^2/Vs
Logic family	P-type	P-type
Operation	accumulation	inversion
Technology	5 µm	10 µm
Bus width	8 bit	4 bit
Production year	2011	1971
Wafer scale	6”	2”
Substrate	flexible	rigid

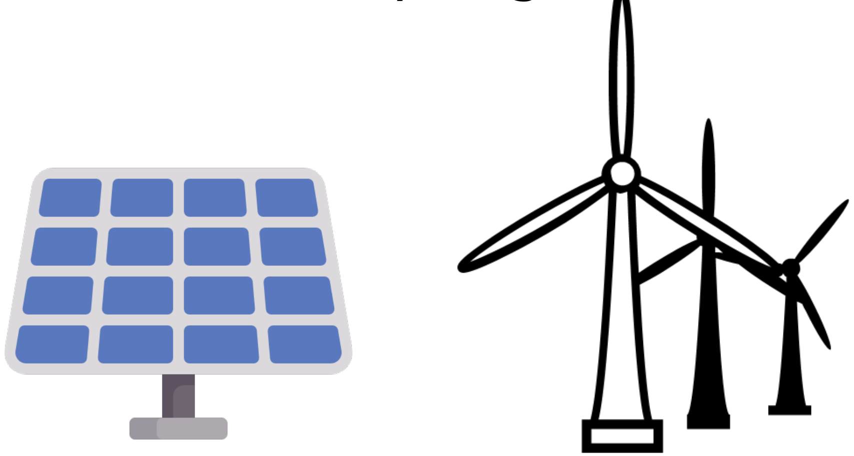
Organic materials change everything



Wet & low power
CHNOPS* chemistry
Evolved to be renewable
About 2.5 billions years !

“Organic human societies"
Since the neolithic (~12k Years)
up to the end of the 18th
century

Dry, high-power mineral
chemistry.
Optimized for power, not (yet?)
for recycling.



Mineral and fossil fuel societies from
the 19th century to the present day
Could last about 3 centuries ? (2
centuries have already passed)

Les trois missions des nouveaux technologues

Dézombifier

Mission 1

Gérer l'existant, s'adapter aux chocs, fermer, rediriger

Sortir de la prison du présent, des dépendances au chemin

Mission 2

Avec les technologies existantes faire de la soutenabilité faible pour gagner du temps pour la mission 3

Sortir des zombies et passer aux technologies vivantes

Mission 3

Inventer de la soutenabilité forte, nouveau métabolisme technique

2020 2050 2075 2100 2125 2150 2175 2200

Soutenabilité faible
Durée 1 siècle

Soutenabilité forte
Durée des siècles