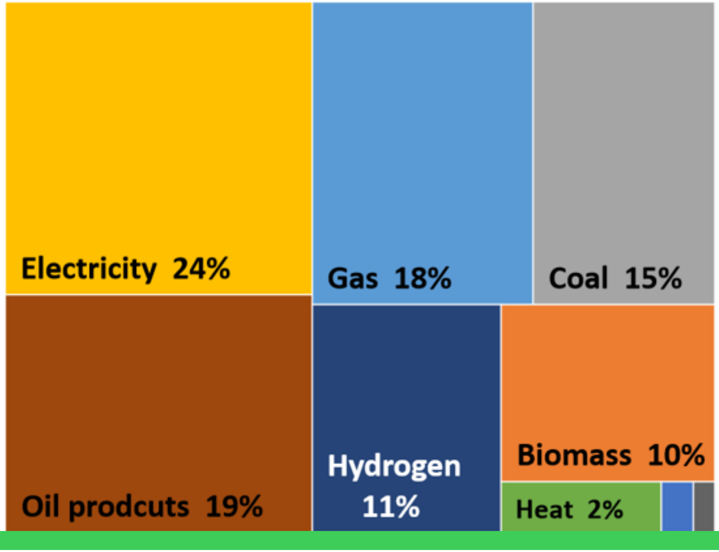
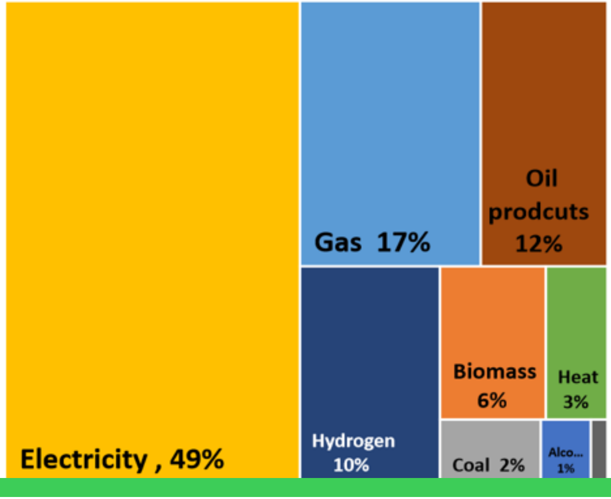
BAU: 642 EJ

Total final energy consumption



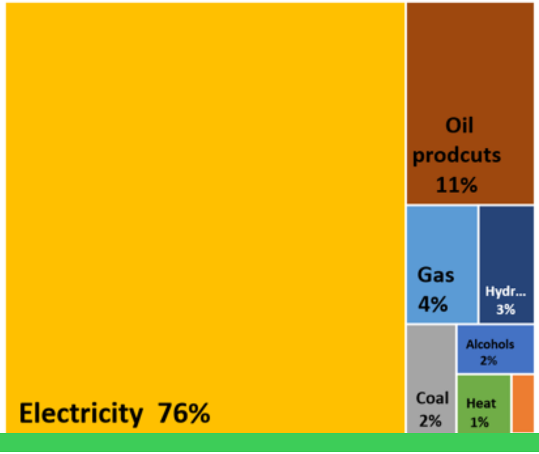
INTERMEDIATE: 584 EJ

Total final energy consumption



ALL ELECTRIC: 549 EJ

Total final energy consumption



Material intensity of decarbonated power systems

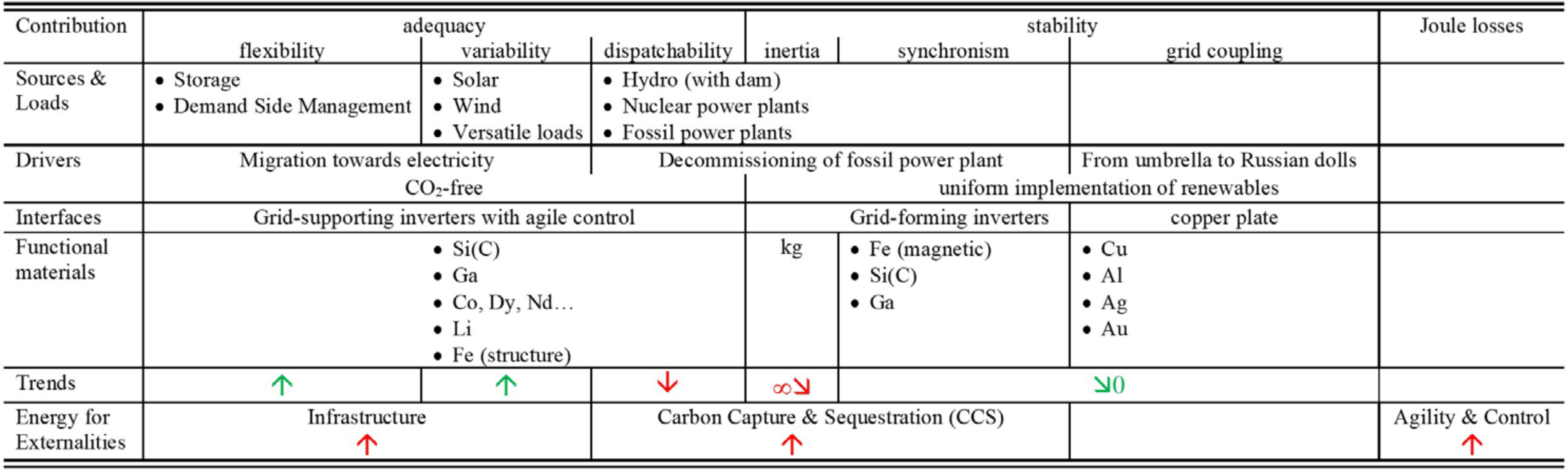
in Resources to achieve a just transition: levers & limits (COP 29 Side-Event)

Vincent Mazauric

Intermediate 2050 vision is adapted from: https://www.irena.org/Energy-Transition/Outlook/Renewable-energy-roadmaps

Power system evolution under CO_2-free constraint

Naturally derived from the thermodynamic Second Law



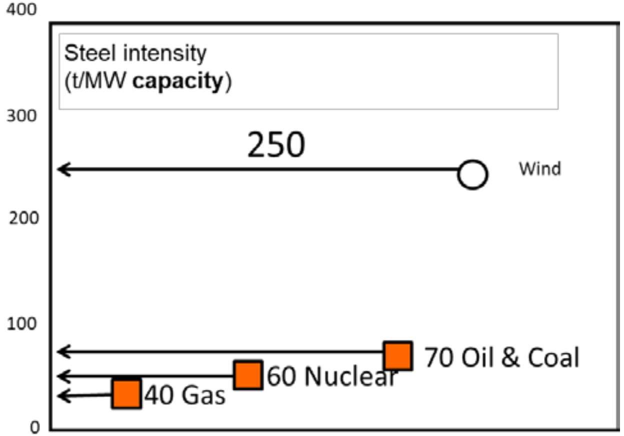
Contribution	adequacy			stability			Joule losses
	flexibility	variability	dispatchability	inertia	synchronism	grid coupling	
Sources & Loads	• Storage • Demand Side Management	• Solar • Wind • Versatile loads	• Hydro (with dam) • Nuclear power plants • Fossil power plants				
Drivers	Migration towards electricity		Decommissioning of fossil power plant			From umbrella to Russian dolls	
	CO_2-free			uniform implementation of renewables			
Interfaces	Grid-supporting inverters with agile control			Grid-forming inverters		copper plate	
Functional materials	• Si(C) • Ga • Co, Dy, Nd… • Li • Fe (structure)			kg	• Fe (magnetic) • Si(C) • Ga	• Cu • Al • Ag • Au	
Trends	↑	↑	↓	∞↘	↘0		
Energy for Externalities	Infrastructure ↑		Carbon Capture & Sequestration (CCS) ↑				Agility & Control ↑

V. Mazauric, "Entanglement of Energy, Material, and Informational Challenges for Attaining a Sustainable Global Future (distinguished lecturer)," presented at the Tohoku Forum for Creativity/Future Society Design Program: Sustainable Structural Integrity for Energy Infrastructure, Sendai, Japan, November 21, 2023. https://www.tfc.tohoku.ac.jp/future-society-design-program/event/3012.html

Energy system materiality

Dilution of energy infrastructures under decarbonation :

- Material intensity of renewables is higher than conventional



Geostrategic stake:

- From primary energy to functional material tension
- Low potential in developed countries

Business model constraint for mining industries:

- Change the merit order and subsequent value of ores
- Modify the profitability of extraction sites


Kennecott Copper Mine (Utah) **3.2 x 1.2 x 1.2 km^3**

ICT in energy systems

Control:

- Provide energy efficiency strategies in a context of tension between demand and supply
- Balance supply and demand in “real time” in a context of decreasing inertia
- Manage highly diluted assets and versatile loads within a general migration of the energy towards electricity
- Signal quality under variability: Enforce synchronism (clock) to provide the lowest dissipative grid

Forecast:

- Local weather to mitigate intermittency
- Predictive maintenance for highly dispersed energy assets

Role:

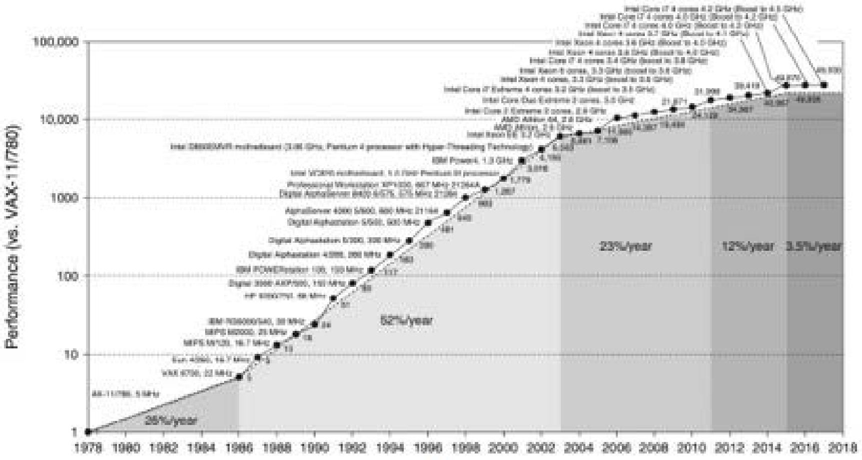
- Increase the knowledge on the energy system by decreasing its missing information
- Ensure trusted transactions in a competitive and open market (blockchain)

but

- Spoil the natural evolution of a system (2nd principle)
- Require a **processor** to gain information on the system…
  And reject a larger amount of missing information (heat) elsewhere!

Issue:

- Is accurate information (local, real-time) sustainable from a thermodynamic viewpoint? In a context of:
  - data-deluge
  - Koomey’s law faltering



From: J.L. Hennessy and D.A. Pattersson, “Fundamentals of Quantitative Design and Analysis” in Computer architecture: A quantitative approach (5th edition), Amsterdam, Netherlands: Elsevier (2018): 1-97.
The Koomey’s law is derived in: Koomey, Jonathan; Berard, Stephen; Sanchez, Marla; Wong, Henry; “Implications of Historical Trends in the Electrical Efficiency of Computing”, IEEE Annals of the History of Computing, vol. 33, no 3, 29 mars 2010, p. 46–54.

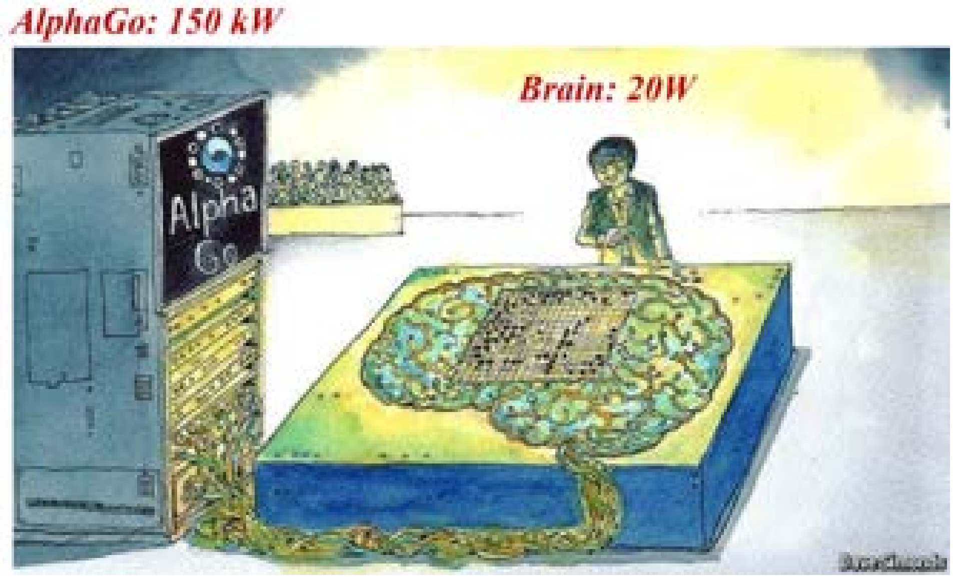
Digital Technology: Perspectives

Intrinsic energy weaknesses of ICT:

- ambiguity *vs.* switching barriers of binary information
- memory volatility
- information erasure (Turing machine)

Game changers for the future:

- Mid-term: Decouple reading and writing in memory
  - Spintronics (merging of electronics and magnetism at nanoscale)
  - Bio-inspired (neuromorphic) architecture
- Long-term:
  - HP Computing allowing ramping polarization (superposition)
  - Reversible computing avoiding erasure (intrication)
  - Quantum computing dedicated to energy supremacy



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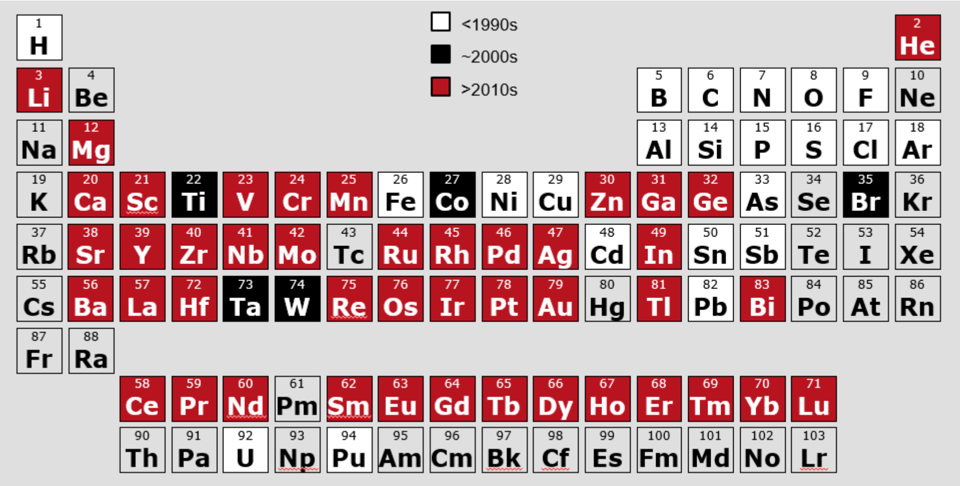
J. Torrejon et al.: Neuromorphic computing with nanoscale spintronic oscillators, Nature, vol. 547, no. 7664, pp. 428-431, 2017.
C.H. Bennett: Logical reversibility of computation, IBM J. Res. Develop. 17(6), pp.525-532 (1973); Notes on the history of reversible computation, IBM J. Res. Develop. 32(1), pp.16-23 (1988).
M. Konopik, T. Korten, E. Lutz, and H. Linke, "Fundamental energy cost of finite-time parallelizable computing," Nature Communications, vol. 14, no. 1, p. 447, 2023,

Power system footprint (including ICT)

60 elements are used, less than 15% is recycled

Due to energy footprint of digital solution:

- Digital and energy transitions (2050-70) appear intricated
- Functional resources availability require long-term planning exercises endogenizing energy, information and material processing
- Magnetism is at the crossroads between energy generation and digitalization!



☐ <1990s
⬛ ~2000s
🟥 >2010s

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 🟥	57 La 🟥	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 ☐																
		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 🟥		
		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 ☐		

Adapted from: T. Ernst, "Vers une électronique soutenable dans un monde digital: Enjeux et perspectives," *Revue de l'électricité et de l'électronique, vol. 5, pp. 18-24, 2022.*

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