Pathways for 1000× Energy Efficiency

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CEA-Leti, Deputy Director and CTO

July 1st, 2025

1. Context
Who are we?

FROM HARDWARE TO SOFTWARE - A GLOBAL R&D PARTNER ADDRESSING SEMICONDUCTOR CHALLENGES

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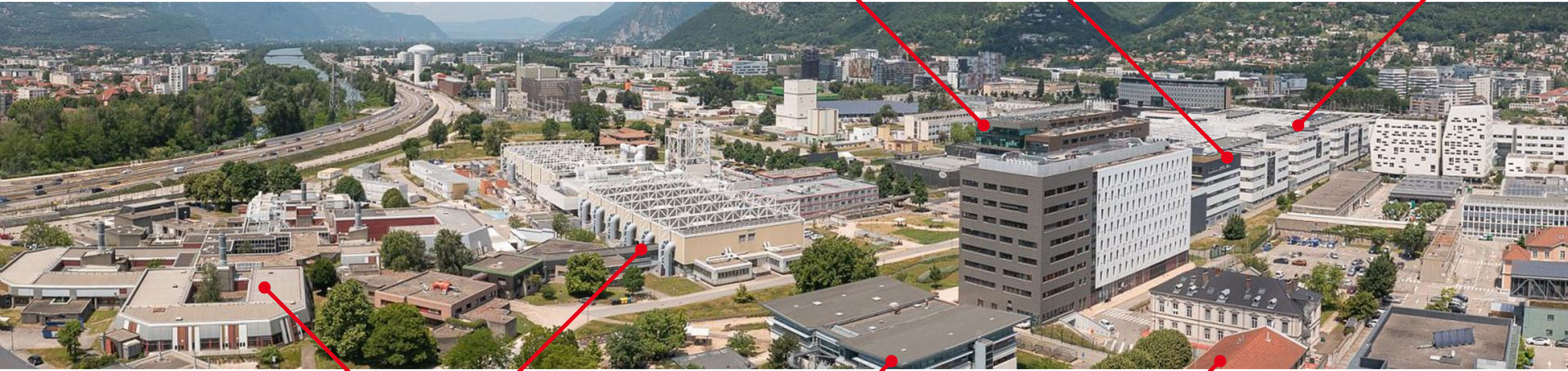
- 2,000 scientists & engineers
- € 500M budget
- 3,400 patents
- 11,700 m² cleanrooms
- 700 tools
- 78 startups
- 700 publications / year

cea list

- 1,000 scientists & engineers
- € 130M budget
- 700 patents
- 26 startups
- 300 publications / year

- We collaborate with semi-conductor players in industry and research organizations
- To meet societal and market challenges via bilateral projects
- Anticipating electronic trends with a global vision and R&D programs
- Leveraging state of the art semiconductor technologies and tools, and a lab-to-fab approach

A WIDE RANGE OF WORLD-CLASS R&D FACILITIES
ON A SINGLE CAMPUS



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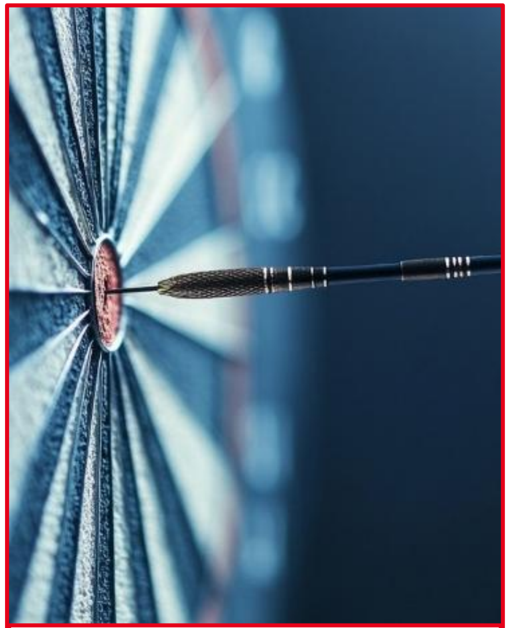
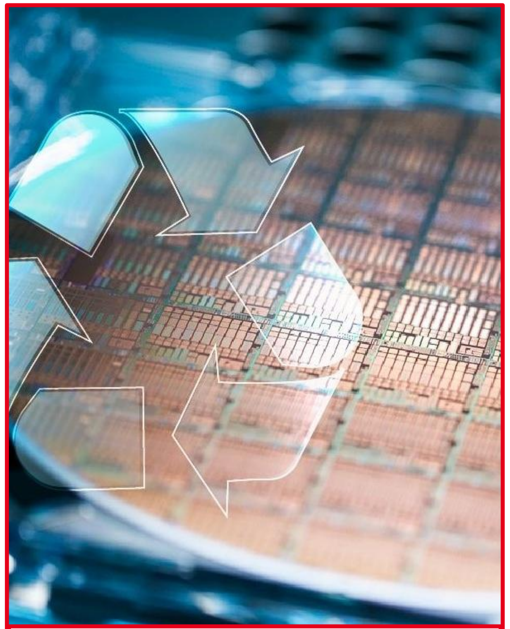
WE NEED A DIGITAL WORLD THAT IS
COMPETITIVE, SECURE, ETHICAL, AND SUSTAINABLE,
IN LINE WITH OUR VALUES



COMPETITIVE
(performance & cost)

SECURE

ETHICAL



SUSTAINABLE

AS SOCIETY'S DIGITALIZATION ACCELERATES, BREAKTHROUGH INNOVATIONS ARE NEEDED

Major challenges to address:

- **Energy efficiency**
- **Sustainable electronics**

Breakthrough innovations are required:

- in semiconductor technologies
- in circuits and chip architectures
- in systems, algorithms, and EDA tools

ENERGY EFFICIENCY GAIN
×1,000
by 2032

We need to improve the energy efficiency of chips and electronic systems by a factor of 1,000 by 2032

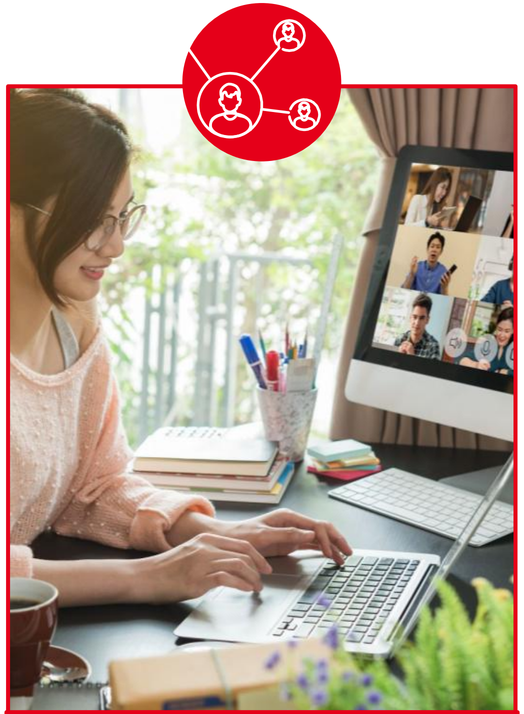
CONTEXT
1

Data Deluge & Energy Demand

The irreversible trend.

A DATA-DRIVEN ERA
2024 GLOBAL FIGURES

World population
8.2 billion



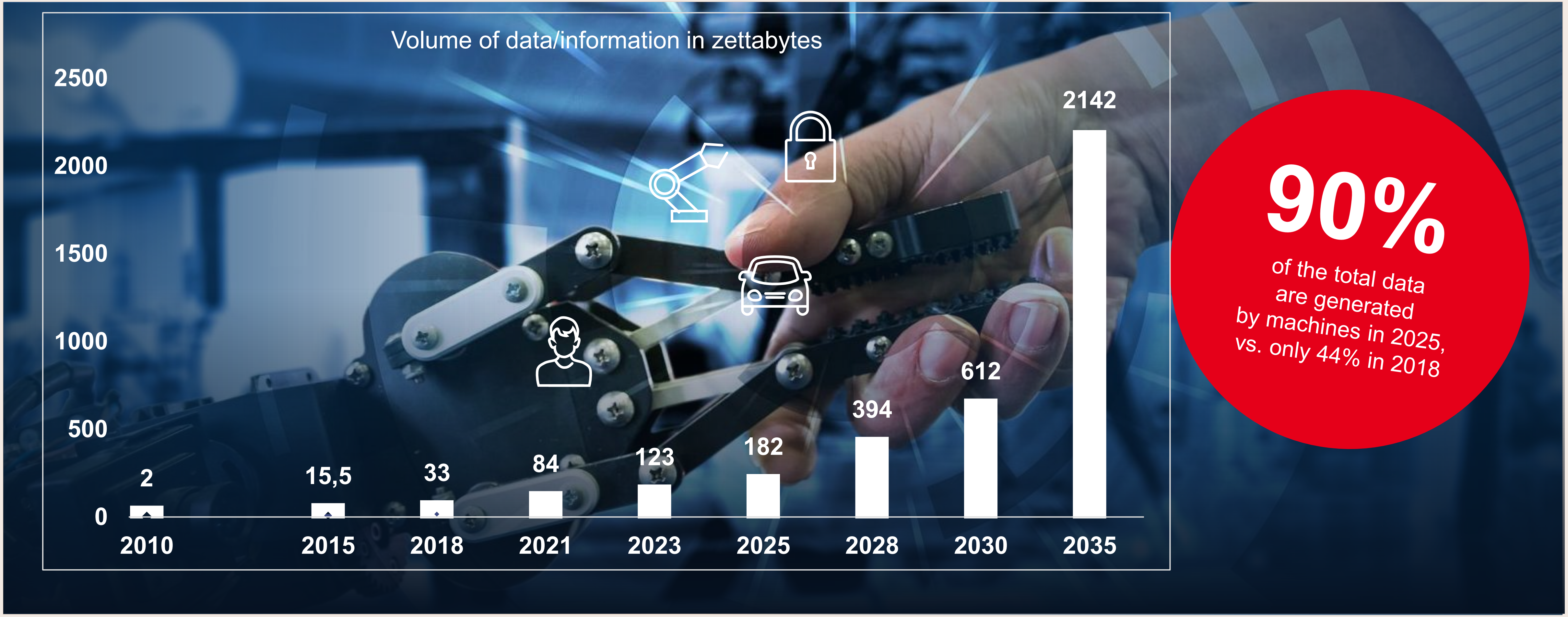
Internet users
5.35 billion (60%)

Mobile users
6.4 billion

Internet traffic
33 Exabytes per day

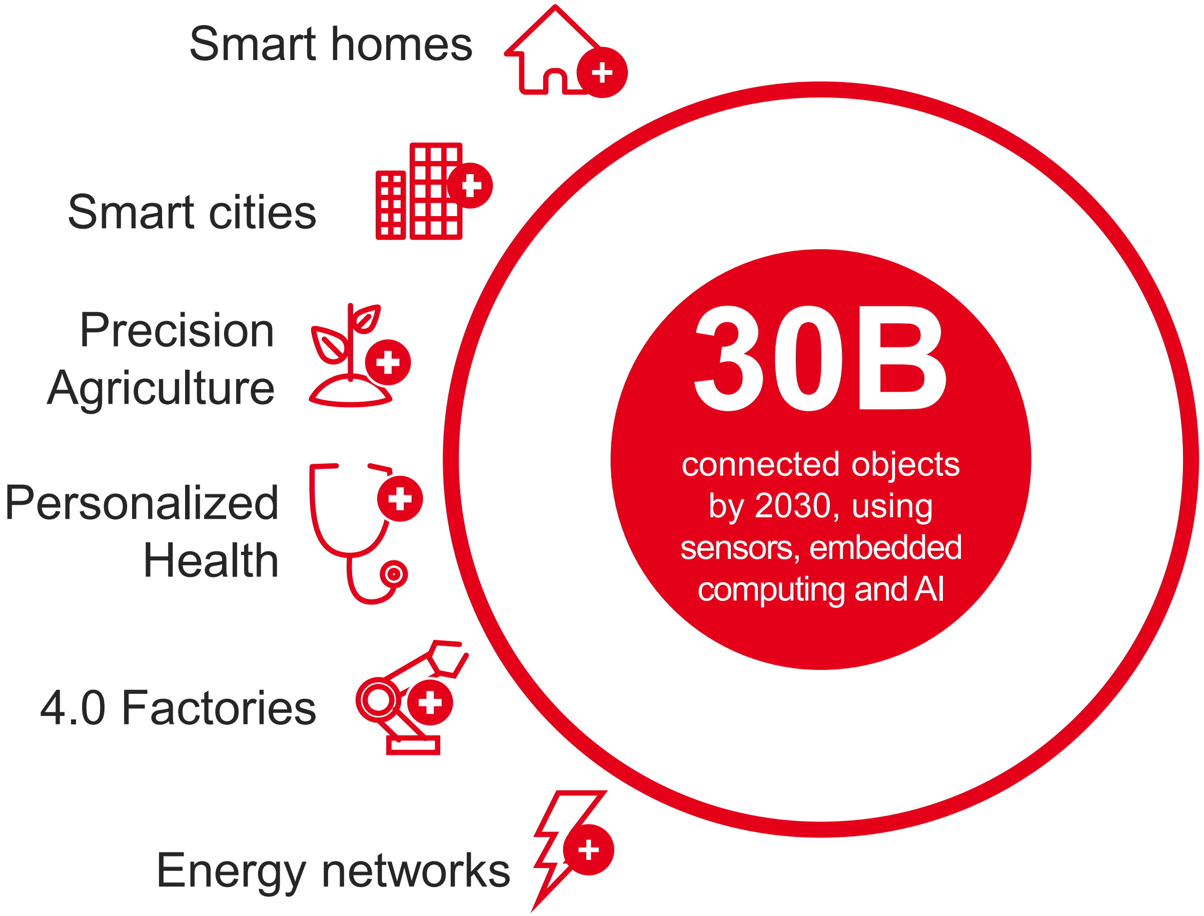
https://fr.statista.com/statistiques/1350675/nombre-utilisateurs-internet-reseaux-sociaux-monde/
https://www.google.fr/search?q=Poupulation+mondiale+en+2024&rlz=1C1GCEA_enFR988FR988&oq=Poupulation+mondiale+en+2024&gs_lcrp=EgZjaHJvbWUyBggAEEUYOdIBCDkyMzFqMGo3qAIAsAIA&sourceid=chrome&ie=UTF-8

FACING THE DATA DELUGE
THE YOTTA ERA (10^{24})



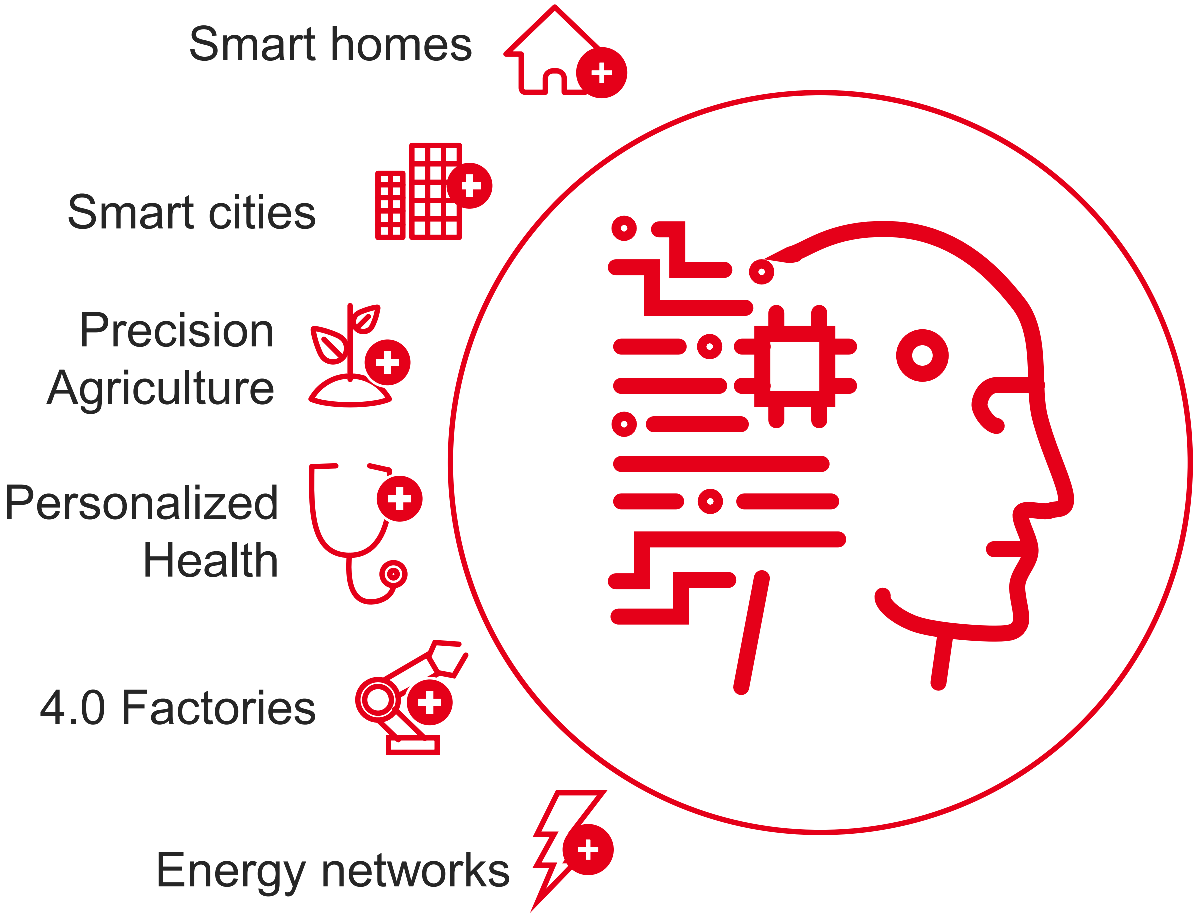
IDC, Statista 2018 and 2025

DIGITALIZING THE ECONOMY TO PROVIDE NEW SERVICES



https://webdesobjets.fr/etude-gartner-8-milliards-objets-connectes-en-2017/

DATA-BASED DIGITALIZATION
OF THE ECONOMY

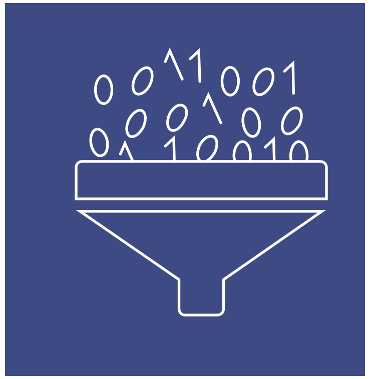


IoT, AI and digital twins will help:

- Run factories and optimize raw materials and energy usage
- Manage decentralized and intermittent energy production
- Design new materials and new medication
- And more

Iot Analytics

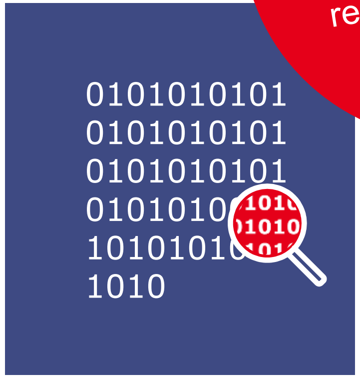
DATA MANAGEMENT
AND SERVICES GENERATED



DATA COLLECTION

DATA TRANSMISSION

DATA STORAGE AND ELEMENTARY PROCESSING



DATA EXPLOITATION

50% of the data are real-time by 2025 (dark data)

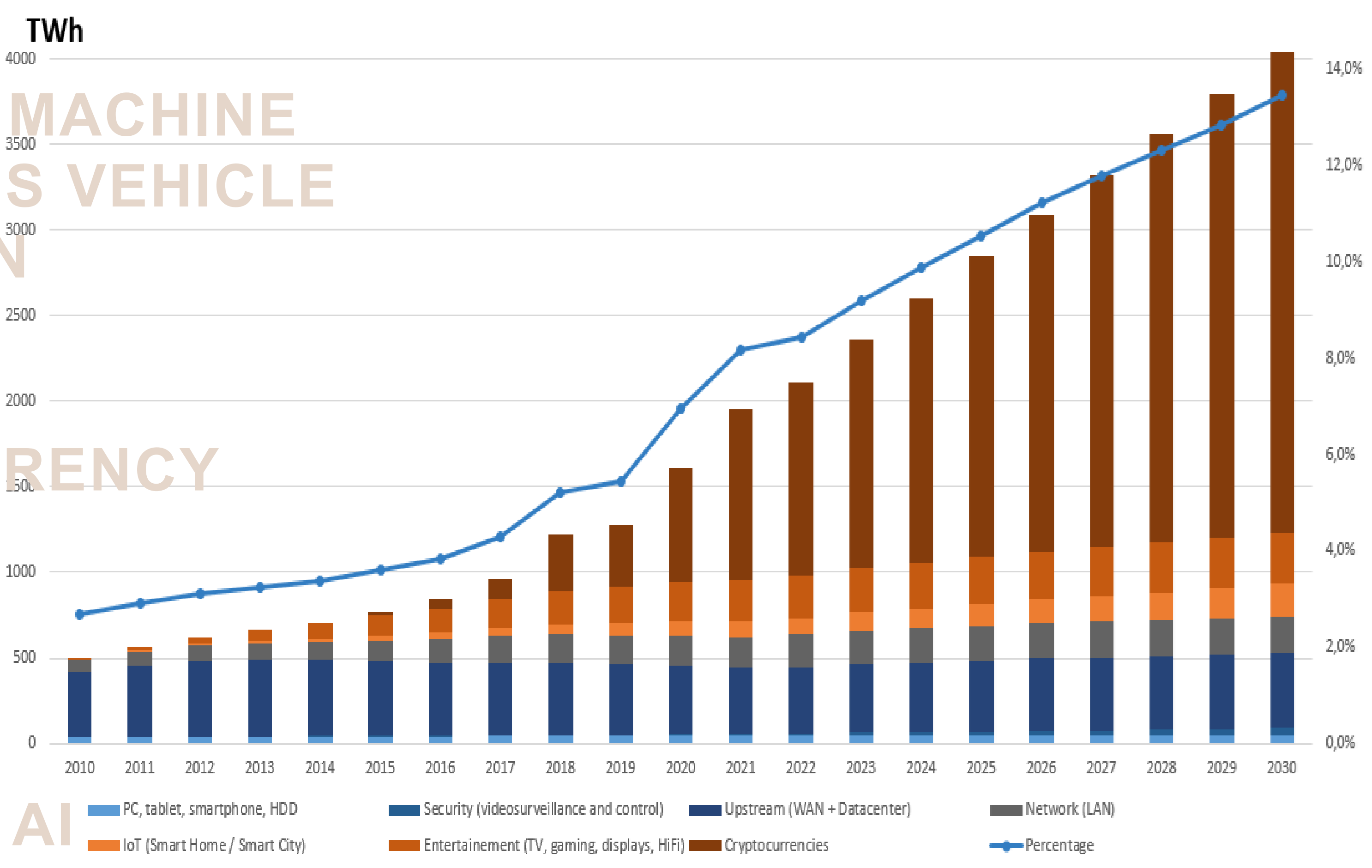
80% of data will be processed locally or at the edge in 2030

AI will be implemented in the computing continuum from edge to cloud:

- Deep edge AI (sensors)
- Edge AI
- AI in the cloud

TOMORROW'S COMPUTING CHALLENGES
A NEW DATA TSUNAMI?

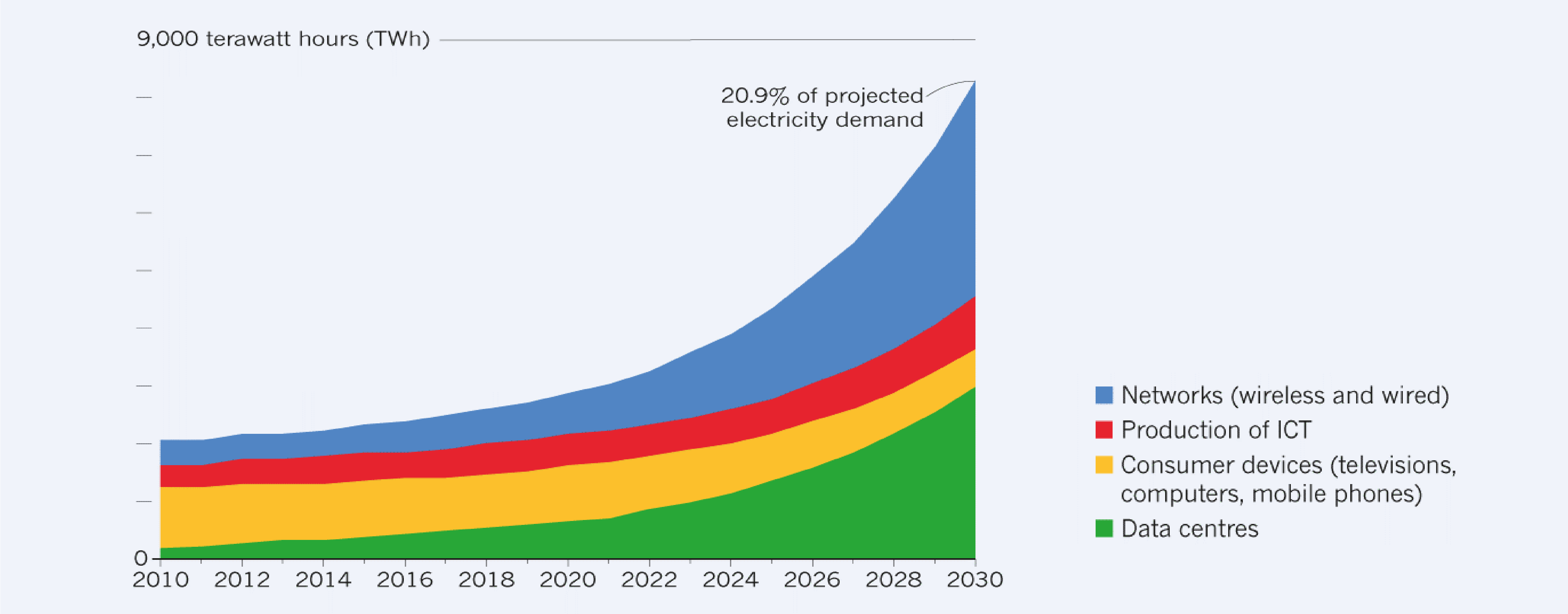
SENSORS
MACHINE TO MACHINE
AUTONOMOUS VEHICLE
BLOCK CHAIN
INDUSTRY
GENOMICS
CRYPTO CURRENCY
HPC
GAMING
NEW SPACE
SMART TV
GENERATIVE AI



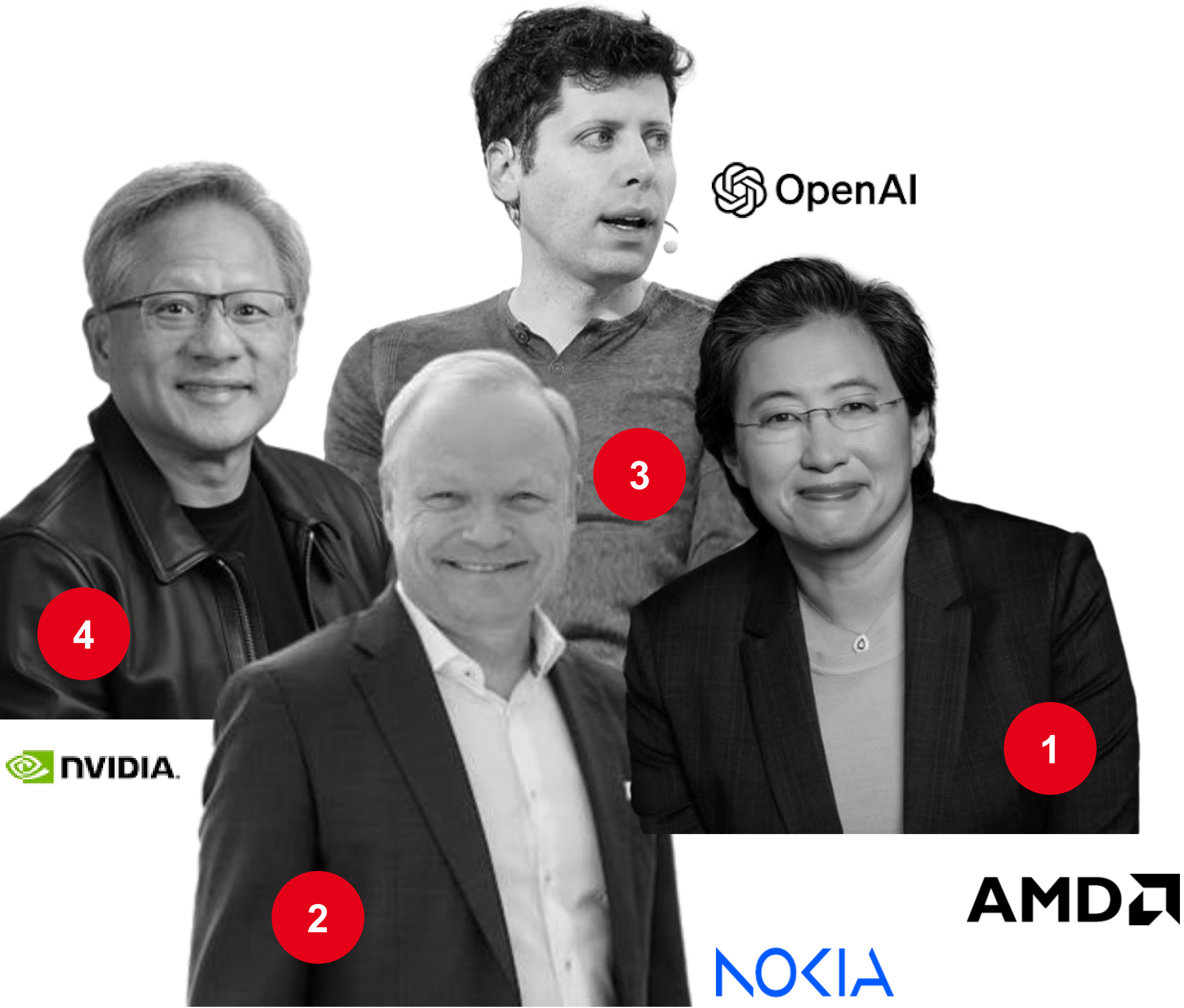
Towards **14%** of the global electricity demand?

IEA global-electricity-demand-by-scenario-2010-2030, Enerdata, Cambridge Bitcoin Electricity Consumption Index 2021, Total Energy Model V2.0 for Connected Devices EDNA 2021

INFORMATION COMMUNICATION TECHNOLOGIES
ENERGY FORECAST



ENERGY EFFICIENCY IS THE MAIN CHALLENGE



1 **Lisa Su**, CEO of AMD (February 2025)
“ Over the next decade,
we must think of energy efficiency
as the most important challenge

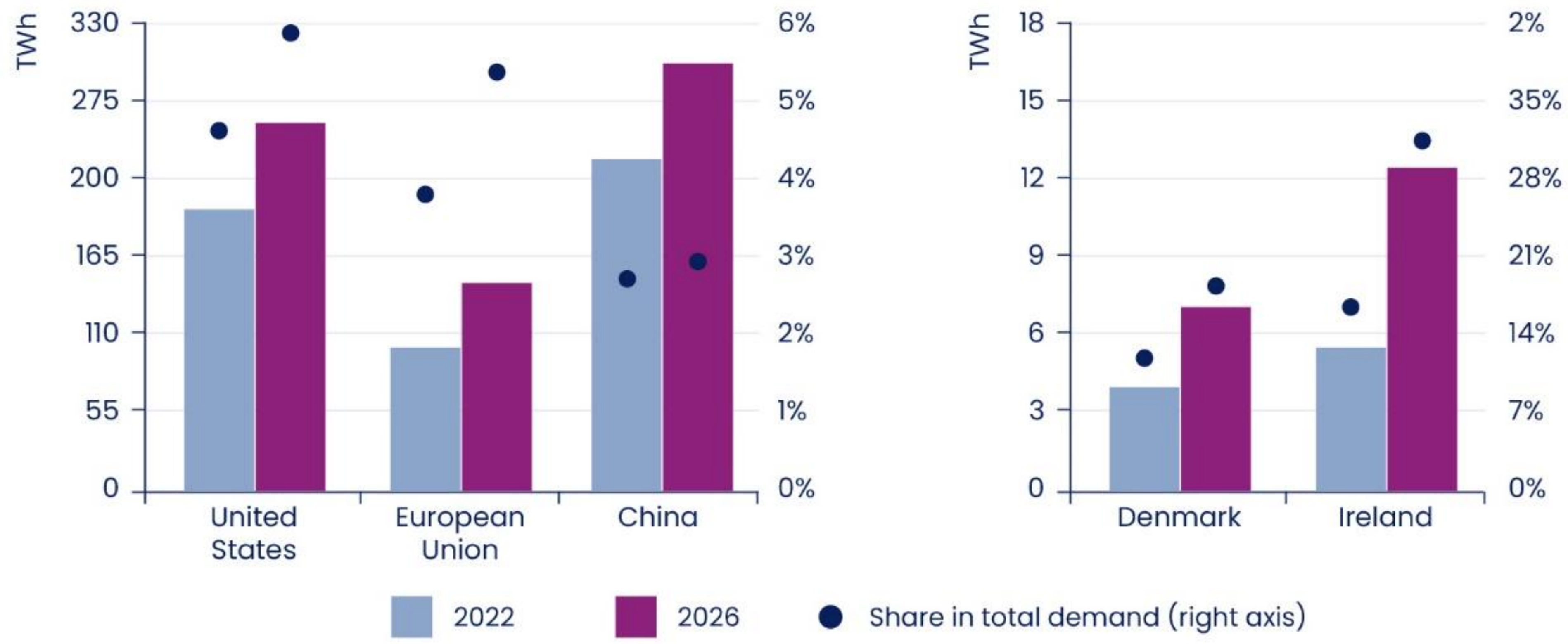
2 **Pekka Lundmark**, CEO of Nokia (January 2025)
“ Making AI greener starts
with a smarter data center design

3 **Sam Altman**, CEO of OpenAI
“ Future AI depends on energy
*breakthroughs (*Davos, January 2025*)*

4 **Jenseng Huang**, CEO Nvidia (September 2024)
“ AI will Impact the future of energy

GLOBAL ELECTRICITY DEMAND GROWTH:
THE PART OF DATA CENTERS

Evolution (2022-2026) and share in total electricity in selected regions

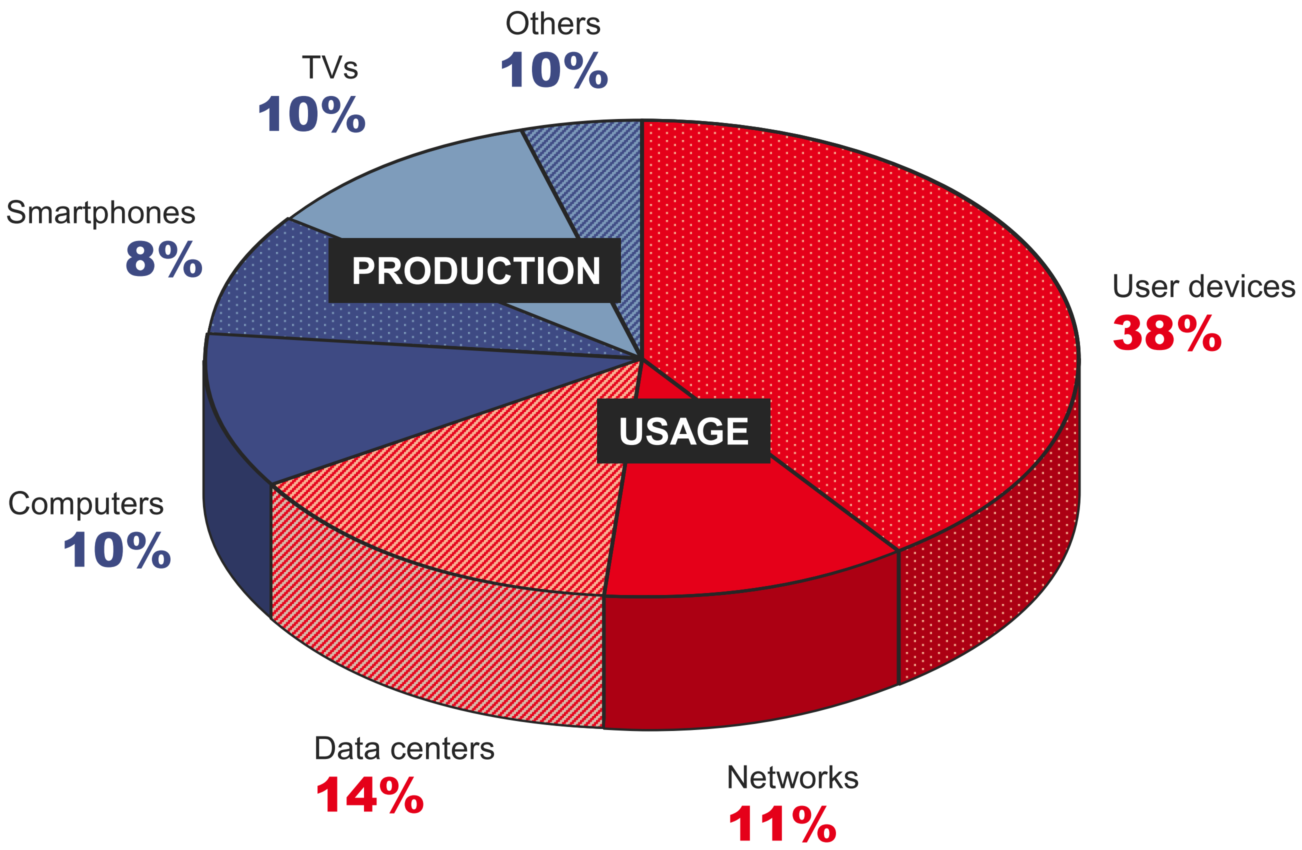


https://www.iea.org/reports/world-energy-outlook-2024

REDUCING ENERGY CONSUMPTION IN ELECTRONIC DEVICES:
A TWO-LEVEL APPROACH

37%

of the energy
is consumed
during **production**



63%

of the energy
is consumed
by **using** the
devices

Source: The Shift Project - Forecast model 2021/2018

Innovation will be key to move towards greener electronics and to limit the environmental footprint of chips and electronics systems

2. Solutions

What can we do?

SOLUTIONS 2

A New Flagship Initiative

Launched by CEA-Leti

ENERGY EFFICIENCY GAIN
×1,000
by 2032

R.E.S.O.L.V.E

GREENER CHIPS

Reducing
Energy consumption for
SOvereignty and
Leadership in
VAlue-added
Electronics products

15 KEY TECHNOLOGIES
TO IMPROVE ENERGY EFFICIENCY

ENERGY EFFICIENCY GAIN
×1,000
by 2032

New Semiconductors Technologies	**New Memories (embedded, standalone)**	**3D Heterogeneous Integration & co-Packaged Optics**	**3D Monolithic, GAA, CFET FD-SOI, 2D Materials**	**Optical & RF Links** (Photonic, GaN LED, mmWave)	**Wide Band-gap Power Devices**
Circuits and Disruptive Chip Architectures	**Energy-efficient HMI** (Displays, others)	**New Computing Paradigms** (Neuromorphic, Analog, Quantum…)	**Dedicated Versatile Accelerators**	**Avoid moving data** (Alternative to von Neumann Architectures)	**Energy-efficient Power Converters** (AC/DC, DC/DC…)
Systems, Algorithms, EDA Tools	**Smart Sensors** (Deep Edge) **Edge AI Computing**	**New Algorithms** (Frugality in Data and Energy)	**Sustainable Electronics**	**AI-based EDA tools STCO(1), ATCO(2)**	**Cybersecurity** (End-to-End Solutions)

(1) STCO: System Technology Co-Optimization
(2) ATCO: Application Technology Co-Optimization

ADDRESSING STRATEGIC MARKETS


AUTOMOTIVE


AERONAUTICS


TELECOMS


SMART DATA CENTER


DEFENSE


SPACE


INDUSTRY 4.0


BIOMEDICINE


MEDICAL DEVICES


AGRICULTURE


IoT - SENSORS


DISRUPTIVE HMI

IMPROVING ENERGY EFFICIENCY
15 KEY TECHNOLOGIES

Energy efficiency Gain
× 1,000
by 2032

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R.E.S.O.L.V.E

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NEW SEMICONDUCTORS TECHNOLOGIES

A set of new disruptive technologies, currently under development and ready to be used by industry

ENERGY EFFICIENCY GAIN
×1,000
by 2032

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Smart Sensors (Deep Edge) **Edge AI Computing**	**New Algorithms** (Frugality in Data and Energy)	**Sustainable Electronics**	**AI-based EDA Tools, STCO, ATCO**	**Cybersecurity** (End-to-End Solutions)

Watch the video


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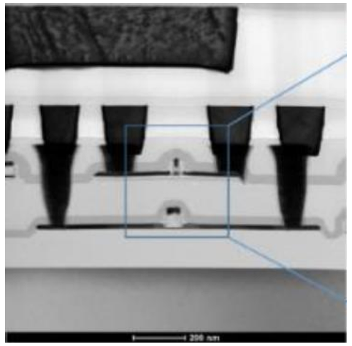
READY-TO-USE
FERROELECTRIC MEMORIES

GAIN @SYSTEM LEVEL **100**

Programming Power **Reduction ×20,000**

	FLASH	ReRAM (HfO_2)	FeRAM (HfO_2)
Programming power	**~200 pJ/bit**	~100 pJ/bit	**~10 fJ/bit**
Write speed	20 µs	10-100 ns	14 ns @ 2.5 V
Endurance	10^5 - 10^6	10^5 - 10^6	> 10^{11}
Retention	> 125°C	> 125°C	85°C
Extra masks	Very high (>10)	Low (2)	Low (2)

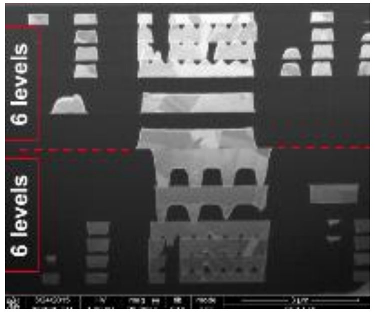
READY-TO-USE
3D-STACKING & PACKAGING
(from device to SIP integration)



3D sequential Integration

2 tiers including
Photodiodes, LED, high- and low-temp. transistors

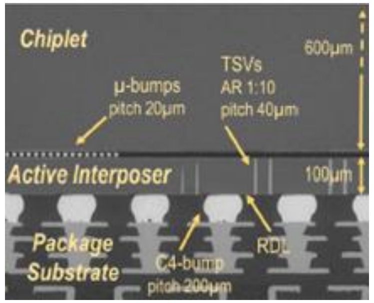
nm



Direct hybrid bonding

Wafer-to-wafer
Min pitch: 1 µm
Die-to-wafer
Min pitch: 4 µm
Self-assembly

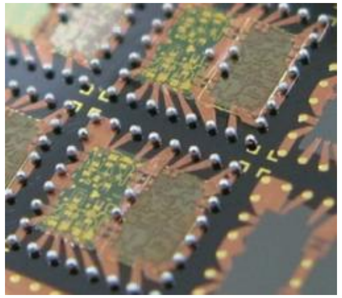
1 µm



Active interposers

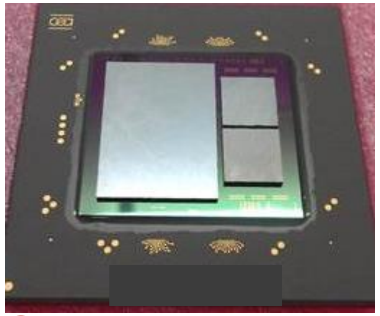
Through-silicon-Vias
TSV 0,3 to 80 mm Φ
RDL 20 µm pitch
Cu pillars 10 mm Φ

10 µm



Fan-Out-Wafer-Level-Packaging
(FOWLP)
Heterogeneous
System-in-Package
Thermal extraction

100 µm



Die-level packaging

Harsh environments
Power modules
Cryo-packaging for quantum computing

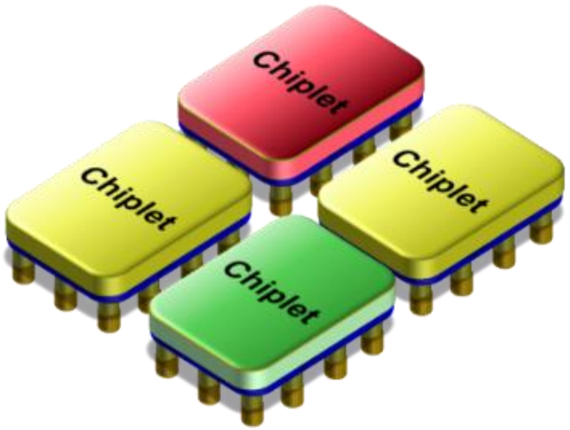
mm

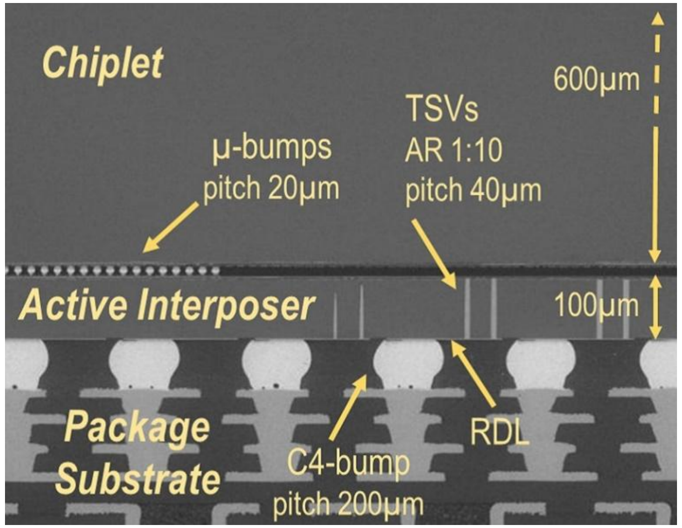
Large range of interconnect dimensions and materials from device to system

READY-TO-USE
3D-STACKING TECHNOLOGIES

Energy Efficiency Gain
×10

Chiplets and Active Interposer Integration Demonstrator





Interposer:
65 nm
BULK

Concept

- Improve parallelism, reduce power consumption, reduce NRE cost, bring versatility and scalability with a modular architecture based on smaller chips

Achievement

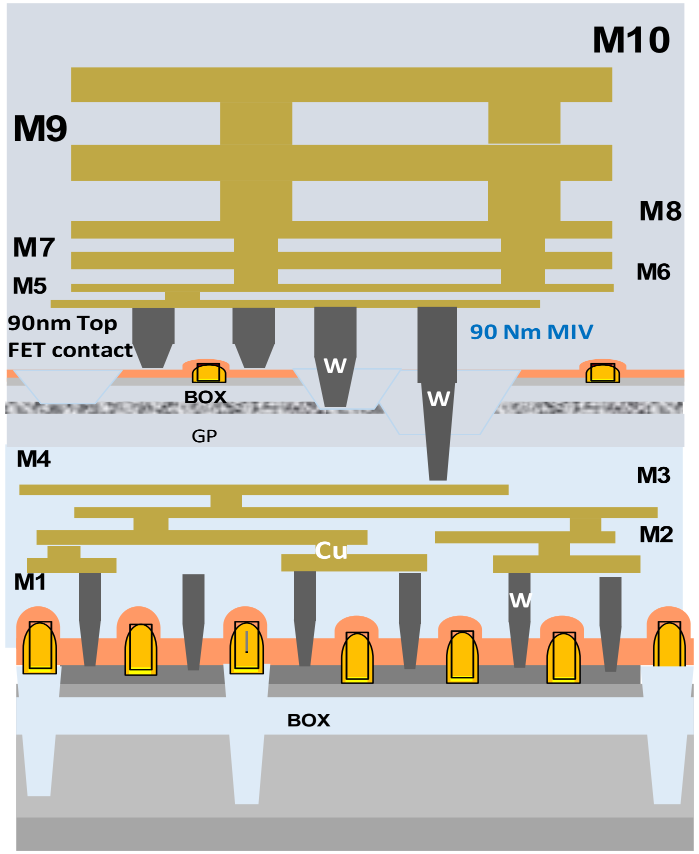
- The power of 10 laptops with a surface of only 200 mm²
- 100 GOPS, 10 GOPS/Watt

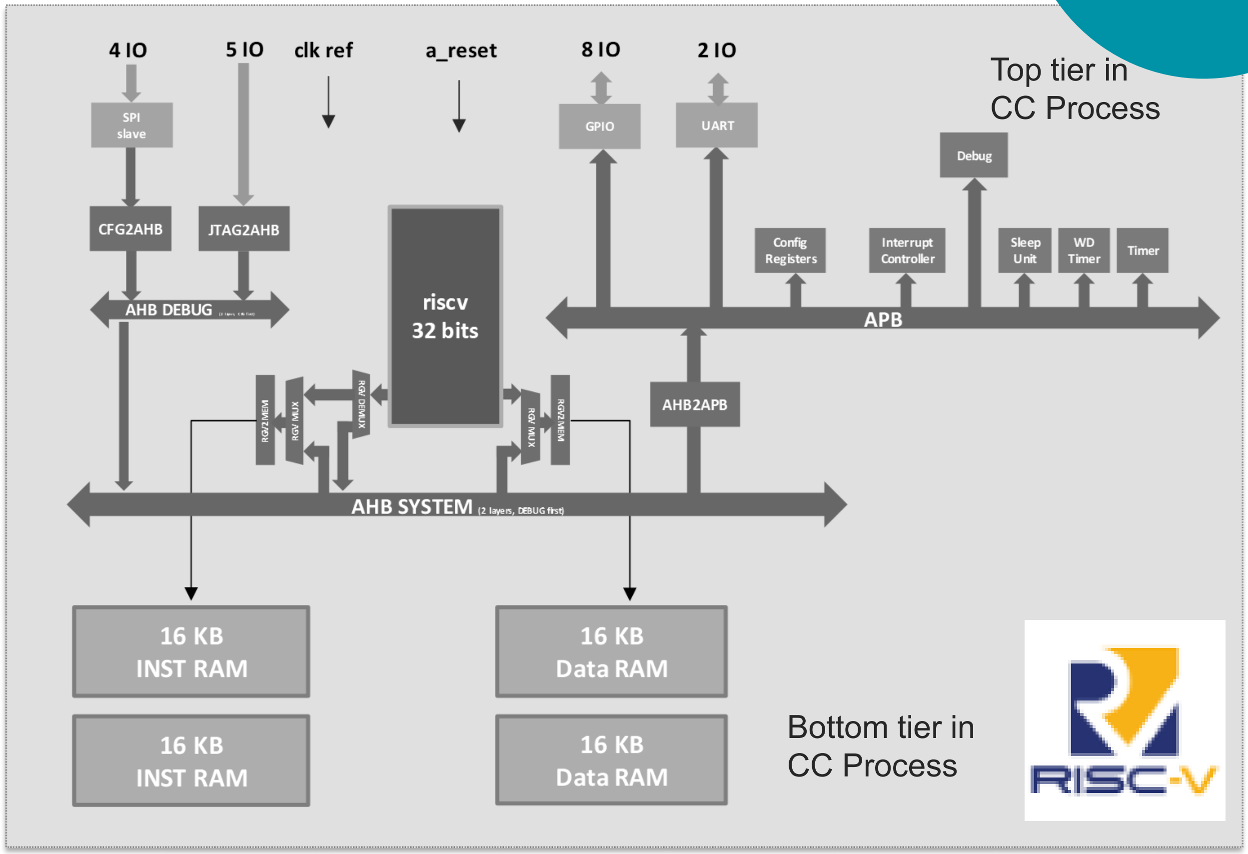
P. Vivet et al., "IntAct: A 96-Core Processor With Six Chiplets 3D-Stacked on an Active Interposer With Distributed Interconnects and Integrated Power Management," in IEEE Journal of Solid-State Circuits, vol. 56, no. 1, pp. 79-97, Jan. 2021, doi: 10.1109/JSSC.2020.3036341

READY-TO-USE
3D SEQUENTIAL INTEGRATION

Energy Efficiency Gain
×2-10

CoolCube 3D Sequential Integration Technology





O. Billoint, K. Azizi-Mourier, G. Cibrario, D. Lattard, M. Mouhdach, S. Thuries, P. Vivet, "Merging PDKs to Build a Design Environment for 3D Circuits: Methodology, Challenges and Limitations, IEEE International 3D Systems Integration Conference (3DIC), Sendai, Japan, October 2019

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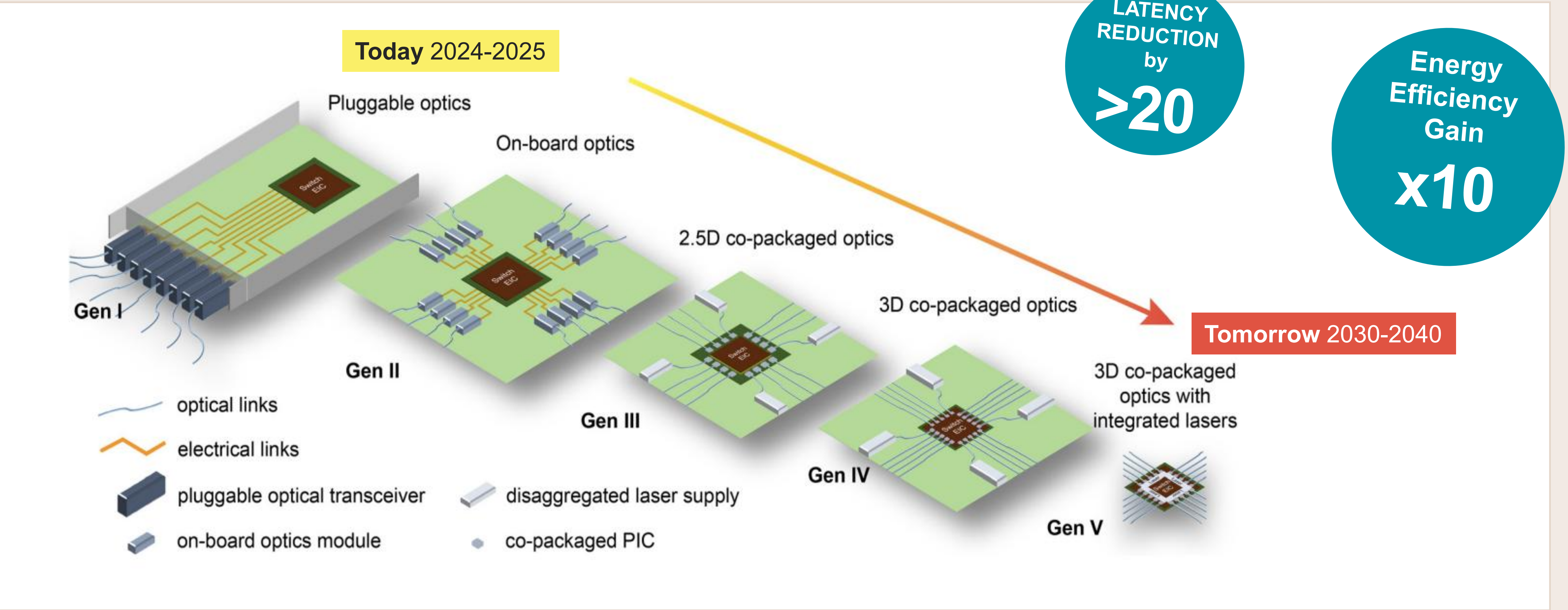
ADDRESSING HPC & AI CHALLENGES (EIC, PIC)
A MOVE TO CO-PACKAGED OPTICS (CPO)



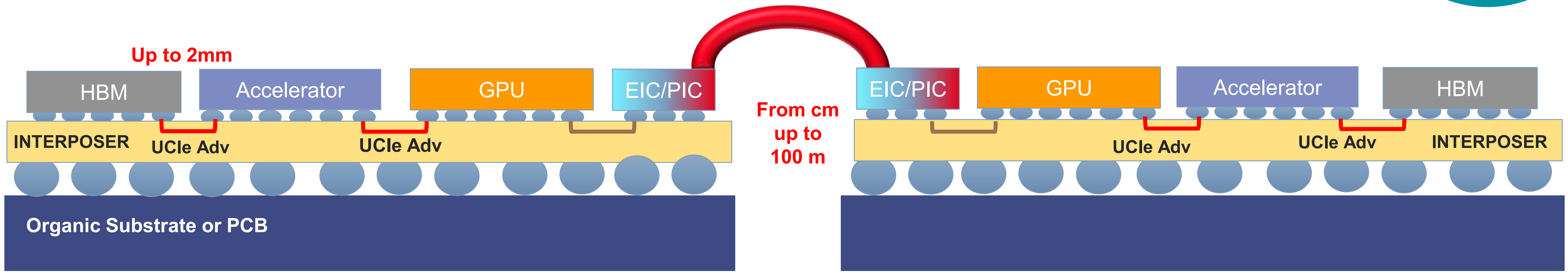
Appl. Phys. Lett. 2021 (Broadcom, UCSB, Intel)

ADDRESSING HPC & AI CHALLENGES WITH OPTICAL INTERCONNECTS

Energy Efficiency Gain using LED

~10

Electro-optical Communication Between Chiplet-based Circuits



Silicon Photonics Serial Link

Mature technology

- **Very-high Data Rate (DR)** per Optical Fiber
- DR/Fiber: 400/800/1600 Gbps for 8 wavelength
  High-complexity transceiver (linear)
- Medium latency
- Energy efficiency: 3 to 5 pJ/bit

µLED/µPD Array Highly Parallel Link

Disruptive technology

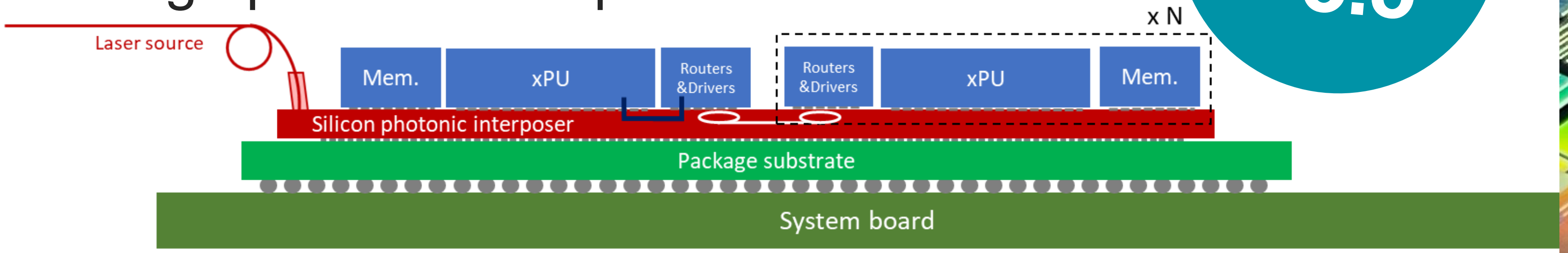
- **1 to 4 Gb/s per MicroLED**
- **Combined with parallelization: >10 Tb/s/mm²**
- **Very-low latency**
- **Energy efficiency: 0.5 pJ/bit**

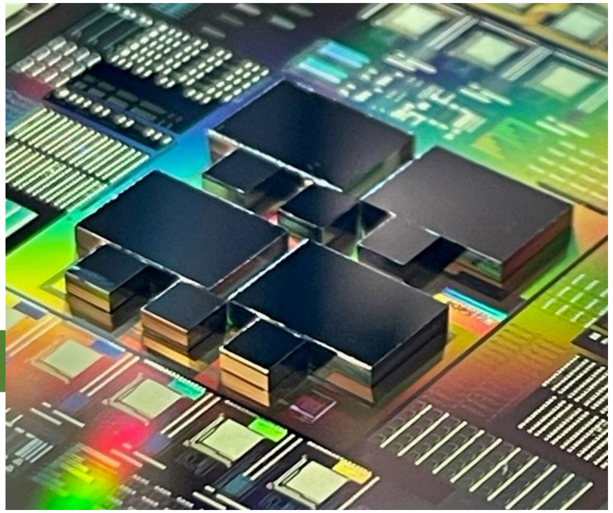
A WORLD FIRST : A PHOTONIC INTERPOSER WITH AN OPTICAL NETWORK-ON-CHIP (O-NOC)

STARAC DEMONSTRATOR

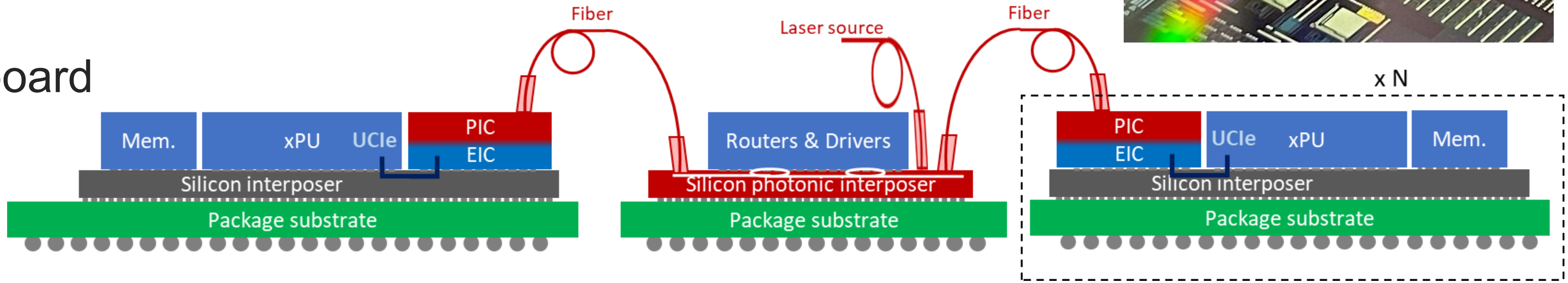
Energy Efficiency Gain
×3.5

On large photonic interposer





On board



CIRCUITS AND DISRUPTIVE CHIP ARCHITECTURES

New computing and partitioning paradigms under development and ready to be used by industry

ENERGY EFFICIENCY GAIN
×1,000
by 2032

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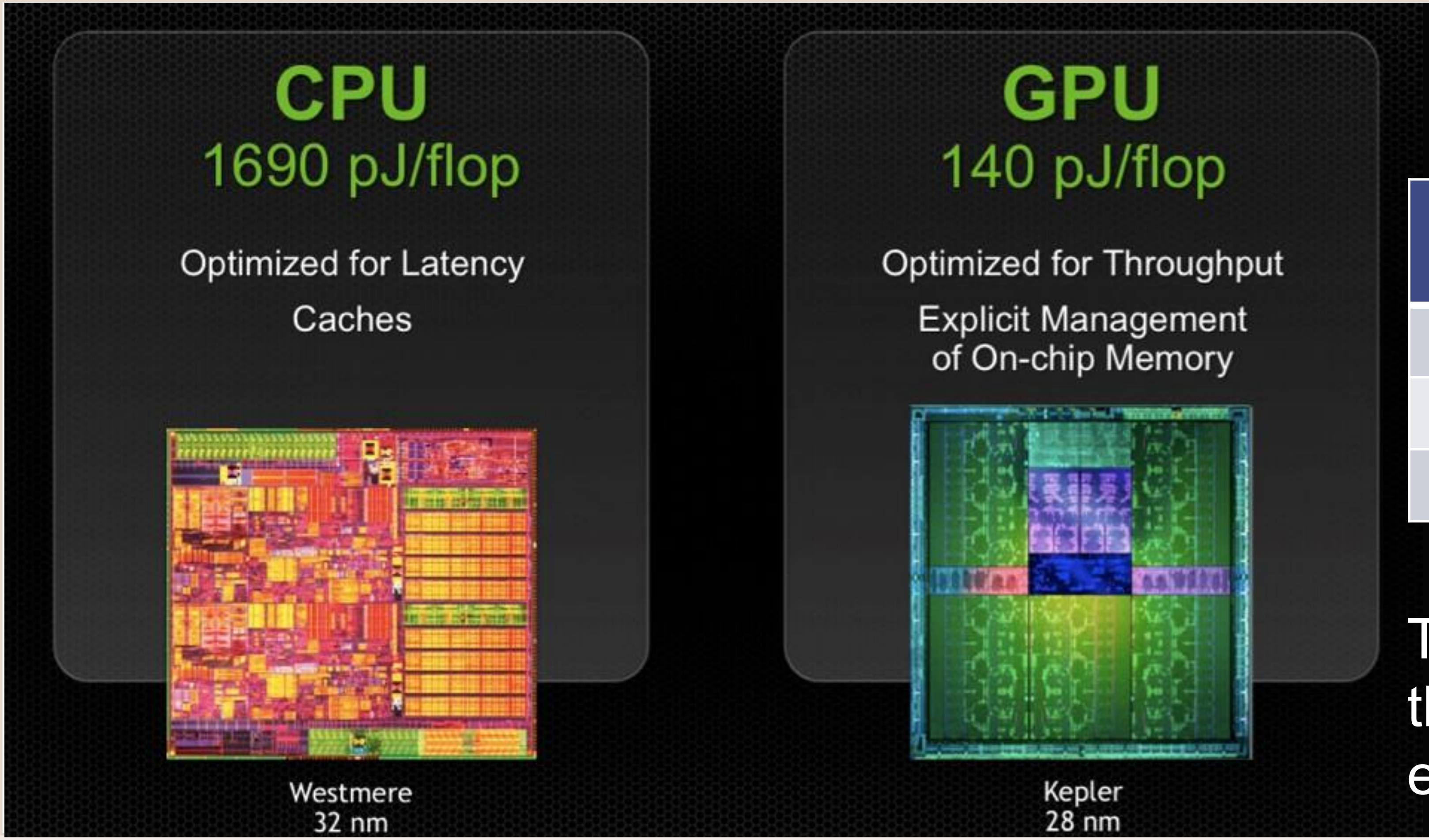
SPECIALIZED ARCHITECTURES LEAD TO MORE EFFICIENCY

Energy Efficiency Gain

×150



Type of device	Energy / Operation
CPU	1690 pJ
GPU	140 pJ
Fixed function	10 pJ

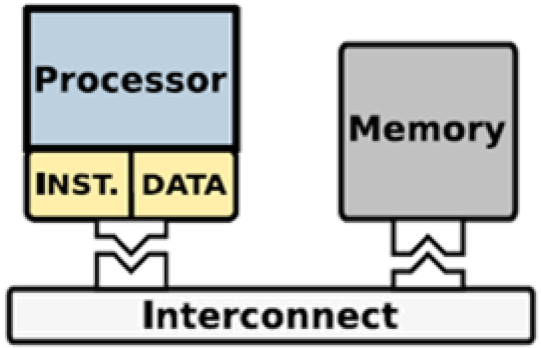
The more you specialize, the more you gain in energy efficiency

From Bill Dally (nVidia) “Challenges for Future Computing Systems”, HiPEAC conference 2015

ADDRESSING THE ENERGY CHALLENGE
WITH NEW NON-VOLATILE MEMORIES

Energy Efficiency Gain
×10

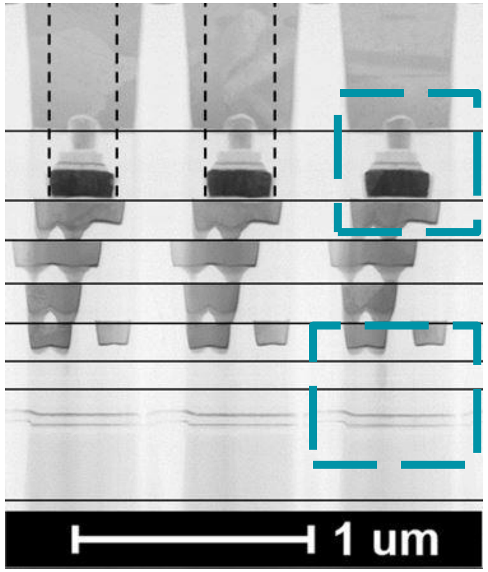
Von Neumann



How data consumes energy

Operation	Energy
Addition of data (fixed point)	1×
Accessing data (onchip cache)	60×
Accessing data (offchip RAM)	3500×

Data movement between storage and processing units consumes
90%
of the energy



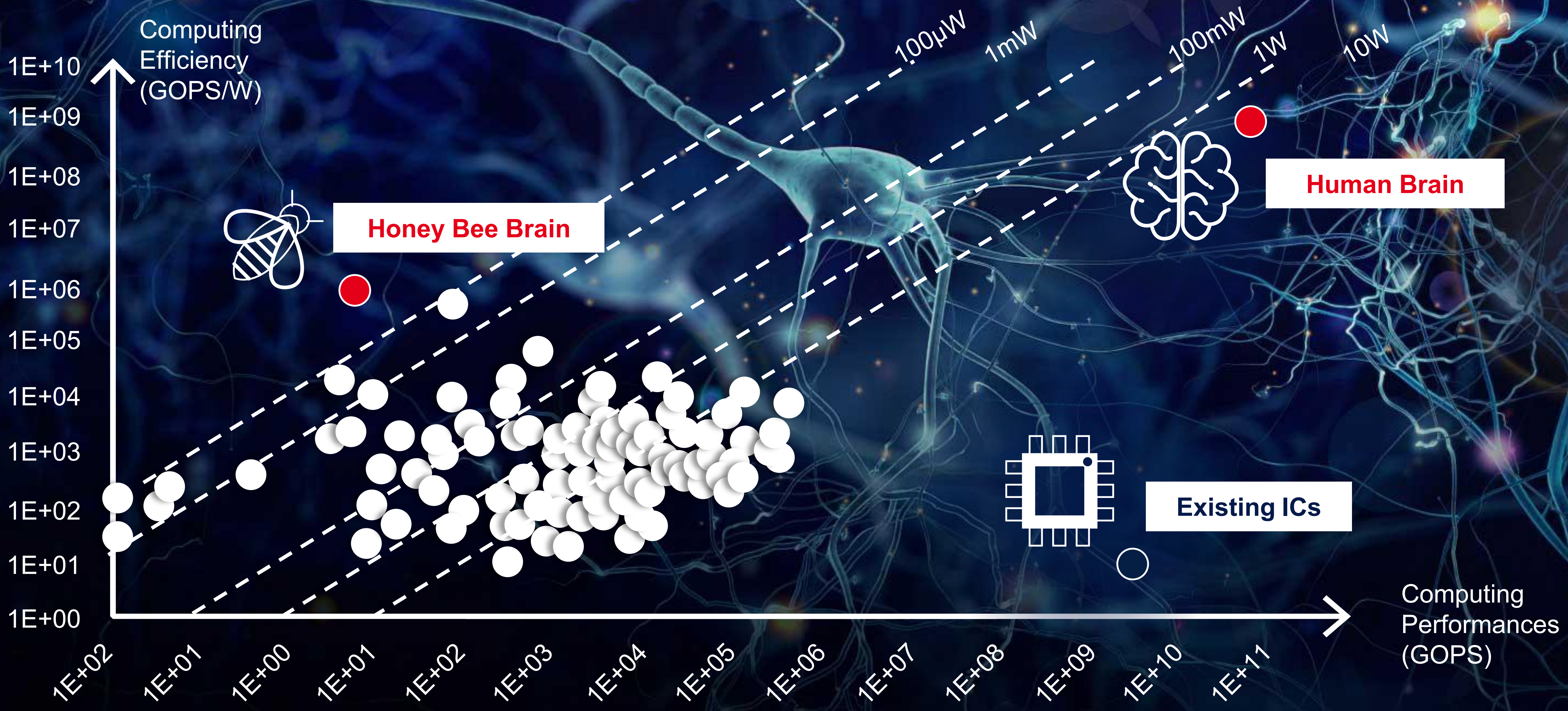
Resistive memory

FD-SOI

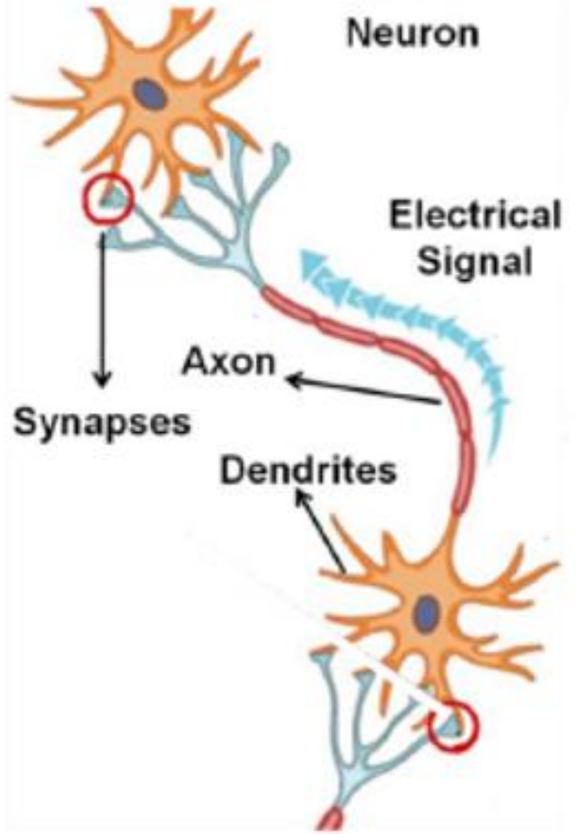
High-density on-chip non-volatile memories are needed

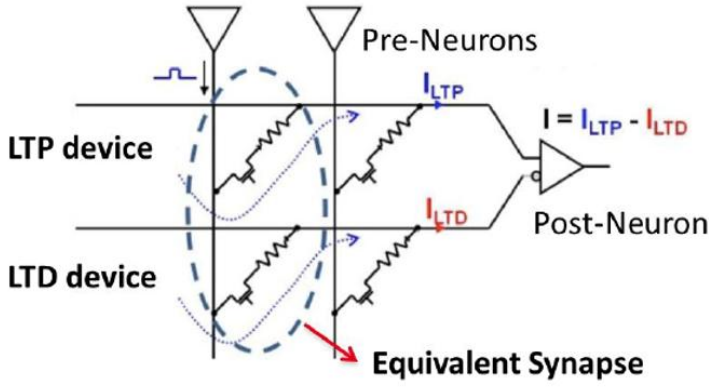
ENERGY EFFICIENCY: FAR BEHING BIOLOGICAL SYSTEMS

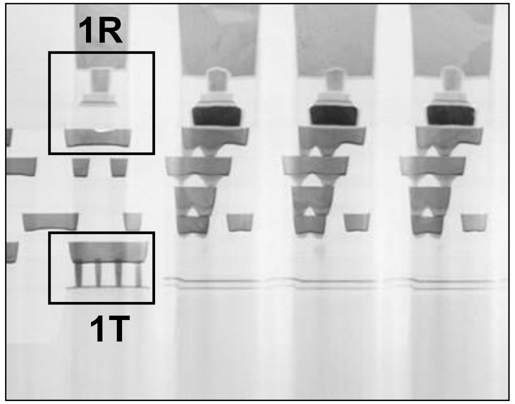
NATURE IS A SOURCE OF INSPIRATION

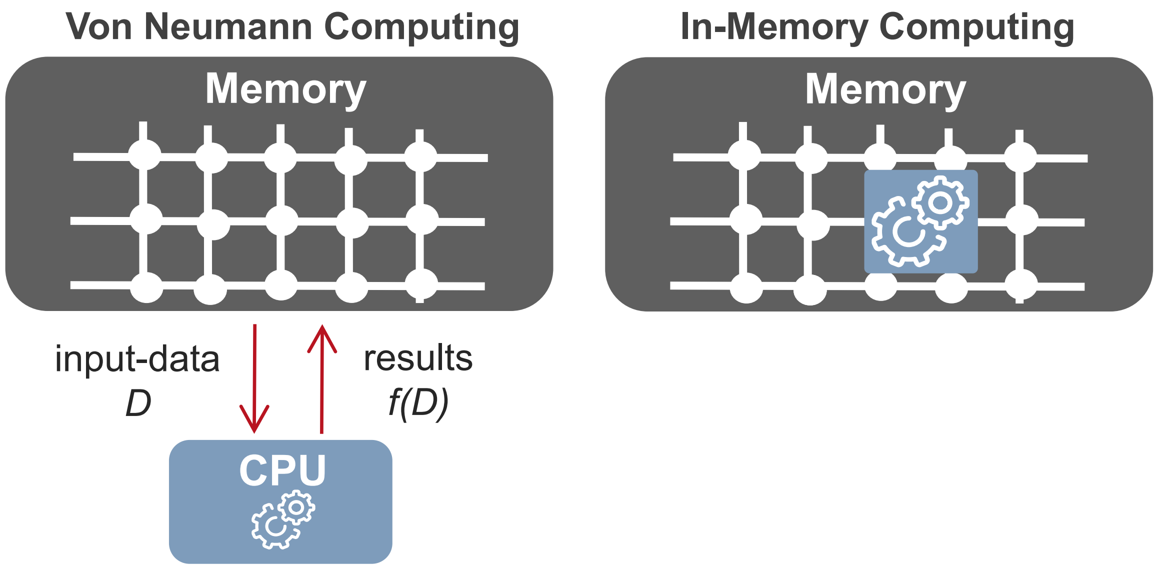


MIMICKING THE BRAIN'S BEHAVIOR WITH NEUROMORPHIC-BASED RRAM CIRCUITS





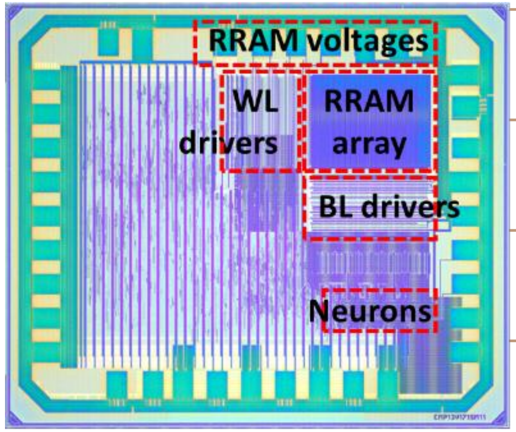


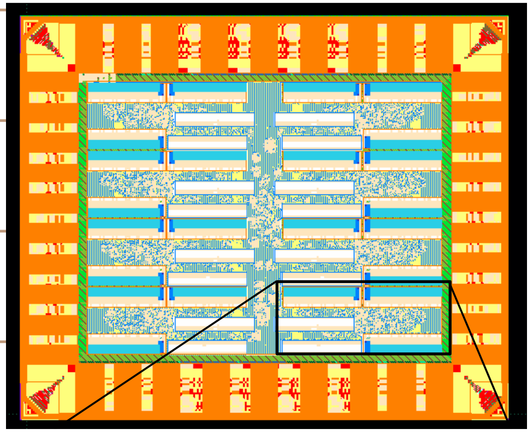


BRAIN-INSPIRED SPIKING NEURAL NETWORK
TO REDUCE ENERGY CONSUMPTION

From SPIRIT to LARGO Analog Asynchronous Spiking Neural Networks

nature COMMUNICATIONS





SPIRIT		LARGO
130 nm	CMOS node	28 nm
10	Nb of Neurons	131 k
144	Nb of Synapses	75 M
3,6 pJ	Energy / spike	0,5 pJ
1	Nb of cores	8
5 mm²	Die size	3 mm²

SPIRIT: A. Valentian, F. Rummens, E. Vianello, T. Mesquida, C. Lecat-Mathieu de Boissac, O. Bichler, C. Reita, "Fully Integrated Spiking Neural Network with Analog Neurons and RRAM Synapses," IEEE International Electron Devices Meeting (IEDM), San Francisco, CA, USA, December 2019

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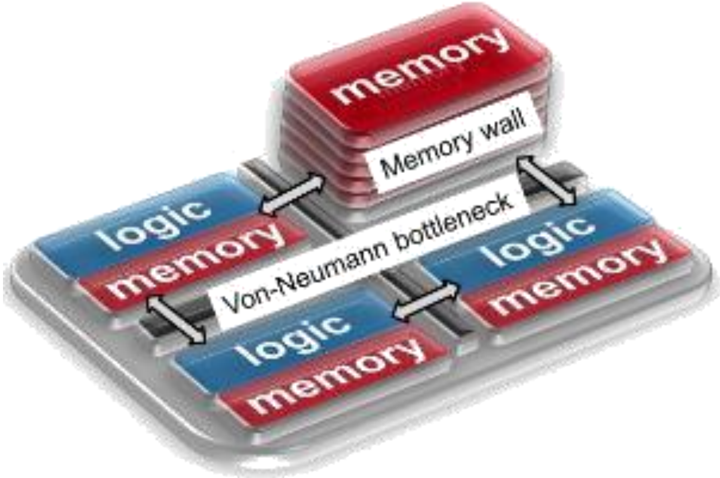
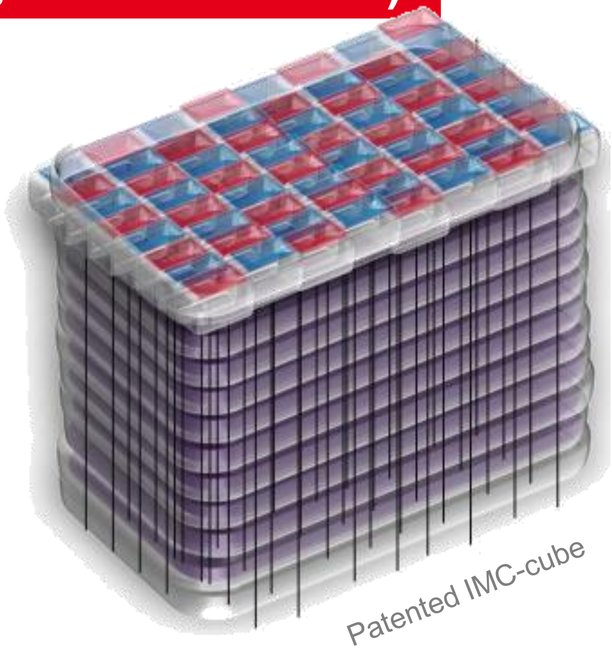
TOWARDS THE ULTIMATE
IN-MEMORY COMPUTING

Energy Efficiency Gain
×100

ERC MYCUBE (12 patents, 16 publications, 2 Best Awards)





- Vertical memories
- 3D stacks
- Vertically stacked nanowires
- Circuit demonstrators
- Software tools

The problem today

- Energy efficiency in data-abundant integrated circuits

A solution for tomorrow

- Highly parallel in-memory computing

www.leti-cea.fr/cea-tech/leti/Pages/Leti/Programmes-et-projets-soutenus/Liste-des-projets/MYCUBE

SYSTEMS, ALGORITHMS AND EDA TOOLS

Cost-effective solutions for significant energy savings

ENERGY EFFICIENCY GAIN
×1,000
by 2032

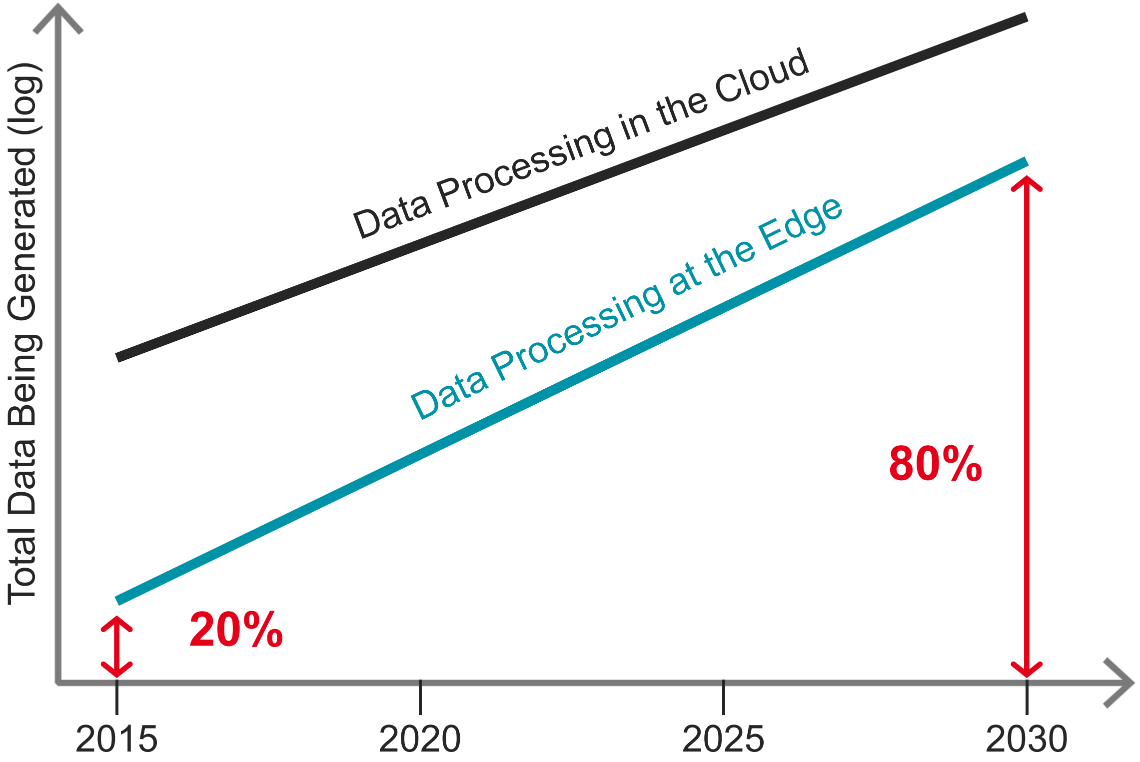
New Memories	3D Heterogeneous Integration & co-Packaged Optics	3D Monolithic, GAA, CFET FD-SOI, 2D Materials	Optical & RF Links (Photonic, GaN LED, mmWave)	Wide Band-gap Power Devices
Energy-efficient HMI (Displays, others)	New Computing Paradigms (Neuromorphic, Analog, Quantum…)	Dedicated Versatile Accelerators	Avoid moving data (Alternative to von Neumann Architectures)	Energy-efficient Power Converters (AC/DC, DC/DC…)
Smart Sensors (Deep Edge) **Edge AI Computing**	**New Algorithms** (Frugality in Data and Energy)	Sustainable Electronics	AI-based EDA Tools, STCO, ATCO	Cybersecurity (End-to-End Solutions)

TOWARDS ENERGY-EFFICIENT SOLUTIONS

EDGE-AI SOLUTIONS

Energy Efficiency Gain

10^6



International Business Strategies, Inc. (IBS) – sept 2020

Transferring or storing 1 GB of data through the Internet uses ~5 kWh, **instead of 5×10^{-6} kWh if done locally**

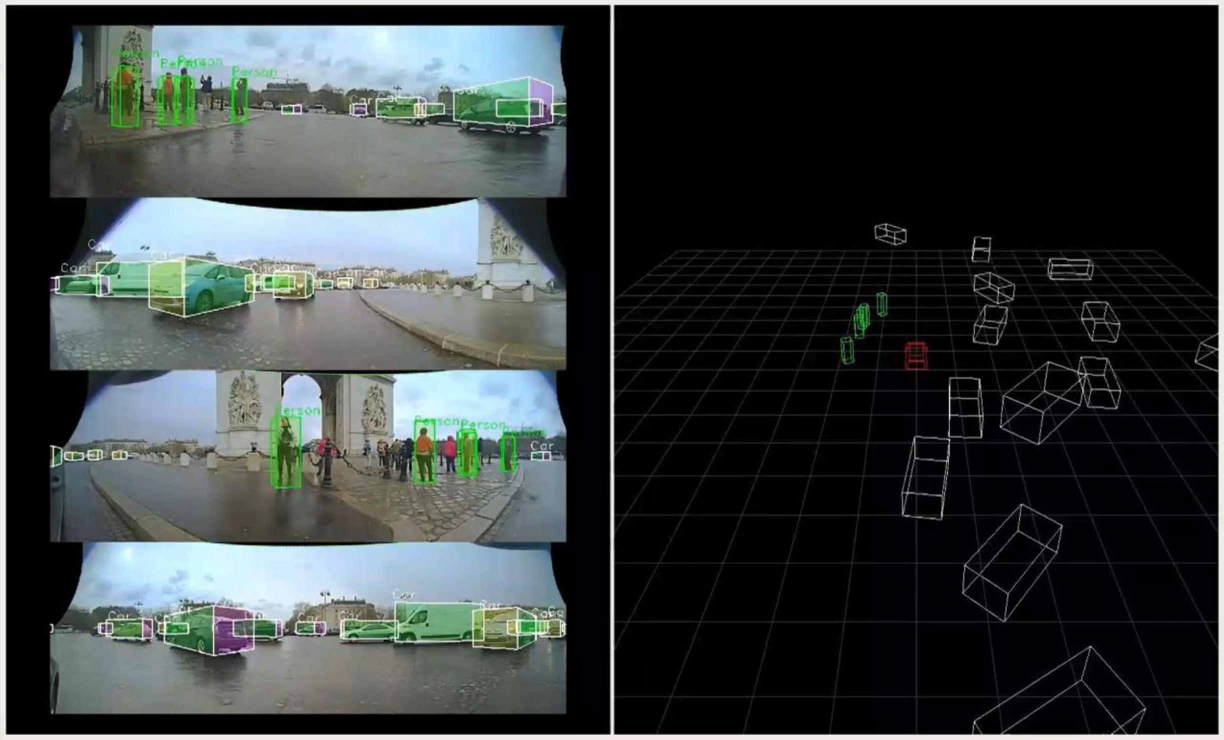
Benefits of Local Processing:

- Reduce network bandwidth
- Lower latency
- Reduce overall energy consumption
- No need for cloud connection
- Ensure data protection

TOWARDS EFFICIENT
EDGE-COMPUTING SOLUTIONS

Energy Efficiency Gain
~10

The N2D2 Deep Learning Platform



A software tool to explore DNN with hardware constraints :

- Computing power
- Memory
- Data accuracy
- Power consumption

…and develop energy-optimized perception algorithms for ADAS

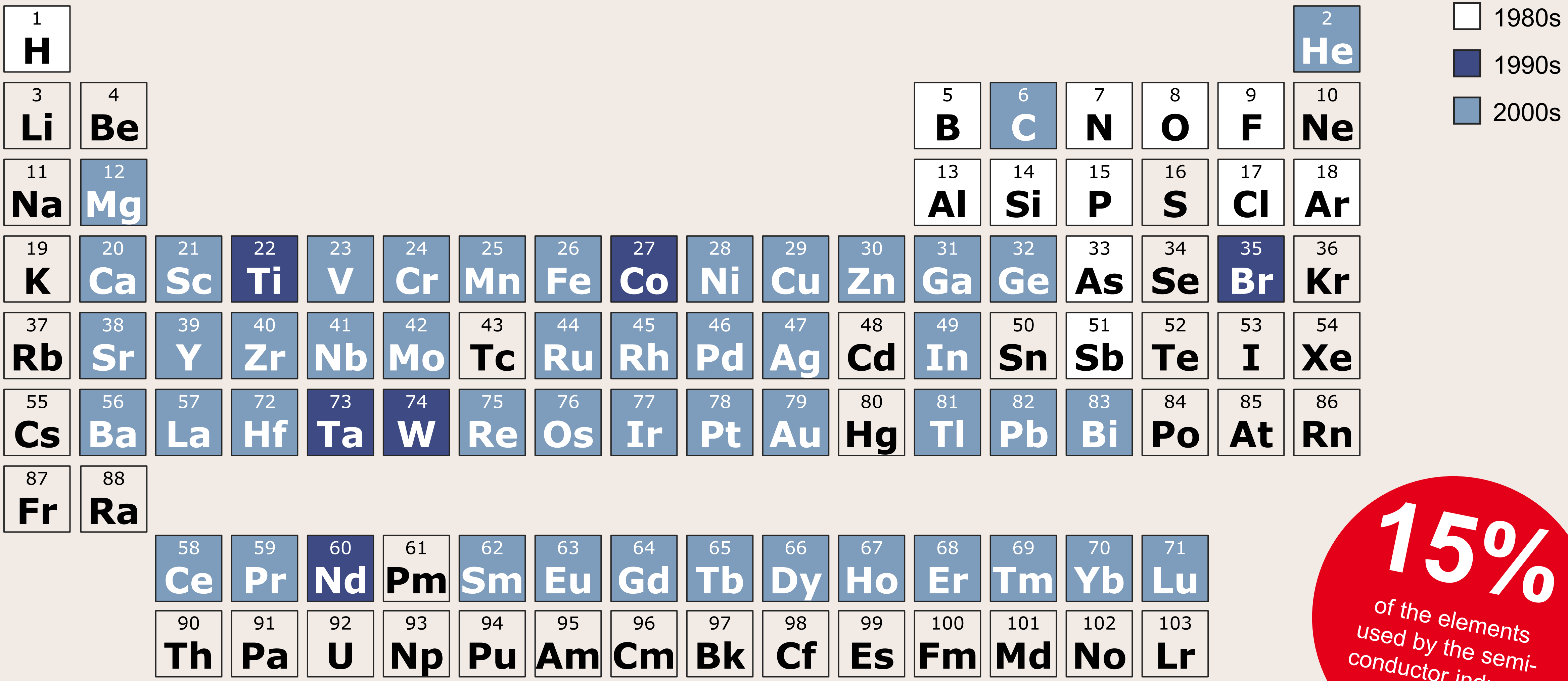
list.cea.fr/en/page/n2d2-design-and-implementation-of-neural-networks-optimized-for-embedded-systems/

CHALLENGE 2

Sustainability & Sovereignty

Toward resilient chip manufacturing

THE SEMICONDUCTOR INDUSTRY'S GROWING NEED FOR ELEMENTS

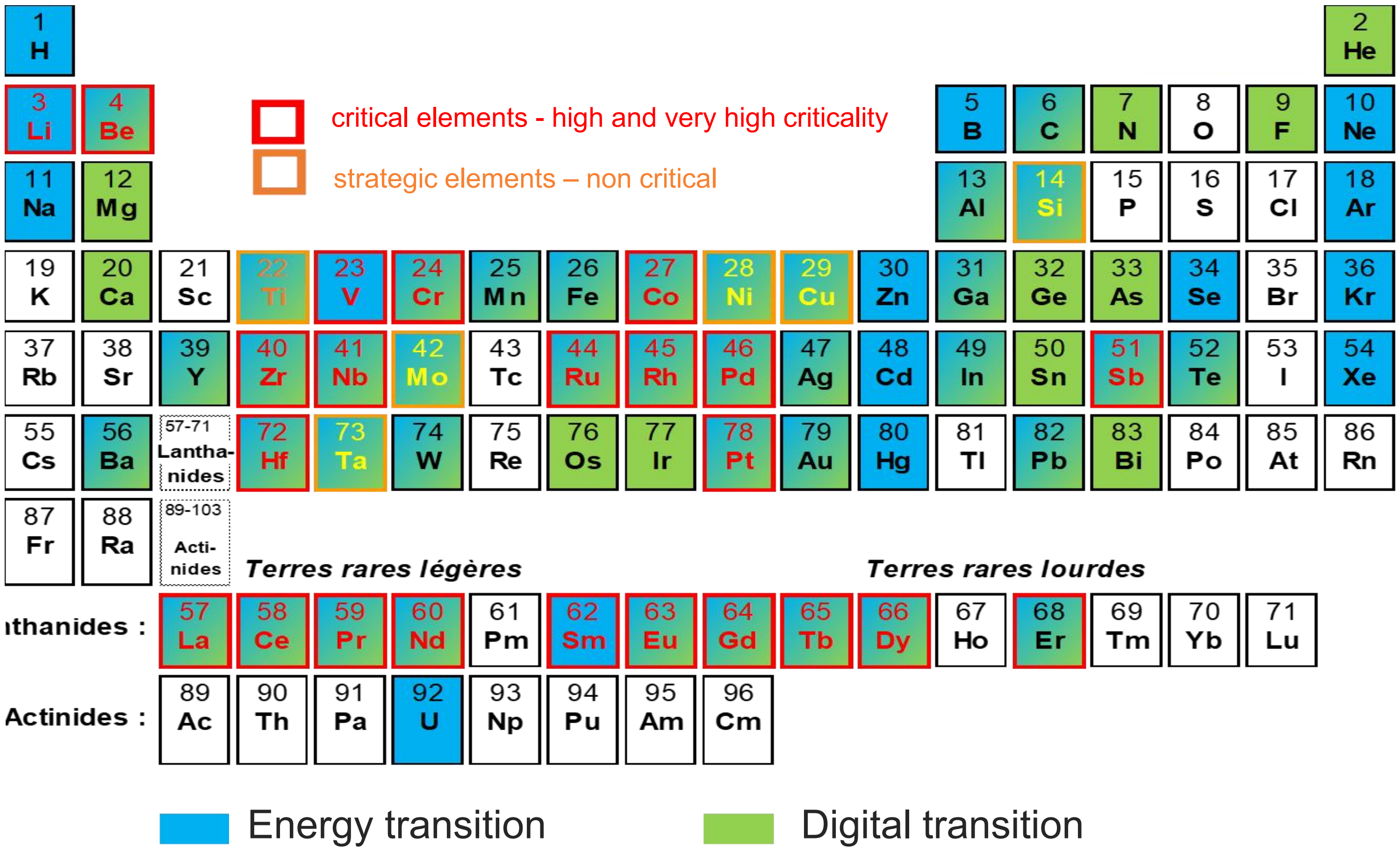


15%

of the elements used by the semi-conductor industry is recycled

ENERGY AND DIGITAL TRANSITIONS:
A SIMILAR NEED FOR RESOURCES

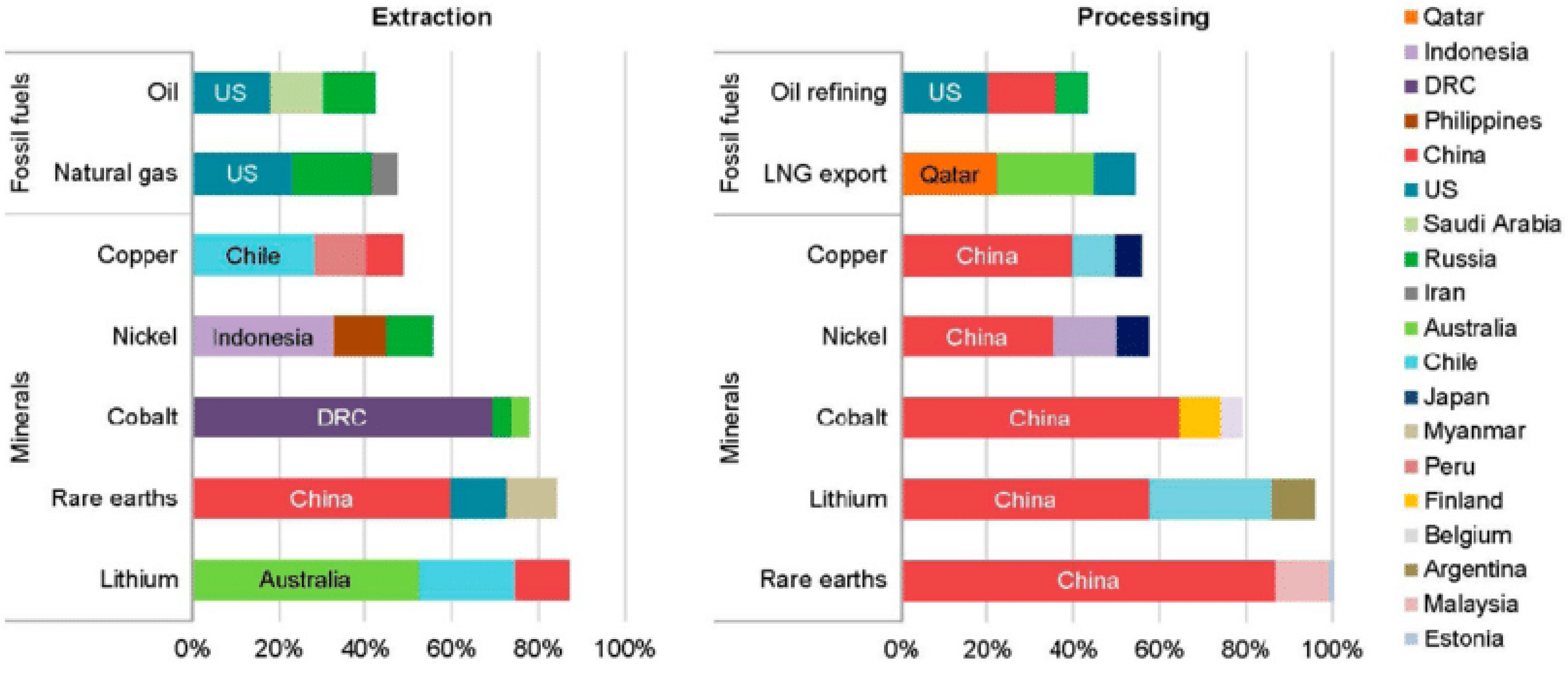
Only 15% of the elements used is recycled



- **Diversity**: A large number of metals are needed for low-carbon and digital technologies
- **Quantity:** More mineral resources will need to be produced by 2050 than since the beginning of human history, including for major metals
- **Conflict over use:** Exploding demand will put different uses in competition

BRGM, 2025

MINERAL SOURCING
CHINA'S DOMINANT PROCESSING POSITION



Share of top three producing countries in production of selected minerals and fossil fuels, 2019
LNG = Liquefied natural gas; The values for copper processing are for refining operations
Sources: IEA (2020); USGS (2021), World Bureau of Metal Statistics (2020); Adamas Intelligence (2020)

ENVIRONMENTAL IMPACT OF DIGITAL TECHNOLOGIES

4%
Share of digital in global greenhouse gas emissions

5 Critical Materials for Digital

- 49 **In** — **INDIUM**: *Displays (touch screen)*
- 31 **Ga** — **GALLIUM**: *Semiconductors (smartphones, laptops…)* — *Chinese BAN*
- 73 **Ta** — **TANTALE**: *Capacitance (videos, RF, Smartphone)*
- 60 **Nd** — **NEODYMIUM**: *Magnets (microphone)*
- 32 **Ge** — **GERMANIUM**: *Semiconductors, optical fiber and infrared imagers* — *Chinese BAN*

++ Growth of uses

+++ Water

\+ Geopolitical tensions and competition for energy and resources

→ **Digital technologies must reduce their ecological footprint**

BRGM 2025

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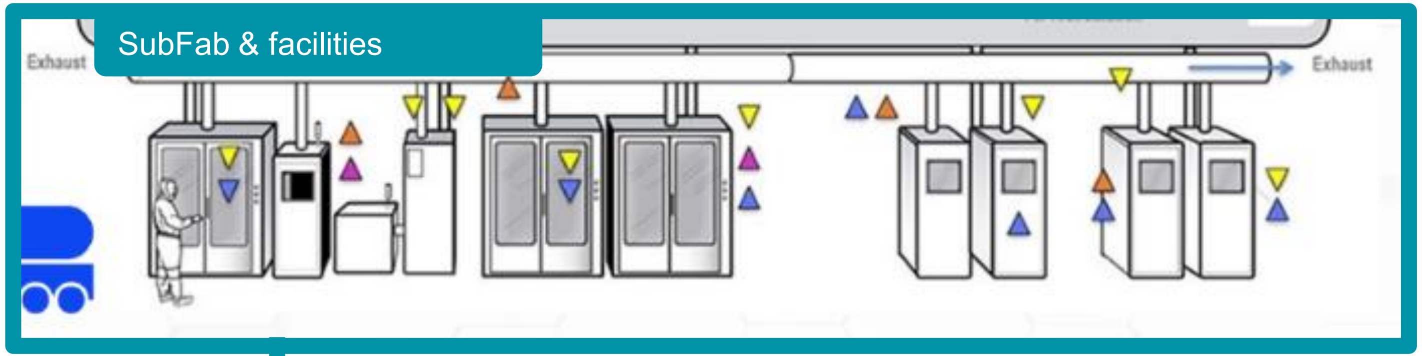
As ecosystems and living conditions decline,
and the demand for rare, hard-to-recycle minerals increases,
we must find alternatives.

PERSPECTIVES 3

RESOLVE : Toward Energy-Efficient and Sustainable Electronics

TOWARDS SUSTAINABLE MANUFACTURING
CEA-LETI COORDINATES "GENESIS EU-PROJECT"

58 partners involved from 12 countries



1 GASES & CHEMICAL

- PFAS free materials (litho, bonding, eqpt)
- Low GWP gas (etch & clean)

2 PROCESS

- Technology sustainable alternatives (FEOL-BEOL – Packaging)
- Optimized use of rare earths, Ga, Ge…

3 WASTE MONITORING & TREATMENT

- By-products & wastes sensing & monitoring
- Filtration and adsorption solutions (PFAS…)
- Reuse

4 AIR EMISSIONS

- Reduce gas emissions
- Abatement
- H2 gas carrier re-use (MOCVD)

5 FINAL TREATMENT

- Reduce aqueous emission
- Water abatement
- Develop CRM recycling & valorization solutions

A NEW PARADIGM IS NEEDED
TO FAVOR SOBRIETY/FRUGALITY VS. DECLINISM...

SPEED+

PERFORMANCE+

MINIATURIZATION

COST REDUCTION

DECLINISM

Pessimist's approach

Reducing or limiting performance

SOBRIETY

Athlete's approach

Maximizing performance with given resources

...and drastically reduce the energy and environmental footprint of electronic devices

R.E.S.O.L.V.E

GREENER CHIPS

2032

ENERGY EFFICIENCY GAIN

×1,000

by 2032

2030

2025

The Challenge: Capitalize on hardware and software advances to master global digitization and preserve the planet

If you share the same vision,

Join us!

jean-rene.lequepeys@cea.fr

R.E.S.O.L.V.E