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NIST Microelectronics & Advanced Packaging Technologies (MAPT) Roadmap: Sustainability & Energy Efficiency

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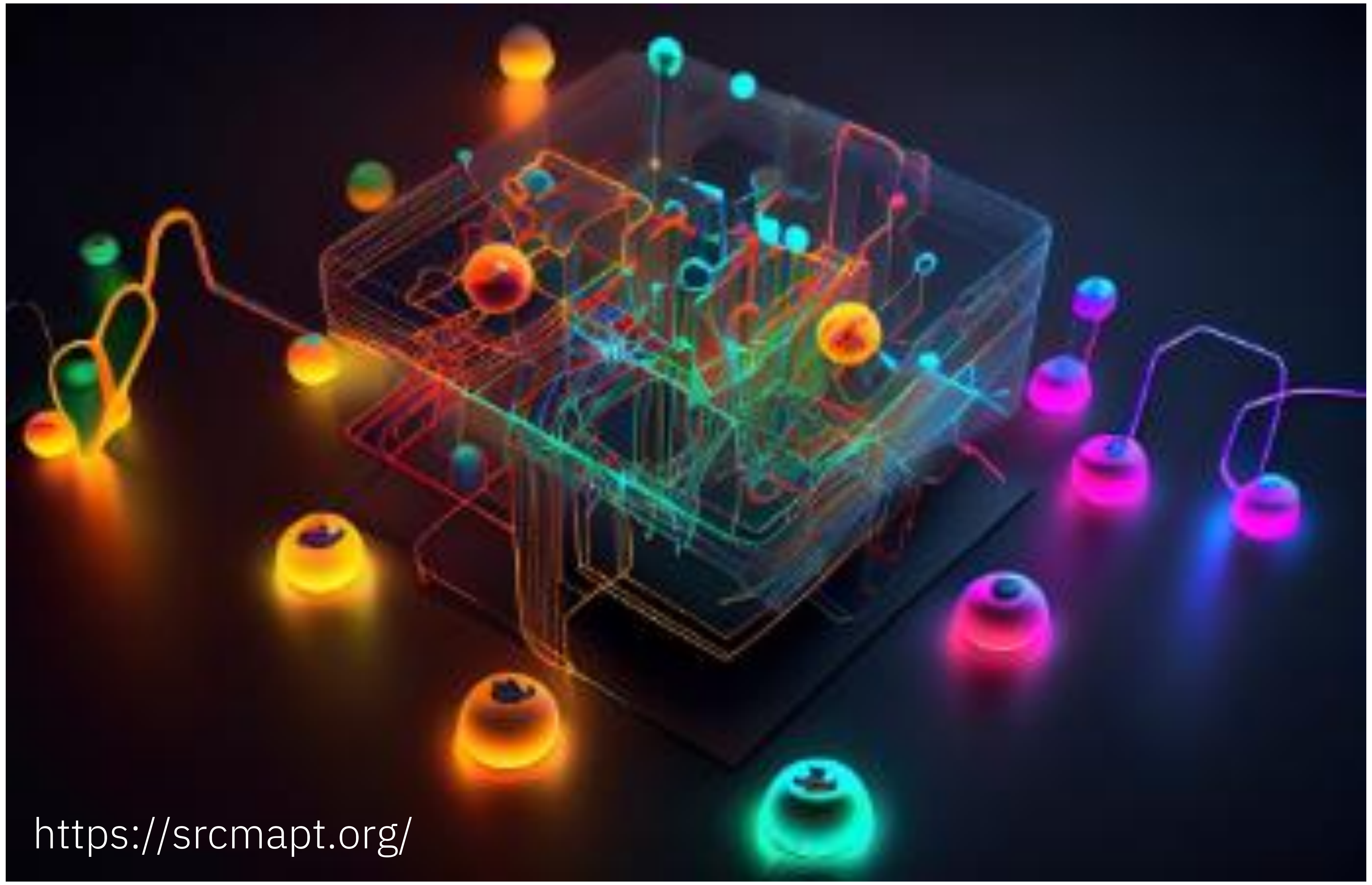
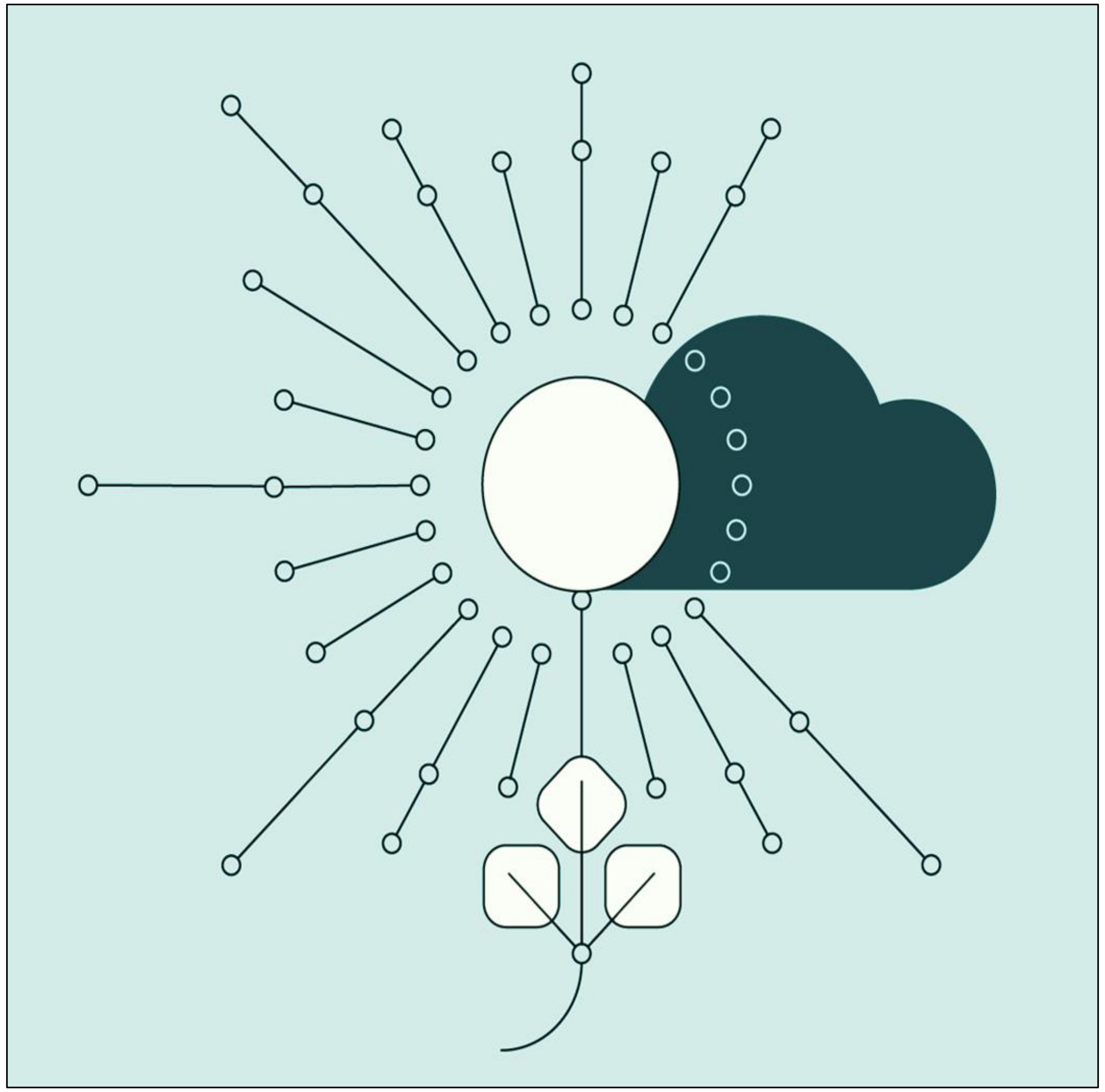


IBM

Discussion Guide



Background

Industry Challenges & Opportunities

Path Forward

Top 4 business risks

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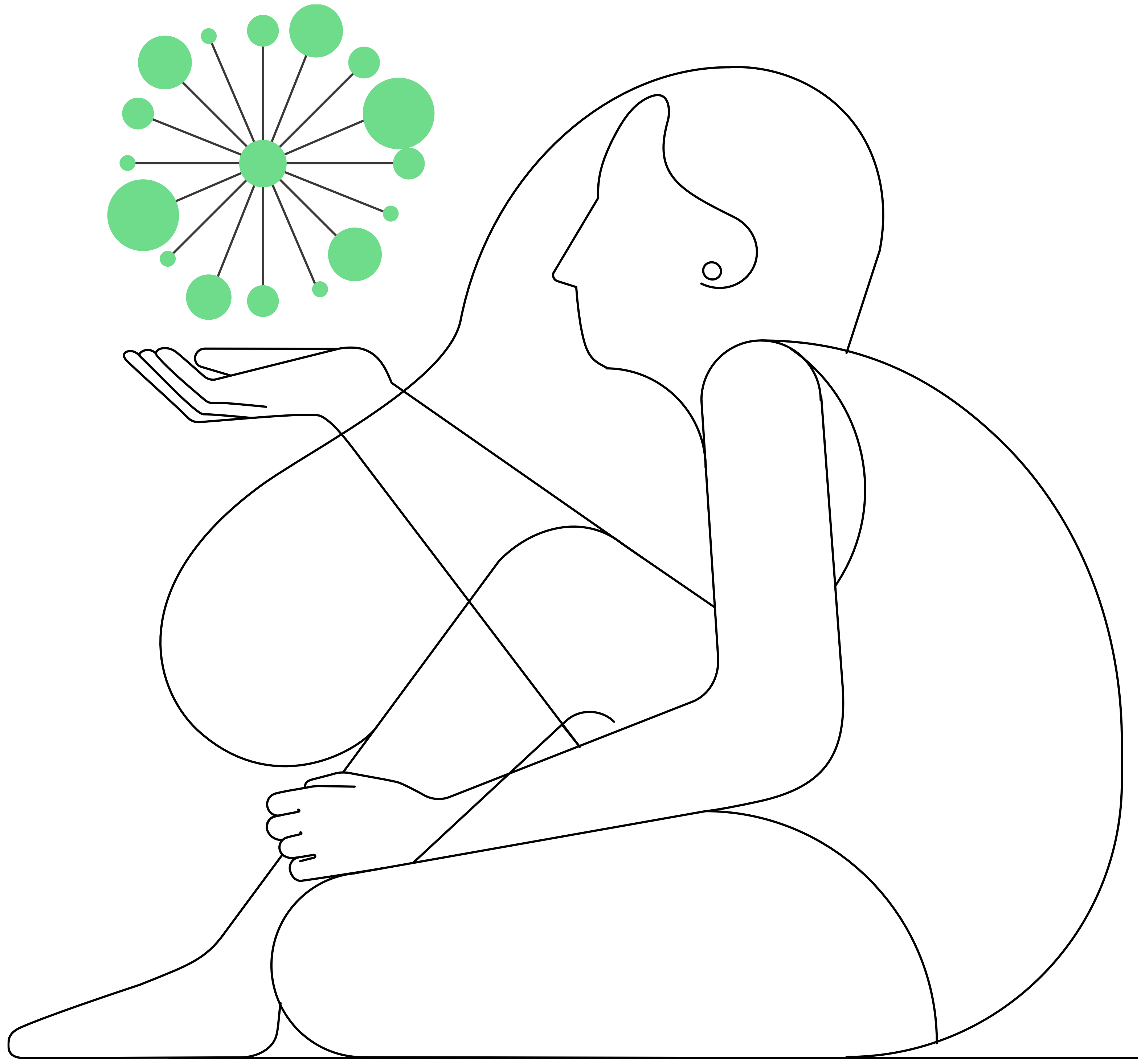
are related to the environment

Source: World Economic Forum 2023

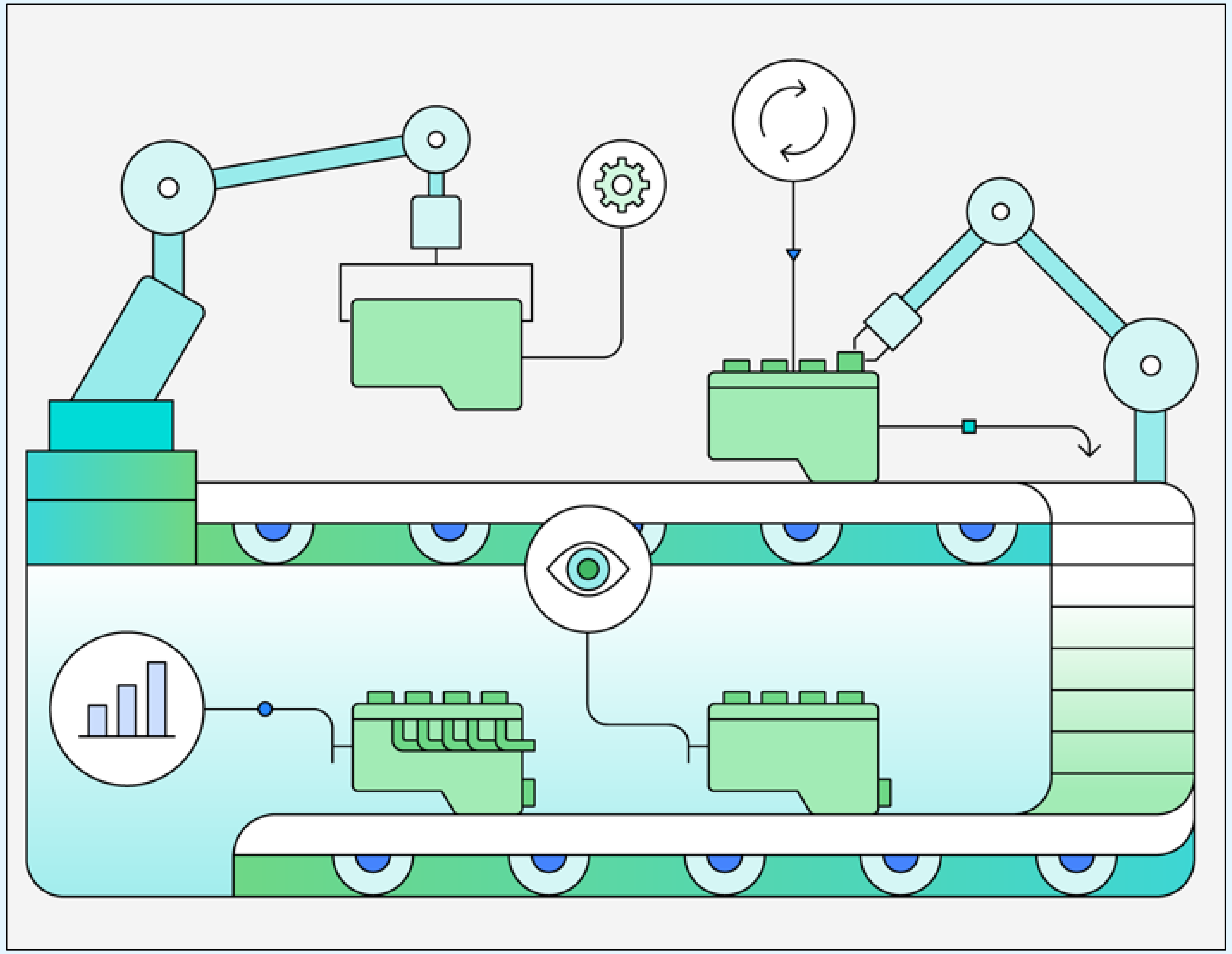
Sustainability is the key to a better future



Environmental Sustainability

What is the goal?
Decrease the overall environmental impact of microelectronics across all phases of a product's life cycle

Challenges?
1. Energy efficiency & power management
2. Resource conservation & waste reduction
3. Chemical usage & minimizing environmental releases
4. Developing circular economy pathways
5. Proactively integrating environmental considerations

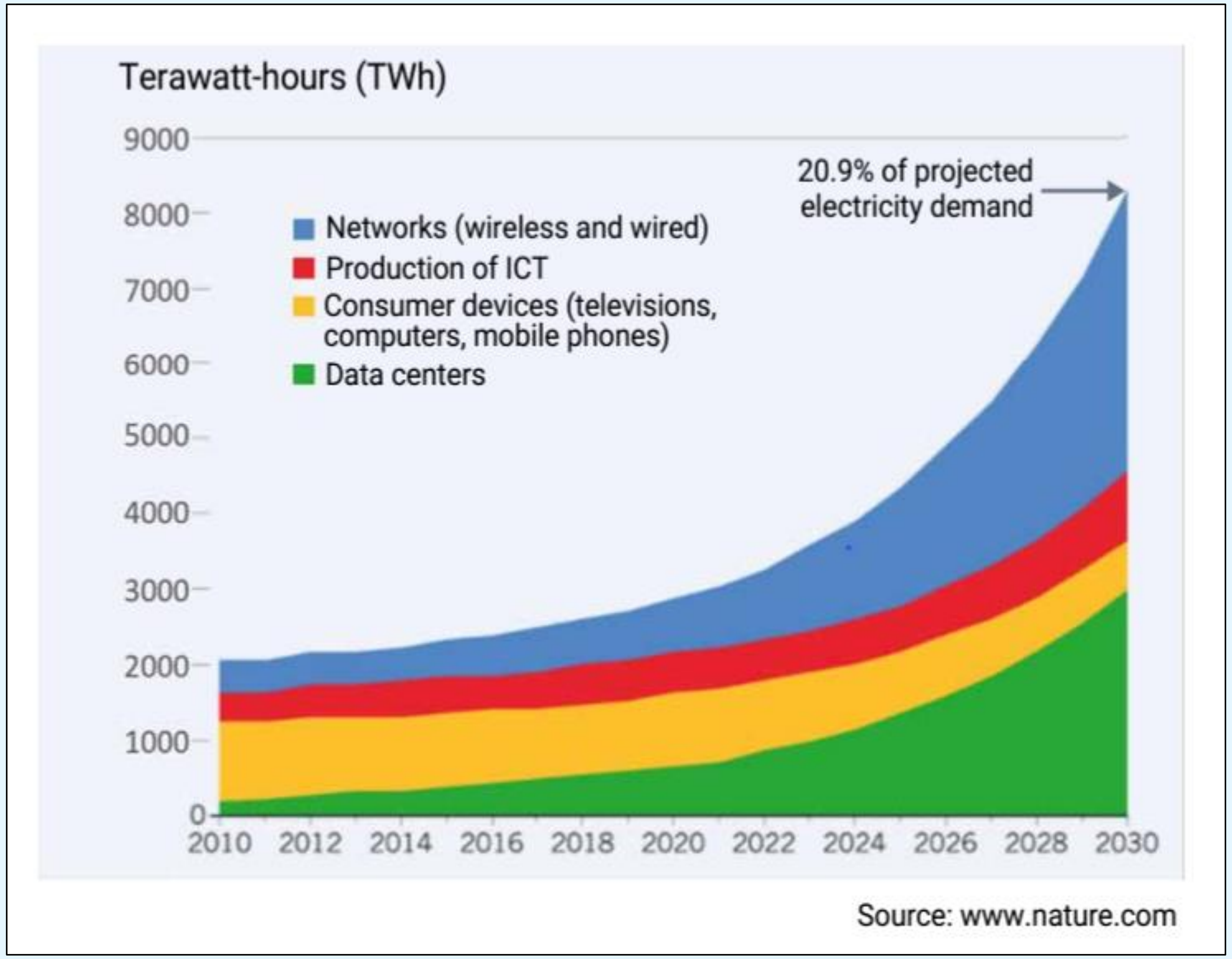


Energy Efficiency & Power Consumption

What is the goal?
Achieve a 1000x to 1,000,000× increase in computing energy efficiency over the next two decades.

Challenges?

1. Scaling
2. Power consumption
3. Thermal constraints



Opportunities to Increase Energy Efficiency & Decrease Power Consumption

New Technologies & Architectures

Complementary FETs (CFETs)

Vertical transport nanosheet FETs (VTFETs)

In memory computing

Non-volatile memory technologies

Optical interconnects

Low-Power Design Techniques

Heterogeneous computing

Approximate computing

Backside power distribution

Fine-Grain power gating

Non-volatile processors

Leakage power reduction

DVFS and Advanced Packaging

Frequency scaling

Adaptive voltage scaling

Systems-in-package (SiP)

3D stacking

Thermal management

- Thermal interface materials
- Thermoelectric cooling

Energy Aware Design Guides

Circuit design

System-level optimization

Energy aware algorithms

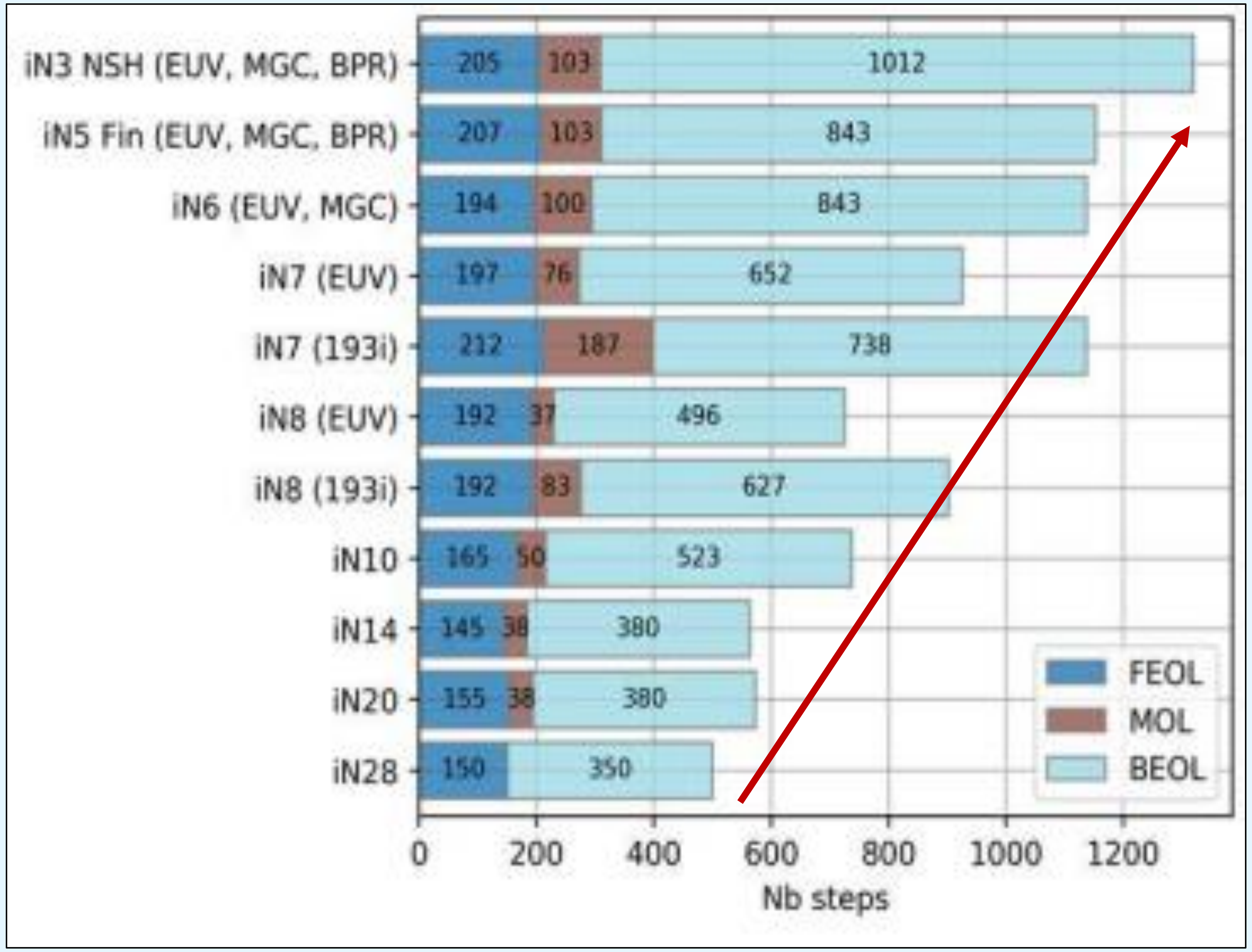
Optimize software for energy efficiency

Resource Conservation & Waste Reduction

What is the goal?
Design manufacturing processes to be more resource and energy efficient while reducing waste and emissions

Challenges?
As complexity increases from node to node so does:

- Number of processing steps
- Chemical and raw material use
- Volume of emissions, effluents & other waste streams



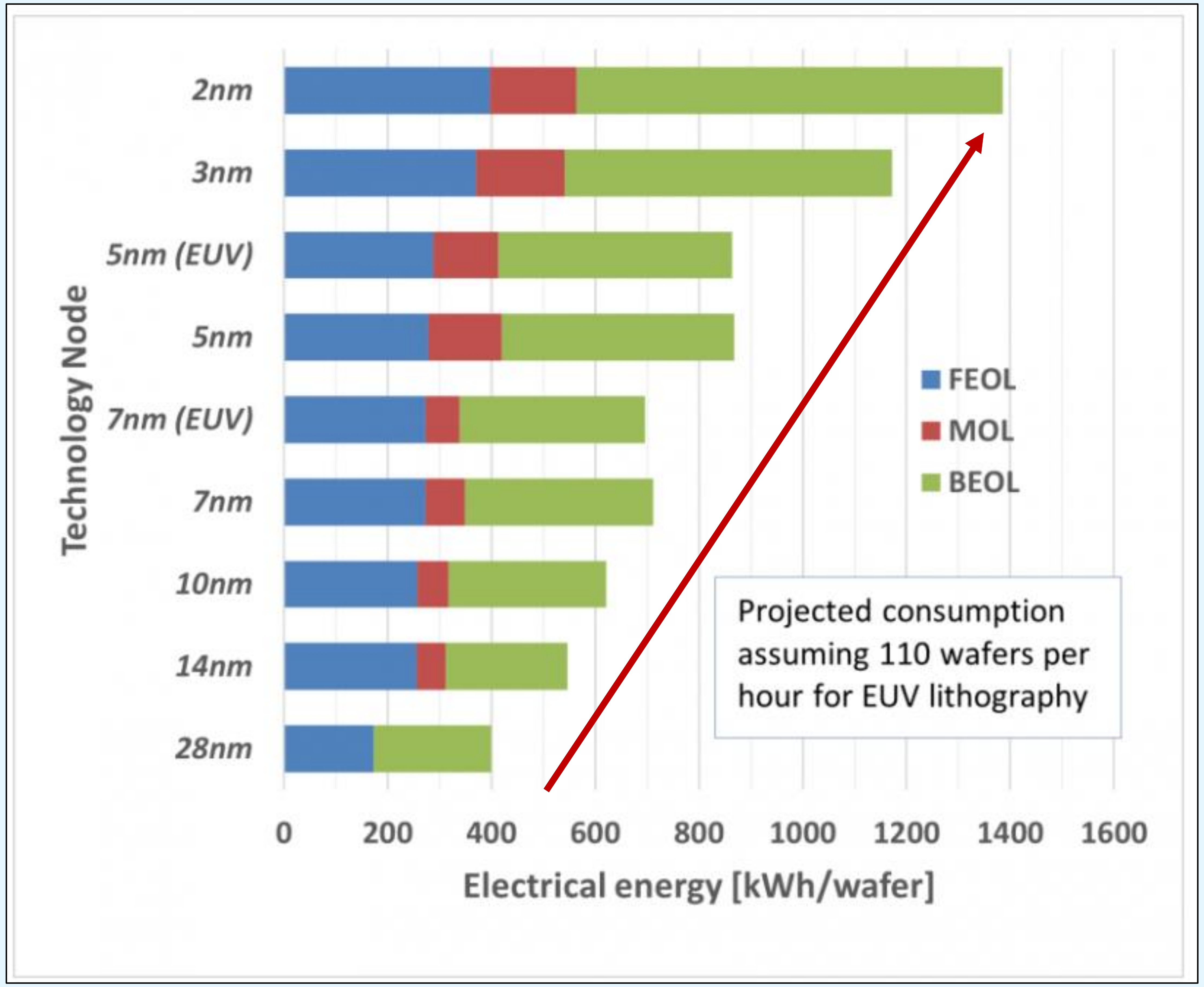
Ragnarsson et al., The Environmental Impact of CMOS Logic Technologies , 2022 IEEE

Increasing Environmental Impact with Advancing Nodes

Power-Performance-Area-Cost-Environmental (PPACE) Analysis for Logic Technologies from the 28nm to the 2nm node showed significant increases in:

- Electricity (x3.46)
- Water (x2.3)
- GHG Emissions (x2.5)

Energy increases due to the increase in the number of metal layers, interconnects, and in multiple patterning for tight pitches



Ragnarsson et al., The Environmental Impact of CMOS Logic Technologies , 2022 IEEE

Opportunities to Conserve Resources & Minimize Waste Generation

Optimize Manufacturing Processes

Enhance yield rates
- Additive processes
- Atomic layer deposition (ADL)
- Plasma-enhanced chemical vapor deposition (PECVD)

Develop equipment to measure resource consumption
- Optimize material usage
- Reduce material losses

Utilize AI and/or digital twins

Energy Consumption

More energy efficient tools
- Improve efficiency and power consumption of EUV tools

Process Innovation
- Optimize process recipes
- Combine steps and processes
- New deposition techniques
- Materials innovation

Adopt renewable energy sources

Waste heat recovery

Waste Management

Maximize material efficiency
- Deploy fully autonomous tools

Reclaiming & reprocessing chemistries and materials
- Development of effective collection & separation systems for valuable materials
- Chemical treatment, recovery and purification techniques
  - Improved technology for separating and recovering photolithography and other chemicals from wastewater streams

Water Consumption

Water-saving technologies
- Water-efficient scrubbers
- Dry etching systems

Develop more efficient recovery and purification processes to increase reuse of water
- More benign and/or easily treatable surfactants, chelating agents, biocides
- Concentrating techniques for separation of water/ solvents
- Point of use recycling or wastewater treatment methods

“Greener” Chemistries & Minimizing Environmental Releases

What is the goal?

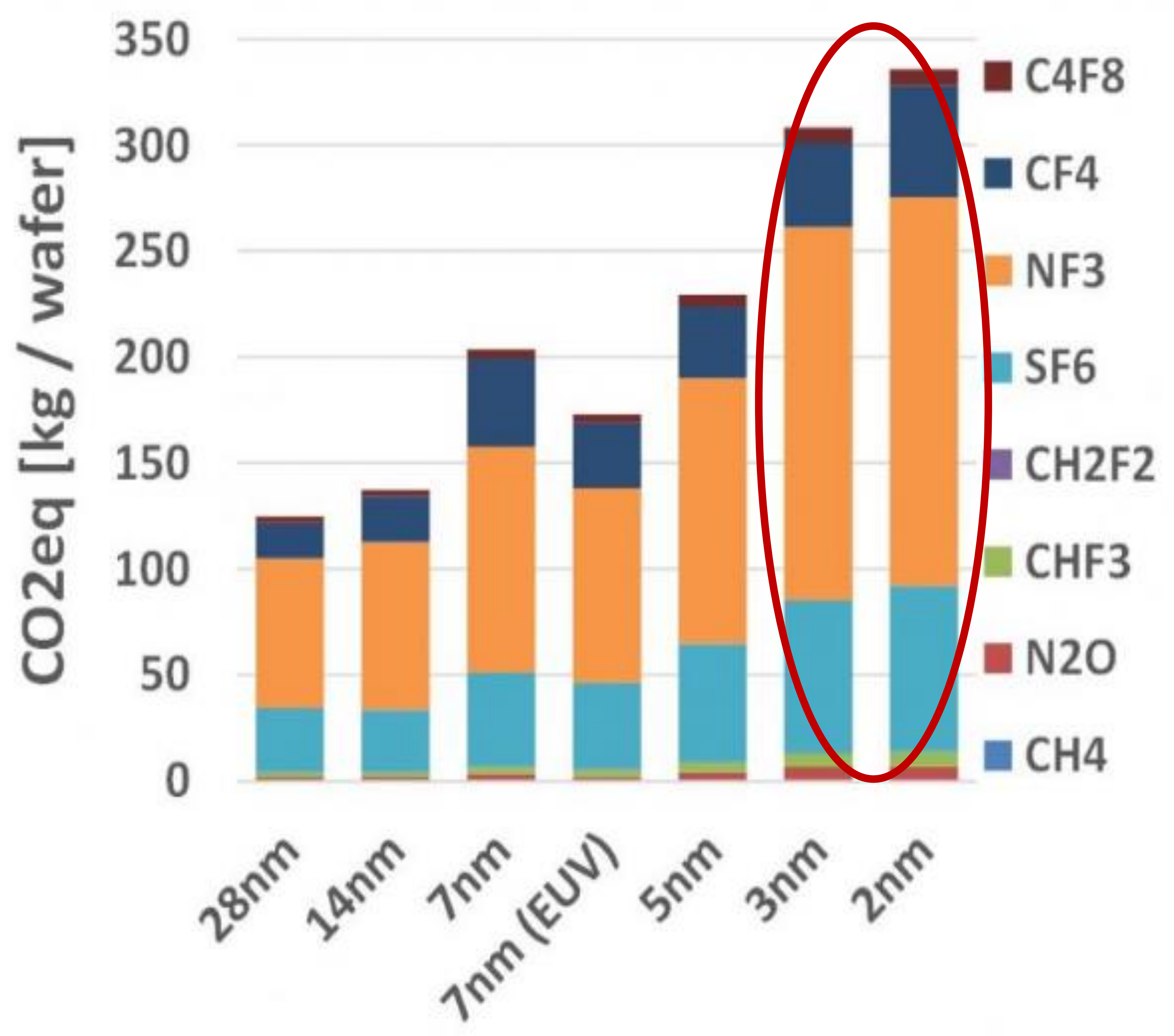
Use more environmentally preferable chemistries and recover more materials to minimize releases

Challenges?

1. Increasing complexity & stringent performance requirements
2. Compatibility with existing processes
3. Lack of information
4. Chemical laws and regulations

Industry Challenges: Fluorochemicals in plasma-enabled etch and deposition

Process Gas		Global Warming Potential (GWP_{100yr})	Atmospheric Lifetime (yrs)
CF_4	Tetrafluoromethane	7,380	50,000
C_2F_6	Hexafluoroethane	12,400	10,000
C_3F_8	Octofluoropropane	9,290	2,600
c- C_4F_8	Octofluorocyclobutane	10,300	3,200
CHF_3	Trifluoromethane	14,600	228
NF_3	Nitrogen trifluoride	17,400	569
SF_6	Sulphur Hexafluoride	24,300	1,000



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Opportunities for “Greener” Chemistries & Minimize Releases

More Environmentally Preferable Chemistries

Per- and polyfluoroalkyl substances (PFAS)
- Photolithography
- Etching gases/ chamber cleans
- Advanced packaging materials
- Wet etch chemistries
- Heat transfer fluids
- Lubricants/ greases / oils
- Article containing fluoropolymers

Etching, Process and Cleaning Gases with Lower Global Warming Potential

Onium PAGs

Solvents
- NMP
- Chlorinated solvents

Sustainable Packaging Materials

Biodegradable or recyclable components

Developing data standards

Minimizing Releases

Reduce use of HFCs, PFCs, NF_3, & SF_6
- Improve process efficiencies
- Stack optimization
- Low-density plasmas
- Reduce nozzle flushing
- Optimize use for cleaning steps

Hydrogen recovery system and hydrogen dilution

NO_X Abatement Options

HFC and PFC Abatement Systems
- High DREs (99.99%) without generating HAPs, NO_x, CO, etc.

Membrane separation to help purify and recycle process chemicals

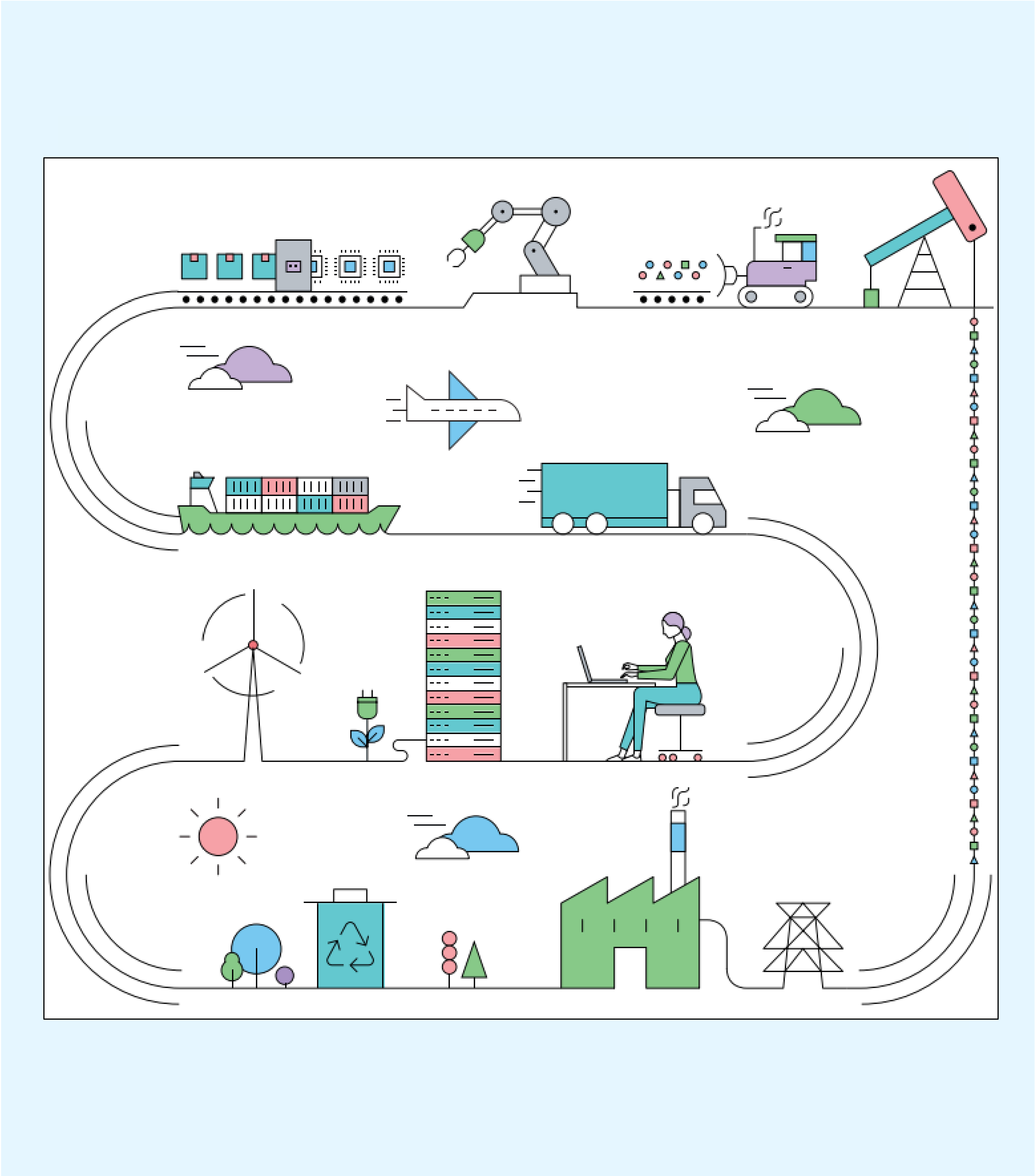
Better control leakage of heat transfer fluids

Circular Economy Pathways

What is the goal?
Develop circular economy pathways for process materials and end of life finished goods to increase reuse or recycling and minimize the use of virgin material

Challenges?

1. Complex supply chains
2. Limited recycling infrastructure
3. Complexity & composition of materials
4. Rapid technology advancement
5. Protecting IP



Opportunities to Develop Circular Economy Pathways

Design for the Environment

Design devices and products that can be reused, repaired, refurbished, and upgraded

Choose materials that can be recycled

Minimize use of hazardous materials

Design products that can be easily disassembled

- Design devices and PCBs to enable recovery and reuse of materials
- Design systems (snap in/out) that enables the reuse of certain parts and components
- Design innovative package architectures
- Can chiplets be designed like Lego blocks

Manufacturing

Sustainable manufacturing

- Optimize resource usage through more intelligent tools that are enabled by integrated sensors and control loops to validate material consumption and monitor air emissions and wastewater discharges
- Design manufacturing tools to enable better reuse of spare parts and recycling
- Design tool layouts to better optimize factory processes
- Chemical recycling and material separation

Lifecycle Management

Reuse products, chips and subsystems

- Identify opportunities and applications for chip reuse

Improve material extraction efficiencies

Conduct recycling and recovery closer to where chips are fabricated

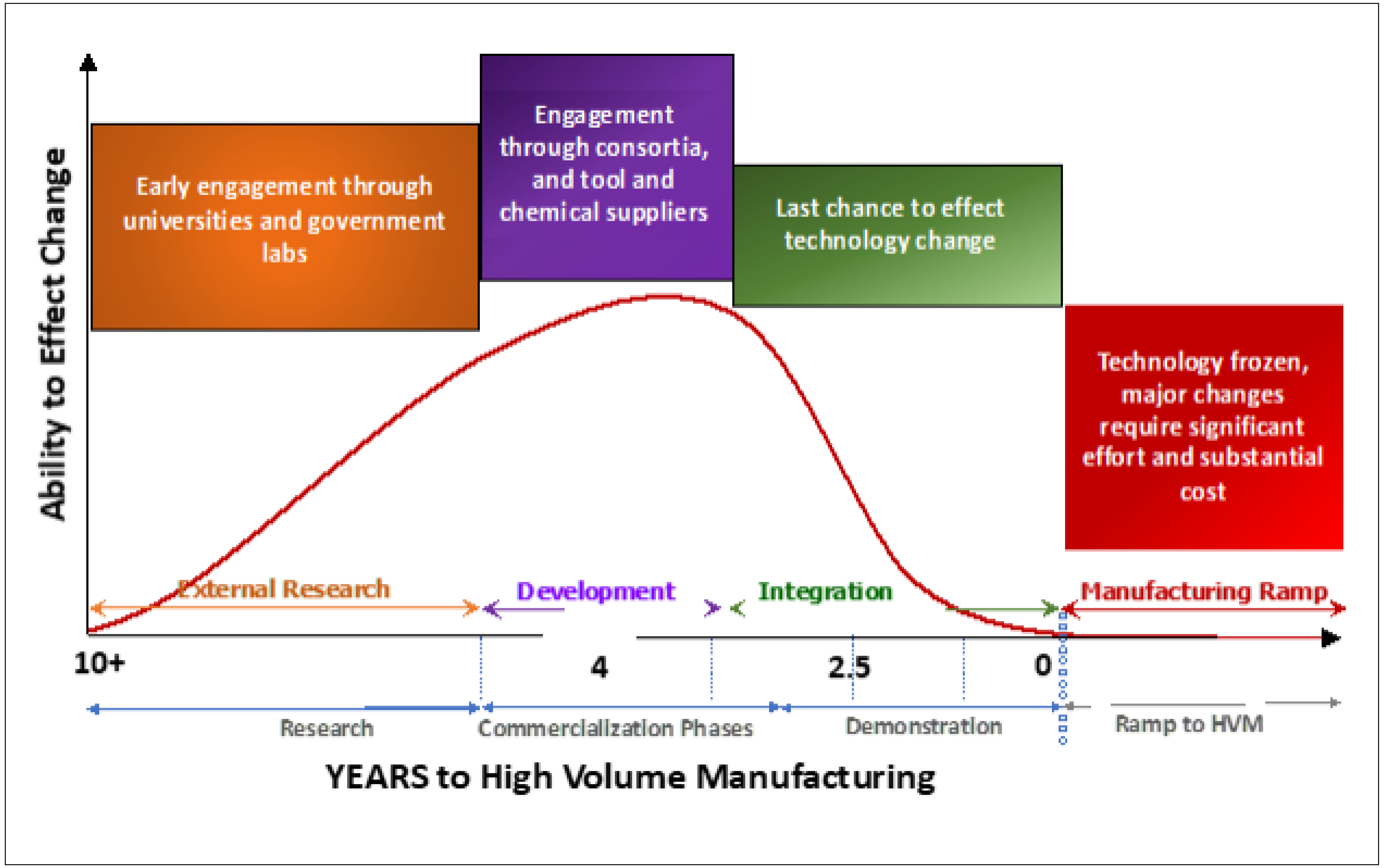
Take-back programs & raising consumer awareness

Proactive Integration of Environmental Considerations

As global demands for semiconductors continue to increase and companies act to increase capacity, environmental sustainability becomes increasingly important

Optimization metrics need to include environmental metrics to assess the impact of new processes and materials

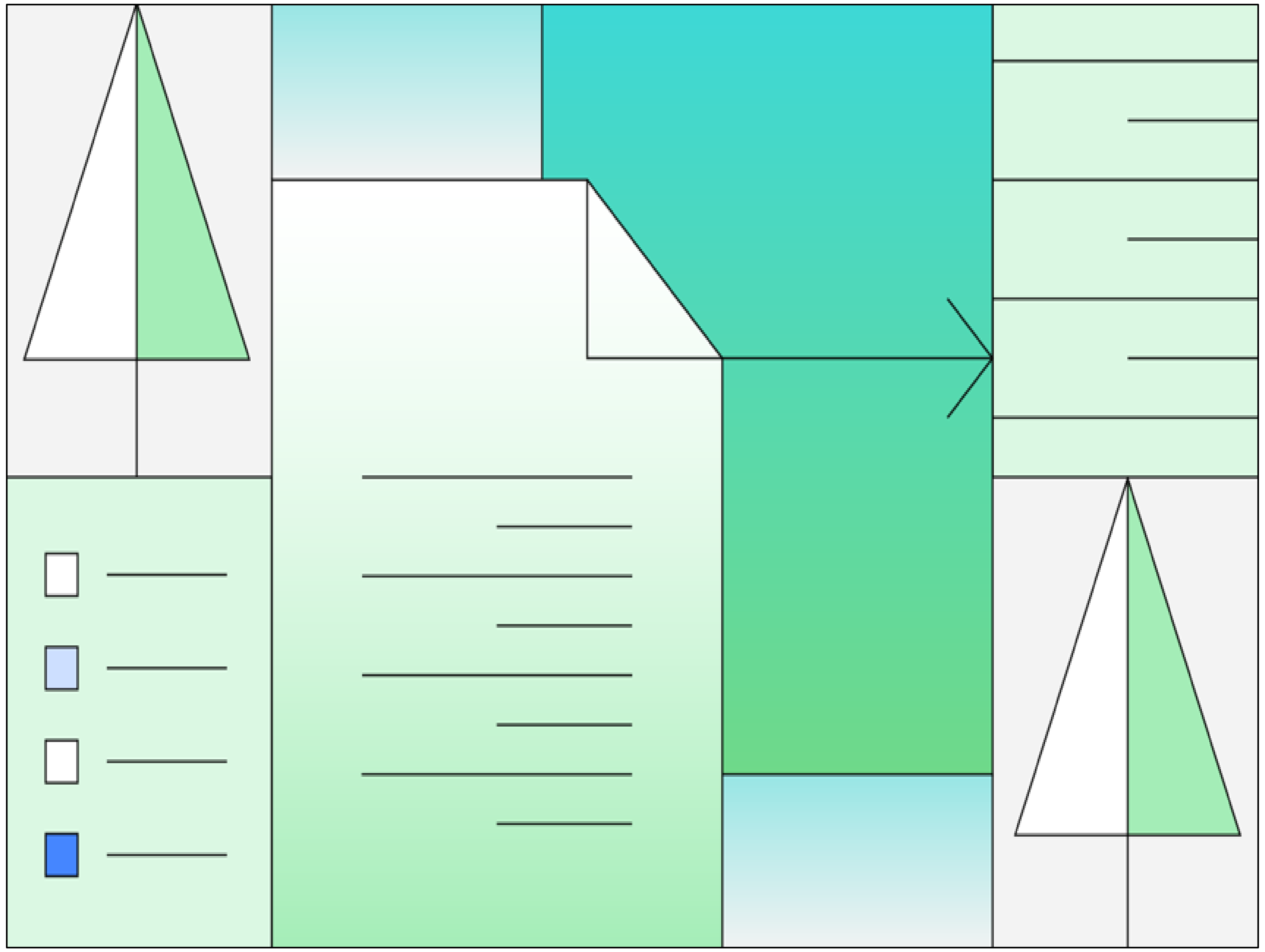
<u>Environmental sustainability can't be an after thought</u>



L. Beu, "Case Study of Semiconductor Industry Collaboration to Address EHS Challenges", SRC/ERC Annual Review 2019.

Conclusions

Digital devices and semiconductors have an important role to play in combatting climate change and can help facilitate solutions to global, regional and local environmental challenges.



01
The environmental impact of the product and of the manufacturing process must be considered in the early phases of development were there is the opportunity to make more environmentally sound choices.

02
Need to define what constitutes success and determine what sustainability targets should be.

03
Need a holistic framework to understand more comprehensively the environmental impact of certain design, material, and chemical choices as it applies throughout the entire lifecycle of semiconductors.

04
Need new, integrated software tools are needed to allow for optimization against not only performance metrics but also environmental, health and safety metrics.

Focus Areas for the Future

Decreasing the environmental impact of microelectronics will require commitment and coordinated collaboration across the entire microelectronic supply chain and ecosystem.

01

Continue to integrate environmental metrics into the design and development phase of microelectronics.

02

Develop alternative chemistries that are safer, more efficient and more effective.

03

Improve processes and systems to reduce the use of raw materials, minimize waste and increase reuse & recyclability of materials/ chemicals.

04

Continue to increase the overall functionality and energy efficiency of chips.