



OVERVIEW OF SUSTAINABLE AND CIRCULAR ELECTRONICS

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**TALLINN UNIVERSITY
OF TECHNOLOGY**

PRESENTATION OVERVIEW

- Presentation partly based on
 - “Overview of Sustainable and Circular Electronics”, Draft V1.0, 15 December 2024 (Available on request)
- Hands-on extracted from
 - IEE2520 Software Defined Electronics course



Overview of Sustainable and Circular Electronics

Draft V1.0

15 December 2024

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This work has received support from the Estonian Research Council, Project TEM-TA138 Sustainable Artificial Internet of Things (SAIoT)

PRESENTATION OVERVIEW

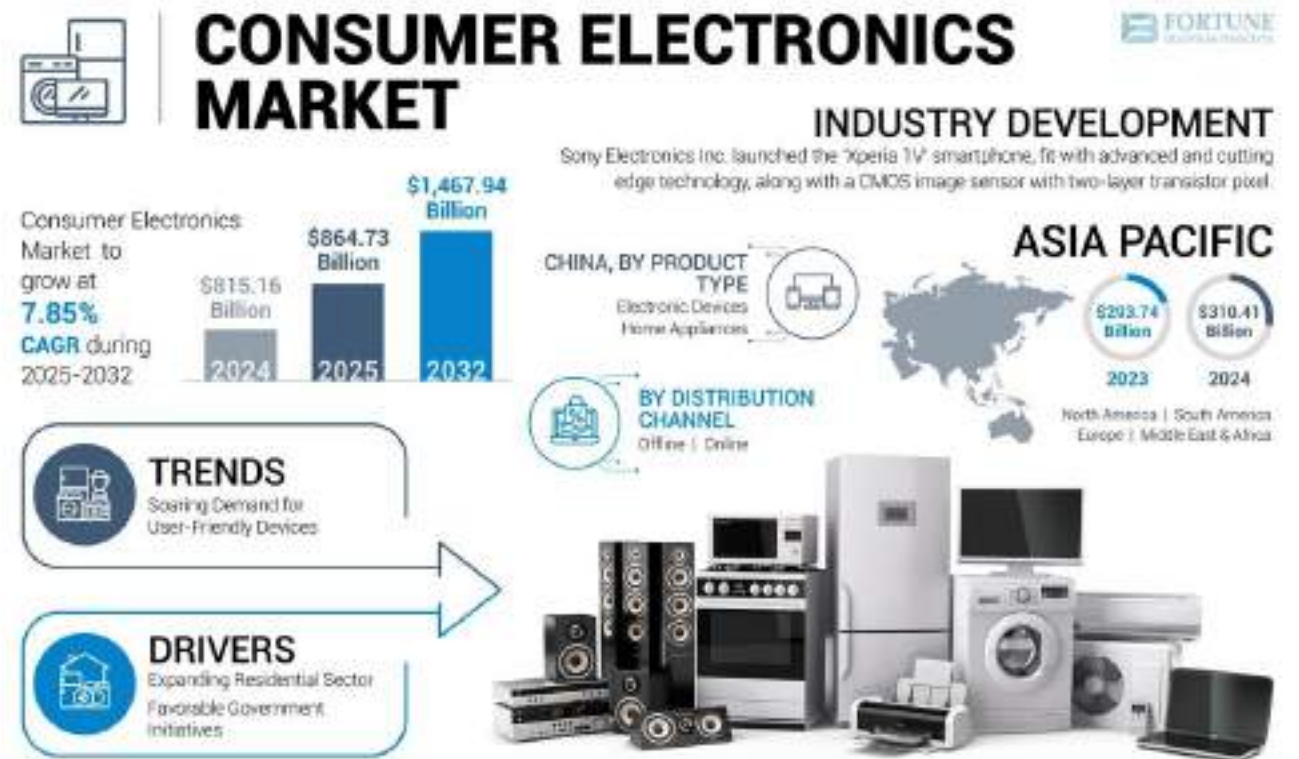
- **Introduction: The Scale of the Challenge**
- **Key Trends Shaping Sustainable Electronics**
- **Stakeholder Ecosystem and Regulatory Landscape**
- **Technologies and Industry Initiatives**
- **Batteries in Sustainable Electronics (Brief Overview)**
- **Future Directions and Roadmaps**
- **Hands-on with the MaixCam board**

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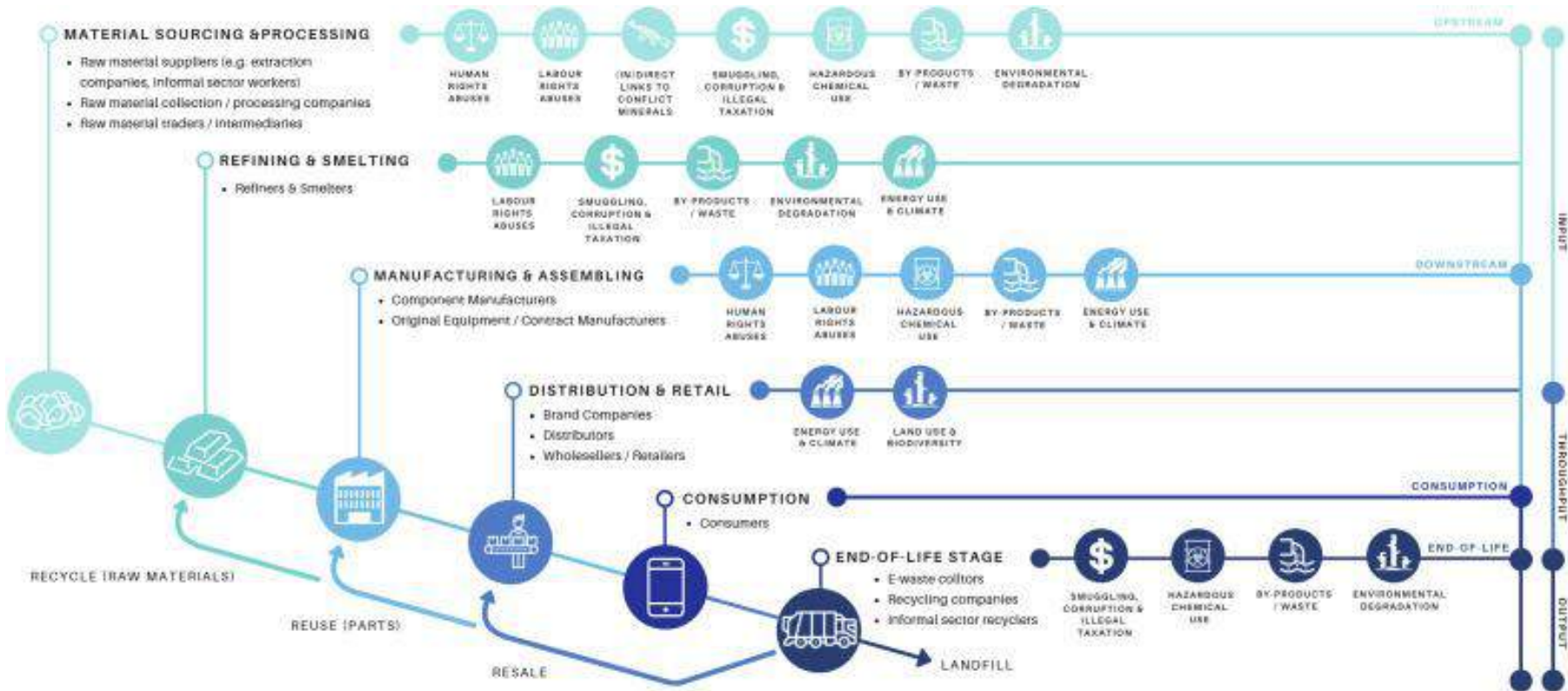
THE ELECTRONICS EXPLOSION

- From 1.3 electronic devices per American household in 1970...
- ...to 11 devices per household in 2020
- Global proliferation following similar patterns
- Accelerating consumption in emerging economies



<https://www.fortunebusinessinsights.com/infographics/consumer-electronics-market-104693>

ELECTRONICS GLOBAL VALUE CHAIN – SUSTAINABILITY RISKS



“Infographic showing the main actors and sustainability risks relating to the electronics lifecycle and their position within various stages of the electronics global value chain”

ENVIRONMENTAL AND SOCIAL IMPACTS

- Resource depletion: critical raw materials with limited supplies
- Toxic pollution: heavy metals, flame retardants, other chemicals
- Energy consumption: manufacturing and usage phases
- Social impacts: unsafe working conditions in extracting and recycling
- Health hazards: improper e-waste handling

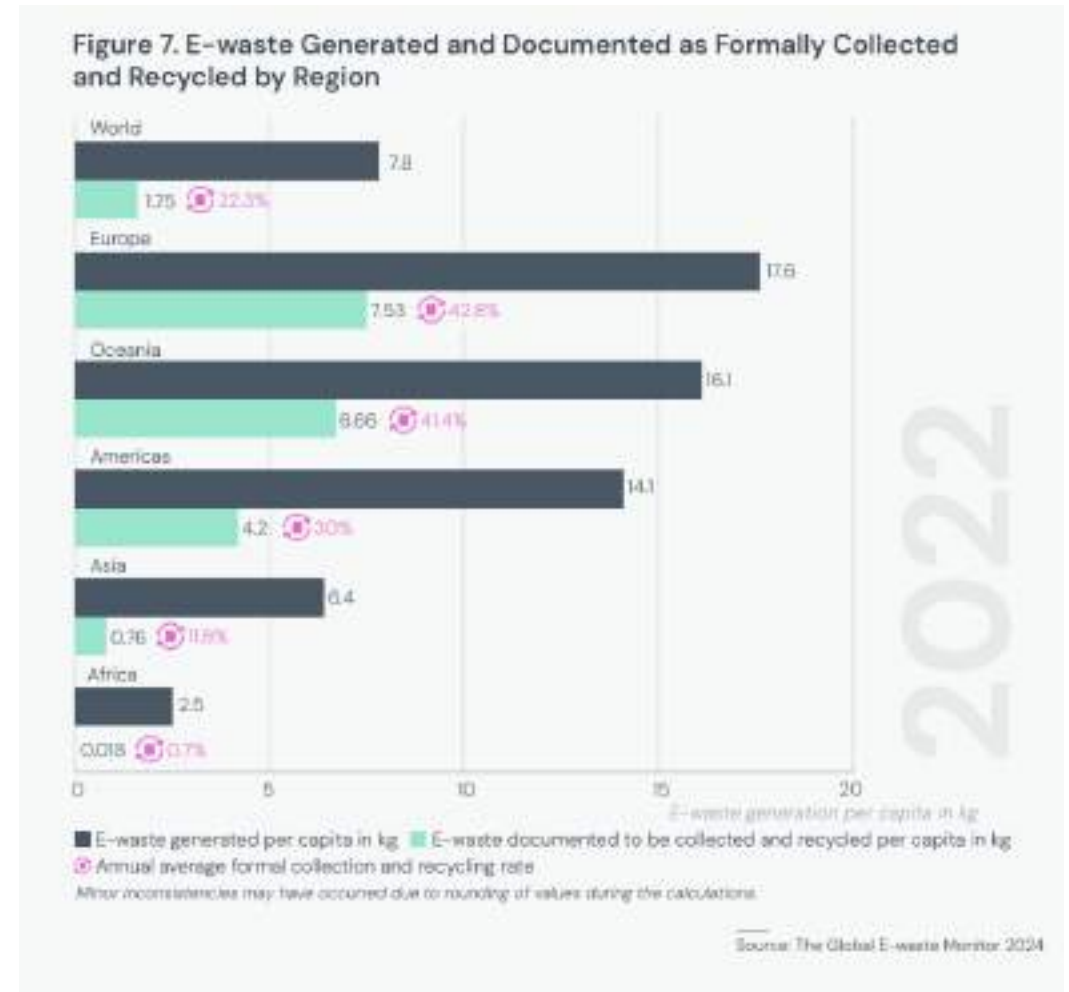


EXAMPLE: THE E-WASTE CHALLENGE

- Source - UN report cited in the document (p.8). This is equivalent to throwing away 800 laptops every second.
- Global e-waste increased 21% between 2014-2019
- Reached 53.6 million metric tons globally
- Projection: 74 Mt by 2030
- Only approx. 20% properly collected and recycled

United Nations, "Global E-Waste Surging: Up 21% in 5 Years | United Nations University." Accessed: Dec. 15, 2024. [Online]. Available: <https://unu.edu/pressrelease/global-e-waste-surging-21-5-years>

VTT Technical Research Centre of Finland, "VTT Study: Environmental impact of flexible | VTT News." Accessed: Dec. 15, 2024. [Online]. Available: <https://www.vttresearch.com/en/news-and-ideas/vtt-study-environmental-impactflexible-electronics-can-be-reduced-almost-90>



<https://ewastemonitor.info/electronic-waste-rising-five-times-faster-than-documented-e-waste-recycling-un/>

THE URGENCY OF ACTION

Key Milestones:

- 1970s: Growing environmental awareness begins
- 1992: Energy Star Program launched
- 2003: RoHS Directive introduced
- 2007: E-Waste Recycling Programs emerge
- 2015: Paris Agreement influences tech company commitments
- 2020-Present: Accelerating regulatory and industry response



Example: battery recycling regulations in the EU
Su, D.; Mei, Y.; Liu, T.; Amine, K. Global Regulations for Sustainable Battery Recycling: Challenges and Opportunities. Sustainability 2025, 17, 3045.
<https://doi.org/10.3390/su17073045>

DEFINING CIRCULAR ELECTRONICS

The Circular Approach

- Design for longevity, repairability, and recyclability
- Keep products and materials in use for as long as possible
- Regenerate natural systems
- Eliminate waste and pollution

From IEEE and European Parliament

“The concept of a circular economy encompasses the practices of sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products.”



<https://retronix.com/component-reclaim-circular-economy/>

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KEY TRENDS

8 Trends Shaping the Future of Sustainable Electronics

1. Sustainability Merging with Geopolitics

- Critical raw materials (CRM) becoming national security issue
- European Green Deal connecting sustainability to strategic autonomy
- Resource dependencies complicating low-carbon transition
- Sustainability now a key business concern due to geopolitical implications

2. EU as a Global Regulator

- “The Brussels Effect” - EU regulations influence global markets
- Strong sustainability regulations setting worldwide standards
- Companies adapting to meet EU requirements regardless of home country
- Importance of monitoring EU policies for future developments

Mining rare-earth materials

How geography compromises the green tech revolution



KEY TRENDS

8 Trends Shaping the Future of Sustainable Electronics

3. Increasing Tracking and Transparency

- European Corporate Sustainability Reporting Directive driving change
- Digital tools (IoT, blockchain) enabling detailed product tracking
- Enhanced information sharing throughout supply chain
- Consumers demanding visibility into product origins and impact

4. Advancement of Circular Economy

- Europe leading in circular practices for electronics
- Modular design enabling longer product life
- Growing repairability movement
- Booming second-hand market driven by sustainability concerns

Consumer Electronics Repair and Maintenance Global Market Report 2025



<https://www.thebusinessresearchcompany.com/report/consumer-electronics-repair-and-maintenance-global-market-report>

KEY TRENDS

8 Trends Shaping the Future of Sustainable Electronics

5. Proliferation of Electronics in Products

- Electronics increasingly integrated into everyday items
- Advances in semiconductors and batteries driving miniaturization
- Rising concerns about new sources of e-waste
- Need for circular business models for “smart” products

6. New Ownership Models

- Subscription, leasing, sharing challenging traditional ownership
- Digital technology enabling flexible access models
- Alignment with modern lifestyles prioritizing access over ownership
- Questions about responsibility for reuse and recycling

KEY TRENDS

8 Trends Shaping the Future of Sustainable Electronics

7. AI's Role in Transition

- Generative AI enhancing efficiency across industries
- AI improving electronics materials recovery
- Advanced sorting and disassembly using AI
- Robotics becoming more flexible for recycling operations

8. Consumer Demand Evolution (*really?*)

- Younger generations favoring brands with ethical values
- “Comfortable sustainability” - eco-friendly but convenient
- Consumers unwilling to sacrifice functionality for sustainability
- Complex decision-making balancing multiple priorities



“AI Powered High-Precision Metrology Drives Intelligent Disassembly of Electronics for Remanufacturing and Recycling”

<https://metrology.news/ai-powered-high-precision-metrology-drives-intelligent-disassembly-of-electronics-for-remanufacturing-and-recycling/>

KEY TRENDS

Question to the audience: which trend do you think has the most potential for positive impact?

1. Sustainability-Geopolitics Connection?
2. EU Regulatory Influence?
3. Tracking & Transparency?
4. Circular Economy Advancement?
5. Proliferation of Electronics in Products?
6. New Ownership Models?
7. AI Applications?
8. Evolving Consumer Demand?

KEY TRENDS

Circular Electronics in Practice

Example: Fairphone

Approach: modular smartphone design, ethically sourced materials, repair-focused

Claimed results:

- 53% reduction in CO₂ equivalent emissions vs industry average
- 5+ years of software support
- 1.7 million phones kept in use longer through repair program
- Fair materials sourcing benefiting mining communities



<https://www.fairphone.com/fr/2023/08/30/is-the-fairphone-5-the-most-sustainable-phone-in-the-world/>

KEY TRENDS

Challenges Ahead

Obstacles to Implementing Sustainable Electronics

- Complex global supply chains with limited transparency
- Economic pressure for rapid product cycles
- Consumer expectations for constant innovation
- Technical limitations for recycling processes
 - “Manual” approaches: risks for human health, ethics
- Market fragmentation hindering standardization
- Legacy systems and compatibility requirements

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STAKEHOLDERS & REGULATIONS

Regulatory Timeline

Evolution of Electronics Regulations

- 1990s: First voluntary initiatives
- 2000s: Initial mandatory requirements (RoHS, WEEE)
- 2010s: Expansion of scope and substances covered
- 2020s: Shift toward circular economy and whole-lifecycle approach
- 2030s: Projected integration of digital tracking and full transparency

Trend: Increasing stringency and comprehensive coverage

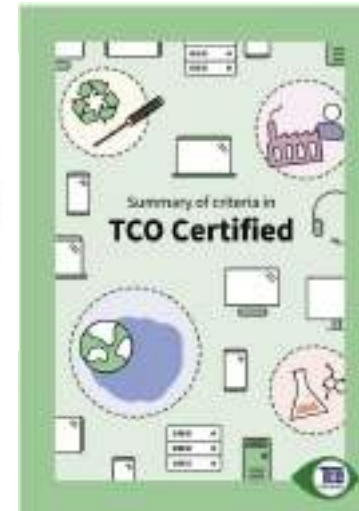
STAKEHOLDERS & REGULATIONS

Certification Bodies

Some Key Certification Organizations

- **TCO Certified:** Sustainability certifications for IT products (3500+ certified products from 25 brands)
- **Energy Star:** Energy-efficient product certification (saved 430 billion kWh in 2019)
- **Cradle to Cradle:** Circular economy principles certification (600+ companies across 54 countries)

Impact: Drive manufacturer adoption of sustainable practices through market recognition



STAKEHOLDERS & REGULATIONS

Examples of International Organizations

Global Organizations Driving Sustainability

- **IPC (Association Connecting Electronics Industries):** Standards adopted by 3000+ member companies
- **ITU (International Telecommunication Union):** Global standards for sustainable telecommunications
- **UNEP (UN Environment Programme):** Solving the E-waste Problem (StEP) Initiative
- **GEC (Global Electronics Council):** EPEAT ecolabel with 4,400+ registered products

Sustainability Leaders: Taking Charge of Solutions



IPC Sustainability for Electronics Council – made up of EMS, OEM, and PCB industry leaders, the group serves as a resource for associates in creating "standards, education, workforce training, advocacy, industry intelligence and events" towards sustainability

Circular Electronics Partnership (CEP) – brings together "the biggest names in tech, waste management, and consumer goods" to work towards a circular economy

UN's International Telecommunications Union (ITU) – 900 companies strong, an agency for information and telecommunications technologies (ICTs)

<https://www.global-imi.com/blog/electronics-leaders-weigh-sustainability-challenges>

STAKEHOLDERS & REGULATIONS

Industry Associations

Some Industry-Led Sustainability Initiatives

- **RBA (Responsible Business Alliance):** 180+ companies representing 7.7 million workers
- **ITI (Information Technology Industry Council):** Policy advocacy for sustainable innovation
- **iNEMI (International Electronics Manufacturing Initiative):** Collaborative R&D consortium
- **IPC (Association Connecting Electronics Industries)**
- **CTA (Consumer Technology Association):** Annual CES showcasing sustainable technologies



Collective Impact: Industry associations drive voluntary adoption of standards ahead of regulation



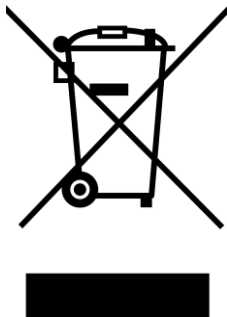
STAKEHOLDERS & REGULATIONS

European Regulations

EU Regulatory Framework

- WEEE Directive: Collection, recycling, and recovery targets for electrical goods
- RoHS Directive: Restricts 10 hazardous substances in electronics
- ESPR (Ecodesign for Sustainable Products Regulation): Framework for sustainability requirements
- Digital Product Passport: Will store and make accessible sustainability information

Key Focus Areas: Durability, repairability, recycled content, carbon footprint, product information



STAKEHOLDERS & REGULATIONS

European Regulations

Global Regulatory Landscape (examples, outside the EU)

United States

- EPEAT voluntary certification
- Energy Star Program (20-30% energy reduction in certified products)

China

- China RoHS restricting hazardous substances
- Unique labeling requirements and catalogue-based compliance

Japan

- Home Appliance Recycling Law covering TVs, air conditioners, refrigerators, washing machines
- 14.95 million units collected for recycling (2022)

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TECHNOLOGIES AND INDUSTRY INITIATIVES

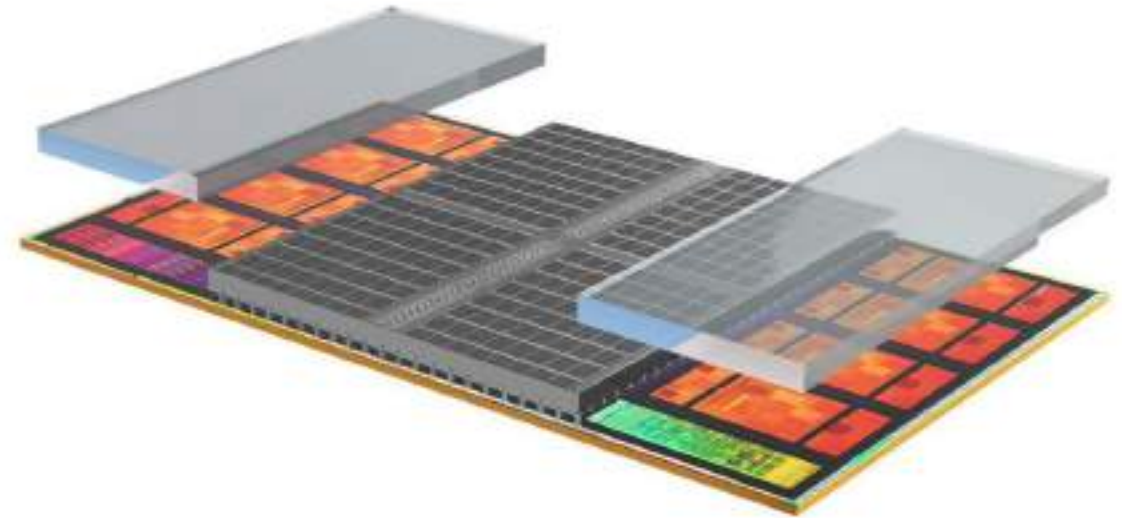
Energy Efficiency Innovations

Advanced Power Management

- Dynamic Voltage and Frequency Scaling (DVFS)
- Sleep states (C-states) and power states (P-states)
- Adaptive brightness control

Component Efficiency

- Smaller transistor sizes (5 nm, 3 nm processes)
- 3D chip stacking technology
- High-k metal gates reducing leakage current



<https://spectrum.ieee.org/amd-3d-stacking-intel-graphcore>

TECHNOLOGIES AND INDUSTRY INITIATIVES

Sustainable Materials Revolution

Bio-based Alternatives

- Biopolymer-based printed circuit boards
- Organic semiconductors
- Mycelium-based packaging materials
- Cellulose-based composites

Recycled Content

- Post-consumer recycled (PCR) plastics
- Closed-loop recovery systems
- Advanced sorting technologies using AI

Reduced Dependence on Rare Materials

- Ferrite magnets as alternatives to neodymium
- Organic light-emitting diodes (OLEDs)
- Engineered nanomaterials



<https://newatlas.com/materials/vitrimer-recyclable-printed-circuit-board/>

TECHNOLOGIES AND INDUSTRY INITIATIVES

Circular Design Principles

Modular Design

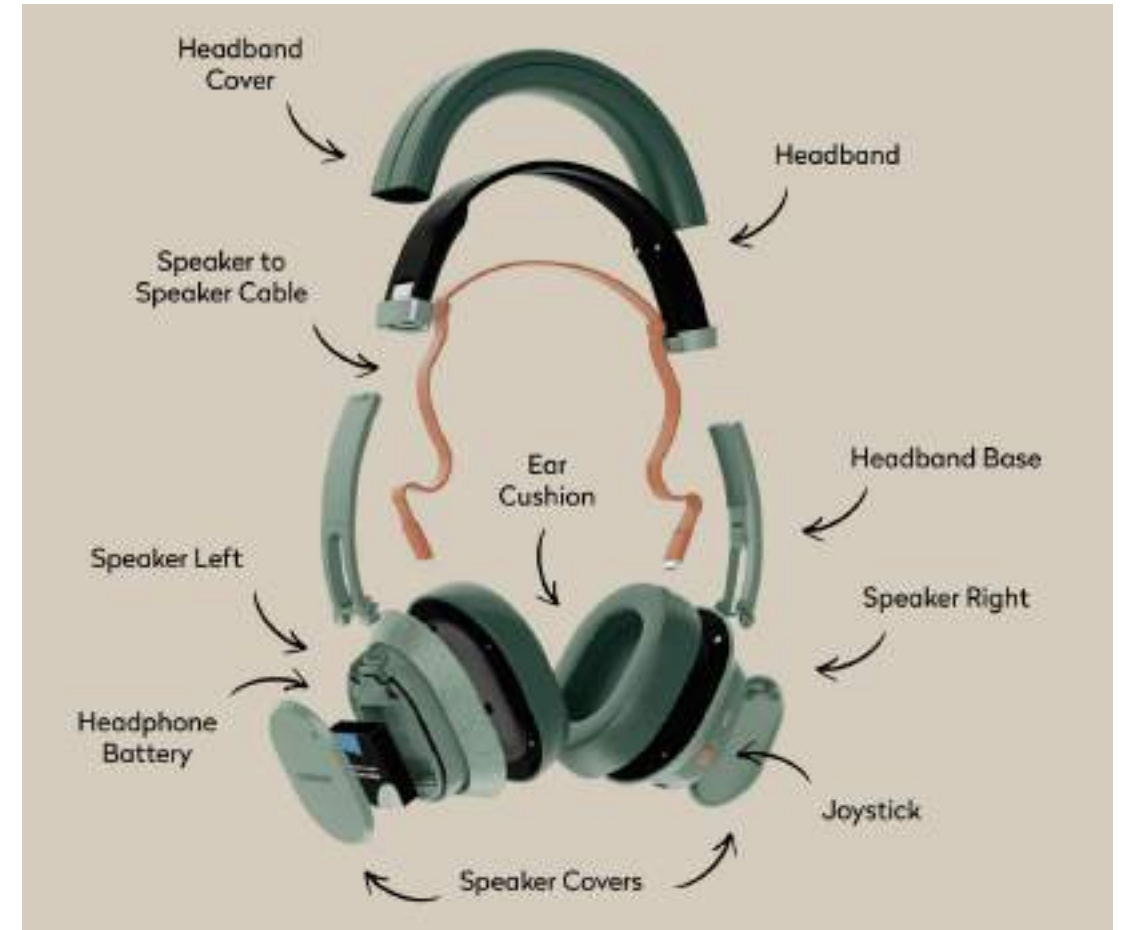
- Easily replaceable components
- Standardized connectors and interfaces
- Software support for component hot-swapping

Design for Disassembly

- Reversible fasteners instead of adhesives
- Clear material labeling for identification
- Avoiding difficult-to-separate composite materials

Repairability Features

- Accessible internal components
- Available repair documentation
- Spare parts availability



TECHNOLOGIES AND INDUSTRY INITIATIVES

Advanced Recycling

Next-Generation Technologies

- Bioleaching: Using microorganisms to extract metals
- Supercritical water oxidation for breaking down hazardous compounds
- Automated disassembly using robotics and AI

Recovery Improvements

- Precious metals recovery rates increasing from 30% to 95% (target, not there yet)
- Rare earth element extraction from electronic waste
- Carbon footprint reduction in recycling processes

TECHNOLOGIES AND INDUSTRY INITIATIVES

Green Manufacturing

Additive Manufacturing

- Aerosol Jet Printing for electronics circuits
- Stereolithography (SLA) for PCBs
- Selective Laser Sintering (SLS) for conductive components

Safer Chemicals

- Water-based cleaning systems replacing organic solvents
- Supercritical CO₂ cleaning
- Plasma cleaning without chemicals

Energy-Efficient Processes

- Advanced thermal management
- IoT-enabled smart manufacturing grids
- Digital Twin simulation for optimization

TECHNOLOGIES AND INDUSTRY INITIATIVES

Industry Initiatives

Collaborative Industry Programs

- IPC Sustainability Policy Priorities focusing on chemical and product policies
- RBA Code of Conduct implemented throughout supply chains
- iNEMI collaborative research projects for eco-design
- Circular Electronics Partnership uniting leaders across the value chain

Industry Commitment

- Certification and validation programs
- Workforce training in sustainable practices
- Knowledge-sharing platforms
- Pre-competitive collaboration on common challenges

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BATTERIES IN (SUSTAINABLE) ELECTRONICS

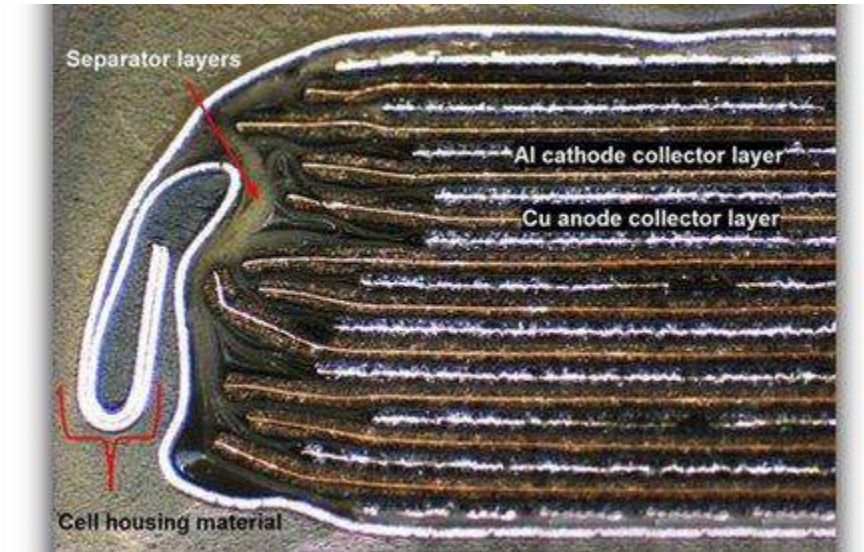
Battery-Electronics Intersection

Sustainability Challenges

- Batteries often determine overall product lifespan
- Resource-intensive materials (lithium, cobalt, nickel)
- Energy-intensive manufacturing
- End-of-life processing difficulties

Emerging Solutions

- Solid-state batteries with higher energy density
- Silicon anodes increasing storage capacity
- Lithium-sulfur batteries as next-generation technology
- Design innovations for easier battery replacement



<https://www.ifixit.com/News/10990/your-smartphone-battery-explained>

BATTERIES IN (SUSTAINABLE) ELECTRONICS

Battery Design Spectrum

From Least to Most Sustainable

- **Integrated Batteries:** Permanently sealed, device disposed when battery fails
- **Service-Replaceable:** Replacement requires professional service
- **User-Replaceable with Tools:** Can be replaced by user with specific tools
- **Standardized User-Replaceable:** Common form factors, easily accessible

TCO Certified Requirement:

“Batteries must be user-replaceable with common tools or provided tools.”

Future Directions

- Self-healing battery materials
- Biodegradable battery components
- Standardization initiatives

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LOOKING AHEAD

iNEMI Roadmap Highlights

- Materials innovation and substitution
- Design for sustainability and circularity
- Manufacturing process optimization
- End-of-life management technologies

Timeline

- 2024-2026: Immediate priorities including PCB alternatives
- 2027-2030: Advanced recycling technologies
- 2030+: Closed-loop systems for all materials

Key Challenges

- Complex material combinations
- Global supply chain management
- Legacy system compatibility



Roadmap Topics

Complex Integrated Systems

Topic Co-chair: Francis Muliany (iNEMI)
Topic Contributors Contributing organizations: Bell Labs Consulting, Nokia, iNEMI, Intel, IPC, Jabil, SEMI, Tejas Net...

Sustainable Electronics

Topic Co-chairs: Thomas Okrasinski (Nokia), Fu Zhao (Purdue University), Pia Tanakanen (Nokia) Topic Contributors Contributing organizations: IBM, Nokia, Pur...

mmWave Materials and Test

Topic Chair: Dr. Umri Ray, iNEMI Topic Contributors Contributing organizations: iNEMI, Intel, NIST, QWED, Keysight Technologies Acknowledgement As part of th...

Printed Circuit Board (PCB)

Topic Co-chairs: Tarja Rapara (EPC), Joe Beers (Gold Circuit Electronics) Topic Contributors Contributing organizations: DuPont, EPC, Four Peaks Innovation...

Board Assembly

Topic Co-chairs: Jasbir Bath (Bath Consultancy LLC), Paul Wang (MITAC) Topic Contributors Contributing organizations: AMD, Bath Consultancy LLC, Celestica, F...

Packaging & Heterogeneous Integration

This is a brief overview of the topic Packaging & Heterogeneous Integration. To avoid duplication, many links here point to specific sections in MAPT, the NI...

Smart Manufacturing

Topic Co-chairs: Don Gamota (Jabil), Ranjan Chatterjee (Cimatrix) Topic Contributors Contributing organizations: Cimatrix, Jabil, Palo Alto Networks, SEMI, IC...

Roadmap Drivers

Under development. Drivers not specific to a given topic, but more related to an application area, are stored here. Full scale narratives and tables will be ...

Contributors to the iNEMI Roadmap

The iNEMI Roadmap depends on the voluntary efforts of a large number of contributors. On behalf of the electronics manufacturing industry, we in iNEMI would ...

Guide to the iNEMI Roadmap

iNEMI Roadmap Taxonomy Color Coding Key for Technology Status Readiness Levels Technology Readiness Levels (TRLs) Manufacturing Readiness Levels (MRLs) Color...

LOOKING AHEAD

TCO Roadmap Focus Areas and Goals:

Climate (2033)

- Verified emissions reductions
- Energy efficiency in supply chain
- Renewable energy through accredited purchases

Substances (2033)

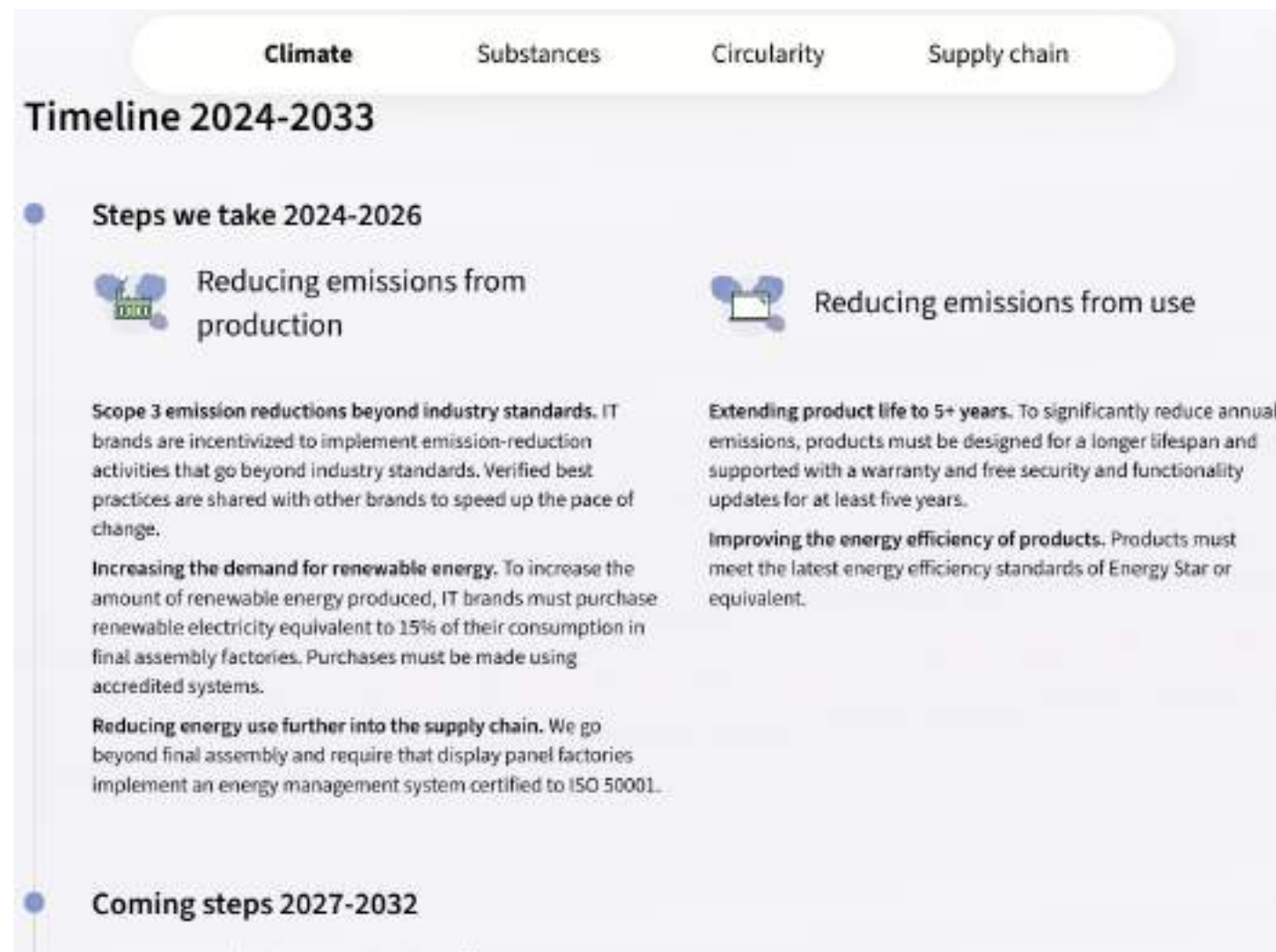
- Safer alternatives in all high-risk categories
- Risk benchmarks covering multiple supply chain tiers
- System addressing emerging hazardous substance hotspots

Circularity (2033)

- 10+ years of supported product life
- Easy maintenance, repair, and reuse
- Digital product passports

Supply Chain (2033)

- Living wage for workers
- Water conservation near manufacturing
- Responsible sourcing of all risk minerals



<https://tcocertified.com/roadmap/#climate>

LOOKING AHEAD

Skills Development

“The urgency is clear: while the economy and society need these skilled professionals now, it will take 5-10 years for graduates with these new competencies to effect change.” (INSA/Shift Project report)

Workforce Needs

- Technical skills for repair and remanufacturing
- Design expertise for circular products
- Supply chain management for sustainability
- Data analytics for impact assessment

Educational Initiatives

- Education in Sufficiency for Sustainable Electronics (ESOS) at INSA Rennes, France
- International Labor Organization (ILO) “Skills for a greener future” framework
- Industry-academia partnerships for curriculum development

CRITICAL REFLECTIONS

The Rebound Effect

Efficiency Paradox

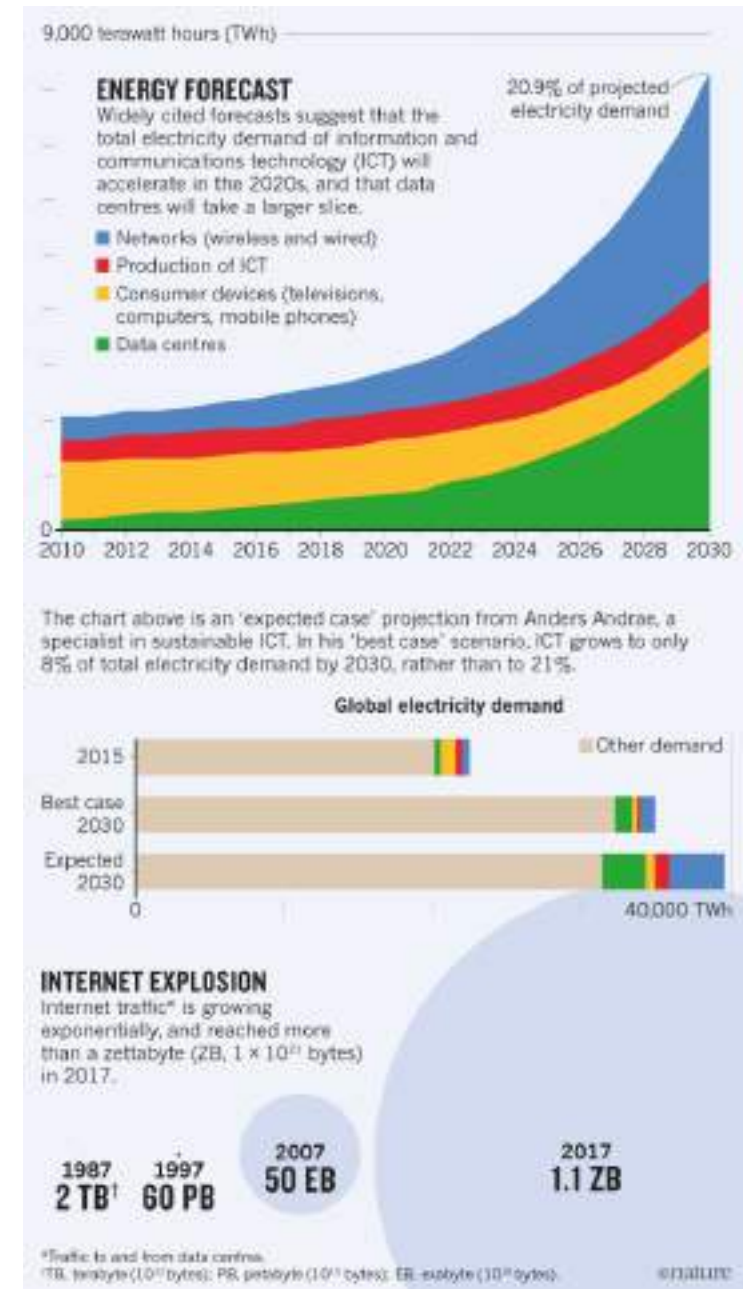
- Efficiency improvements lead to increased consumption
- Named after William Stanley Jevons (1865)
- Total impact = Impact per unit × Number of units × Usage intensity

Electronics Examples

- More energy-efficient devices → More devices in use
- Longer battery life → More screen time
- Cloud efficiency → More data storage and processing

Empirical Evidence

- Global ICT energy use continues to rise despite efficiency gains
- Data centers 10x more efficient but total energy use still increasing



CRITICAL REFLECTIONS

Additive Rather Than Substitutive Transitions

Addition Problem

- New technologies rarely fully replace old systems
- We add new layers of technology while maintaining legacy systems
- Digital and physical infrastructures coexist rather than substitute

Resource Implications

- Critical raw materials demand accelerating
- New materials added to material footprint without reducing others
- Energy demand for digital systems adds to existing energy uses

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HANDS-ON: MAIXCAM AND MAIXVISION (VARIOUS APPLICATIONS)

- Sustainability is not only about recycling or regulation. It's also about intelligent design choices
 - E.g. performing computations where they cost the least --in energy, latency, and carbon emissions
- Focus on edge devices and possible edge-layer, not fog-layer (e.g. not telecom infrastructure)
- Key idea: perform computations **near the sensors**, or even on the sensors
- Examples of boards (non-exhaustive)



ESP32 series



RPI series
Possibly with HAT for accelerating machine learning (TPU: Tensor Flow Unit)



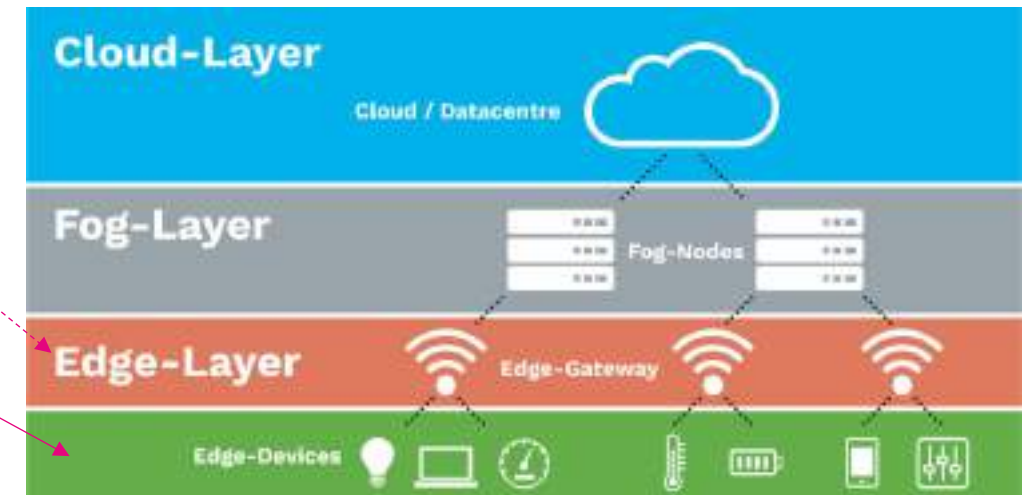
Maix series (includes NPU)



Luckfox series (includes NPU: Neural Processing Unit)



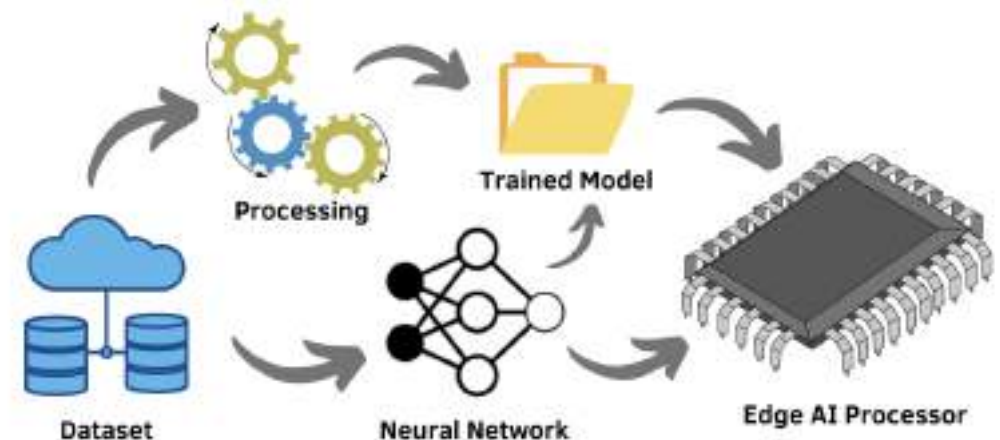
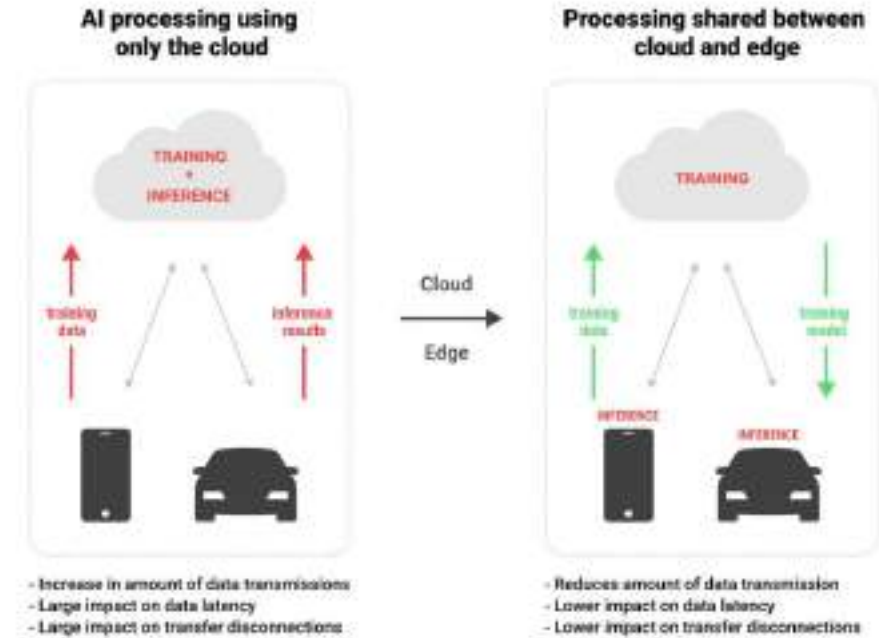
Nvidia series (includes GPU)



ASPECTS OF EDGE COMPUTING FOR SOFTWARE DEFINED SENSING

Machine learning on edge devices (also known as edge-AI)

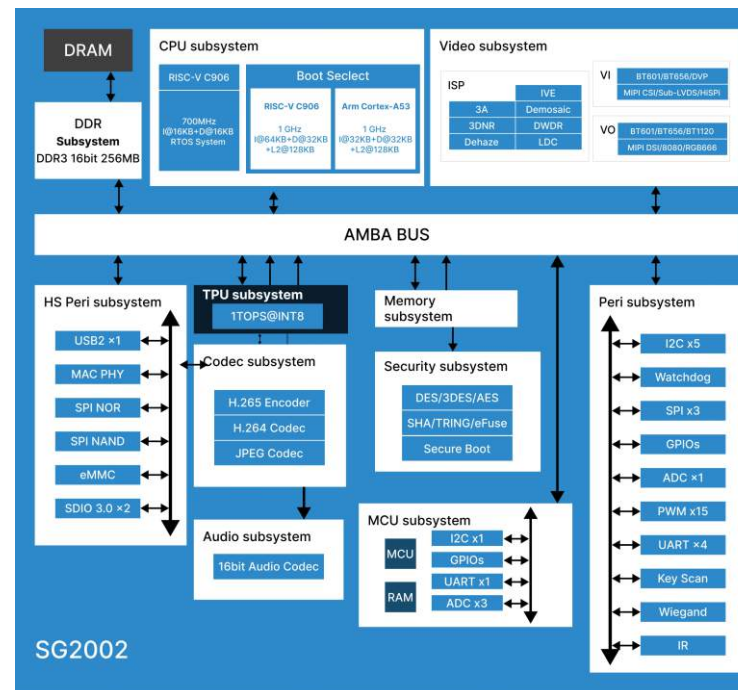
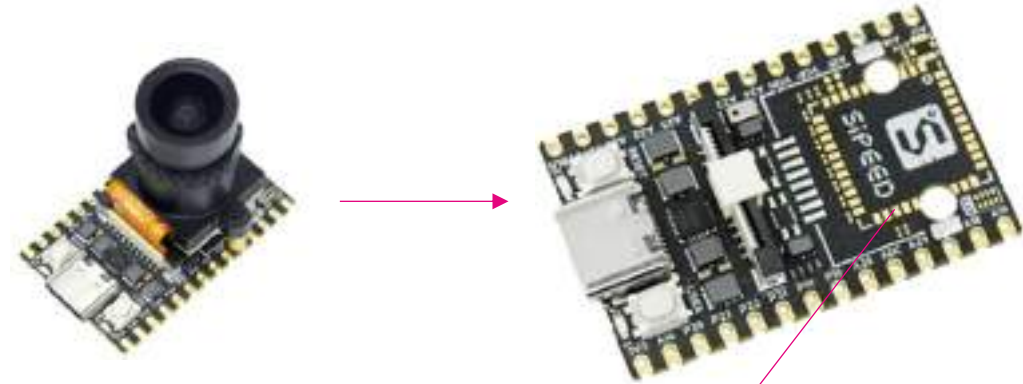
- Primarily refers to inference conducted on edge devices
- Reduces data transmission and cloud dependency
 - Lower carbon footprint by minimizing data movement to power-hungry data centers
- Real-Time, local decision making
 - Reduced latency and energy
- Low-Power AI Hardware
 - Reducing system-level energy use
- Training is (much) more compute demanding
 - Still mostly performed in the cloud, or local powerful PC with GPUs
 - *However, increasing trend towards training, or at least partial training/updating on edge devices too*



ASPECTS OF EDGE COMPUTING FOR SOFTWARE DEFINED SENSING

Hardware example: MAIXCam

- Based on a LicheeRV Nano module (SG2002 chip)
 - Primary 700 MHz RISC-V C906 core
 - Secondary, boot-selectable, 1 GHz RISC-V C906 core or 1 GHz ARM A53 core.
 - Tensor Processing Unit (TPU)
 - Up to 1 TOPS@INT8
- 256 MB DDR3 memory
- Up-to 2.5 W power consumption
- Low-cost (approximately 34 EUR)



HANDS-ON: MAIXCAM AND MAIXVISION (VARIOUS APPLICATIONS)

Objectives

Maixvision

- AI vision IDE for programming, running code, live image preview, and graphical programming

The objectives are to:

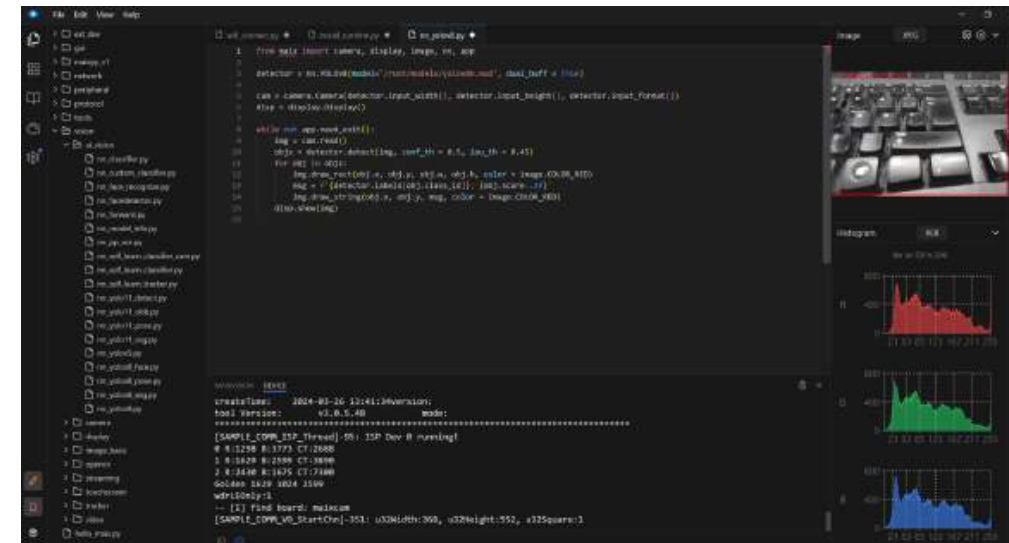
- Install Maixvision
- Configure it and connect to the MaixCam board
- Run some of the provided examples



IAI
TECH



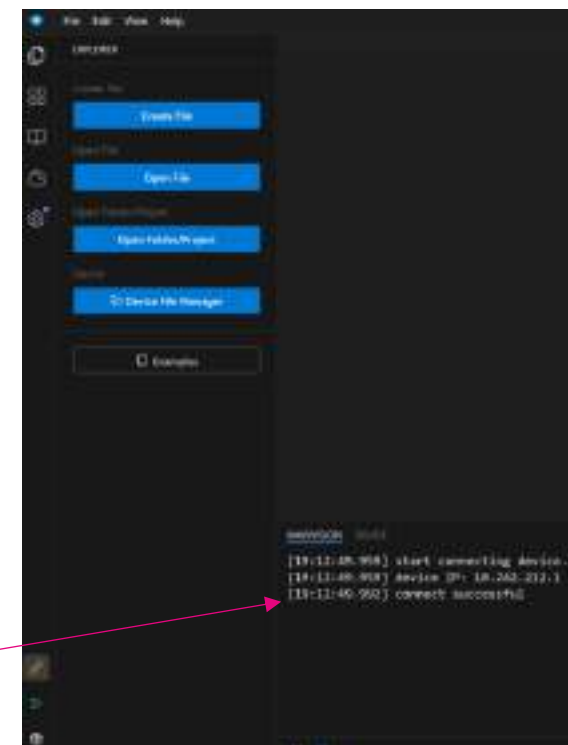
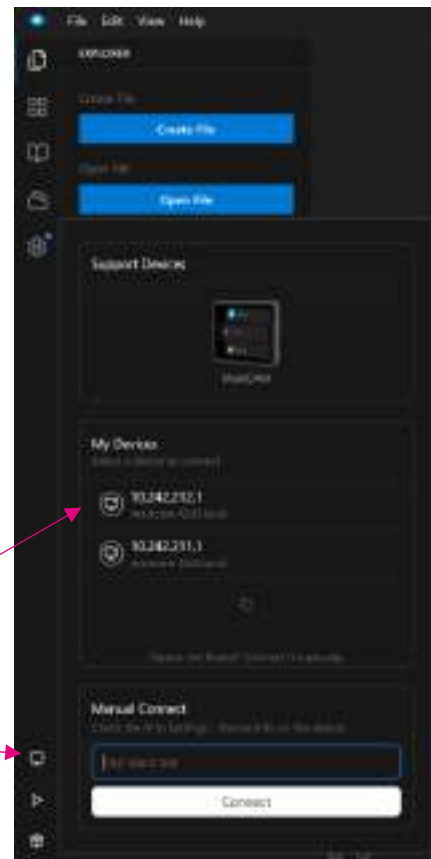
Note: we do not have the touchscreen/display module.
We use the display in MaixVision instead.



HANDS-ON: MAIXCAM AND MAIXVISION (VARIOUS APPLICATIONS)

Setup (1/3)

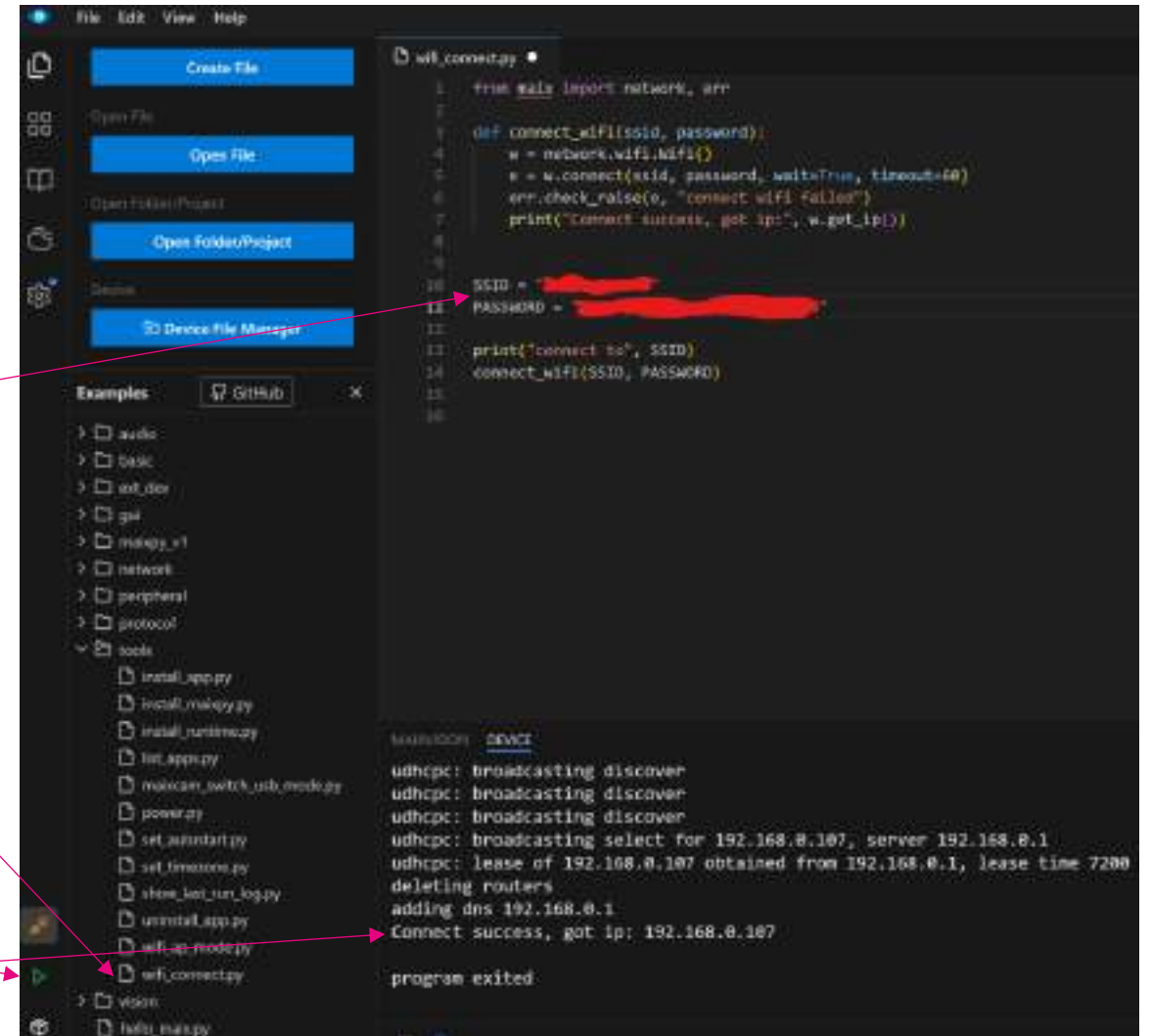
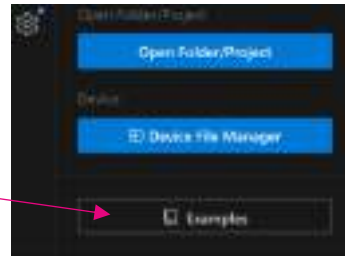
1. Install Maixvision
 - <https://wiki.sipeed.com/en/maixvision.html>
2. Make sure the SD card is inserted in the MaixCam board
3. Connect the MaixCam board to the PC
4. In MaixVision: bottom left: click the computer monitor icon "Connect"
5. Select the first address
6. Verify that the connection was successful



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Setup (2/3) **Optional step**

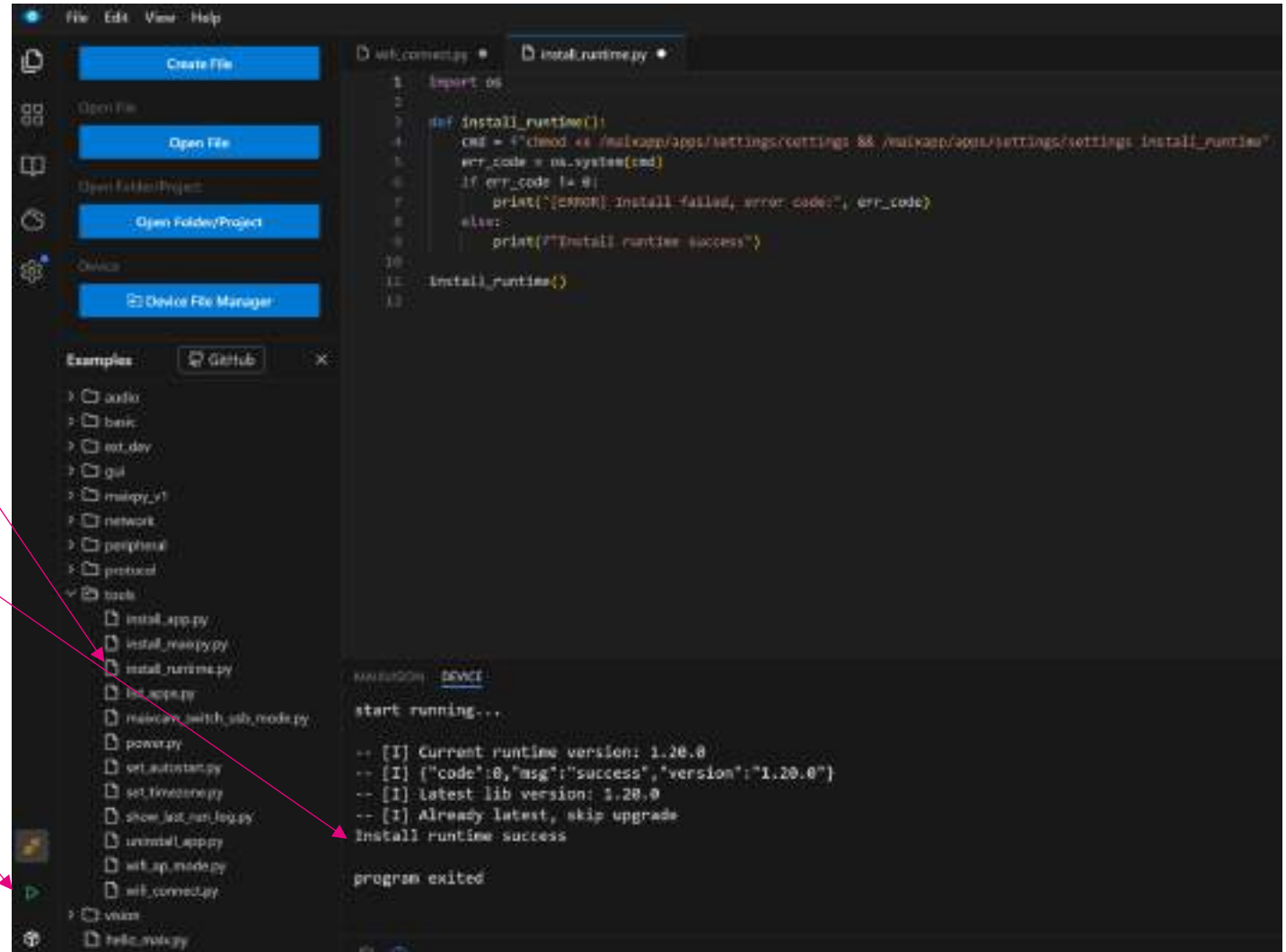
1. Click "Examples"
2. Navigate to tools and click wifi_connect.py
3. Configure as per the actual network:
 - Replace Sipeed_Guest with the network SSID
 - Replace qwert123 with the network password
4. Run the code
5. Verify that the board got connected to the WiFi network



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Setup (3/3)

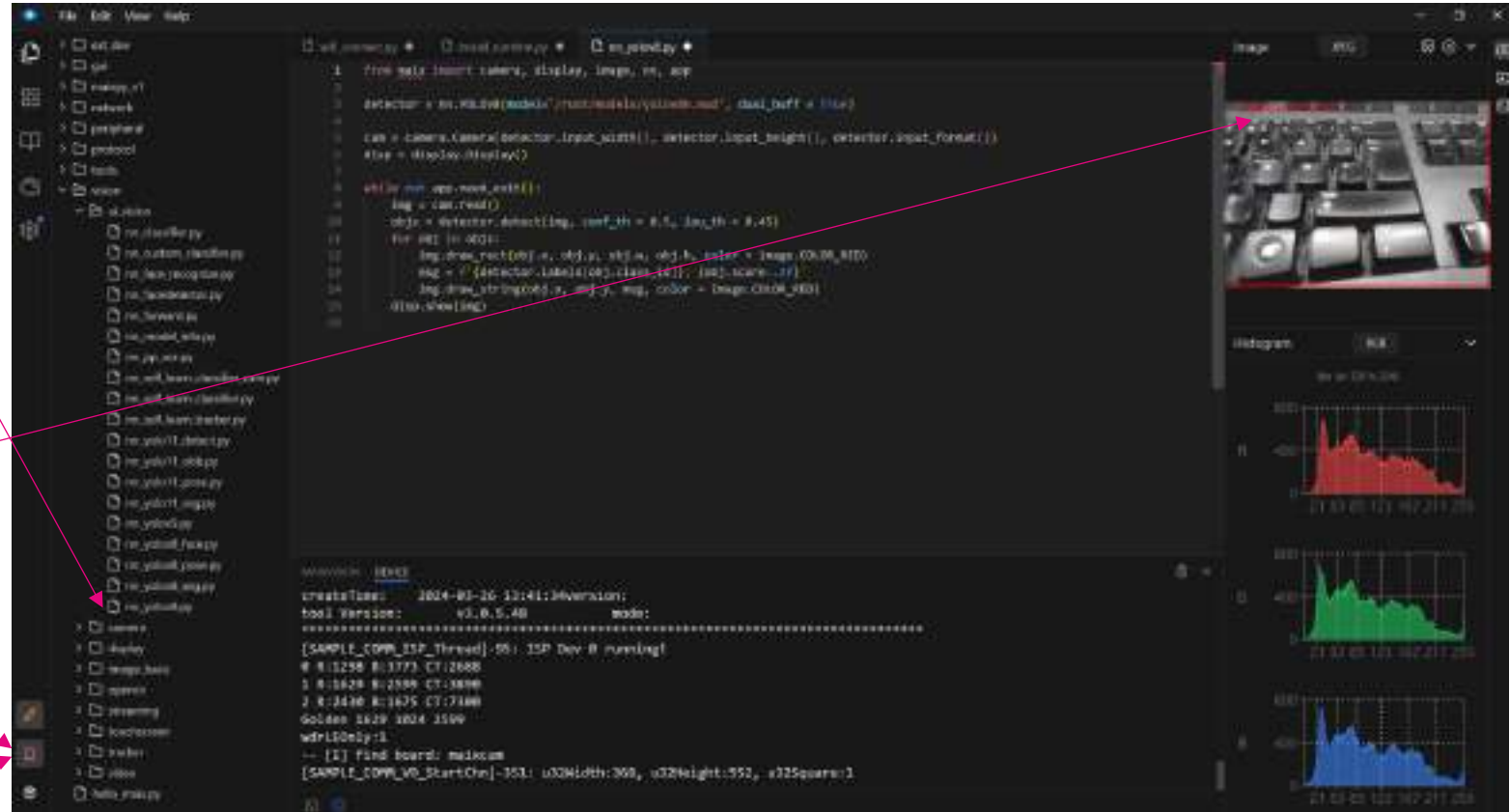
1. Navigate to tools and click `install_runtime.py`
2. Run the code
3. Verify that the runtime was installed



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Experiments

1. Navigate to ai_vision and click nn_yolov8.py
2. Remove the cap from the lens of the camera
3. Run the code
4. Check the results
 1. Adjust the camera's focus ring as needed
 2. Possibly, check the options of the histogram (LAB, RGB, etc.)
5. Press stop when you are done
6. Try other example(s)





THANK YOU!

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