Global Energy Footprint of IoT Semiconductors

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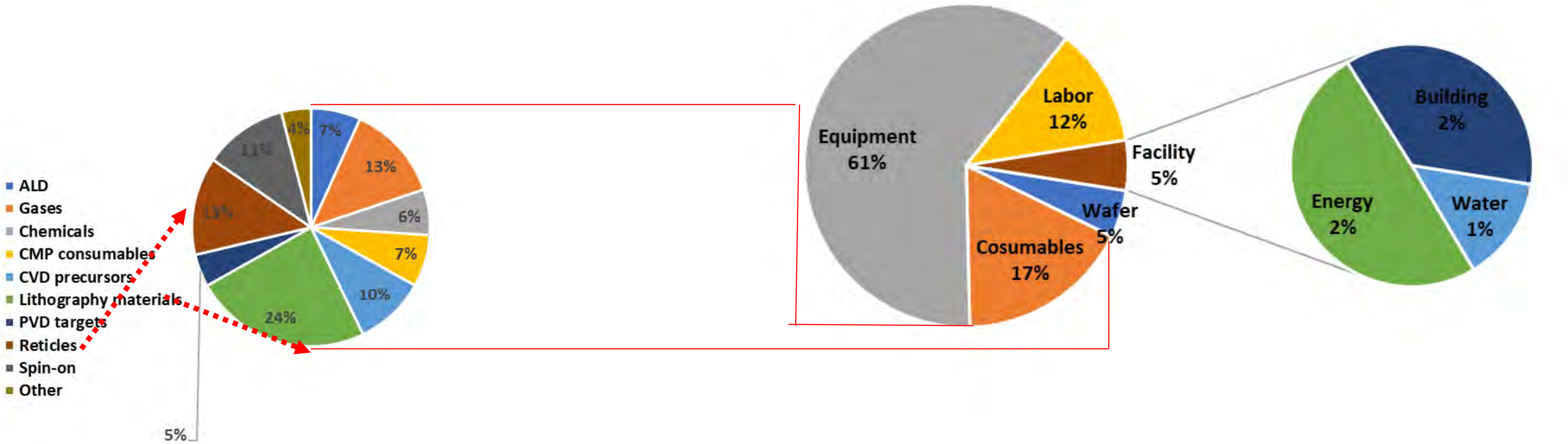
LCA of Semiconductors

- LCAs focus to date have been on *environmental* and not *energy* concerns driven by European regulations (Also more at the final electronic product instead of semiconductor)
- Limited published semiconductor LCA studies using a varying level of aggregation approaches
  - Considerably old estimates at the wafer and final packaged chip level with varying assumptions of chip type without any specific packaging type consideration
  - 2015 GaBi electronics database contains LCI data for a varying range of different packaged ICs
  - At the product level based on teardown studies, e.g., tablets, iPads, and ICs
  - Uncertainty analysis is key to reflect rapid technology change – Under-specification and probabilistic triage methodology (value of additional LCI data on the final results)
- Bottom-up LCAs require at the semiconductor chip level analysis is necessary based on an intensive updated LCI data collection to reflect the rapid chip design change trend in the semiconductor manufacturing industry
  - Worldwide total # of semiconductors use will more than double from 30 B chips 2016 within the next ten years
  - Growing semiconductor technology change -- chip miniaturization, decreasing technology node (increasing no. of functional mask layers ~120 today), application specific (e.g., SoCs, SIPs, ASICs, and ASSPs), and multi-functional chip integration

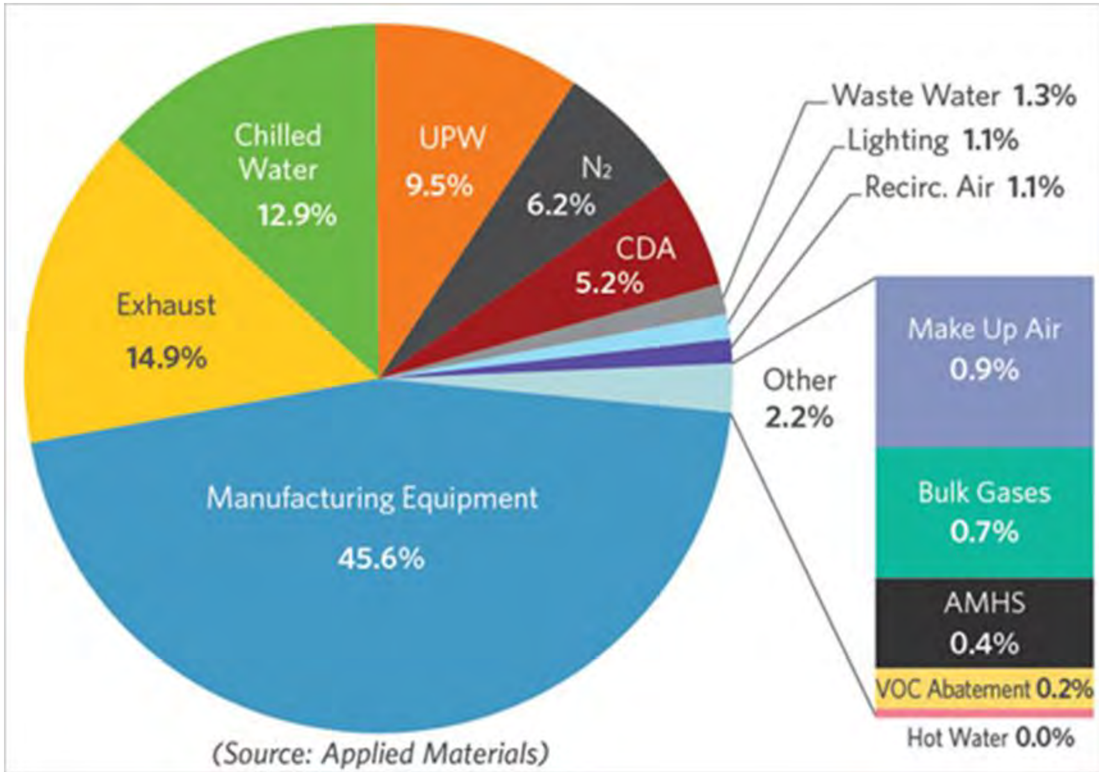
14 nm 300 mm MPU Wafer Manufacturing Cost – Major Categories



Source: Linx Consulting Inc., Sept. 2019

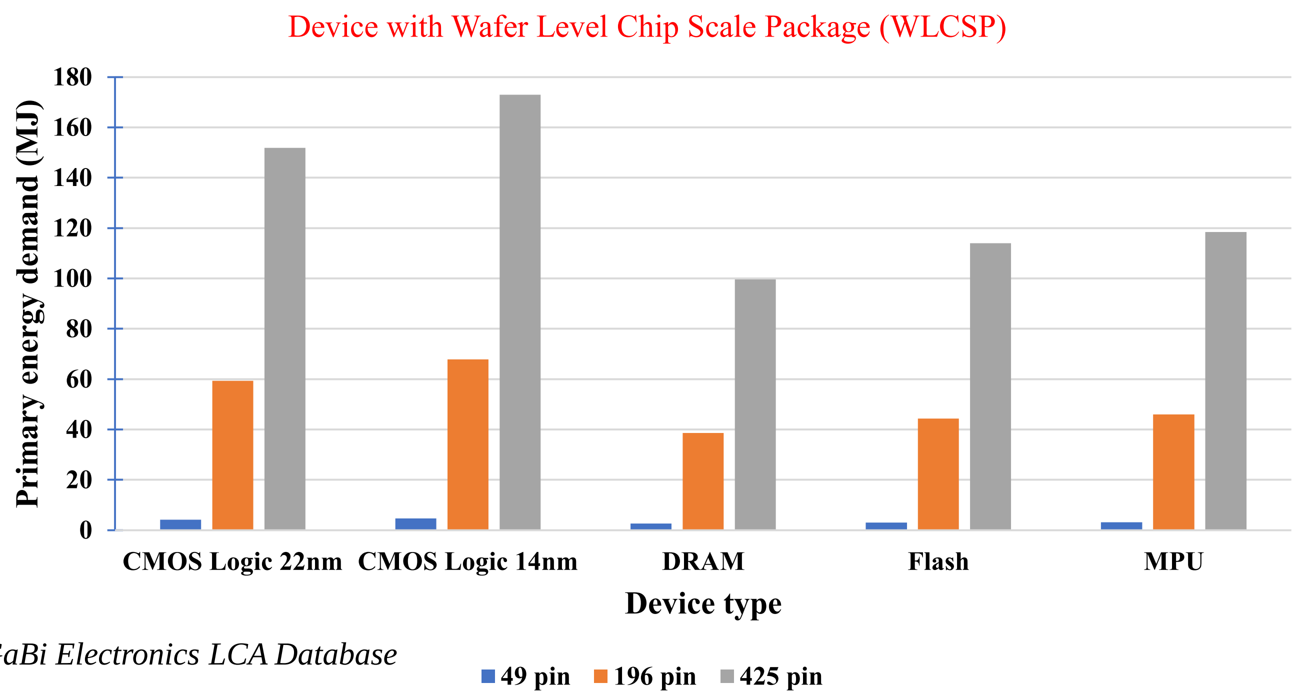
- Equipment followed by consumables have the largest share of total manufacturing cost – a high level of \$7B-\$10B capital investment necessary for ~10K annual wafer capacity
- Lithography materials has the largest share of consumables and gases and reticles each have similar high shares -- Ta, Ti, Hf, Ru, and W are a few of the expensive strategic materials used – *impacts on materials supply chain and embodied energy and emissions*
- Labor (mainly indirect labor) has a significant share and both energy and it will increase with the lower economies of scale from a growing integrated and custom chip design trend

Semiconductor Manufacturing Energy



- Support eqpt. (subfab) consumes more than 50% of total semiconductor manufacturing energy
  - Inclusion of only direct processing energy by manufacturing eqpt. underestimates manufacturing energy use
  - Embodied energy of other major indirect inputs (i.e., exhaust, chilled water, UPW, N2, CDA, and other) are important with a consideration of at least various types of total onsite energy
  - Average electricity used for wafer water use alone: ~ 8 kWh/wafer or ~ 0.05 kWh/chip (assuming 148 chips of 400 mm^2 per 8” wafer) – 0.15 MJ/chip for wafer onsite electricity

Manufacturing Energy Sensitivity – Device Type



Source: 2015 GaBi Electronics LCA Database

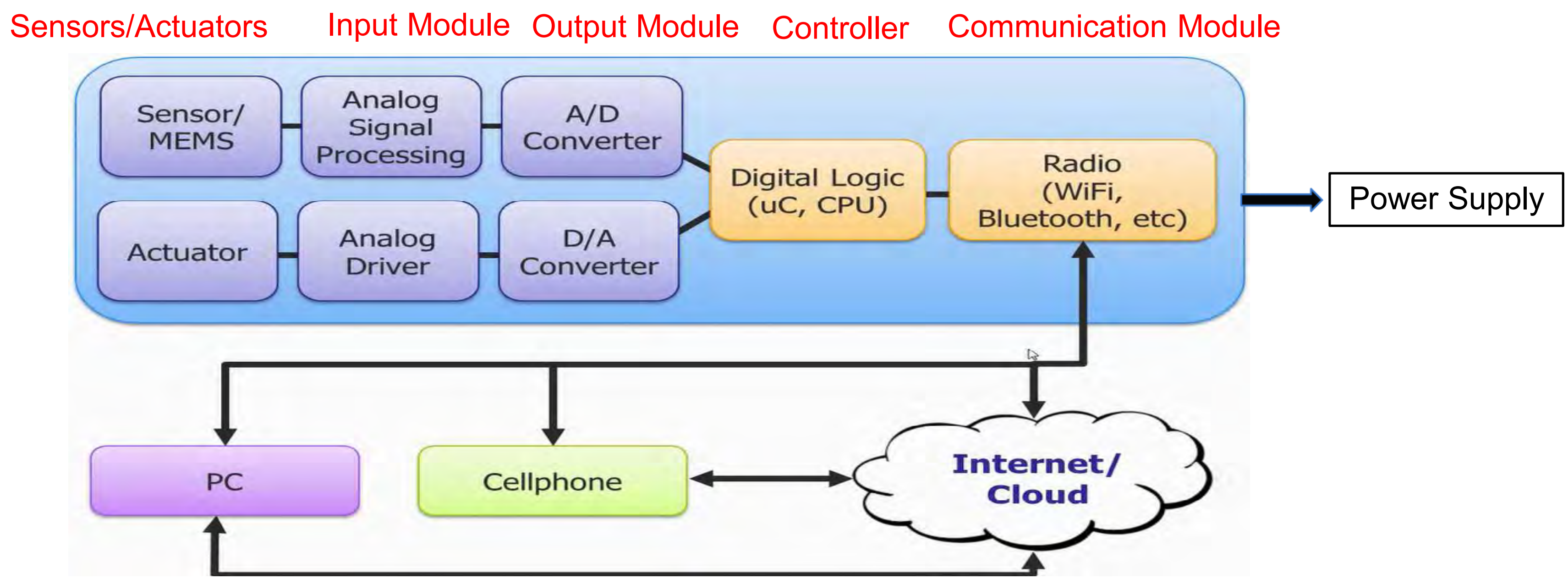
- Energy demand varies with Device Type: CMOS Logic with newer technology node is the most energy-intensive.
- With an increasing trend of pin density and lower chip technology node, chip primary manufacturing energy demand is projected to increase – 2018 IRDS IRDS Roadmap projects logic chip node decreasing from 10 nm in 2017 to 1 nm by 2033

OAK RIDGE National Laboratory

Global Energy Footprint Analysis of IoT Semiconductors -- Approach

- Limited global energy footprint analyses considered to date have been based on final electronic product level
- Focus on various semiconductor chip types in IoT devices within a user facility for various end-use markets during the 2016-2025 period
  - Allows consideration of technology trends by chip types (semiconductor focus w/o consideration of various discrete semiconductor device types with minimal energy impacts)
- Limited to Manufacturing and Operational energy for the Global IoT semiconductor market
- Limited to a representative specific type by three major semiconductor IC types (Sensor, Connectivity, and Processor)
  - Based on worldwide IoT semiconductor market forecasts for 2016-2025 (e.g., IHSMarkit) – avoids the market data of a range of electronic products
  - Primary manufacturing energy estimates from a limited available IC electronic databases (e.g., 2015 GaBi) and published literature
  - Operational energy based on active and passive power from published company technical literature for commercially available chips today
  - Energy use rate per chip estimated for each three major semiconductor IC types was based on the most widely used technology today and long-term technology with a limited use today for the years 2016 and 2025, respectively

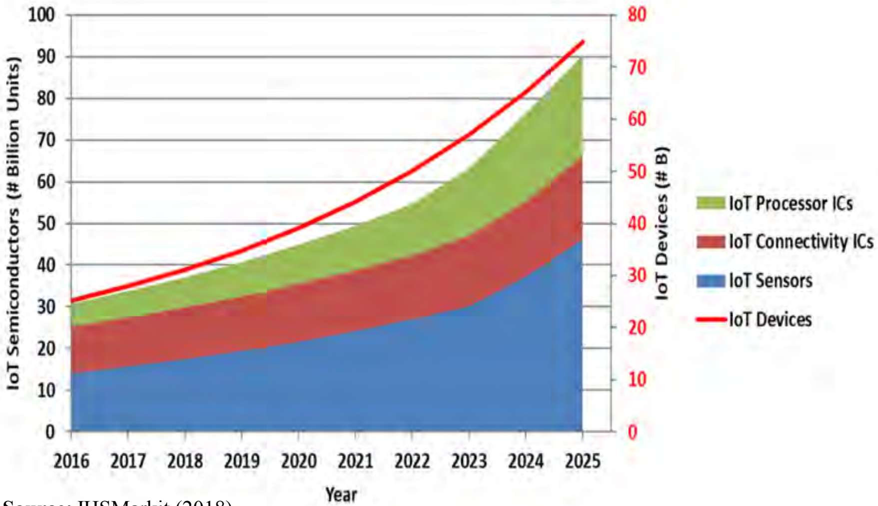
IoT Device – User-End ICT



- Internet-of-Things – ICT electronic device infrastructure enabling advanced information communication services by interconnecting physical and virtual things
- Sensor and actuator interface to the Internet
- Sensor Signal
  - Controlled by an analog driver through a Digital/Analog converter
  - Sent to an analog processing device in the form of an amplifier or a low-pass filter
- Actuator Signal
  - Output signal is digitized by Analog/Digital converter and sent to a digital block/controller containing a or a microprocessor
- Sensor telemetry is sent and control signals are received by a radio/communication module using standard protocols such as WiFi, Bluetooth, or Zigbee, or a custom protocol
- Radio transmits data to the Cloud or through a smartphone or PC. Software platforms and the cloud store and analyze the data for valuable insights

Source: Miller, J. (2018). Addressing the Challenges of IoT Design, Mentor, A Siemens Business

Worldwide IoT Semiconductor Market



Source: IHSMarkit (2018)

IoT Sensors: Pressure/Flow, Environmental/Health, Presence/Motion, Inertial/Vibration, Imaging and Others

IoT Connectivity ICs: Memory, Logic, ASICs, and ASSPs (Wired, WPAN, Wmesh, WLAN, and WWAN)

IoT Processor ICs: MPU, MCU, Application Processors, and Configurable Processors (i.e., ASICs and ASSPs)

- Global IoT semiconductor market growth follows the similar trend in total number of IoT devices (# IoT devices increase from 25B ('16) to 75B ('25) vs. # IoT semiconductors from 31B ('16) to 91B ('25))
- Semiconductor chip usage trend in an IoT device (# of semiconductors/IoT device) will decrease from 4.3 ('18) to 3.1 ('25) – as multi-functional chip integration trend continues
- Among three major semiconductor types, no. of IoT sensors will be nearly equal to other two semiconductor types combined

IC Type	Manufacturing Energy	Operational/Use Energy
Sensor	Flash Memory (GaBi)	Solid State Sensor & Wireless Sensor -- MCU + Flash Memory (Literature)
Connectivity	CMOS Logic/DRAM (GaBi)	Wireless Protocol
Processor	MPU (GaBi)	MCU (Literature)

Energy Footprint Analysis Scope

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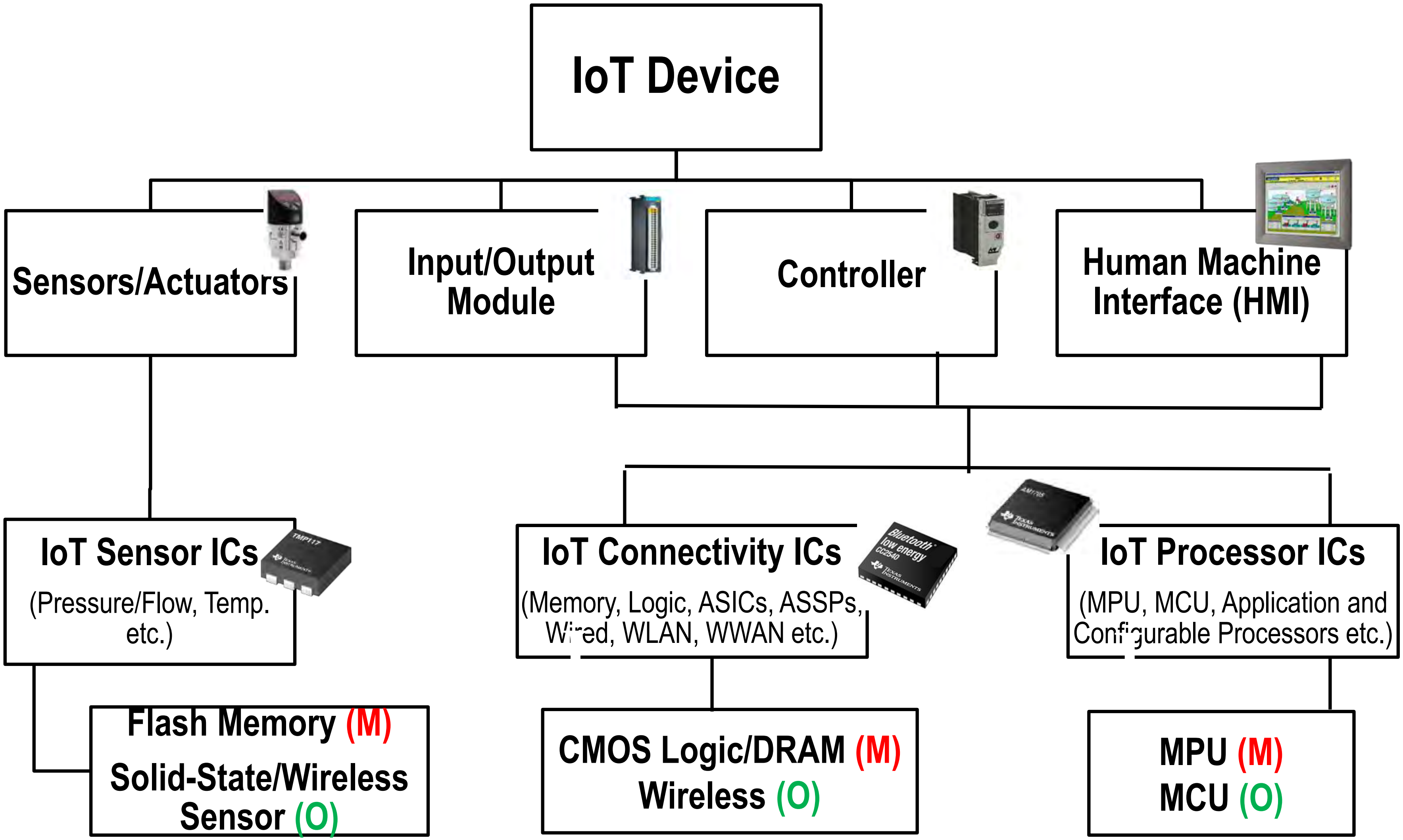
IoT Semiconductors



(M) Manufacturing Energy Use
(O) Operationa/Use Energy Use

IoT Semiconductor Energy Use Trend

Manufacturing	Operational

Manufacturing

Sensor IC

- Flash memory chip energy use is assumed to increase annually 0.75 MJ/chip with an increasing pin density and advanced WLCSP packaging use

Connectivity IC

- MPU 130 nm chip energy use is assumed to increase annually 0.20 MJ/chip with an increasing pin count from 50 (‘16) to 196 (‘25)

Processor IC

- MPU 130 nm chip energy use is assumed to increase annually 0.20 MJ/chip with an increasing pin count from 50 (‘16) to 196 (‘25)

Operational

Sensor IC

- A shift from solid state sensors towards wireless sensors (ultra low-power MCU with a non-volatile memory) will reduce annual energy use by - 0.67 MJ/chip

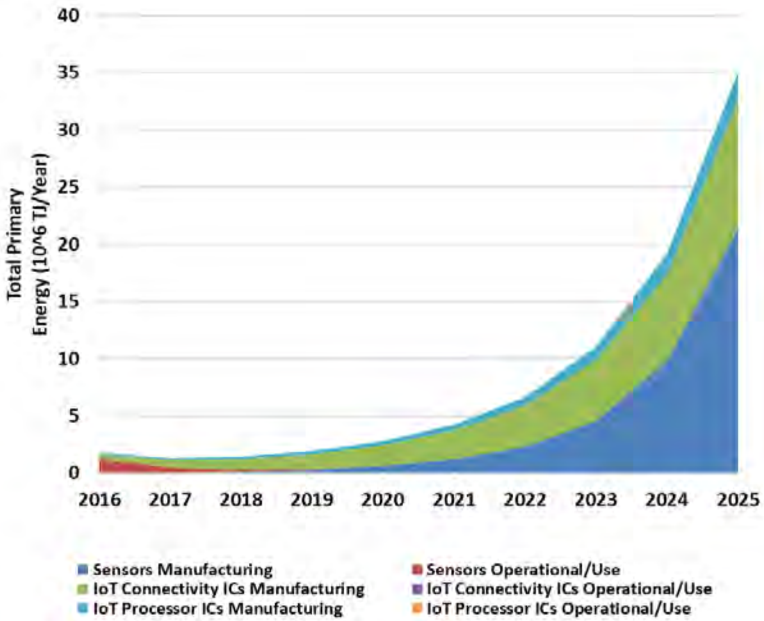
Connectivity IC

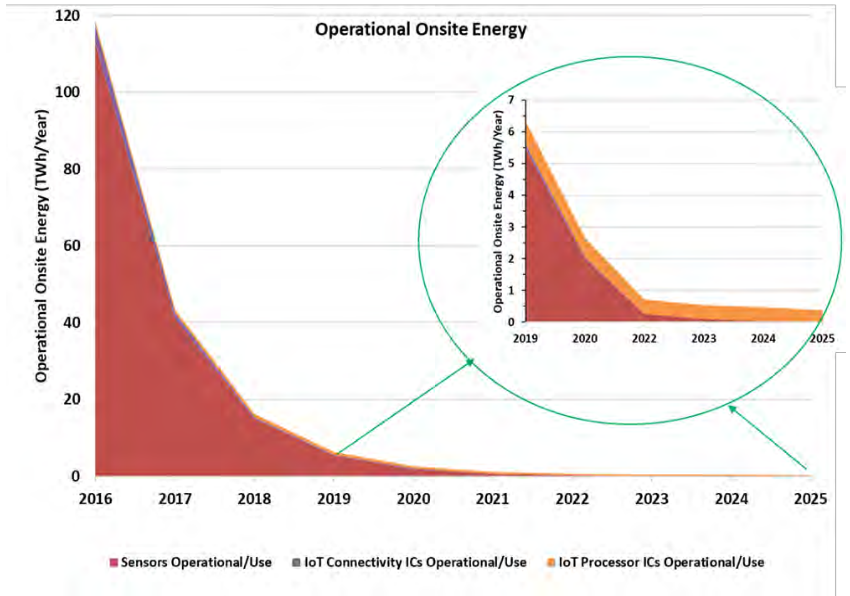
- A historical declining microcontroller annual energy use trend of - 0.26 MJ/chip is assumed to continue during the 2016-2025 period

Procesor IC

- A historical declining microcontroller annual energy use trend of - 0.26 MJ/chip is assumed to continue during the 2016-2025 period

Global Energy Footprint of IoT Semiconductors





- Global annual energy footprint of IoT semiconductors has an increasing trend due to a larger share and growing semiconductor manufacturing energy trend – 2 EJ/y (‘16) → 35 EJ/y (‘25)
- Operational energy has a significantly small share of total energy and a decreasing trend with an advent of low power and energy-efficient IoT semiconductor devices – 118 TWh/y (‘16) → ~ 1 TWh/y (‘25)
- Sensors semiconductors has the largest energy share for both energy categories among three major IoT ICs types considered (largest projected sensor ICs volume)
- Energy distribution may only vary but not total depending on what specific IC semiconductor type considered under each including the potential chip integration opportunity
- Global energy estimates are conservative as limited to only semiconductors and not actual IoT devices