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Hades: A Hardware-Resident Substrate for Energy Admission in Intermittent Computing

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The hidden cost of **tiny sensors**

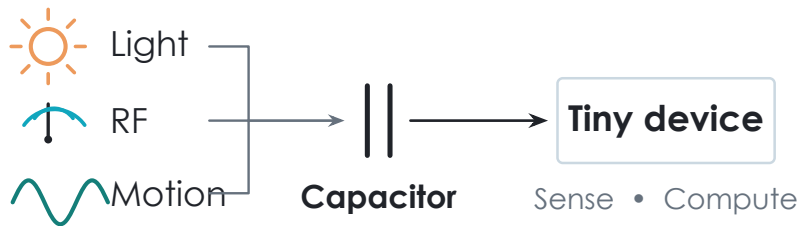
IoT scales. So does battery maintenance.



Battery replacements add maintenance, e-waste, and **carbon footprint** at IoT scale.

What if sensors **harvested energy**?

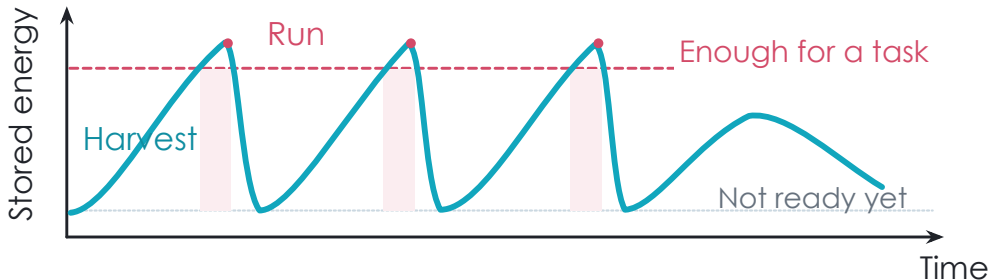
Light, radio waves, and motion can power tiny devices.



The catch: energy arrives in **unpredictable bursts**.

Energy arrives. Tasks wait.

A capacitor charges. A task runs. Then it waits.



Who decides when the next task can safely start?

Related work: different goals

Prior work improves different parts of batteryless operation.

Software-mediated admission

Mementos • Dewdrop
Runtime and scheduling

Hardware-assisted admission

Failure Sentinels • CapDYN
Monitoring and buffering

Post-admission execution

Clank • ReplayCache
Persistence and recovery

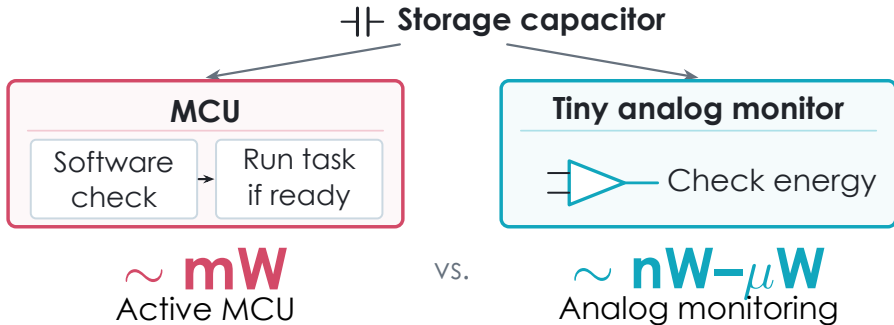
Pre-admission energy intake

AmbiMax • InfiniteEn • MPPT
Harvesting and buffering

Let us zoom in on task admission.

The processor is **power-hungry**

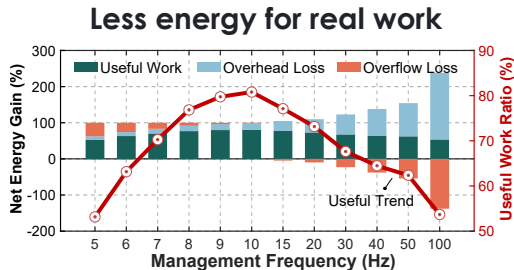
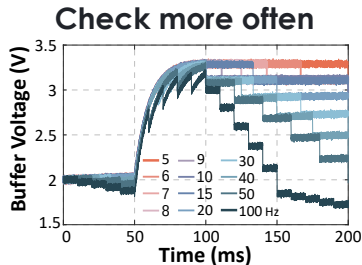
A microcontroller unit (MCU) must be active to run software energy checks.



Why activate an **mW-class MCU** just to check energy?

Checking energy costs energy

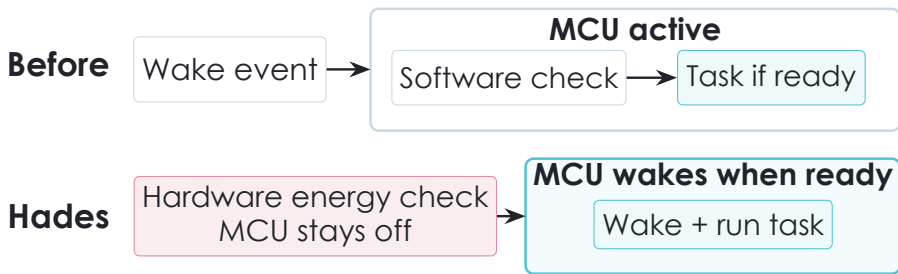
Frequent MCU-side checks improve responsiveness, but consume scarce energy.



More checking means less energy left for useful tasks.

What if the MCU **stayed asleep**?

A tiny circuit can check energy while the MCU is off, then wake it to run a task.

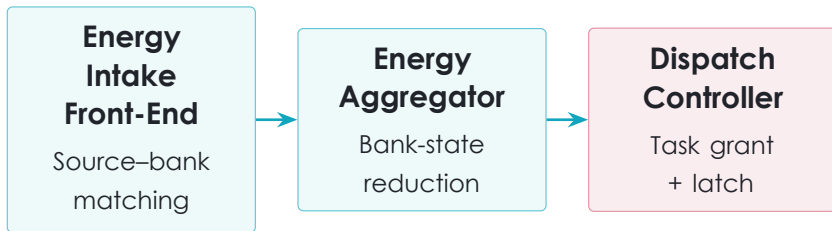


Wake the MCU only for useful work.

Meet Hades: **harvest more, spend less**

Hades brings more energy into storage and admits tasks while the MCU stays off.

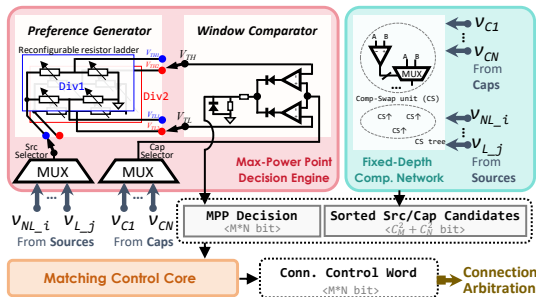
Always-on mixed-signal substrate



More energy in. **Less MCU energy spent on management.**

Near-MPPT, **without costly tracking**

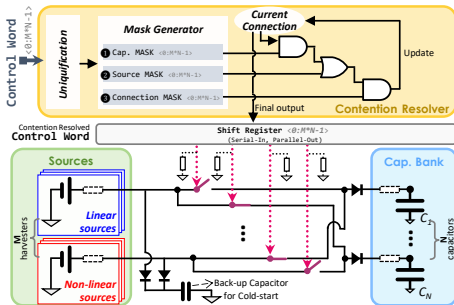
Digital MPPT repeatedly senses and retunes the load.
At μW inputs, the control loop can cost too much.



Insight: Each source has a **productive voltage window**.
Analog comparisons match it to an existing bank voltage.

Compare voltages. Connect safely.

Analog windows identify feasible pairs; arbitration selects a valid connection.



1. Compare

Check voltage windows

2. Resolve

Avoid source-bank conflicts

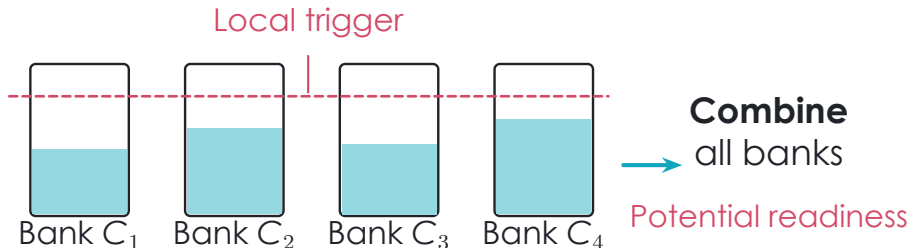
3. Commit

Update the switch paths

No continuous ADC-driven load search at runtime.

One bank looks low. **Together, enough.**

A local voltage trigger can miss energy spread across several banks.



Insight: use the combined reserve, not a single bank voltage.

Let the circuit **compute energy**

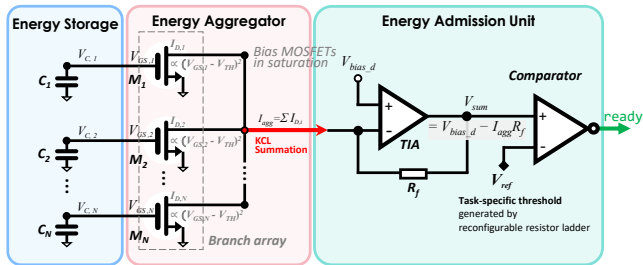
Many banks. One admission decision.

Multiple ADCs **High power**

Comparator ladders **Coarse**

Parallel sampling + digital summation

Quantized bank-state estimates



OUR INSIGHT

MOS saturation
Square-law $V \rightarrow I$

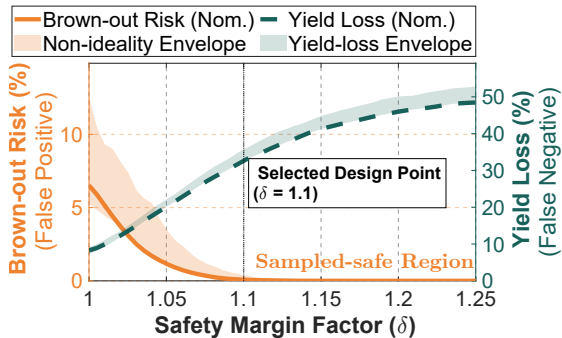
Bank weighting
 $K_i \propto C_i$

KCL summation
Parallel current sum

$$I_{agg} = \sum_i I_{D,i} \longrightarrow V_{sum} \xrightarrow{V_{ref,t}} \text{ready}$$

A fast comparison needs a safe threshold

The analog sum is a proxy for usable energy. Task profiling and calibration turn it into a conservative start decision.



At the edge

Profile each bounded task

On the device

Load its calibrated $V_{\text{ref},t}$

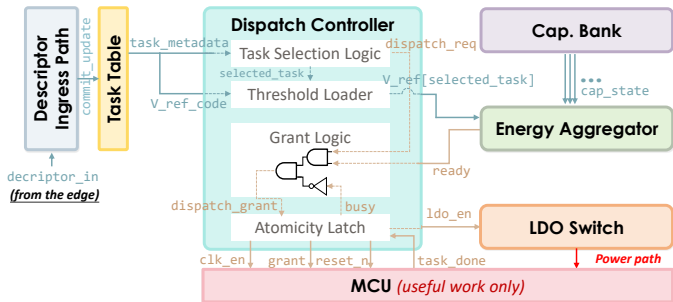
Margin $\delta = 1.1$

0.38%

stressed false positives (95th percentile)

Different tasks, different energy needs

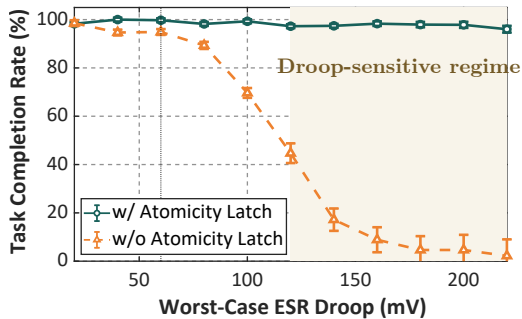
A task's energy demand is profiled ahead of time and stored as a threshold; dispatch needs no MCU-side calculation.



Select task $\longrightarrow$ load $V_{ref,t}$ $\longrightarrow$ grant $\longrightarrow$
release MCU

Once it starts, **keep the window open**

MCU execution drains the capacitor, so a live voltage comparator may change state before the task finishes.



Latch the grant

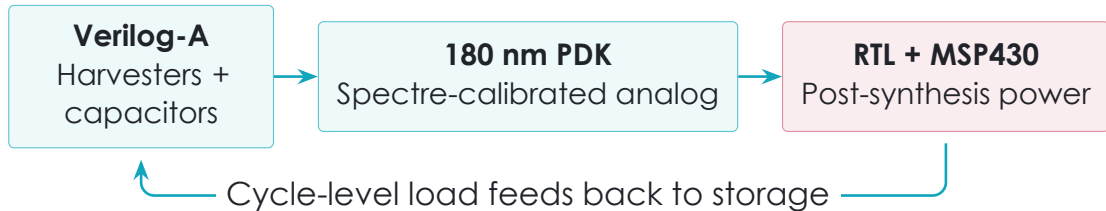
Ignore expected
voltage droop

Block
overlapping
dispatch

Close on task

How we **evaluate** Hades

We model the harvested energy, hardware circuits, and MCU activity together.



12 embedded workloads

AES, FFT, SHA, etc.

4 energy sources

Solar, RF, thermal, motion

180 nm PDK
PDK-calibrated models

Always on, with **little overhead**

The admission circuit stays awake so the expensive MCU does not have to.

0.29%

evaluated SoC
area

542 nW

always-on power

13.13 pJ

dynamic energy /
decision

1.05 μ s

decision response

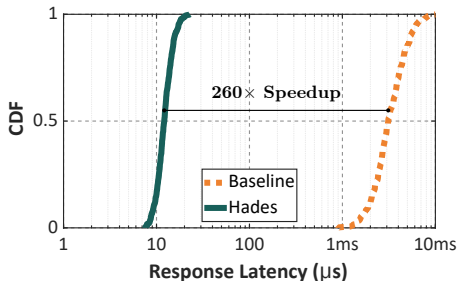
Software: **2.51 μ J** per attempt $\rightarrow$ **>98% lower
modeled admission energy**

Post-synthesis digital estimates + transistor-calibrated analog modeling;
comparison is not measured silicon power.

Act fast on **weak energy**

React faster and operate at lower input power.

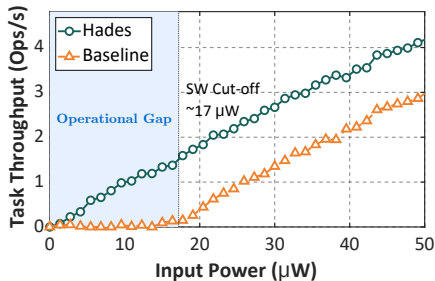
Burst-to-execution latency



12 μs vs. **3.2 ms**

Median $\approx 260\times$ faster

Minimum viable input power

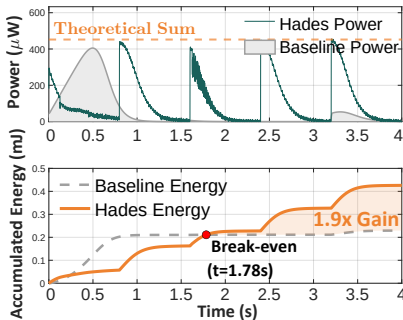


~2 μW vs. **~17 μW**

Under evaluated workload/trace settings

Better matching. More energy stored.

When a source sees a better load, more of its energy reaches storage.

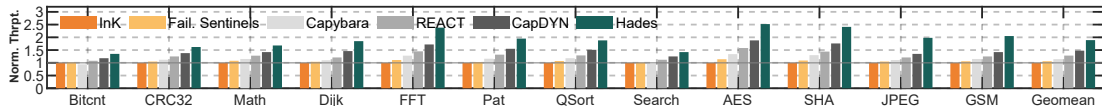


1.9x
energy
delivered to
storage

Solar + RF matching
experiment, 4-second
trace

More work gets **done**

Across 12 workloads, Hades completes more tasks in the same time.



2.2×

geometric-mean vs. InK

1.35×

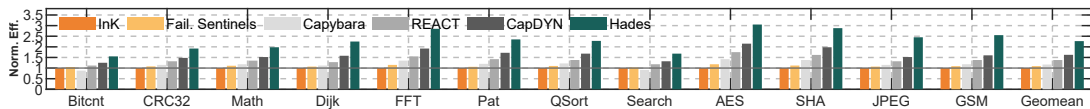
geometric-mean vs.
CapDYN

2.5×

up to vs. InK

More tasks from **every joule**

With less management overhead, more harvested energy becomes useful work.



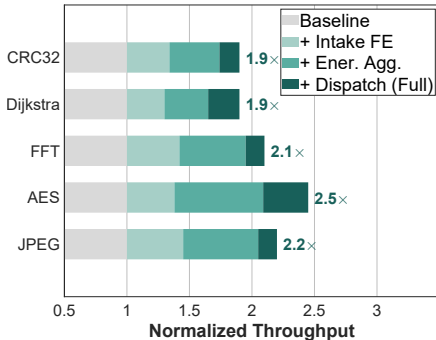
2.4×
geometric-mean
tasks/J over InK

Why it helps

Collect more
Check less
Dispatch wisely

Why **all three blocks** matter

Each block adds value. Together, the gains build up.



Front-End

1.38x

+ Aggregator

1.9x

+ Dispatch

up to 2.45x

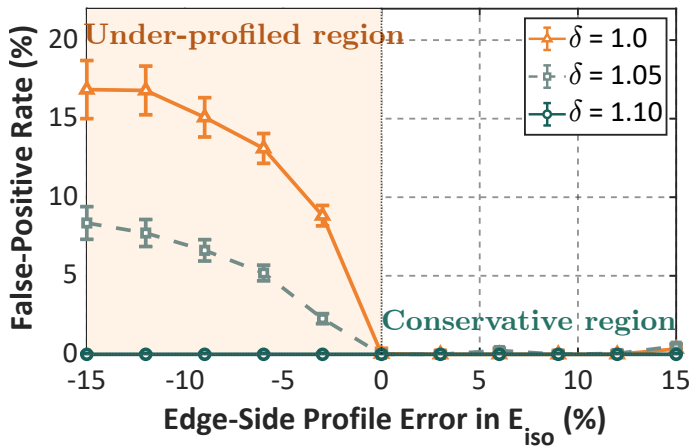
Takeaway

Hades keeps admission in hardware and wakes the MCU for admitted tasks.

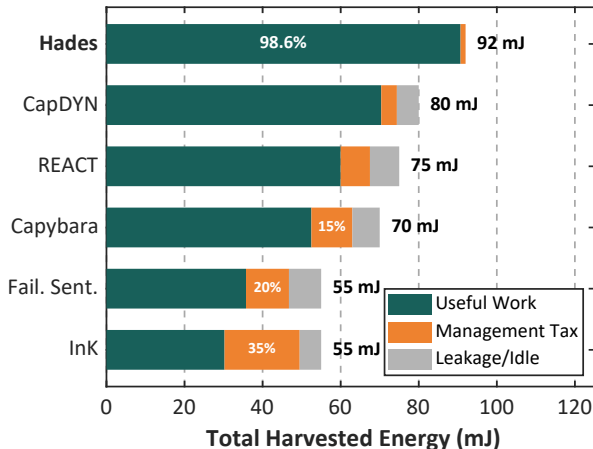
- **Energy Intake:** match sources to storage
- **Energy Aggregator:** check the combined reserve
- **Dispatch Controller:** release the right task

Let hardware decide. Let the MCU work.

Backup: threshold sensitivity to profile uncertainty



Backup: the modeled energy budget breakdown



Backup: storage topology sensitivity

