

Capacity over Capacitance: Exploiting Batteries for a More Reliable Internet of Things

Neal Jackson, Joshua Adkins, and Prabal Dutta

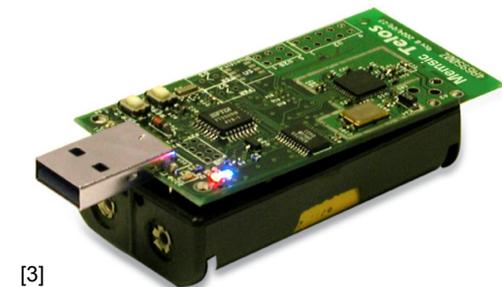
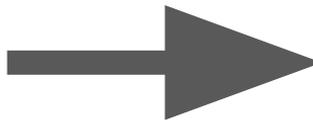


The tragedy of scale and limited lifetimes



[2]

After a few months or years



[4]

Battery-only sensors

[1] Andersen et al. Hamilton-A Cost-Effective, Low Power Networked Sensor for Indoor Environment Monitoring.

[2] Adkins et al. Michigan's IoT Toolkit.

[3] Polastre et al. Telos:enabling ultra-low power wireless research.

[4] Mainwaring et al. Wireless sensor networks for habitat monitoring.

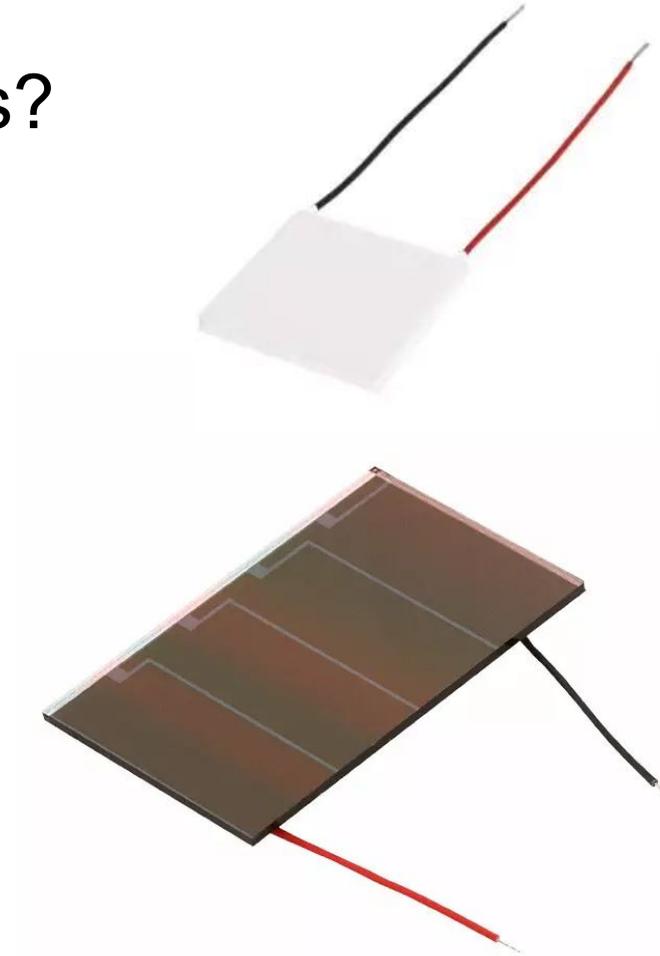
How do we achieve longer lifetimes?

Bigger batteries?

- Lifetime is still strictly finite
- Larger = more obtrusive

Harvest energy?

- Relatively compact
- Solar/indoor light = plenty of energy
- Thermal or kinetic energy harvesters



Sensor power supplies circa 2010

Rechargeable batteries that existed were:

- Expensive
- Inefficient
- Bulky
- Short-lived (limited charge cycles)

Non-rechargeable batteries are bulky and die eventually

Harvested energy is enough to subsist on!

Solution: **get rid of batteries all together**



[5]

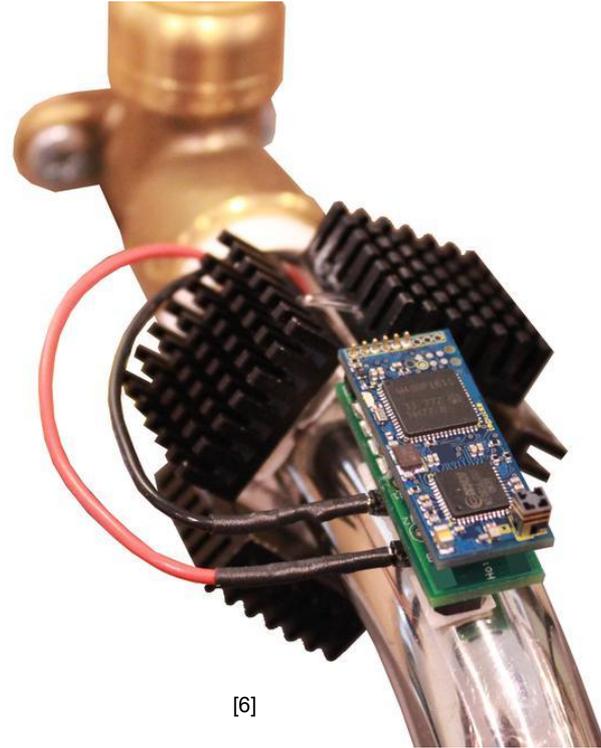
Perpetual sensing is the holy grail

Culmination of

- Diminishing system power
- Aggressive startup

Harvested energy can be buffered in capacitors

- Capacitors have a theoretically infinite lifetime
- If there's energy, sensor operates **“indefinitely”**

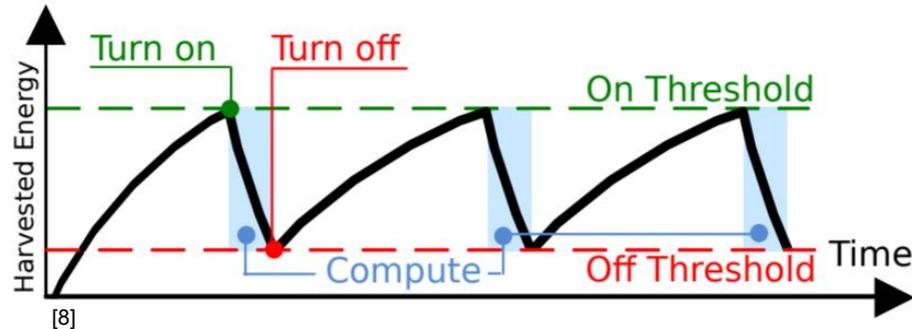


[6]

There's a catch!

Unreliable harvested energy means unreliable operation

- Capacitors can only store enough energy for short tasks
- If the storage is not tuned to the task, it could get stuck in sisyphian loop of startup, compute, turn off.



- In periods of energy drought (like nighttime), the sensor is off

Avoiding a sisyphean loop is a hard problem

Many years have gone toward making intermittent computing more manageable

Programming language primitives enable progress latching [8, 9]

- Checkpointing upon imminent power off
- Manually demarcating atomic tasks

Debugging tools allow intermittent device testing by carefully controlling energy state [10]

Hardware solutions that better partition or tune energy storage for specific tasks [11]

These fixes don't fix everything!

[8] Lucia et al. Intermittent Computing: Challenges and Opportunities

[9] Hester et al. Timely Execution on Intermittently Powered Batteryless Sensors.

[10] Colin et al. An energy interference-free hardware-software debugger for intermittent energy-harvesting systems.

[11] Colin et al. A Reconfigurable Energy Storage Architecture for Energy-harvesting Devices.

Intermittency will always be unreliable

Forget detecting burglars with
intermittent motion sensors at night!

Sensor failure or lack of energy?



Long running computations are infeasible

Progress latching might ensure forward progress, but some tasks are going to take forever while waiting for energy

- Security/firmware updates
- Public key cryptography
- Machine learning tasks

Intermittent band-aids ignore the better solution

Add more energy storage!

How do we explore the effects of more storage?

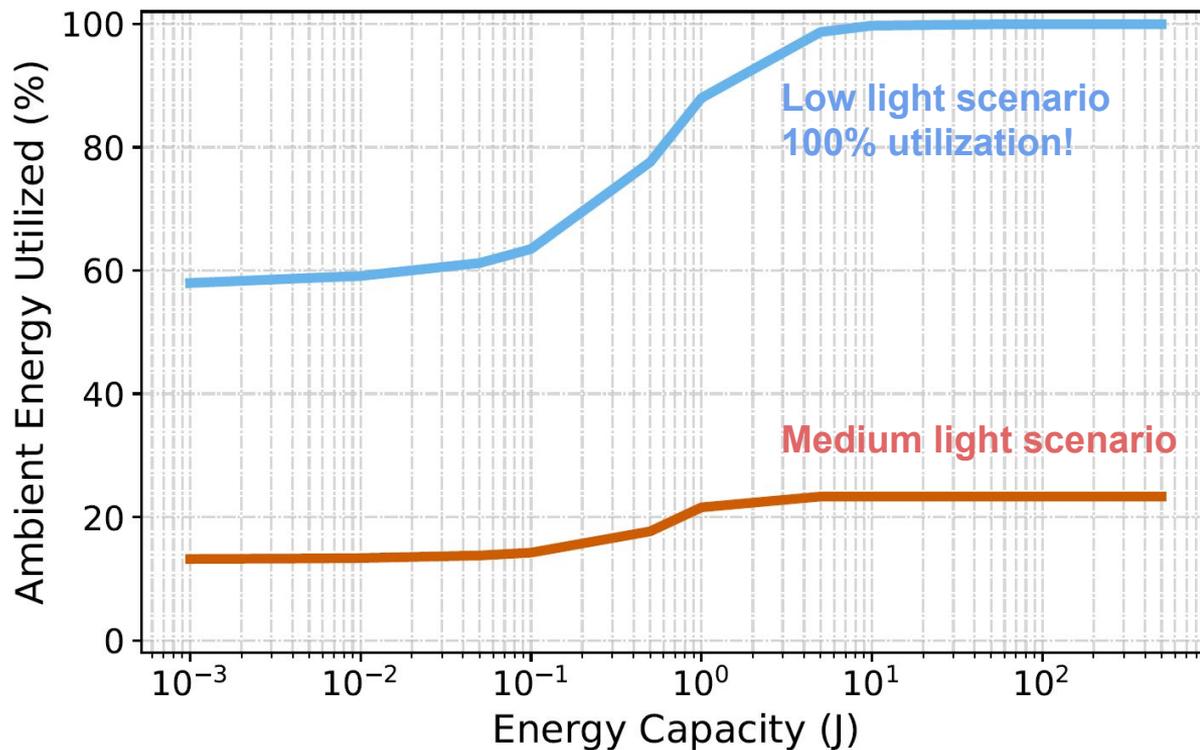
A numerical model that uses

- Real light irradiance traces from the EnHANTs dataset [12]
 - Low, Medium, and High intensity traces are used
- Workloads based on common sensor applications
 - Periodic sense and send
 - Occasional long running events
- Power profiles based on actual hardware

And produces estimates on lifetime, reliability, and energy utilization

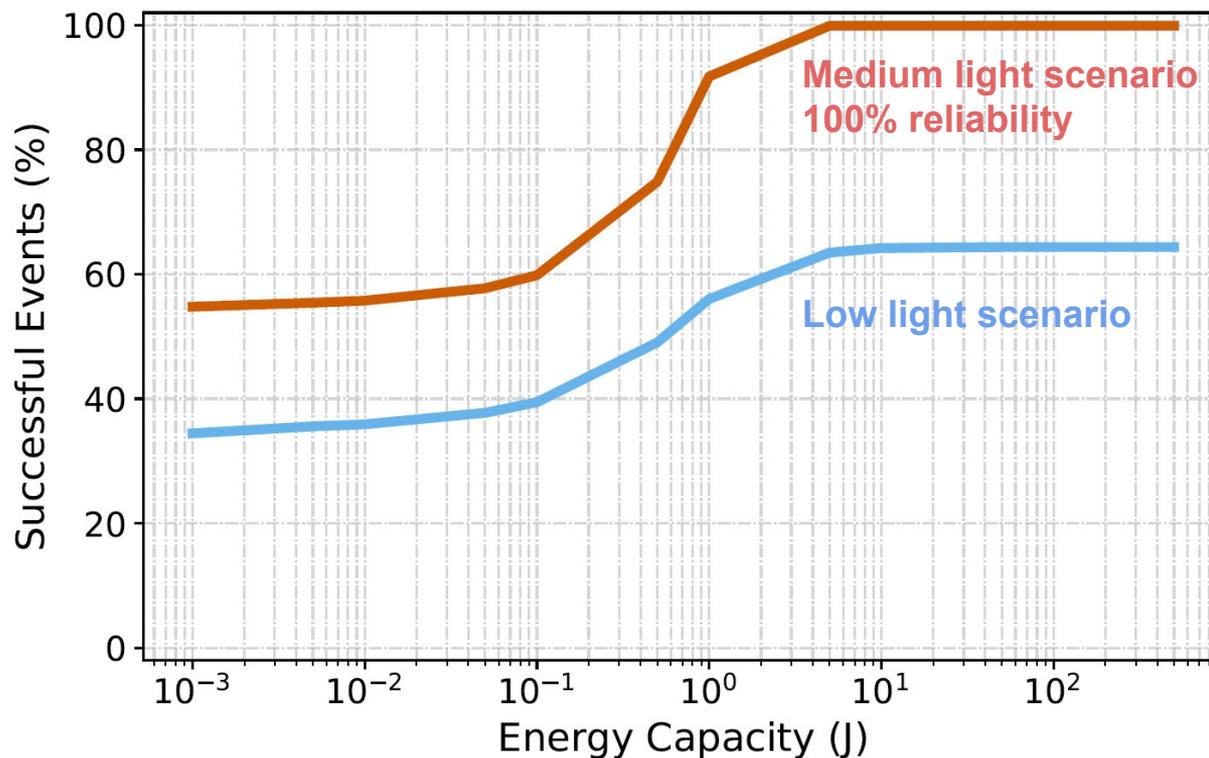
More storage = more energy utilized

Sense and send
every 30 seconds



More energy utilized = more reliable

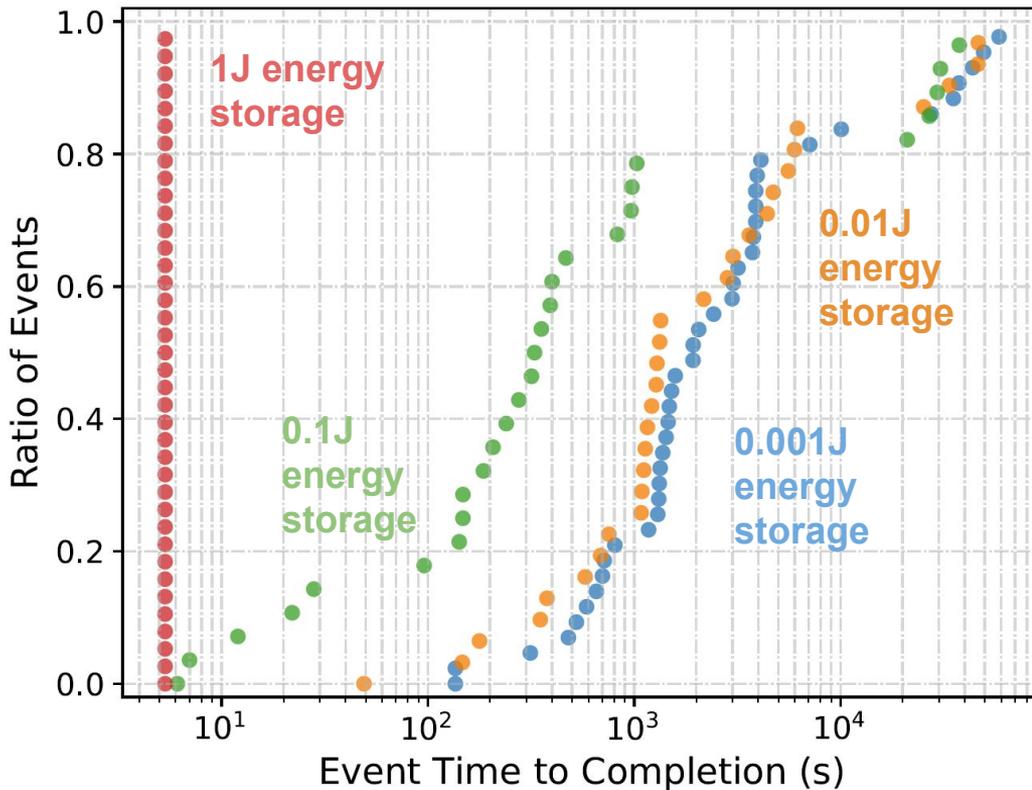
Sense and send
every 30 seconds



Long running computations are now feasible

CDF of time to completion
for 5 second OTA update
Medium light scenario

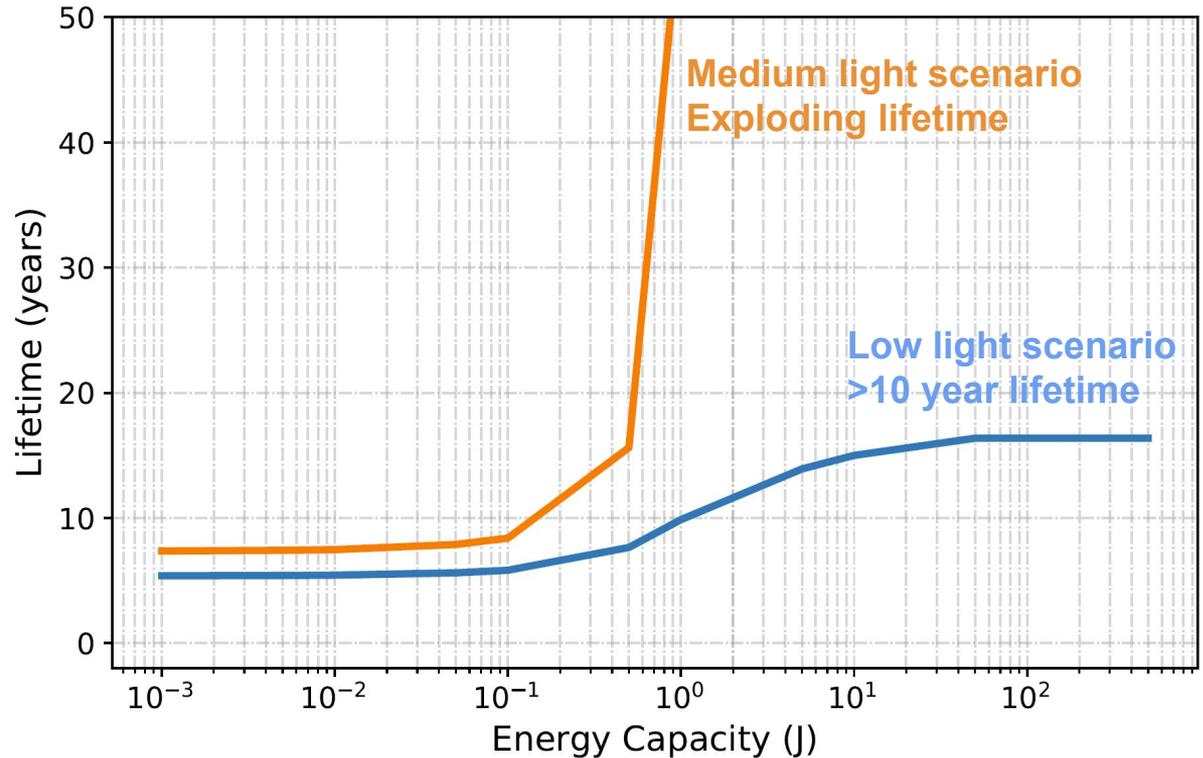
With small storage it takes
3 to 30 hours!



Backup storage ensures a minimum reliable lifetime

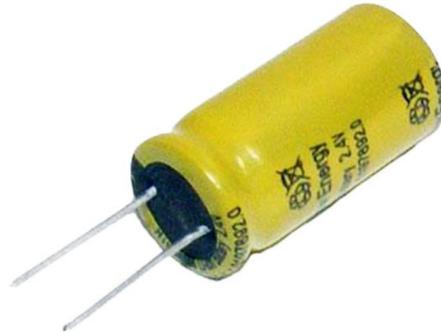
Sense and send every
30 seconds

Coin cell sized backup



Where do we get higher capacity energy storage?

Come full circle back to batteries



Why are energy harvesting sensors not using batteries?

A multitude of arguments that batteries are bad include:

Expensive, short-lived, temperature-sensitive, less efficient, bulky, and dangerous

A lot of these arguments are outdated, or just incorrect assumptions

Batteries are (not) expensive



Tantalum + ceramic capacitors used in Yerva et al. [7]

\$1.85



Tantalum + ceramic + supercapacitors used in Colin et al. [6]

\$5.78



20mAh rechargeable battery + CR2032 non-rechargeable battery

\$6.95

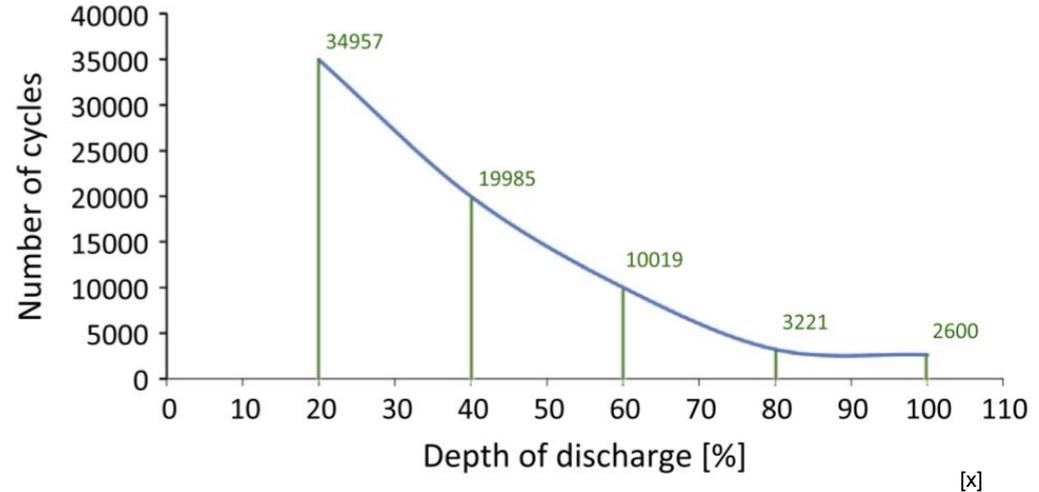
This doesn't take into account the greater capacity and benefits afforded by batteries!

Batteries are (not) short-lived

New technologies and methods

- **LTO** and **LiFePo4** batteries withstand **4-10x** more cycles than other batteries
- Limiting depth of discharge **exponentially** increases cycle lifetime

Supercapacitors also face lifetime limits, mainly rated in total operational hours



Batteries are temperature sensitive

But so are supercapacitors!

Most IoT applications in environments occupied and used by people

Indoors, not the cold of space

Extreme environments will require further design consideration

Kicksat



Batteries are (not) less efficient

Low efficiency is primarily caused by a high **equivalent series resistance (ESR)**

- Losses happen during high current events
- During an 8mA radio transmission, we can expect
 - **0.06%** resistive loss when using ceramic/tantalum capacitors
 - **6.6%** loss when using a supercapacitor
 - **2.1%** loss when using an LTO battery
- Small losses due to self discharge 30-500nA for an lithium-based battery

Batteries are (not) bulky

Batteries are

50-500x more dense than ceramic/tantalum capacitors and

3-5x more dense than supercapacitors

Batteries come in very small packages

Rechargeable
20 mAh



Non-rechargeable
240 mAh



Rechargeable
1.8 mAh



Batteries are (not that) dangerous

Old technology like lithium cobalt and lithium ion are prone to fires and the release of toxic gas upon abuse

Newer technologies like **LTO** and **LiFePo₄** exhibit less thermal runaway and toxic gas release under stress [15, 16]

The FAA suggests a typical failure rate (on airplanes) to be 1:1,000,000,000 [17]

[15] Belharouak et al. Electrochemistry and safety of Li₄Ti₅O₁₂ and graphite anodes paired with LiMn₂O₄ for hybrid electric vehicle Li-ion battery applications

[16] Larsson et al. Abuse by External Heating, Overcharge and Short Circuiting of Commercial Lithium-Ion Battery Cells

[17] Mikolajczak et al. Lithium-ion batteries hazard and use assessment

Battery-based sensors are the actual holy grail

With batteries we can build sensors that last decades and can still do software updates and cryptography

Battery-based sensors are the actual holy grail

With reliability, sensors begin to more closely resemble actual computers

Permamote

An implementation informed by these findings

Hierarchical power supply

Built from lowest power components currently available

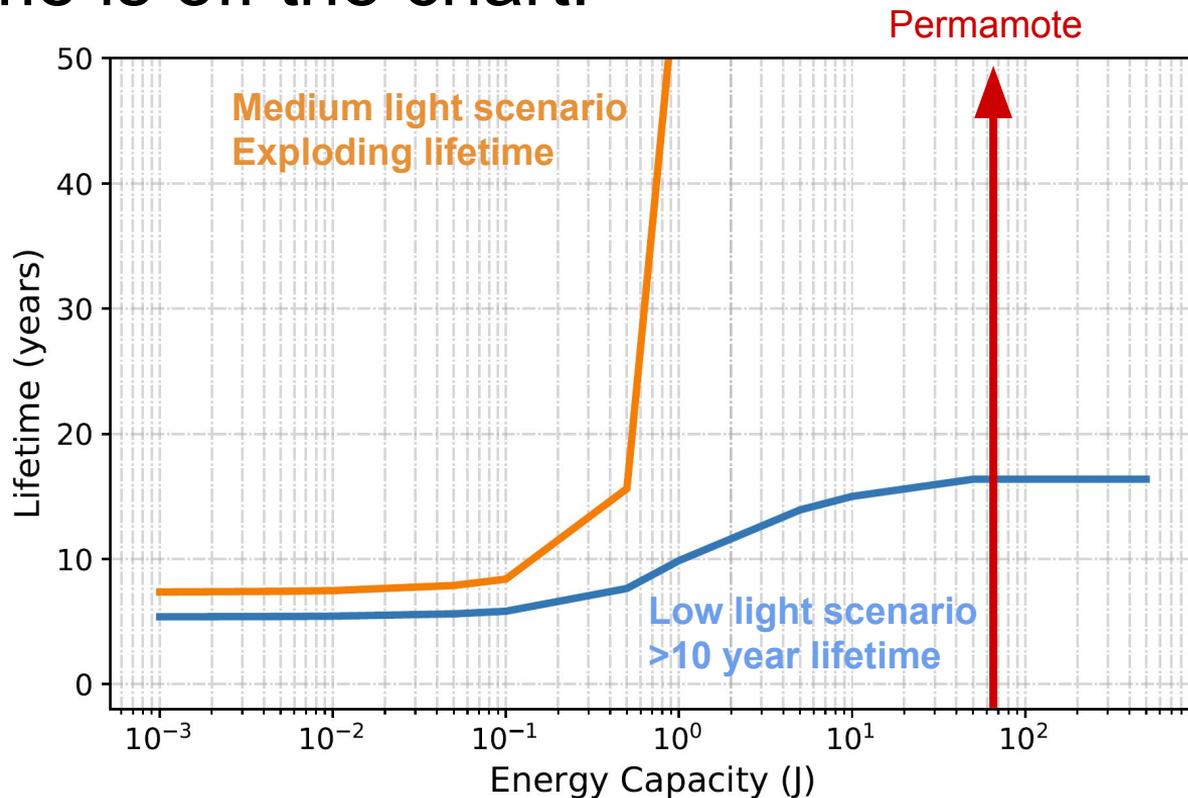
A sensing platform with an integrated processor and BLE/802.15.4(Thread) radio and a variety of environmental, lighting, and occupancy sensors



Permamote lifetime is off the chart!

Sense and send every
30 seconds

1 coin cell backup
battery



Permamote

Permamote's power supply will serve as the base for future sensors and applications

- Plant watering detection
- Distributed lighting control with glare detection

Use it to explore autonomous sensor localization

- Absolute localization
- Semantic localization



Conclusions

More rechargeable capacity gives us:

- More energy utilization
- More lifetime
- More reliability

Non-rechargeable batteries ensure a minimum fully reliable lifetime

We're building next generation devices that use these, enabling exploration in

- Ubiquitous and reliable sensing
- Security/Firmware patches and heavyweight cryptography
- Complex tasks previously thought infeasible

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References

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- [3] Polastre et al. Telos:enabling ultra-low power wireless research.
- [4] Mainwaring et al. Wireless sensor networks for habitat monitoring
- [5] Campbell et al. Energy-harvesting thermoelectric sensing for unobtrusive water and appliance metering.
- [6] Colin et al. A Reconfigurable Energy Storage Architecture for Energy-harvesting Devices.
- [7] Yerva et al. Grafting Energy-Harvesting Leaves onto the Sensornet Tree.
- [8] Lucia et al. Intermittent Computing: Challenges and Opportunities
- [9] Hester et al. Timely Execution on Intermittently Powered Batteryless Sensors.
- [10] Colin et al. An energy interference-free hardware-software debugger for intermittent energy-harvesting systems.
- [11] Colin et al. A Reconfigurable Energy Storage Architecture for Energy-harvesting Devices.
- [12] Gorlatova et al. Networking Ultra Low Power Energy Harvesting Devices: Measurements and Algorithms
- [13] Omar et al. Lithium iron phosphate based battery – Assessment of the aging parameters and development of cycle life model
- [14] <http://kicksat.github.io>. Retrieved on June 5, 2018
- [15] Belharouak et al. Electrochemistry and safety of Li₄Ti₅O₁₂ and graphite anodes paired with LiMn₂O₄ for hybrid electric vehicle Li-ion battery applications
- [16] Larsson et al. Abuse by External Heating, Overcharge and Short Circuiting of Commercial Lithium-Ion Battery Cells
- [17] Mikolajczak et al. Lithium-ion batteries hazard and use assessment

Technology	Capacity	Volume (mm ³)	Energy Density (Wh/L)	Temperature Range (Charge/Discharge °C)	ESR (Ω)	Self-Discharge (nA)	Cycle Life		Cost (USD)	
							100% DoD ^l	10% DoD ^l	US ^o	China ^o
MLCC	47 μF [54]	1.28 ^a	0.046 ^b	-55 - 125	0.001-0.1 ^g	<10 ⁱ	Inf. ^m	Inf. ^m	0.16	0.03
	100 μF [55]	9.2 ^a	0.013 ^b	-55 - 125	0.001-0.1 ^g	<10 ⁱ	Inf. ^m	Inf. ^m	0.31	0.04
Tantalum	100 μF [8]	9.2 ^a	0.013 ^b	-55 - 85	0.2	<10 ⁱ	Inf. ^m	Inf. ^m	0.28	0.17
	220 μF [8]	9.2 ^a	0.027 ^b	-55 - 85	0.07	<10 ⁱ	Inf. ^m	Inf. ^m	0.37	0.16
EDLC	7.5 mF [57]	7.2	0.83 ^c	-30 - 70 ^d	25	—	>10000	—	2.42	—
	100 mF [35]	1128	0.07 ^c	-25 - 70 ^d	100	<10 ^j	—	—	1.10	—
	470 mF [47]	940	0.62 ^b	-40 - 70 ^d	0.045	<1000	100000+/4 yr [46] ⁿ	— ⁿ	5.06	1.00
LiPo	37 mWh [23]	297	125	0 - 40/-20 - 60 ^e	— ^k	30-100 [68]	300-500	10000+ [25, 45]	—	0.80
	148 mWh [17]	660	224	0 - 40/-20 - 60 ^e	0.1	120-400 [68]	300	10000+ [25, 45]	4.50	0.51
	148 mWh [3]	1005 ^a	224	0 - 40/-20 - 60 ^e	3	120-400 [68]	500	10000+ [25, 45]	1.62	—
LTO	4.3 mWh [32]	87	49	-35 - 70 ^{ef}	8	— ^k	2000	10000+ [26]	—	1.01
	60 mWh [31, 32]	685	88	0 - 40/-20 - 60 ^{ef}	2.4	— ^k	2000	10000+ [26]	6.75	1.01
LiFePo ₄	96 mWh [60]	1020	94	0 - 40/-20 - 60 ^e	0.1	160 [62]	2000 [59]	30000+ [48, 56, 66]	—	0.95
Li-Primary	720 mWh [50]	1005 ^a	716	-30 - 60 ^e	N/A ^h	250	N/A	N/A	0.20	0.10
	4500 mWh [49]	7830 ^a	574	-40 - 70 ^e	N/A ^h	1400	N/A	N/A	0.90	0.75
Li-Thin Film	3.9 mWh [61]	119	32.7	-20 - 60 ^e	80	3.5	4000	—	18.24	—
	190 μWh [16]	58	3.2	-40 - 70 ^e	2200	0.2	300	5000	—	—

^a Standard packages in order of increasing volume: 0603, 1206, 2032, CR123A. ^b Assumed 3V for energy calculation. ^c Assumed 2.4 V, the max rated voltage, for energy calculation.

^d EDLCs experience higher ESR at lower temperatures and higher leakage at higher temperatures [46].

^e Lithium batteries experience higher ESR, higher leakage, lower capacity and shorter lifetimes at temperature extremes.

^f We believe these are produced by the same manufacturer, but have different suppliers and datasheets. We are skeptical of the wide temperature range.

^g ESR is frequency dependent. ^h ESR is conservatively calculated into rated capacity [22]. ⁱ Both tested and calculated from insulation resistance after absorption period.

^j Specification after 24 h of charging. ^k We assume value to be similar to other Li cells, but cannot verify this assumption.

^l Measured to 80% rated capacity. ^m We do not consider capacitor derating. With proper design principals these should be nearly infinite.

ⁿ EDLCs are time rather than cycle limited. Assumes 3V, 20 °C. No DoD dependence mentioned [46]. ^o Prices are based on cheapest available equivalent part in quantities of 100.