Powering the internet of things

Yogesh Ramadass

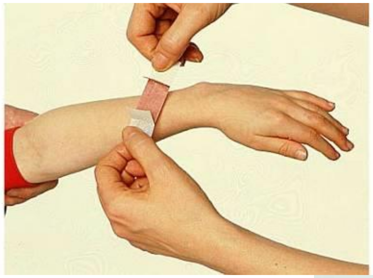
Texas Instruments

Trends in low-power electronics

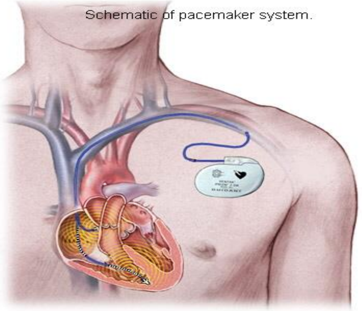
Increasing Energy Criticality

Portable Computers

Wearable Devices



Implantables



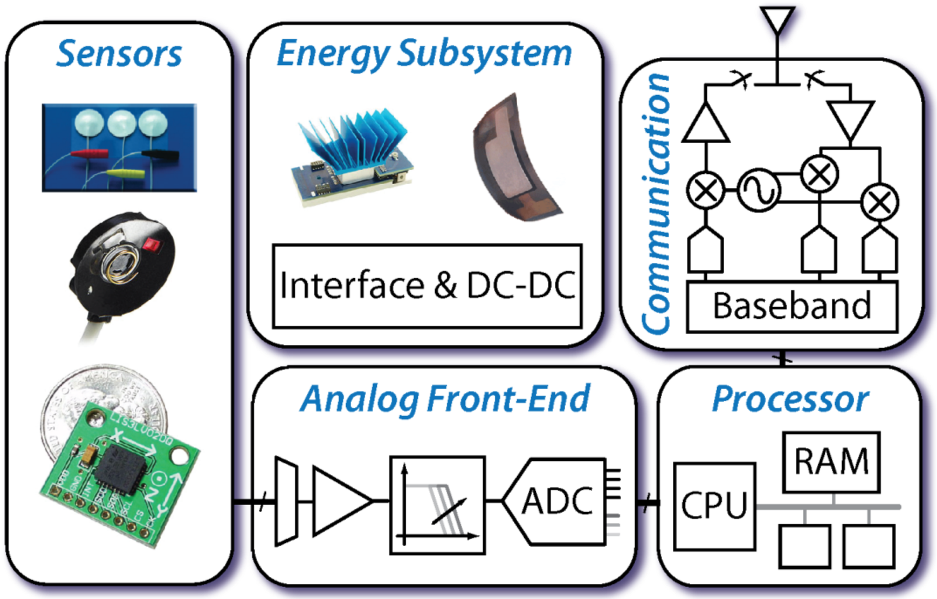
Handhelds

Sensor Networks

- Issues - Size, weight, operating lifetime
- Energy efficiency of IC's is crucial

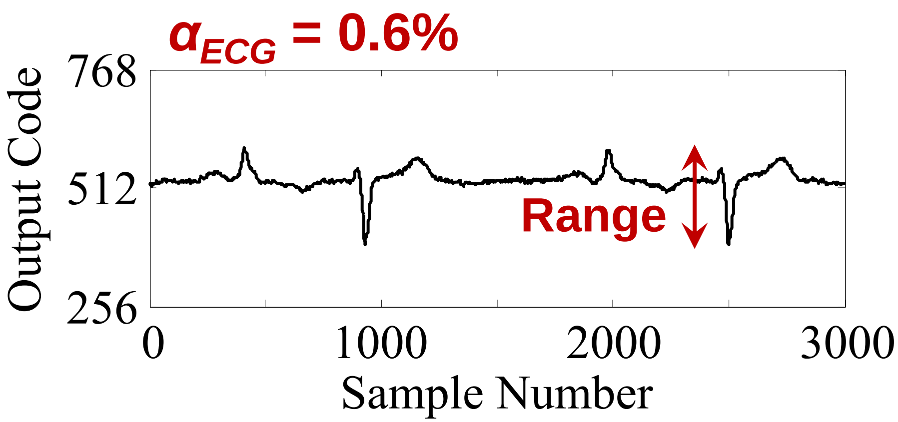
IoT Node for Monitoring

Component	Power	Comments
Inst. Amplifier [Verma, VLSI09]	3.5µW	1V V_{DD}, 1.3µVrms input referred noise
ADC [Yaul, ISSCC14]	3.7µW	1V V_{DD}, 450kS/s, 9.8ENOB
16b µ-cont [Kwong, ISSCC08]	2.72µW	0.5V V_{DD},128kb SRAM, 100kHz
Radio [CC 2550]	33.6mW (active)	3V V_{DD}, 2.4GHz, -12dBm P_{OUT}

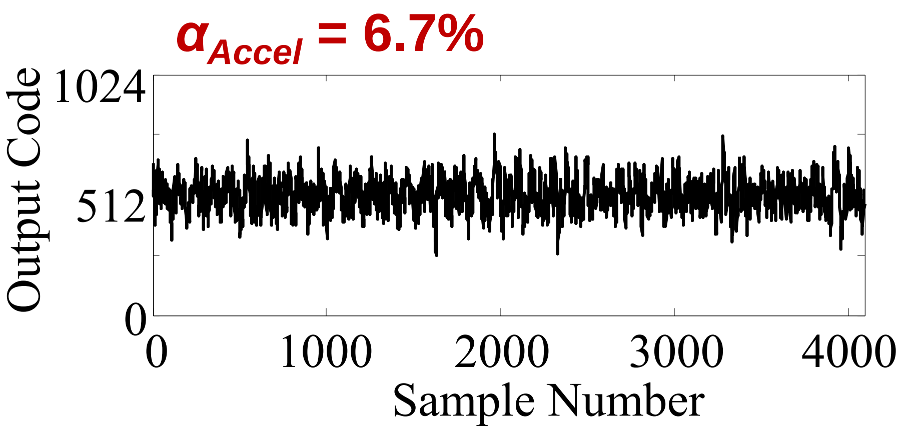


- Power consumption of building blocks steadily decreasing
- Low voltage operation, multi-cores, local processing of information, aggressive duty cycling

LSB-first SAR ADC for Low-Activity Signals



ECG Signal, 1 kS/s



Vibration Signal, 5 kS/s

Technology	0.18µm		
Unit Capacitor (fF)	72		
Supply Voltage (V)	1.0	0.6	0.5
Sample Rate (Hz)	450k	16k	4k
ENOB (bit)	9.82	9.73	9.55
Power (W)	3.7–13µ	47–170n	8.7–31n
FoM (fJ)	9.1–35	3.5–20	2.9–17

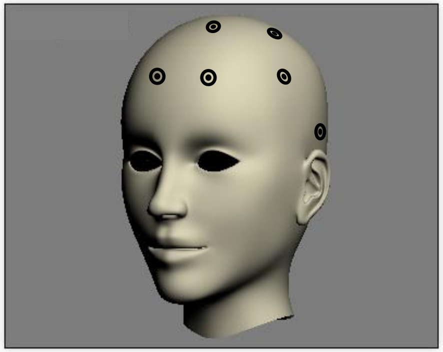
Range is given for best case (DC) and worst case (fullscale Nyquist sinusoid) inputs.

[F. Yaul, ISSCC 2014]

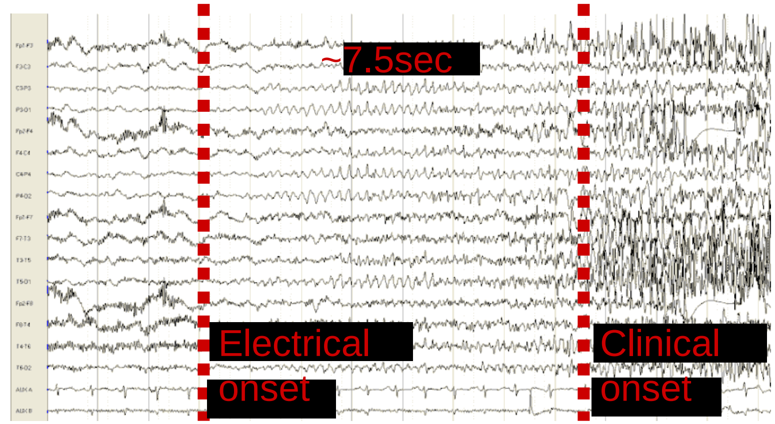
LSB-first predictive algorithm for reduced power

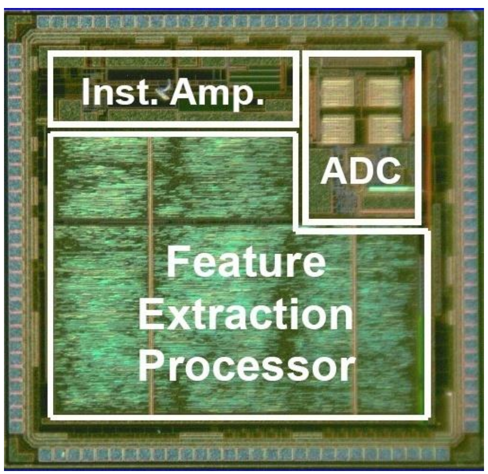
Reduced radio consumption

Epileptic Seizure Onset Detection



On-scalp Field Potentials (EEG):





	Conventional-Wireless EEG	Using Local Processing
Capture	**75 μW**	**75 μW**
Digital processing	**--**	**2 μW**
Radio	**1733 μW**	**43 μW**
Total	**1808 μW**	**120 μW**

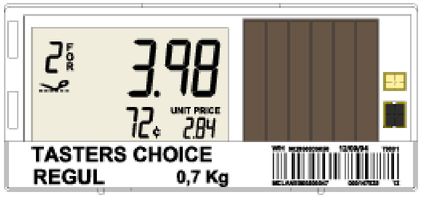
Computation vs. Communication Trade-off

[N. Verma, VLSI Circuits Symposium 2009]

Self-Powered Applications

Low data rate, low duty cycle, ultra-low power

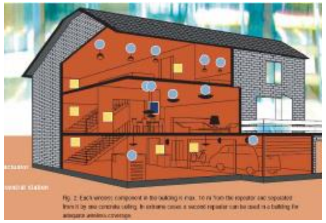
Solar Keyboard



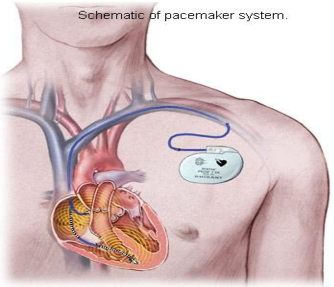
Electronic Shelf Labels

Self-powered switches

Convenience



Occupancy Sensor



Implantables

Pipelines

Oil Rig

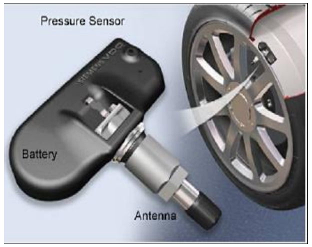
Environmental Awareness

Smoke Detector

Structural sensors

Hard to Reach

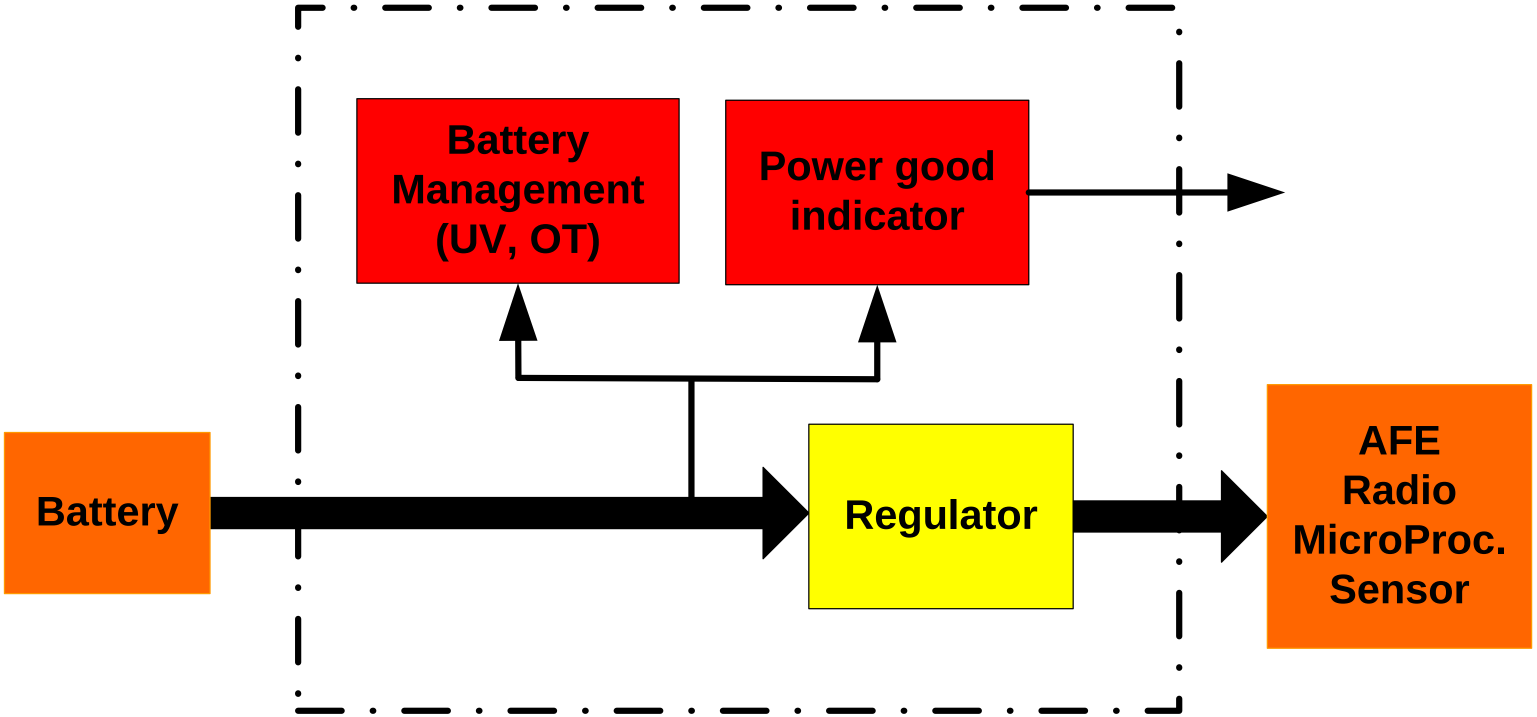
TPMS



Outline

- Energy Sources and Characteristics
  - Energy Harvesting System
  - Solar
  - Thermal
  - Vibration
- Energy Storage Options
- Energy Management Circuits
  - Chargers
  - DC/DC Converters
  - Battery Management
  - Peripherals
- Summary

Battery Operated System

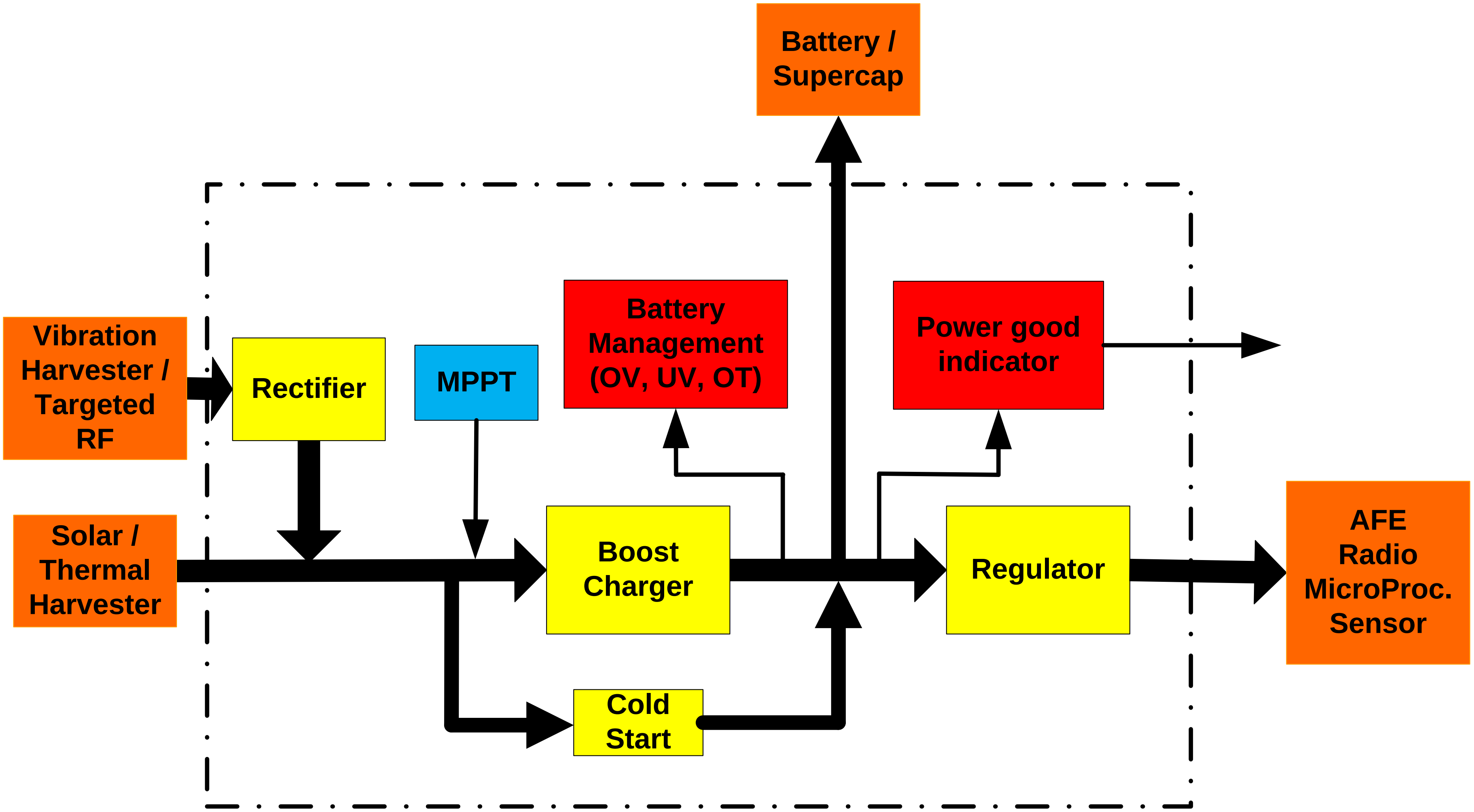


- Battery is an energy source
- System needs to be ON only when the load demands it

1cm^3 Li-ion → 2800J → 1year at 100µW

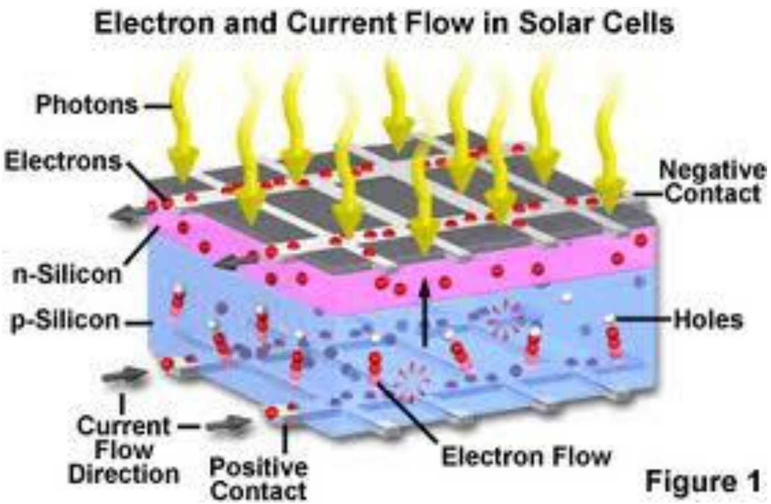
Self-powered solutions desirable

Energy Harvesting System

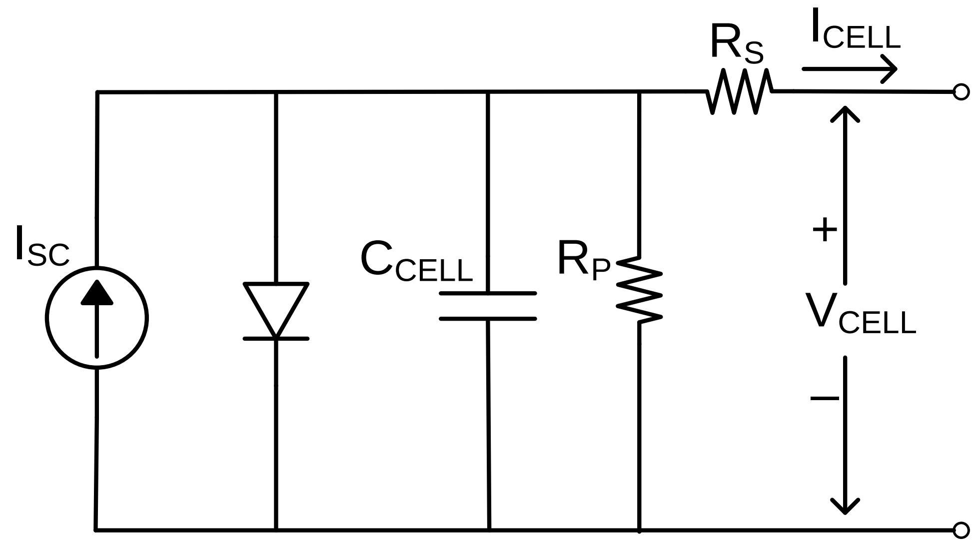


Energy harvesters are power sources

Harvesting Light Energy



*US Department of Energy

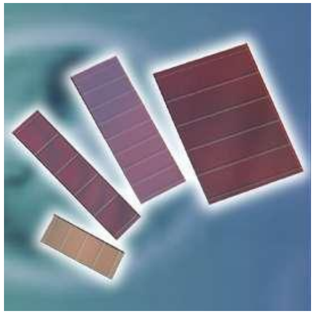


- Incident light generates electron-hole pairs
- I_{SC} proportional to light intensity

Conditions	Power density
Indoor	$10\mu W/cm^2$
Outdoor	$10 mW/cm^2$

Common Solar Cell Types

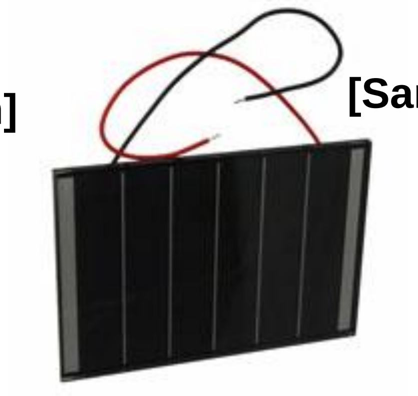
Crystalline



[Sinonar]

[IXYS]

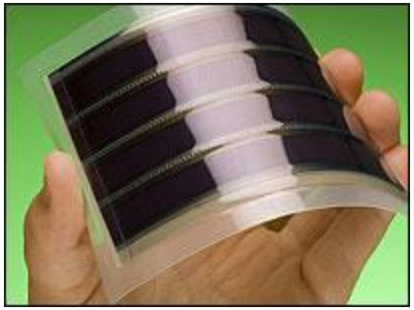
[EnOcean]



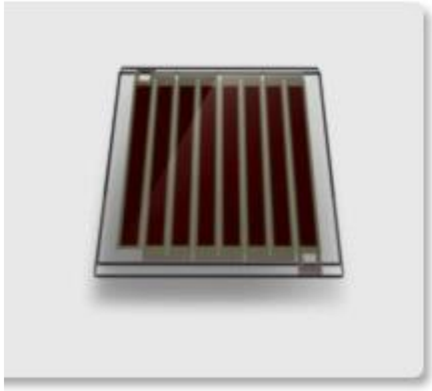
[Sanyo]

Amorphous

[G24i]



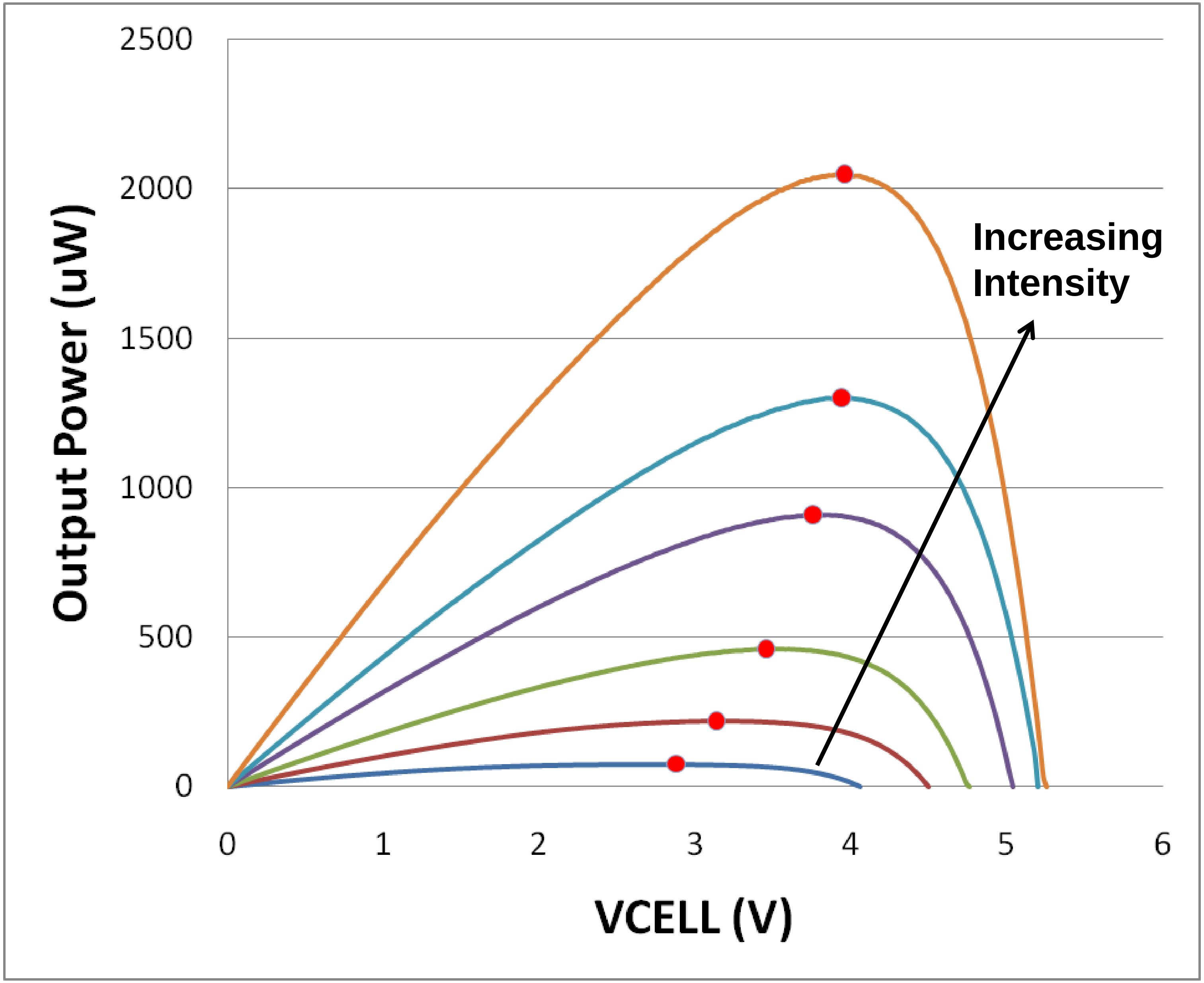
[SolarPrint]



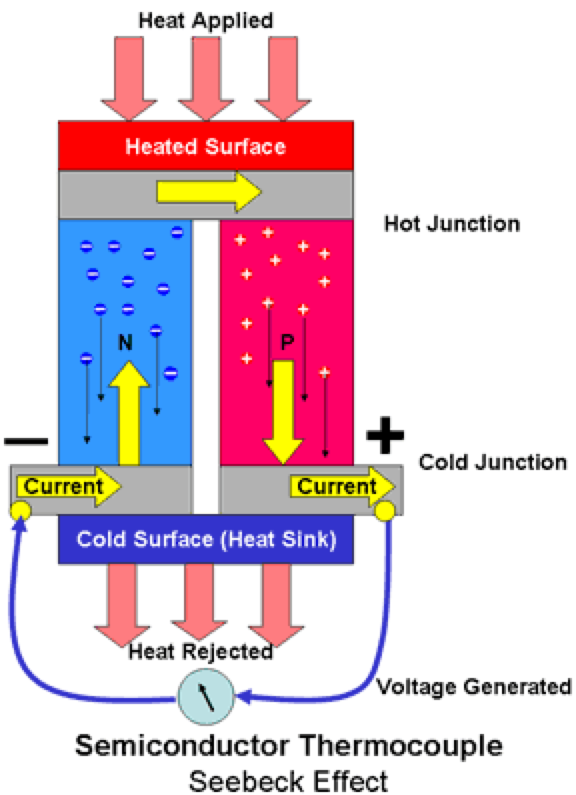
Dye-Sensitized (DSSC)

M. Gratzel, "*Photovoltaic and photoelectrochemical conversion of solar energy*," Philosophical Trans. Royal Society A, 2007

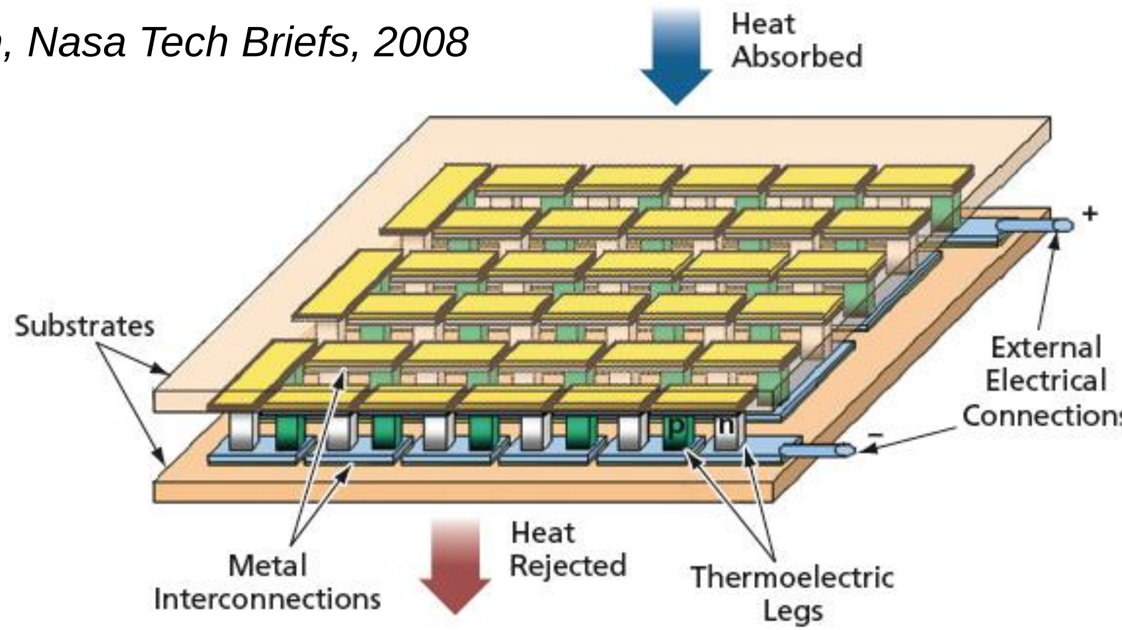
Output power curves with light intensity



Thermoelectric Energy Harvesters



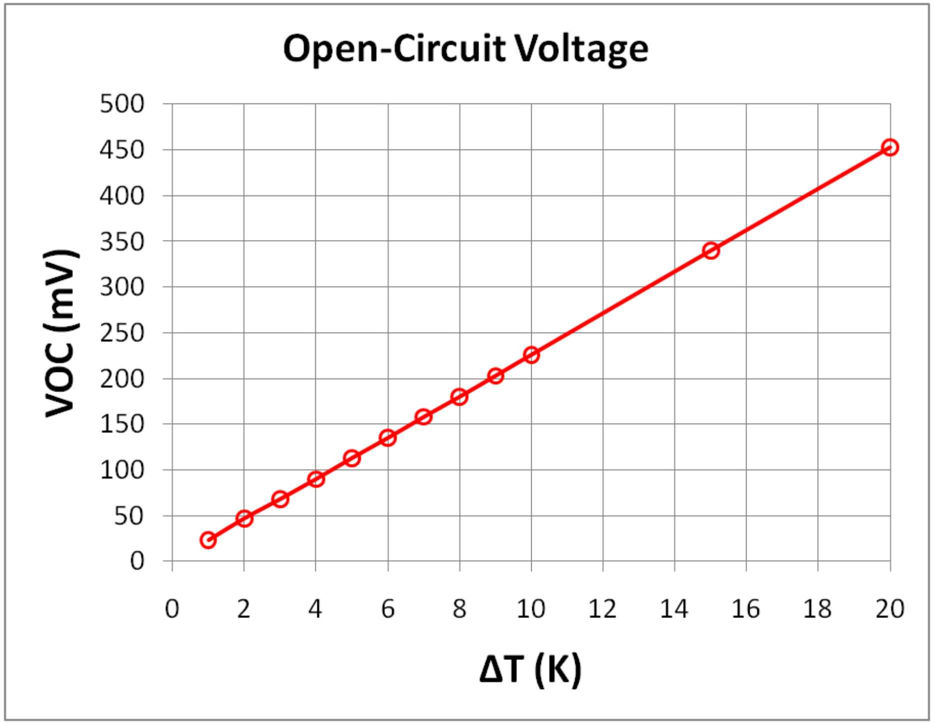
Lim, Nasa Tech Briefs, 2008

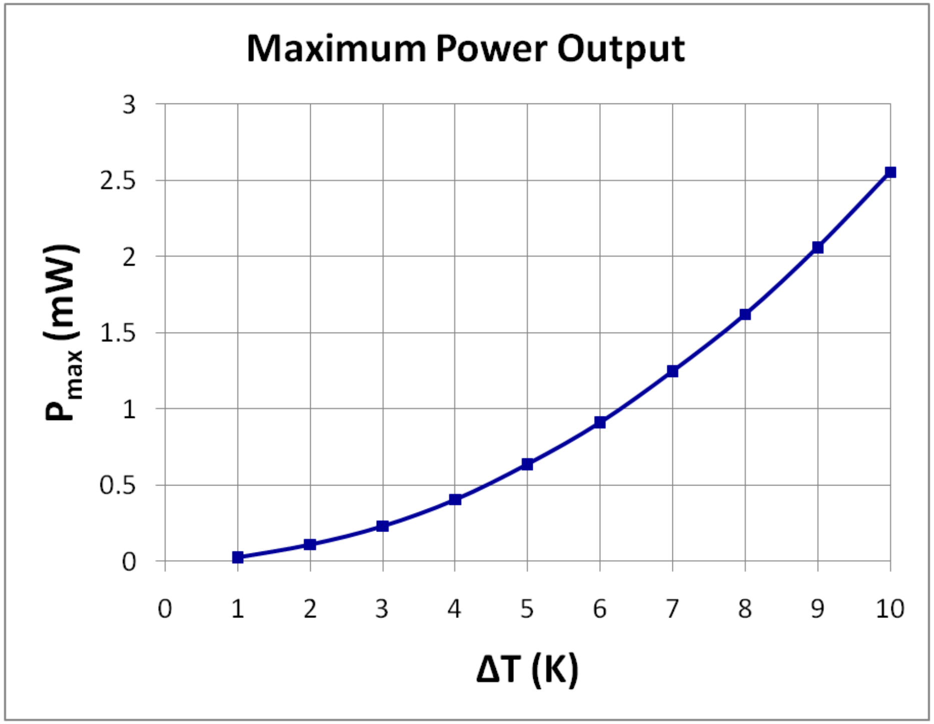


Conditions	Power density
Wearable	60µW/cm^2
Industrial	5mW/cm^2

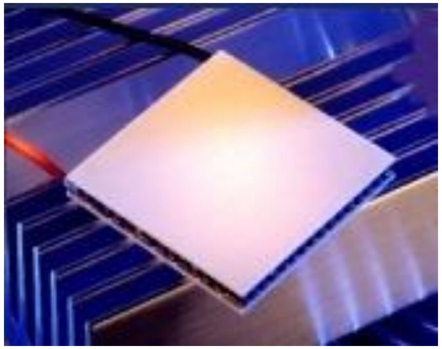
- One p-n leg generates ~ 0.2mV/K
- Open-circuit voltage proportional to temperature difference across TEG

TEG Characteristics



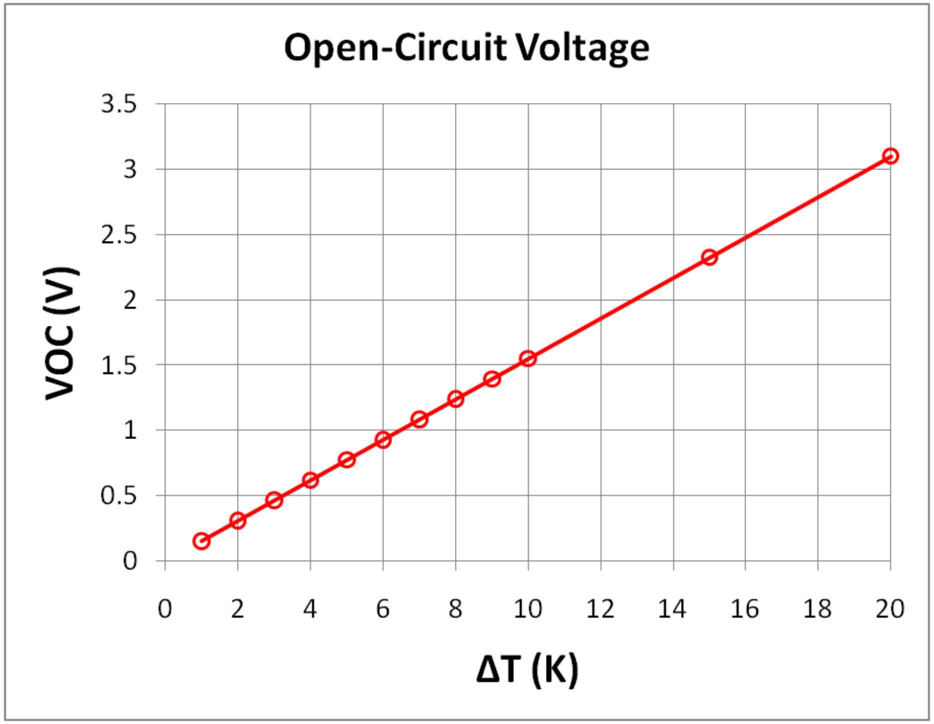


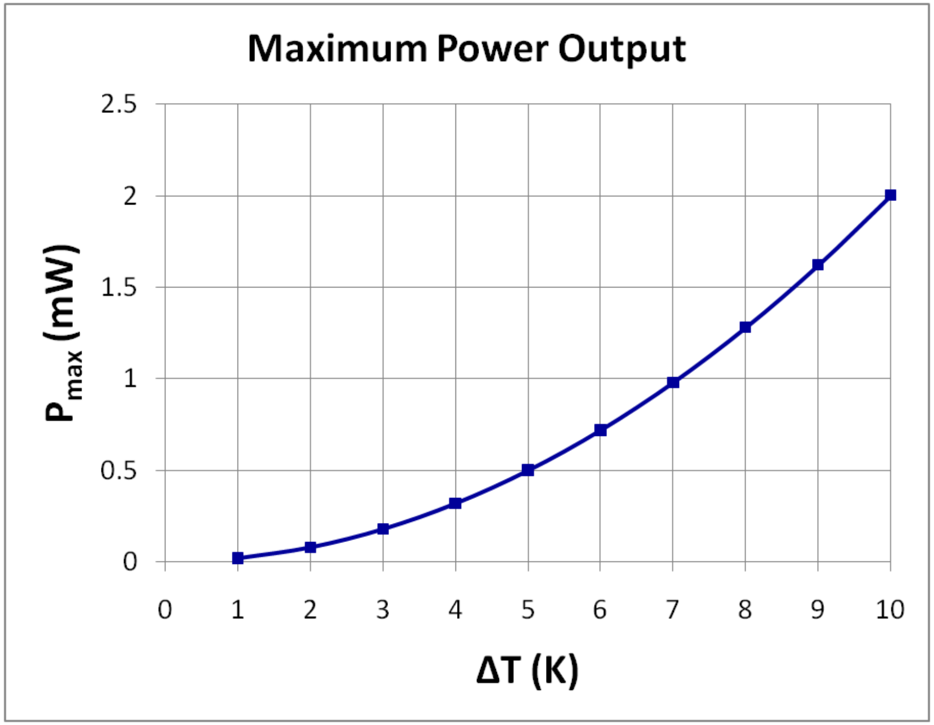
[Tellurex]



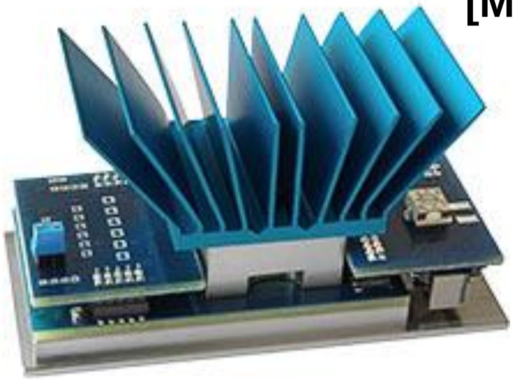
- Tellurex G1-1.0-127-1.27
- $S = 23mV/K$; $R_T = 5\Omega$

TEG Characteristics





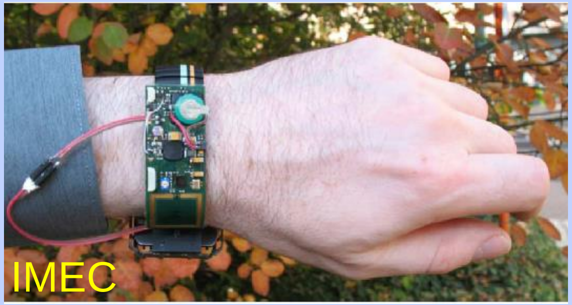
[Micropelt]



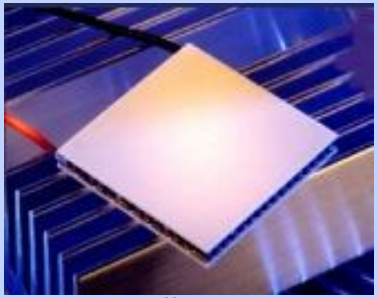
- Micropelt MPG-D751
- $S = 155mV/K$; $R_T = 300\Omega$

Body Heat Powered Electronics

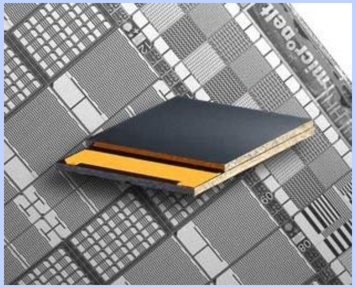
System Concept



Thermo-Electric Devices

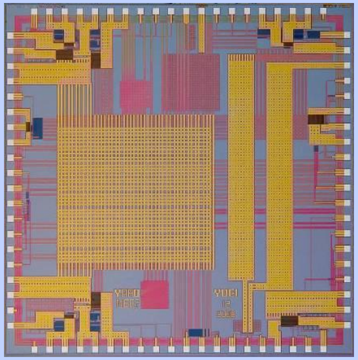


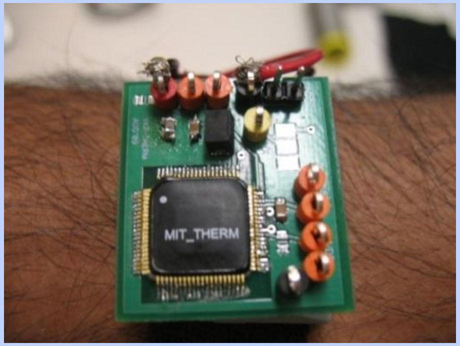
Tellurex



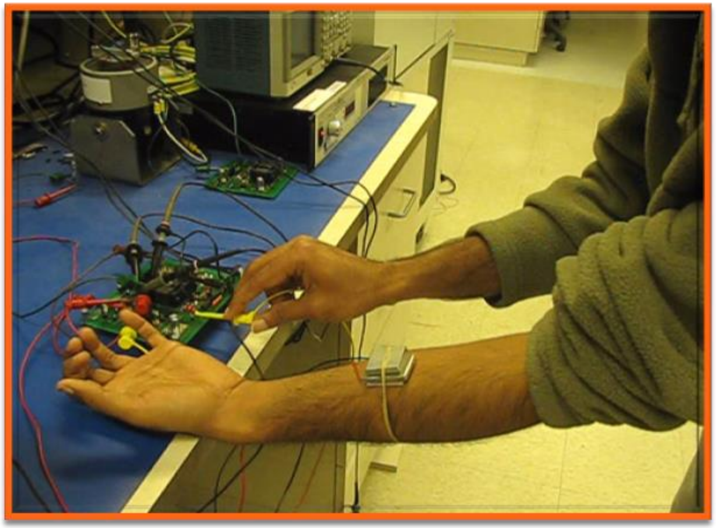
Micro-pelt

Thermal Energy Chip





[Y. Ramadass and A. Chandrakasan, ISSCC 2010]



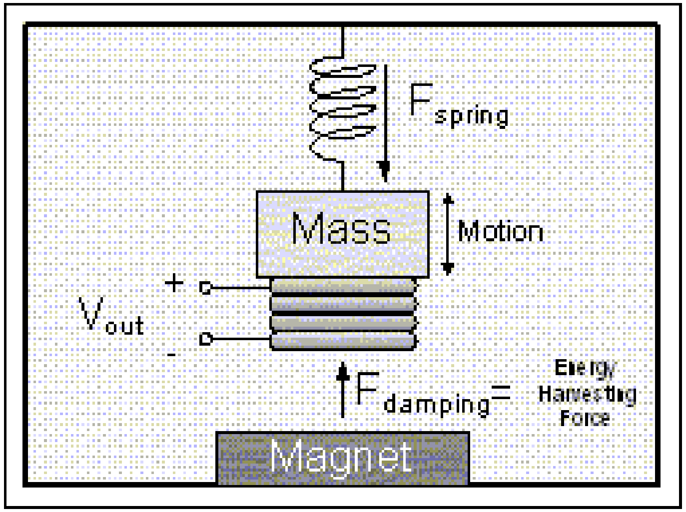
For low-power wearable electronics

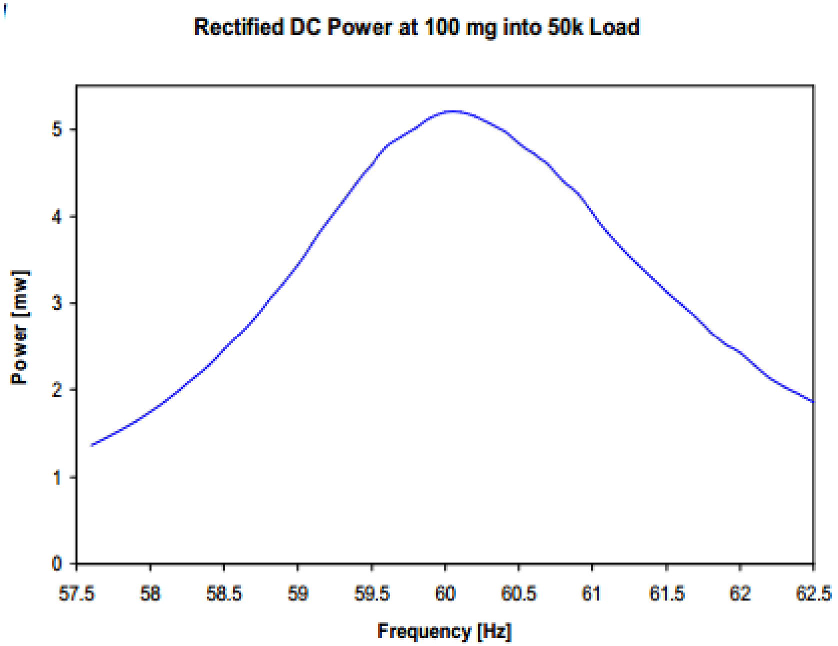
Mechanical Vibration Harvesters

[Mide Volture v22b]

[Perpetuum]

[FerroSolutions]



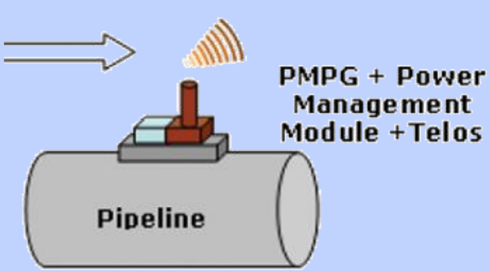


Conditions	Power density
Wearable	4µW/cm^3
Industrial	1mW/cm^3

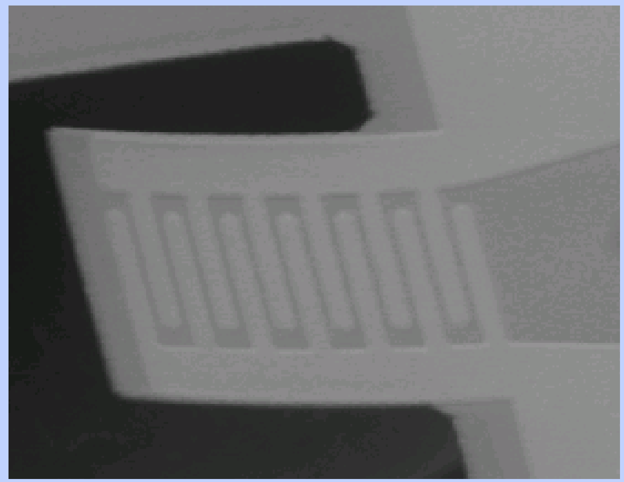
FerroSolutions VEH-460

Vibration-to-Electric Energy

Self-powered Wireless Corrosion Monitoring Sensors

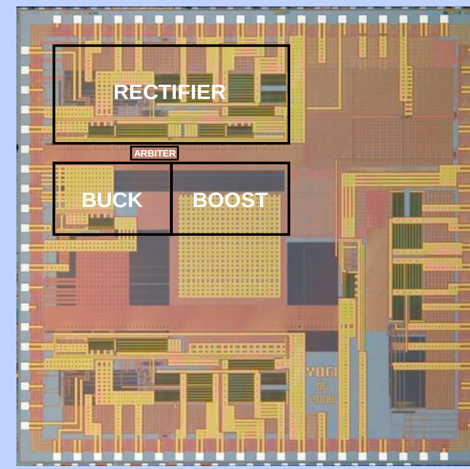


Piezoelectric Micro-Power Generators



Sang-Gook Kim (MIT)

Power Converter



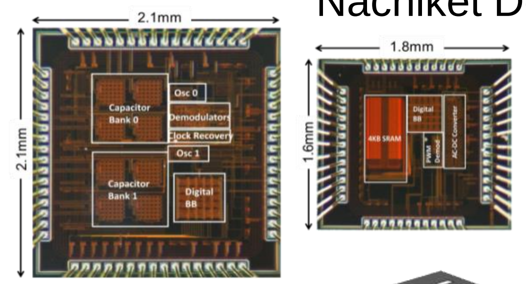
10µW -100µW generated

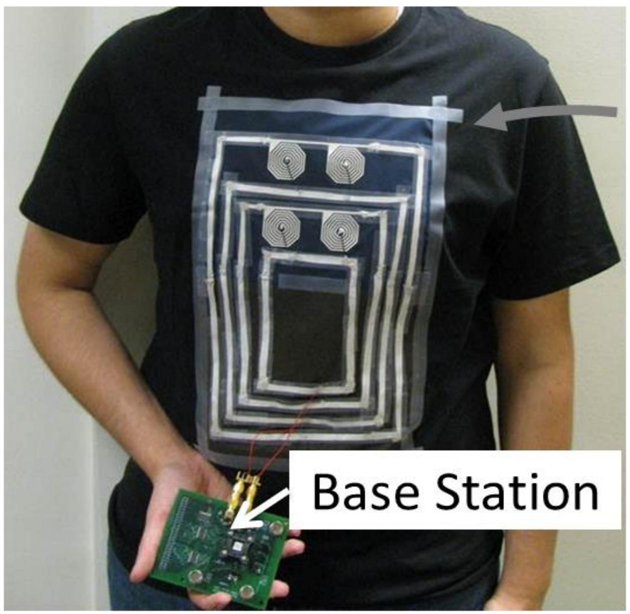
Vibrations Power Distributed Sensor Devices (Battery-less Operation)

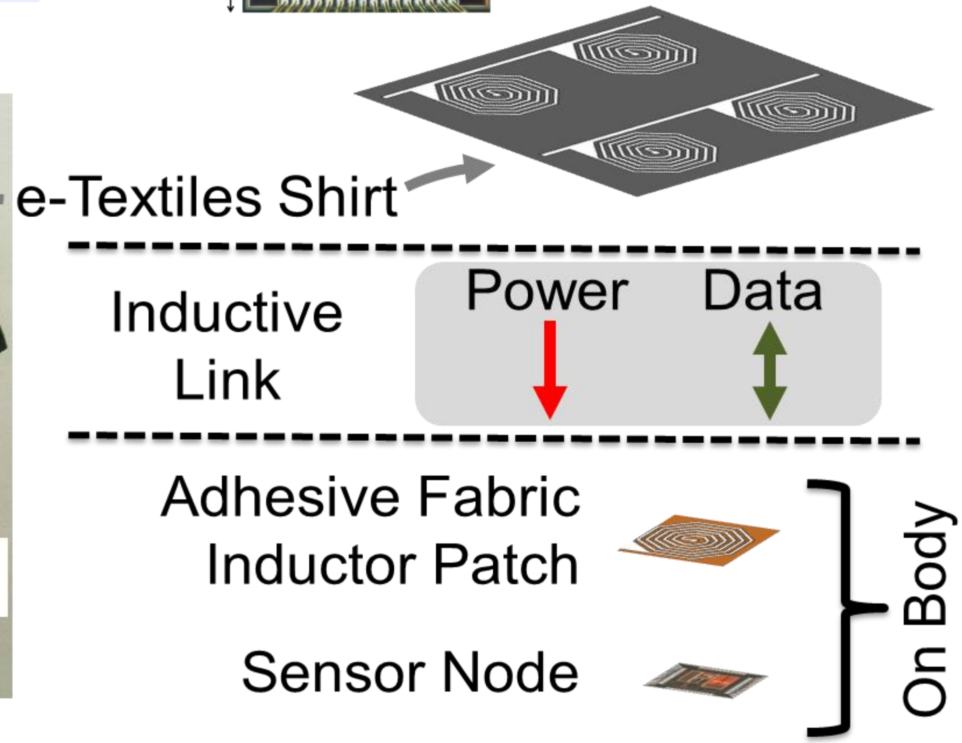
e-Textiles with Wireless Power/Data Transfer

Conditions	Power density
Near field	5mW/cm^2
Far field	<10µW/cm^2

Nachiket Desai, ISSCC 2013

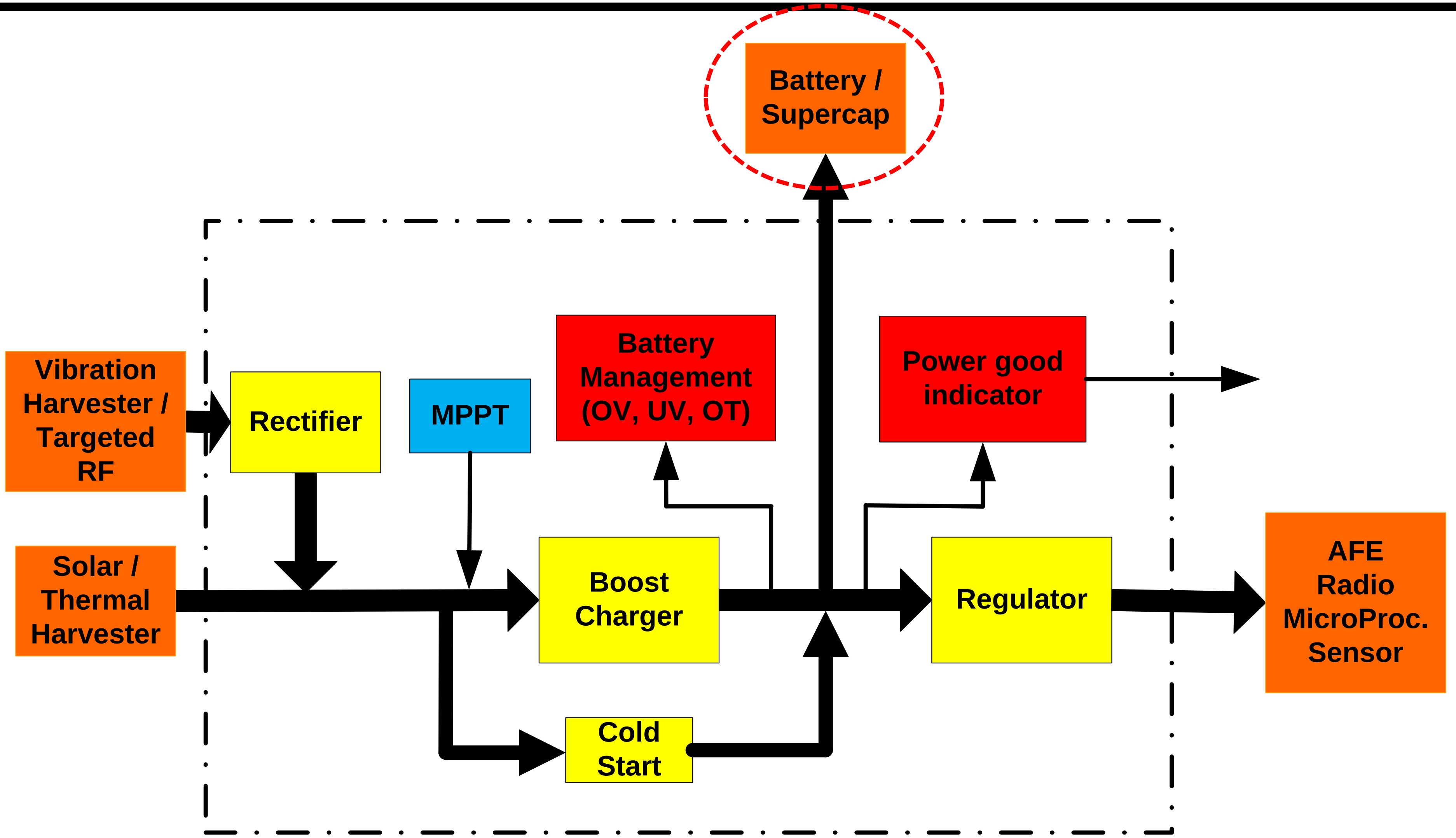






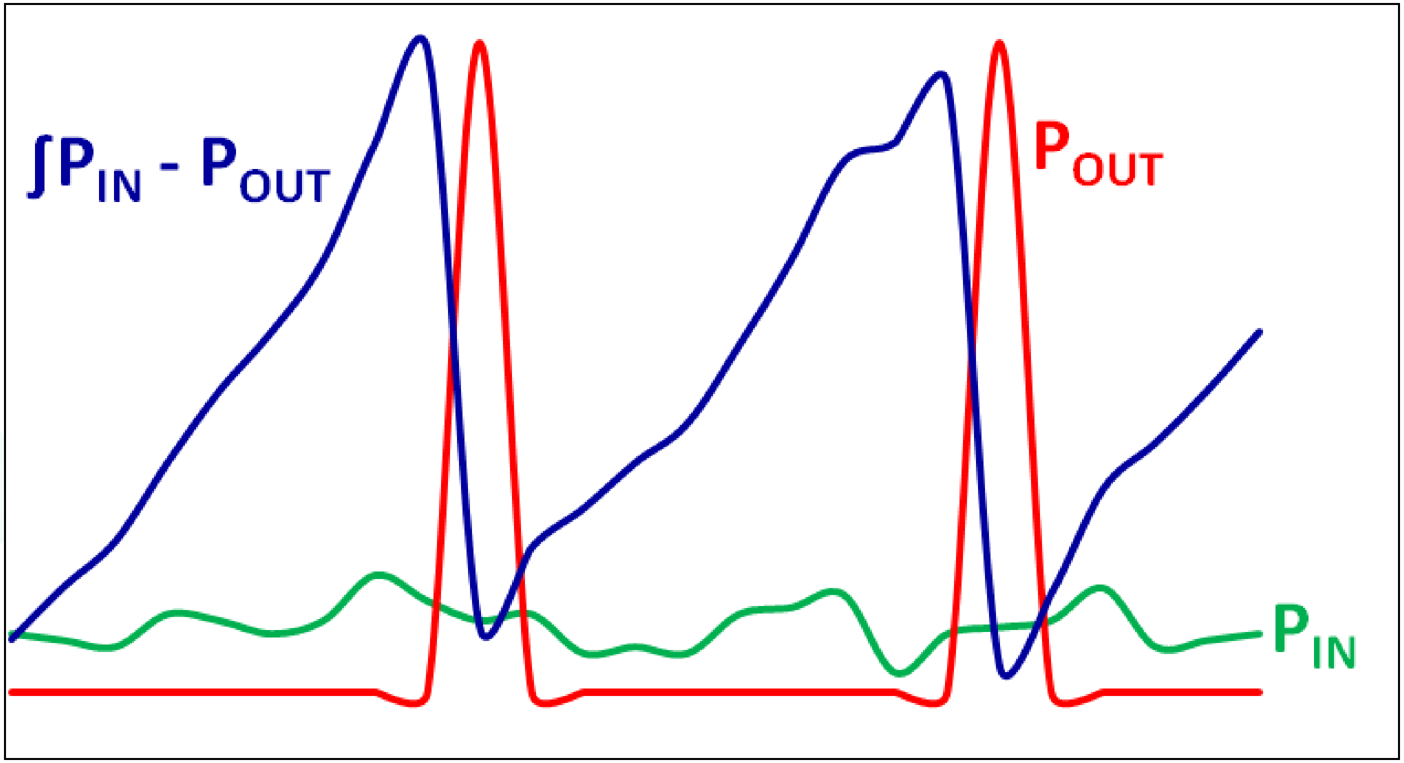
Network of diverse, remotely-powered sensors wirelessly linked to eTextiles

Energy Storage Options



Store extracted energy from harvesters and provide to load

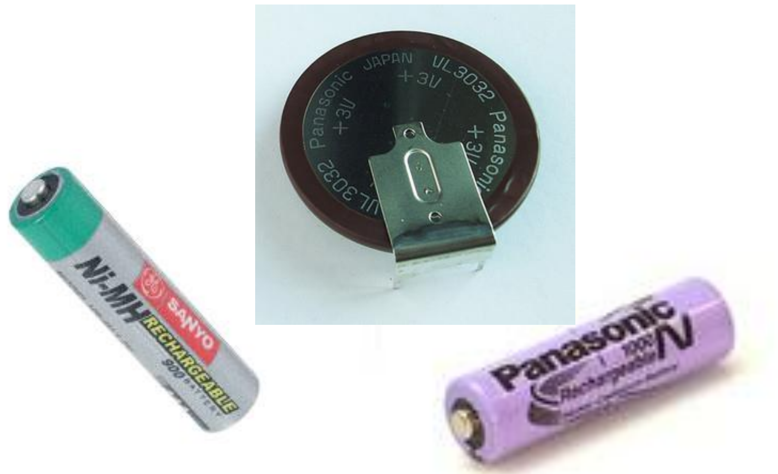
Energy Buffer



- Accumulate input power
- Provide peak output power
- Smooth out input, output power imbalances

Energy Storage Options

	Conventional Batteries
Recharge Cycles	100s
Self Discharge	Moderate
Charge Time	Hours
Impedance	Low - High
Physical Size	Large
Capacity	0.3-2500mAH



- NiCd, NiMH, Li chemistries
- AA, AAA batteries have high capacity, low internal impedance, higher self discharge
- Li coin cells have low capacity, high internal impedance, smaller form factor

Energy Storage Options

	Conventional Batteries	Thin Film Batteries
Recharge Cycles	100s	5k-10k
Self Discharge	Moderate	Negligible
Charge Time	Hours	Minutes
Impedance	Low - High	High
Physical Size	Large	Small
Capacity	0.3-2500mAH	12-2200µAH

- Solid-state LiPON electrolyte
- Higher output currents compared to coin cells
- Extremely low self-discharge
- Variety of form factors, intrinsically safe, high temp.

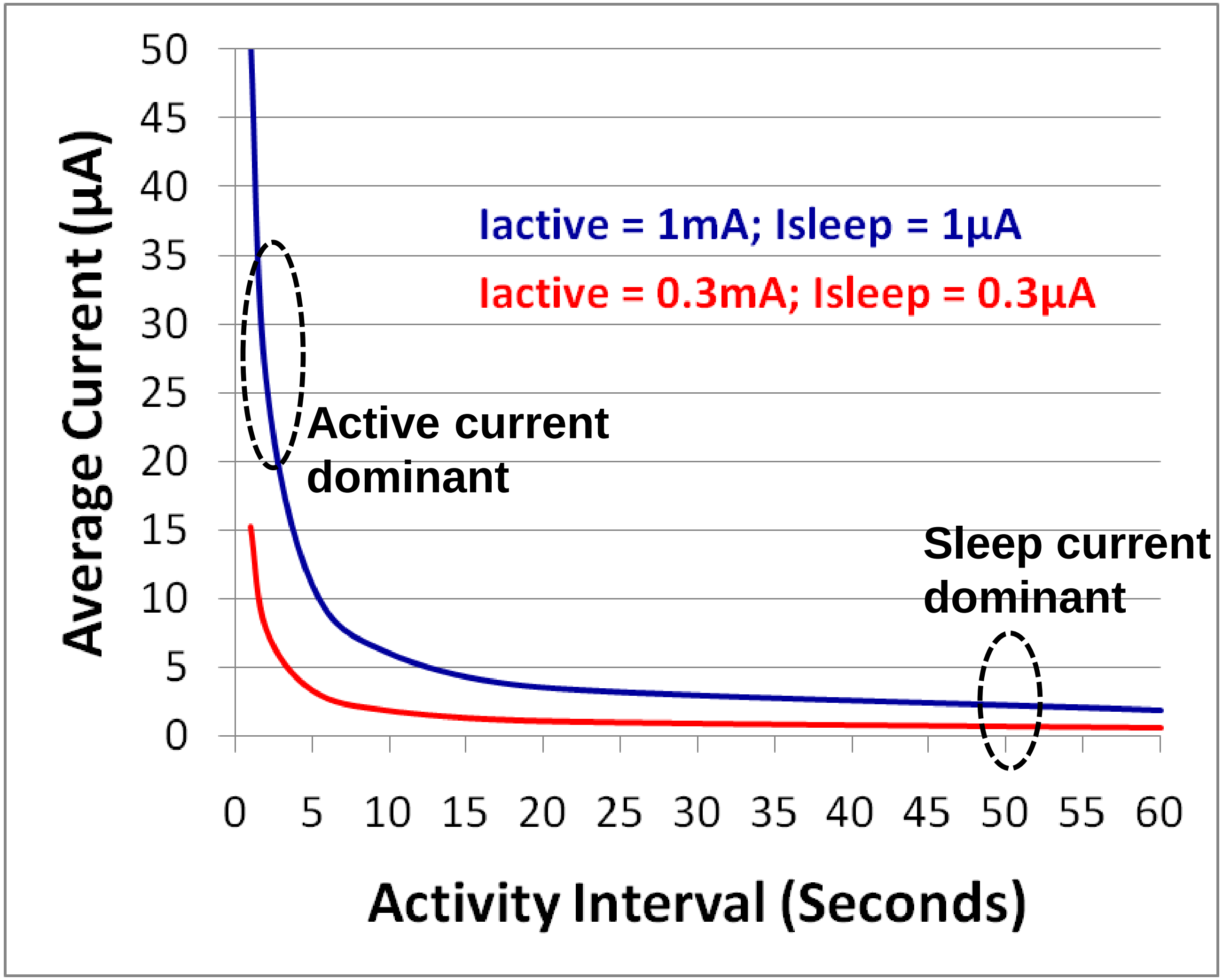
Energy Storage Options

	Conventional Batteries	Thin Film Batteries	Supercaps
Recharge Cycles	100s	5k-10k	Millions
Self Discharge	Moderate	Negligible	High
Charge Time	Hours	Minutes	Sec-Minutes
Impedance	Low - High	High	Low
Physical Size	Large	Small	Medium
Capacity	0.3-2500mAH	12-2200µAH	10-100µAH

[AVX]

- Supports high peak output currents
- Very high leakage currents
- Wide range of operating temperature

Duty Cycle Impact on Current

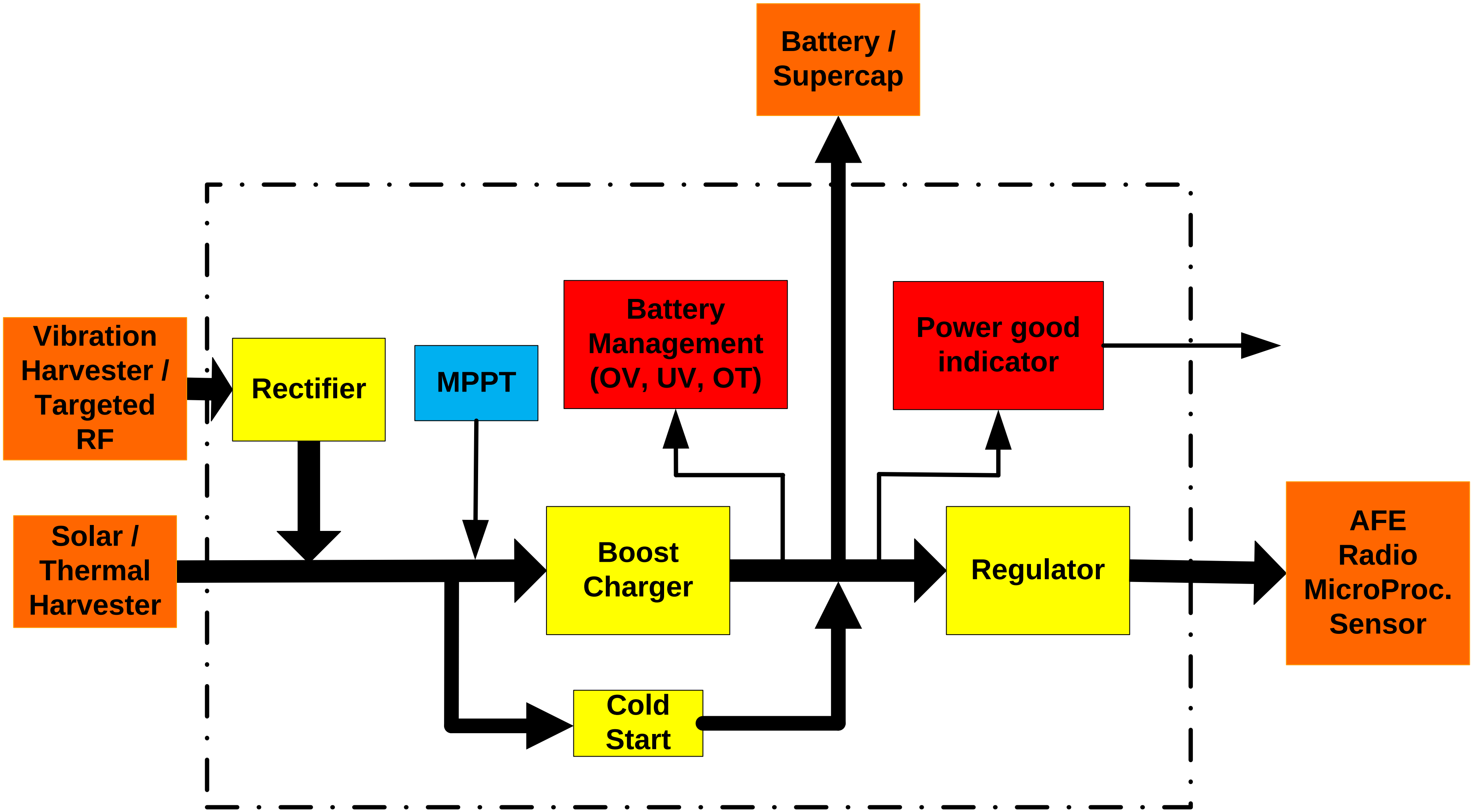


Pulse Width = 50ms

$$D = \frac{Pulse\,Width}{Activity\ Interval}$$

$$\boxed{I(avg) = Iactive * D + Isleep * (1 - D)}$$

Energy Processor



Take input energy from harvester and charge the storage element efficiently

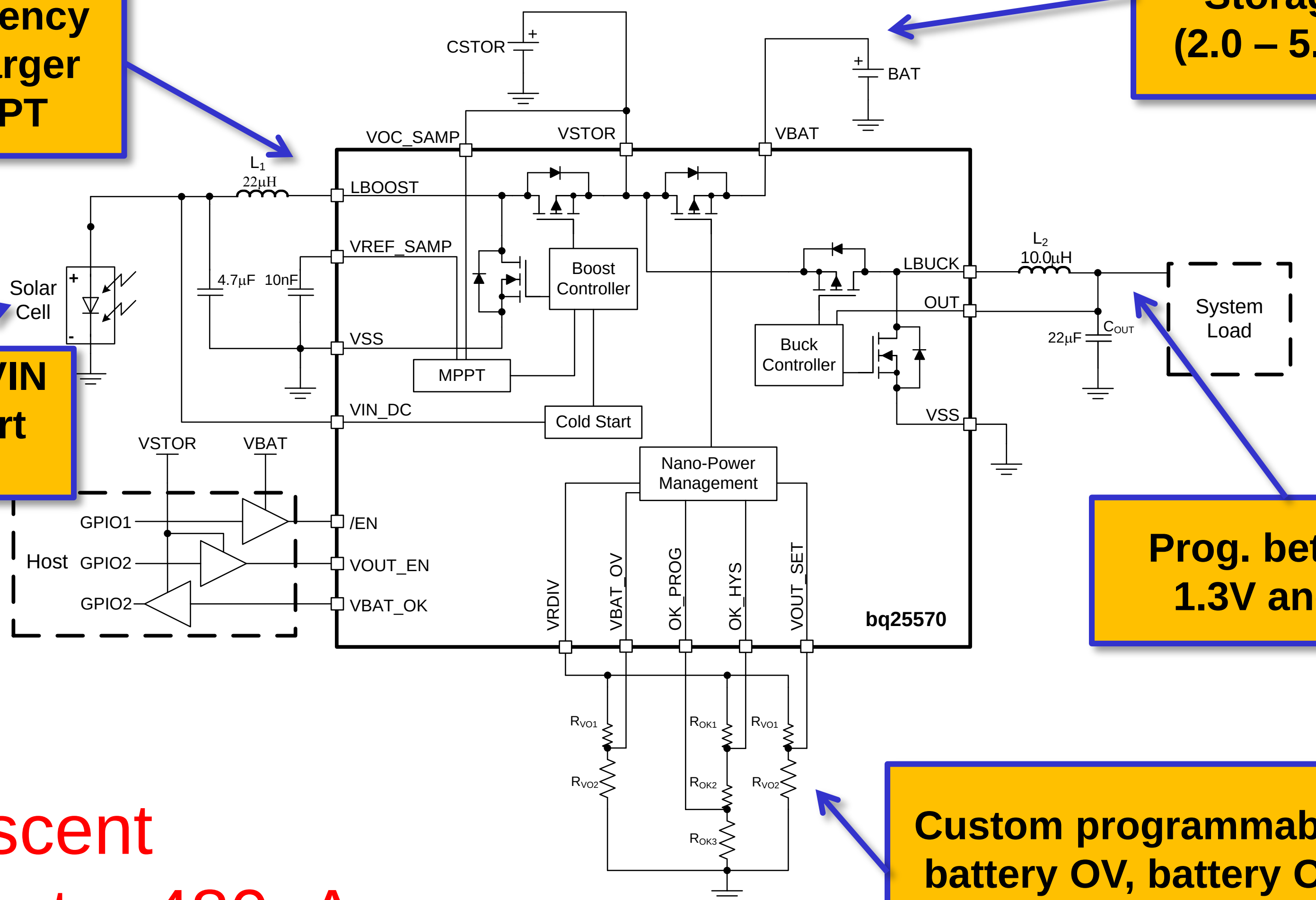
Energy Mgmt. IC -BQ25570

http://www.ti.com/product/bq25570

High efficiency boost charger with MPPT

Harvester Storage (2.0 – 5.5V)

100mV to 4V VIN with cold-start circuit

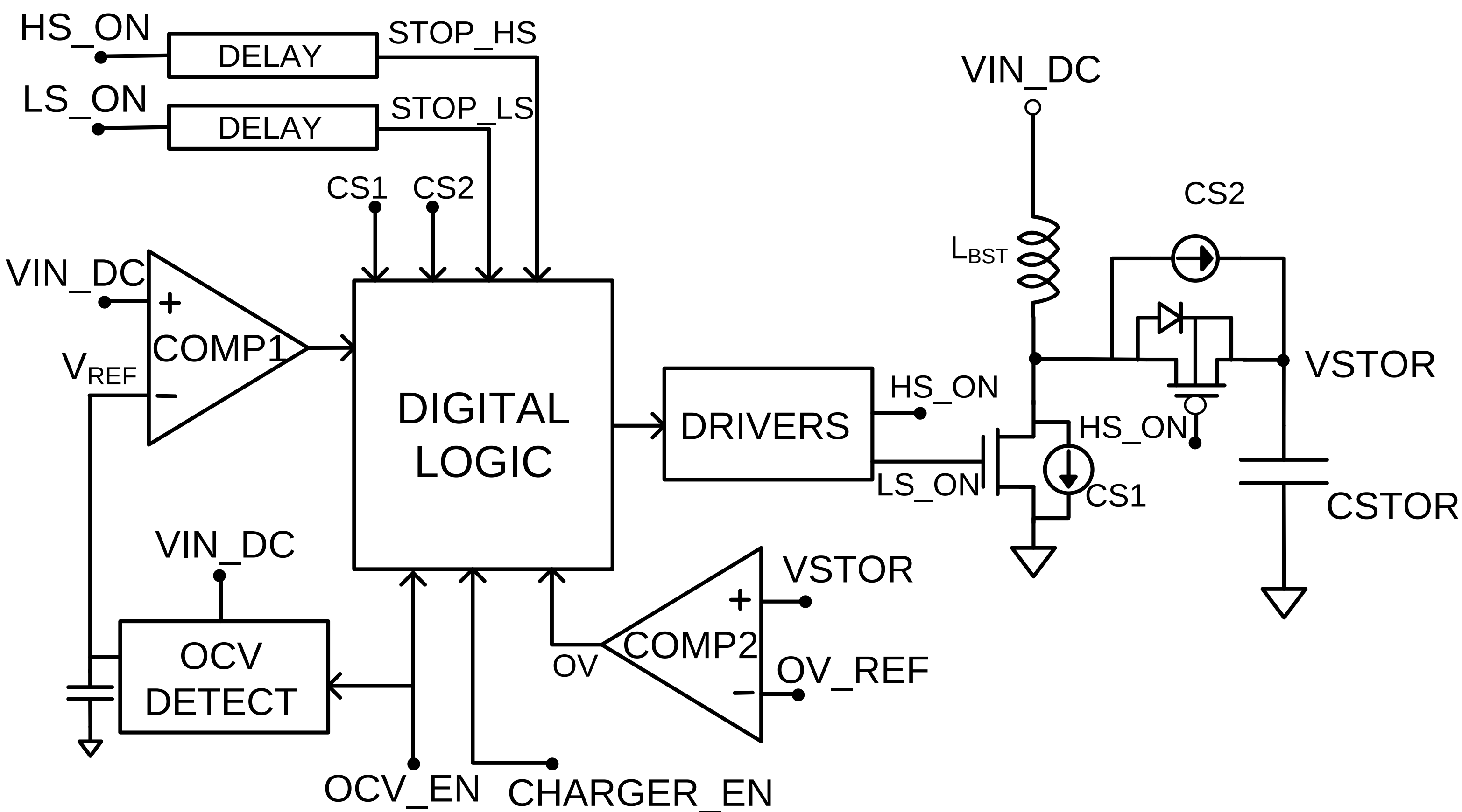


Prog. between 1.3V and 5V

Custom programmability for battery OV, battery OK, and buck output regulation.

Quiescent Current = 480nA

BQ25570 Charger Architecture

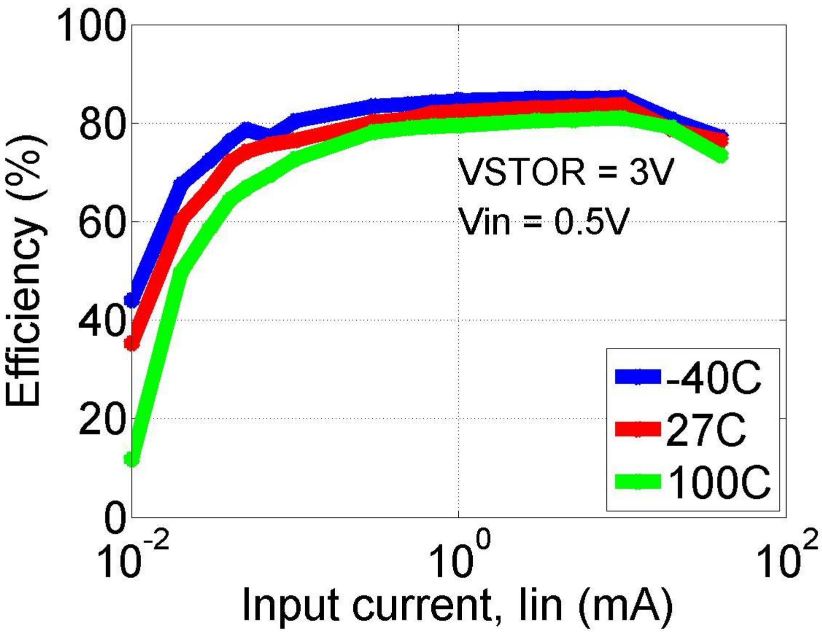


- Synchronous boost converter with input regulation
- 80mV – 4V input voltage
- 10µA – 100mA input current

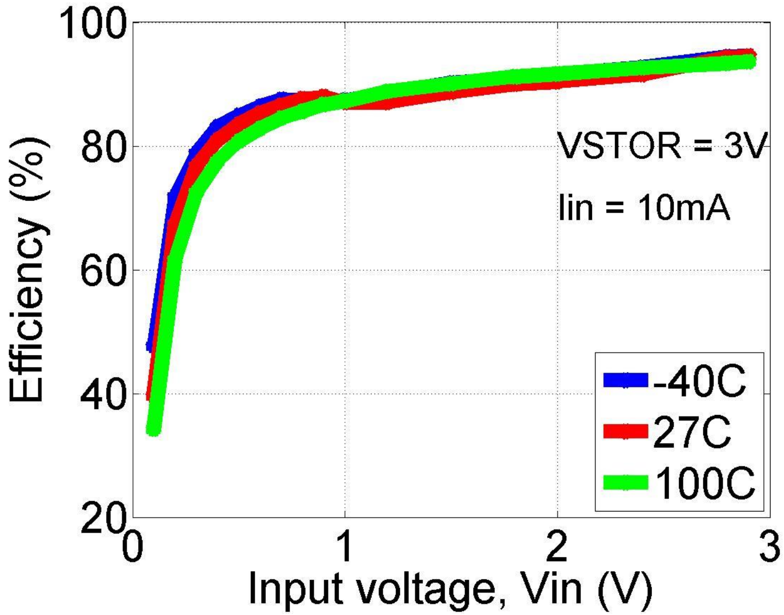
BQ25570 Charger Efficiency

- **Single** cell solar operation in indoor light (200 lux)
- Harvesting from thermoelectric generators

Eff Vs Iin



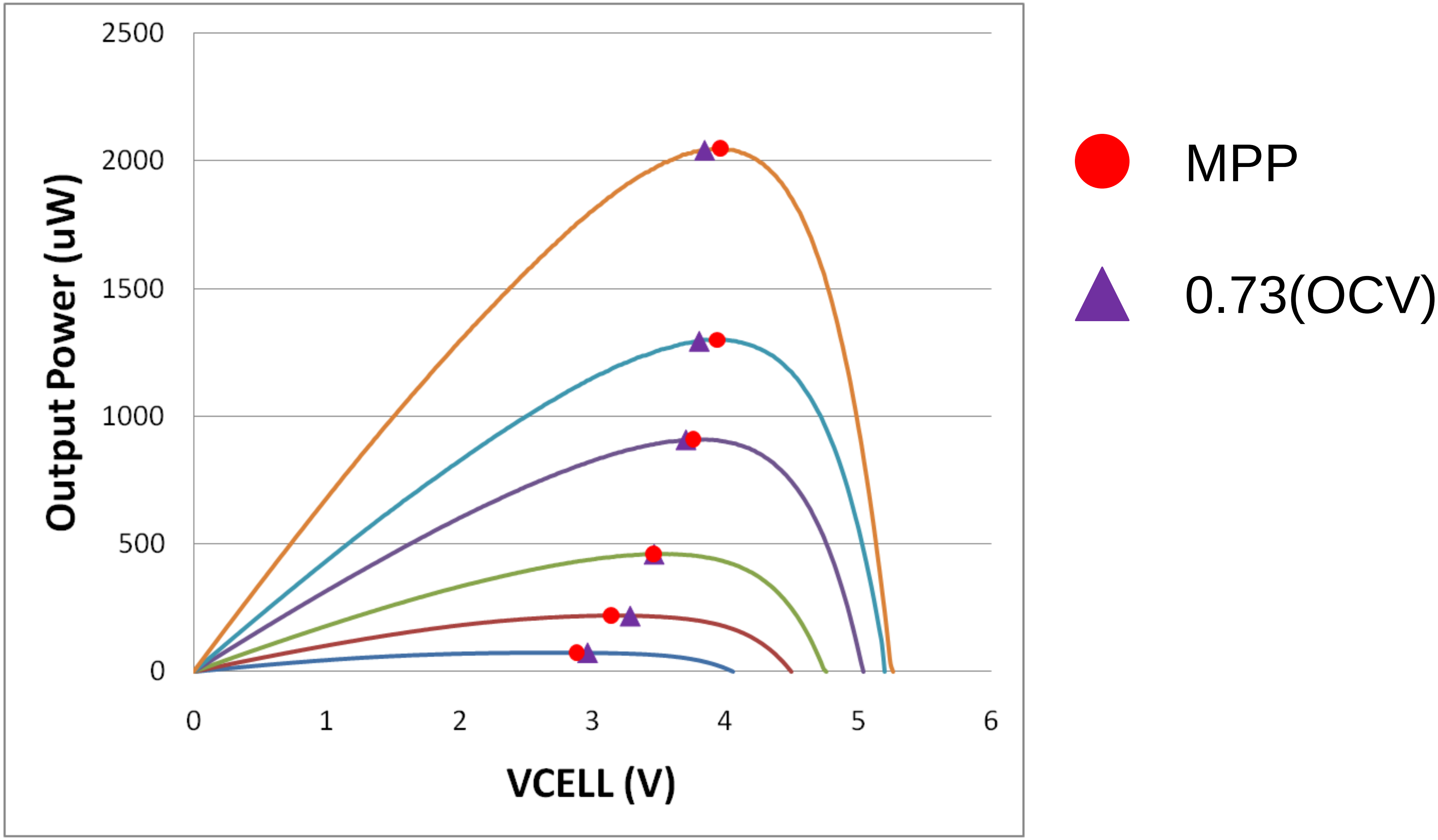
Eff Vs Vin



- 35% efficiency with 10µA input at 0.5V
- > 80% above 100µA.

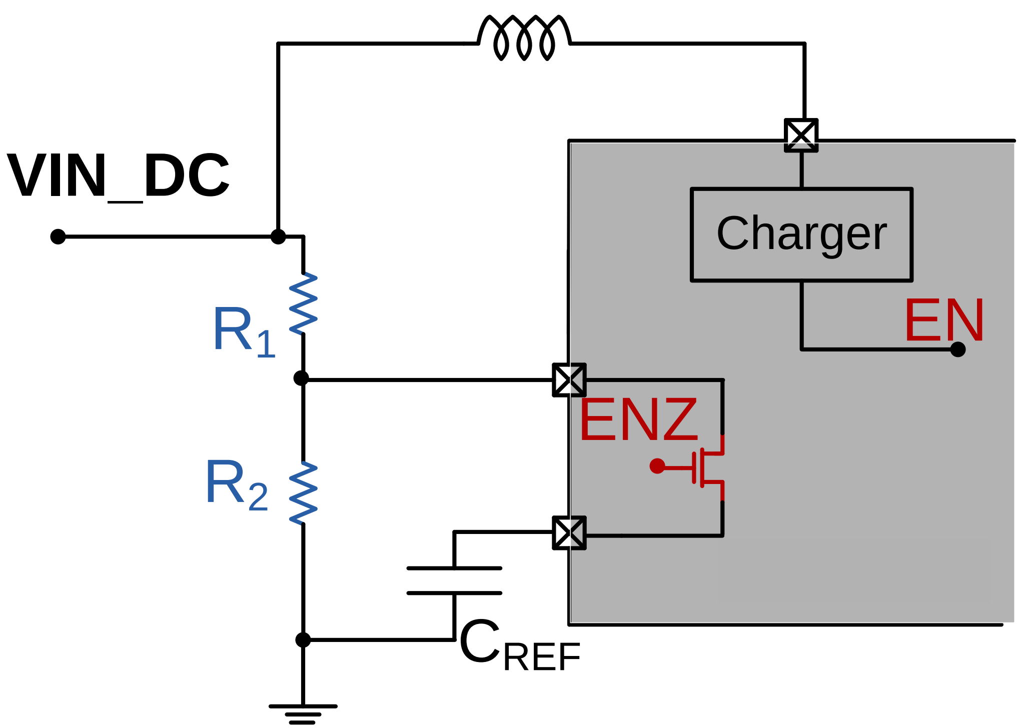
- 38% efficiency with 100mV input at 10mA
- >80% above 0.5V

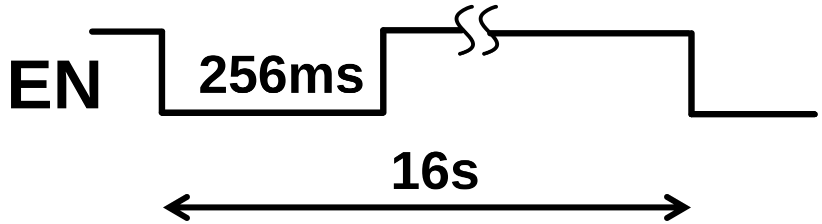
Revisiting solar MPP curves



Output power levels within 0.5%

BQ25570 Maximum Power Point Tracking

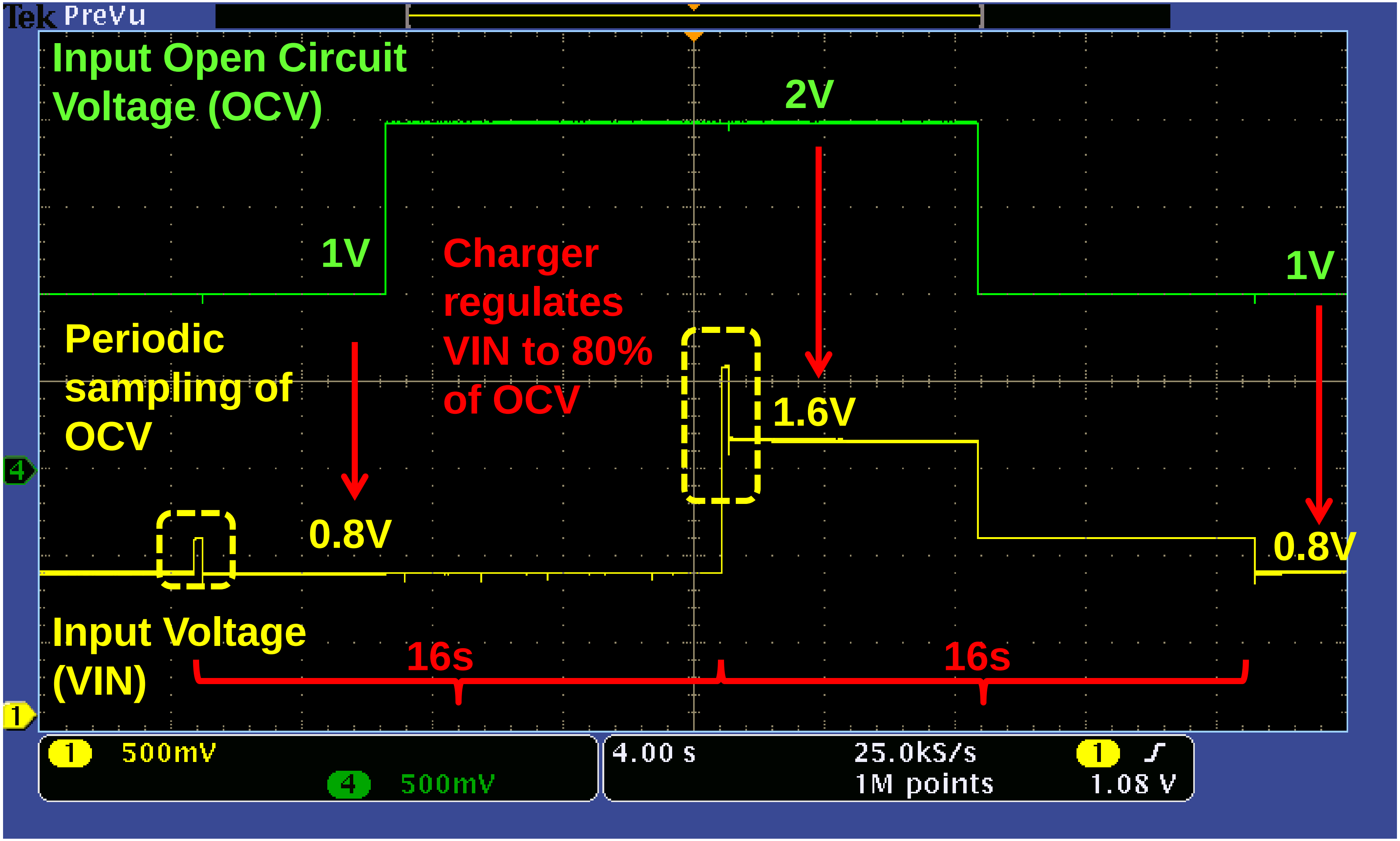




	Solar	TEG
MPPT fraction	~75%	50%

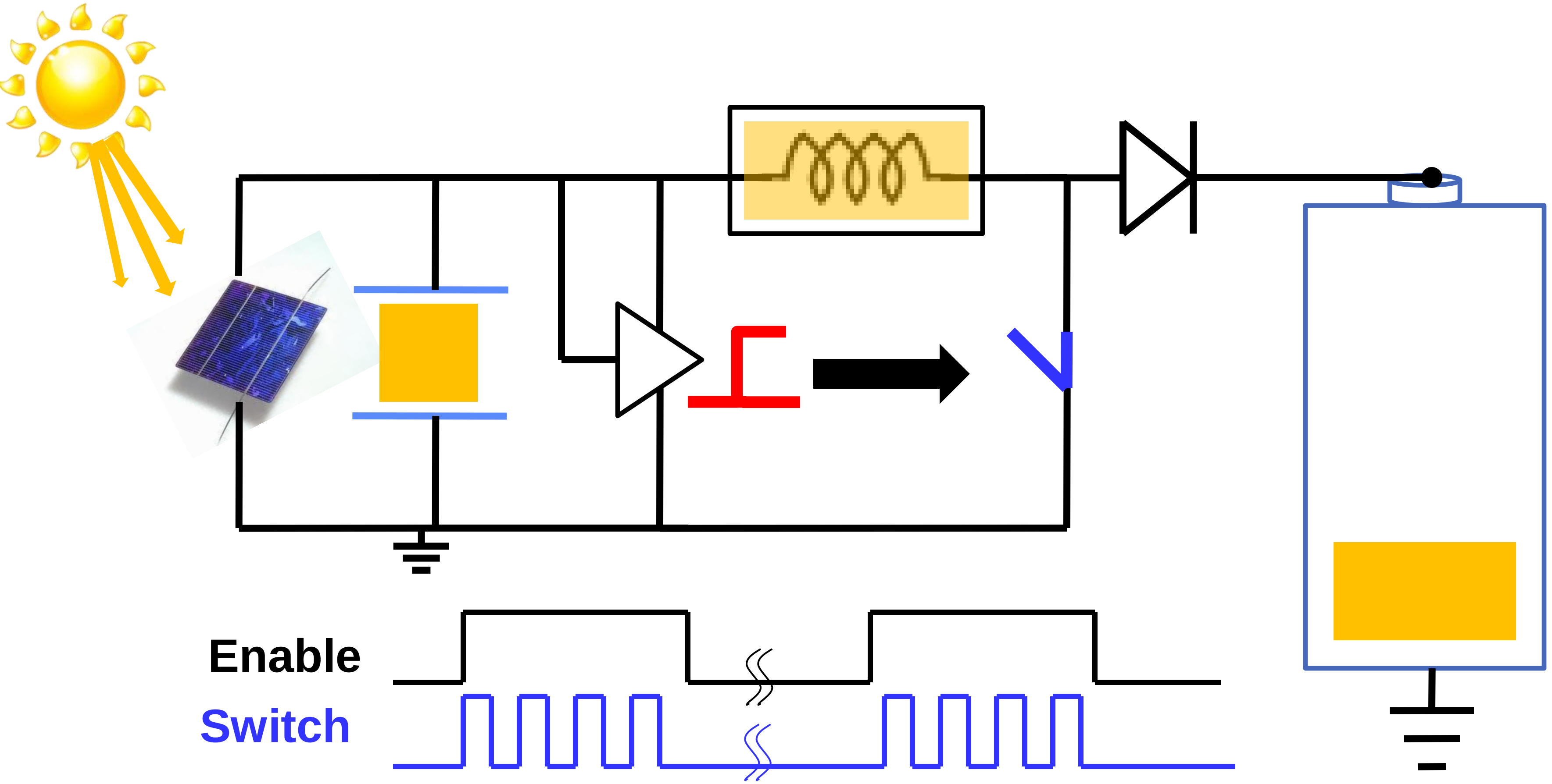
- Open circuit voltage based MPPT
- Charger periodically turned off using **EN** signal
- IC samples and holds fraction of OCV on external capacitor
- Charger regulates input to value held on capacitor

Maximum Power Point Tracking



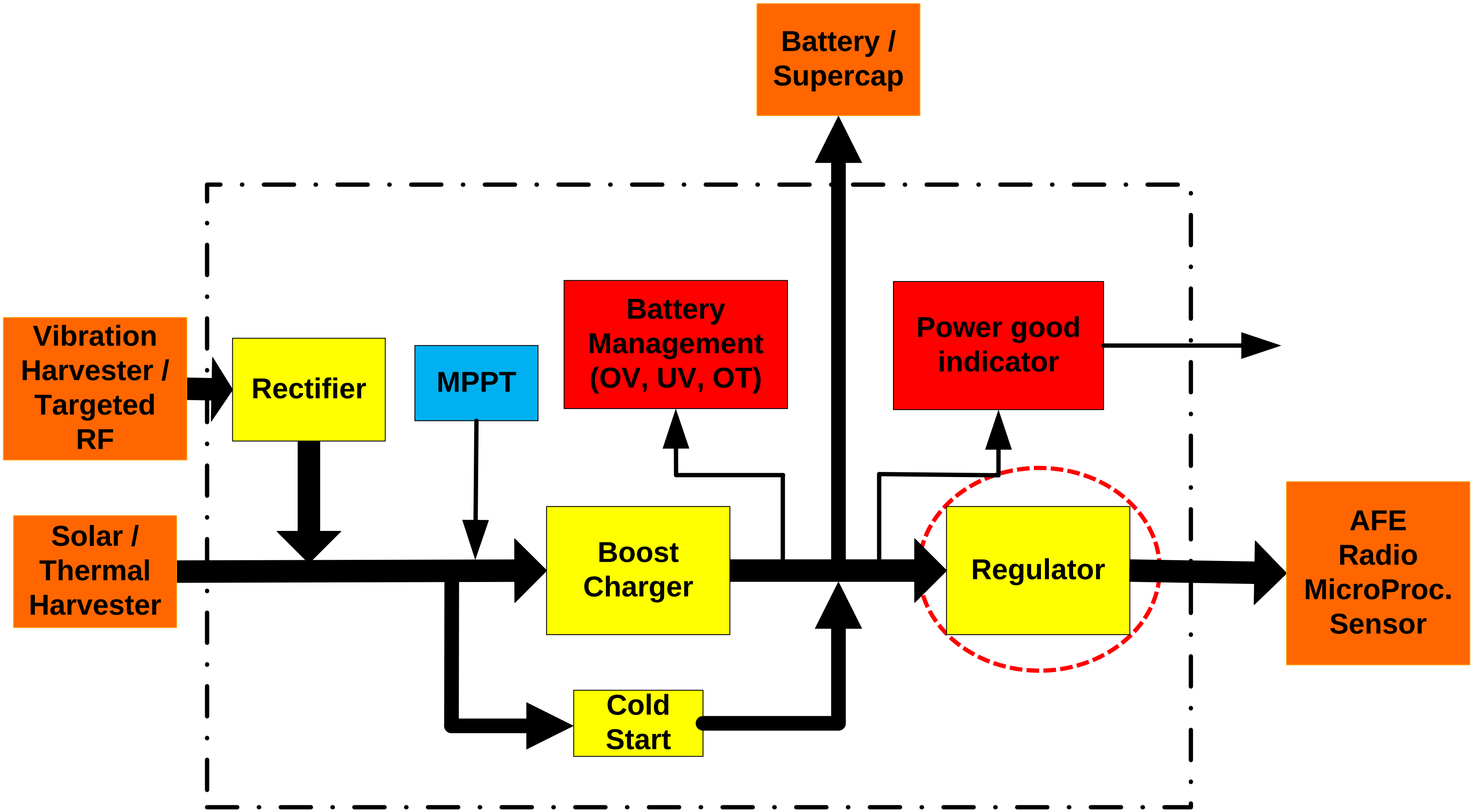
330mV Cold Start

- Function : Start system with depleted storage
- Architecture : **Input** powered boost converter



K. Kadirvel, ISSCC, 2012

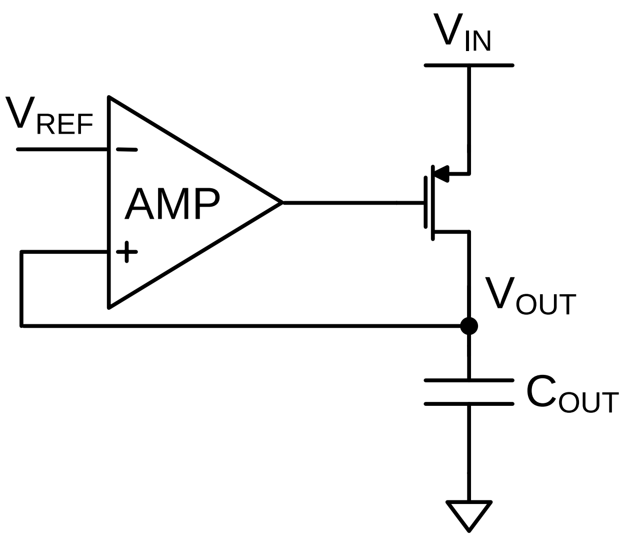
Regulator



Present stored energy as a regulated supply to load circuits

DC-DC Converter Topologies

	Linear (LDO) Regulators		
Fully integrated	√		
High efficiency	X		
Voltage Scalability	√		



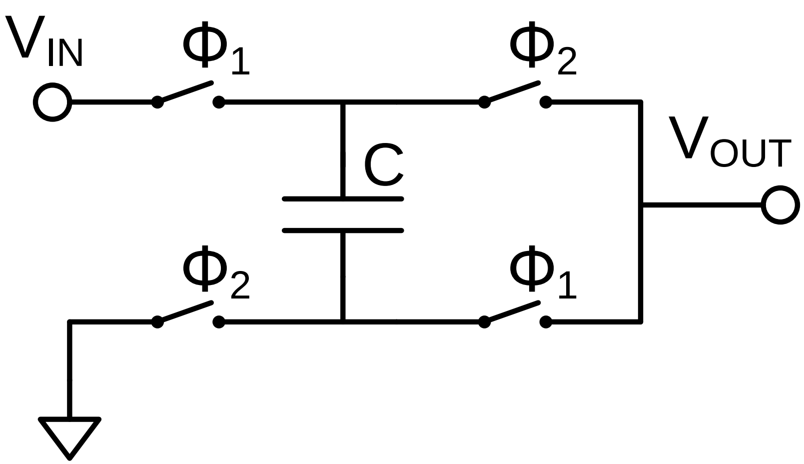
- Linear loss in efficiency
- Compact and easy to control

$$\boxed{\eta = \frac{V_{OUT}}{V_{IN}}}$$

M. Al-Shyoukh et al., "A Transient Enhanced Low-Quiescent Current Low-Dropout Regulator with Buffer Impedance Attenuation" IEEE JSSC, Aug 2007

DC-DC Converter Topologies

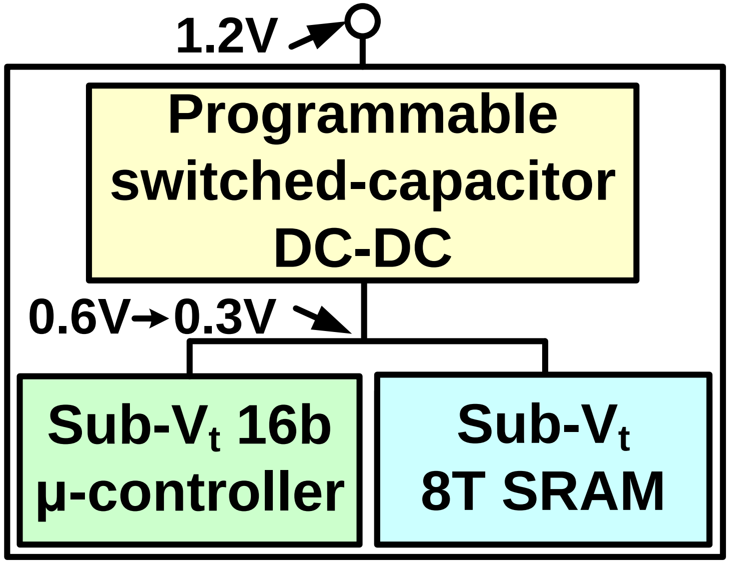
	Linear (LDO) Regulators	Switched Capacitor Converters	
Fully integrated	√	√	
High efficiency	X	√	
Voltage Scalability	√	X	

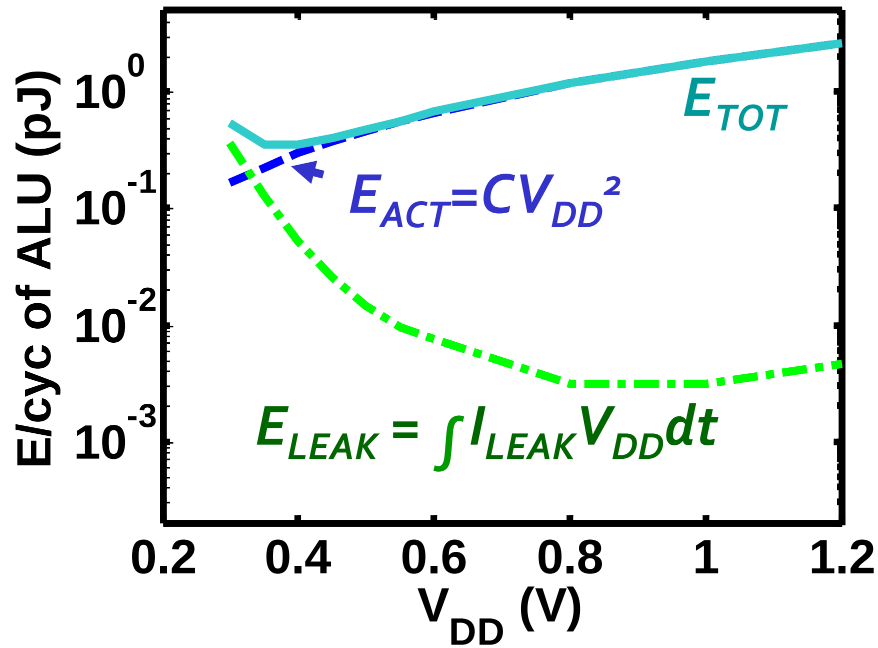


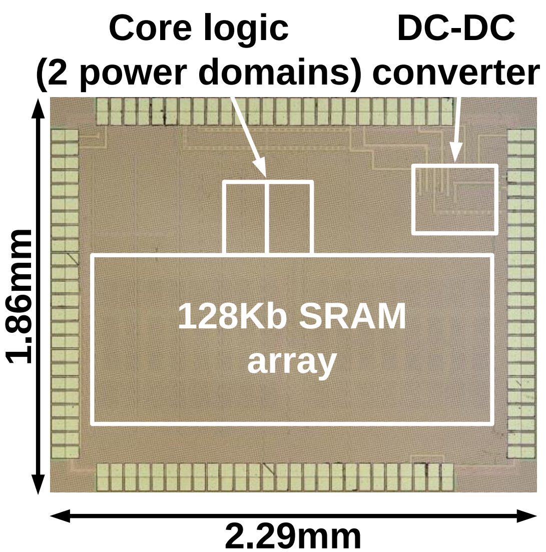
- Maintaining efficiency across load voltages is difficult
- Output current capability is limited

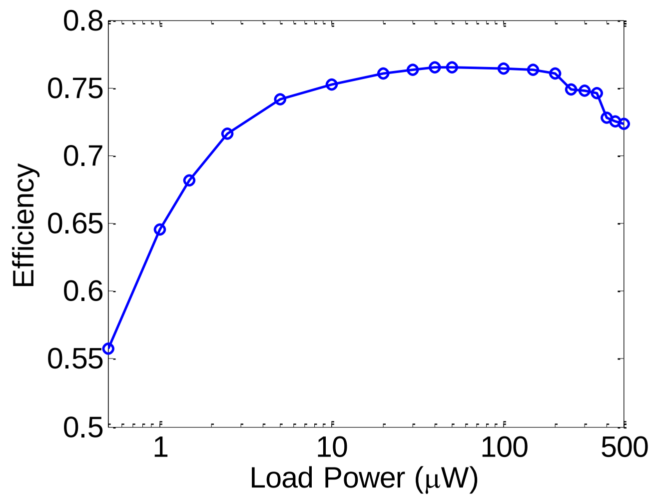
1) *Y. Ramadass et al., "A 0.16mm² Completely On-Chip Switched-Capacitor DC-DC Converter Using Digital Capacitance Modulation for LDO Replacement in 45nm CMOS ," IEEE ISSSC, 2010*
2) *Michael Seeman et al., "A Comparative Analysis of Switched-Capacitor and Inductor-Based DC-DC Conversion Technologies," Control and Modeling for Power Electronics, 2010*

Subthreshold MSP430 Microcontroller







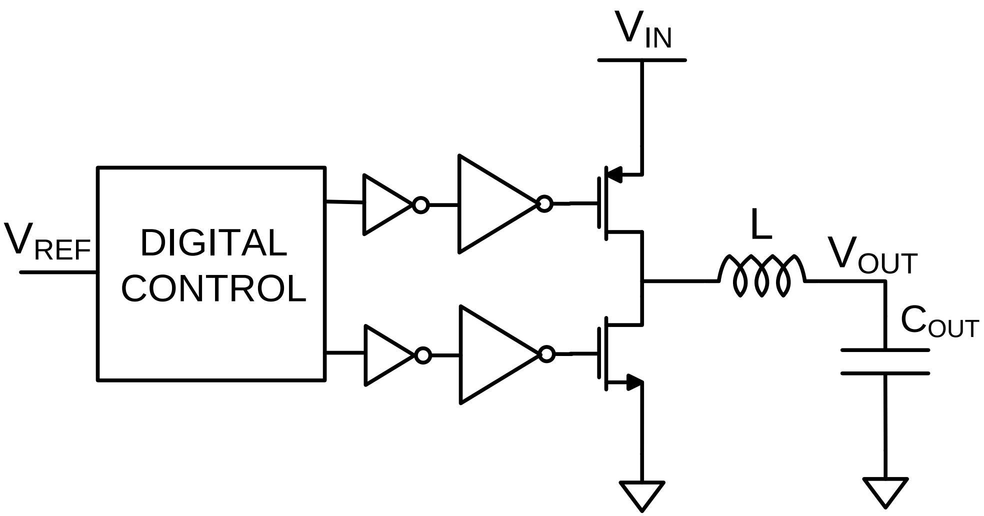


Process	65nm CMOS
Area	
DC-DC Converter	0.12mm²
SRAM	1.36mm²
Logic	0.14mm²
Performance	
Minimum Energy Point	V_{DD} = 500mV
Minimum Functional V_{DD}	V_{DD} = 300mV

Joyce Kwong et. al, ISSCC 2008

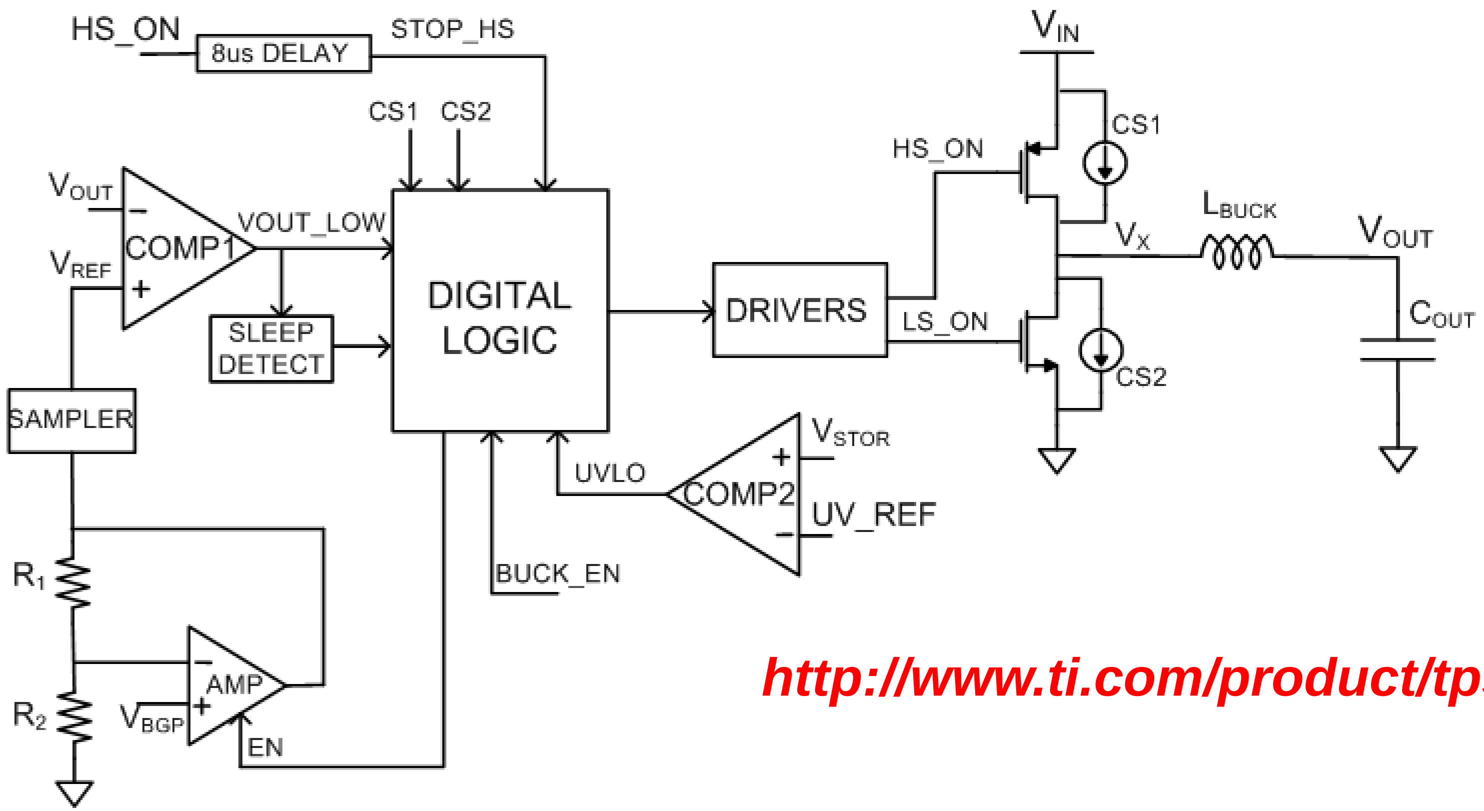
DC-DC Converter Topologies

	Linear (LDO) Regulators	Switched Capacitor Converters	Inductor-based Switching Converters
Fully integrated	√	√	X
High efficiency	X	√	√√
Voltage Scalability	√	X	√



- Needs an external inductor
- Can achieve very high efficiency
- Wide range of output voltages

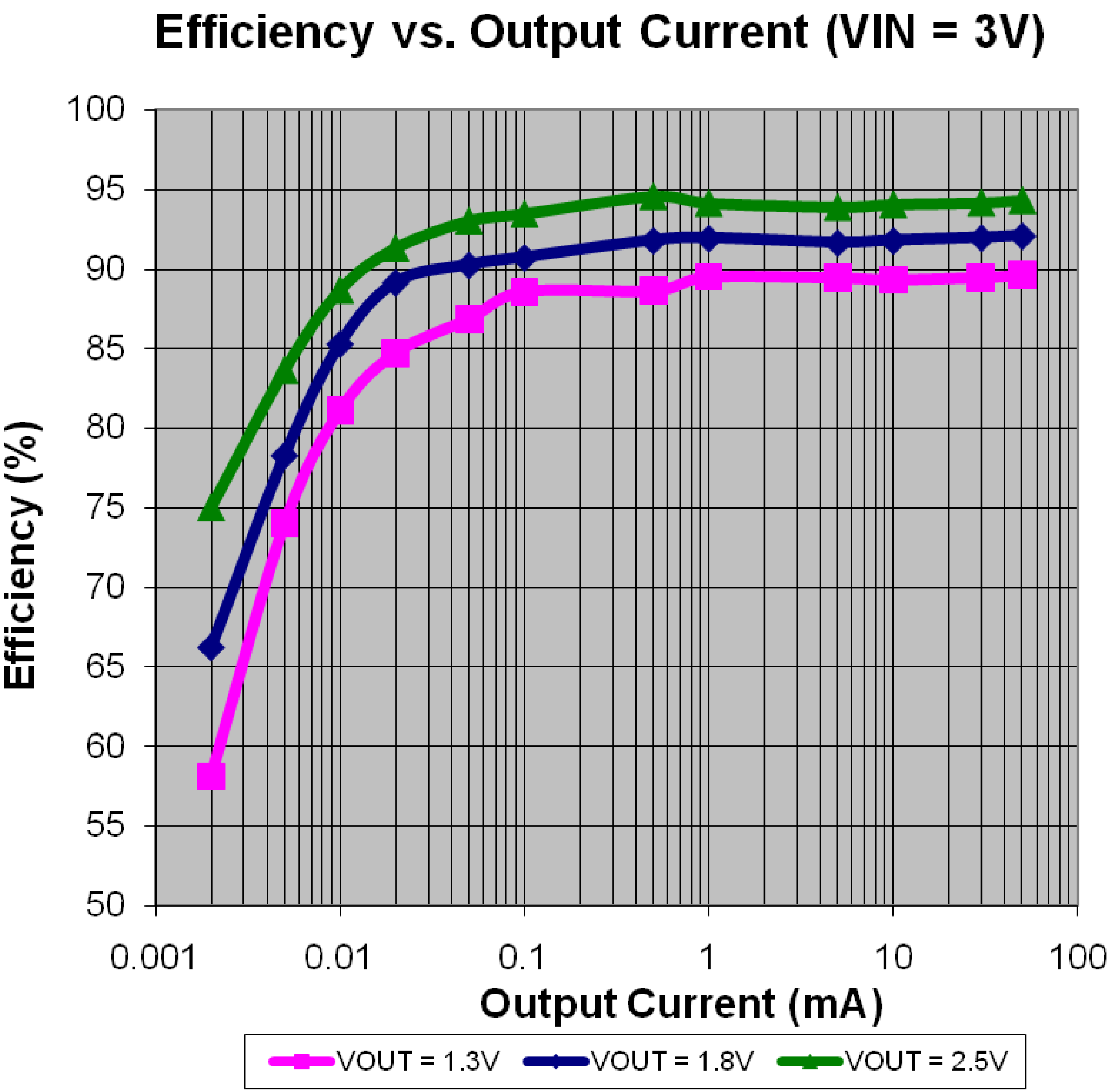
TPS62736 Buck Converter Architecture



http://www.ti.com/product/tps62736

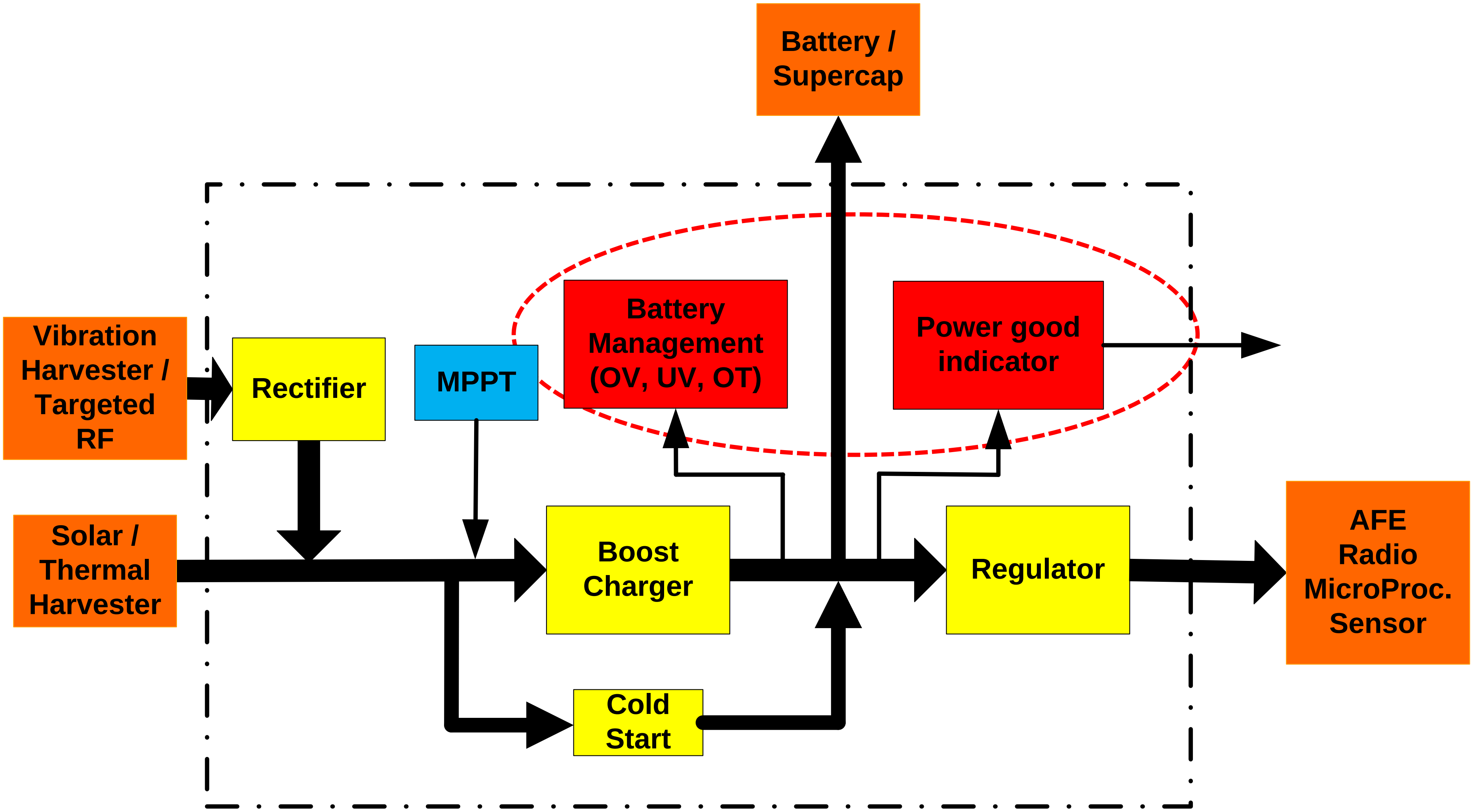
- Input voltage: 2V – 5.5V
- Output programmable between 1.3V – 5.25V
- Up to 50mA load current

TPS62736 Buck Converter Efficiency

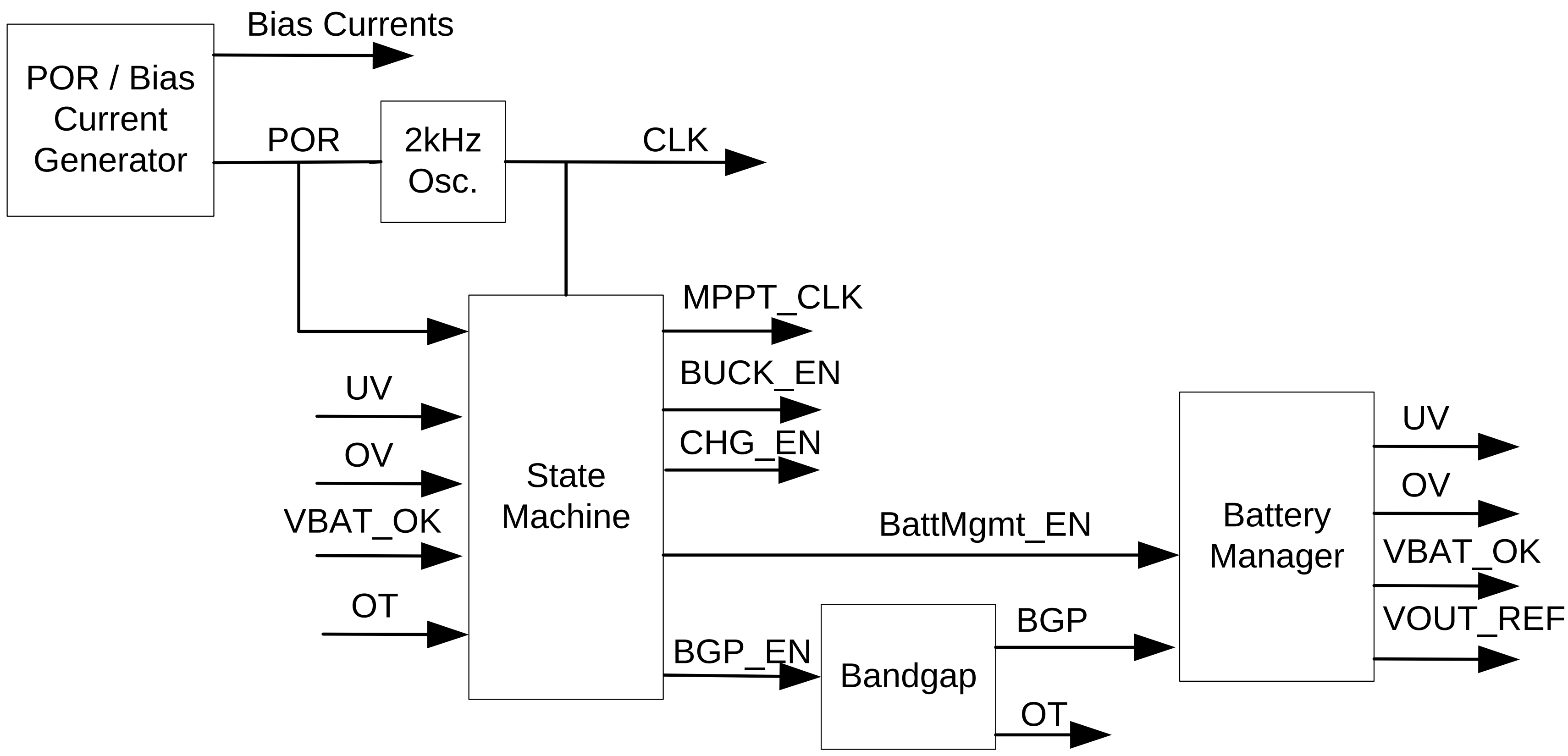


- Maintains constant efficiency from 20µA to 50mA
- >80% down to 10µA
- IQ = 360nA

Battery Management and Peripherals

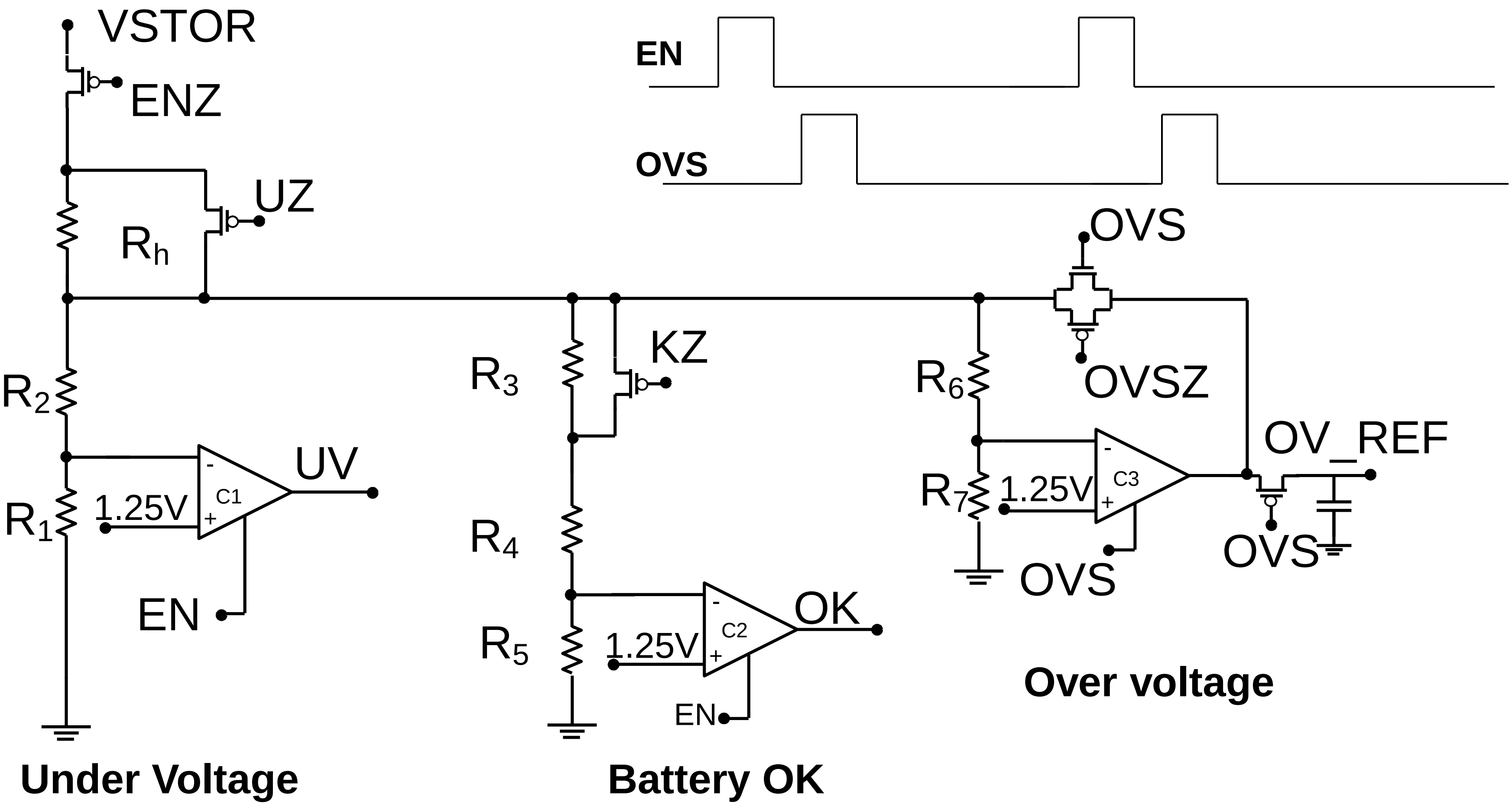


BQ25570 Essential Peripheral Circuits



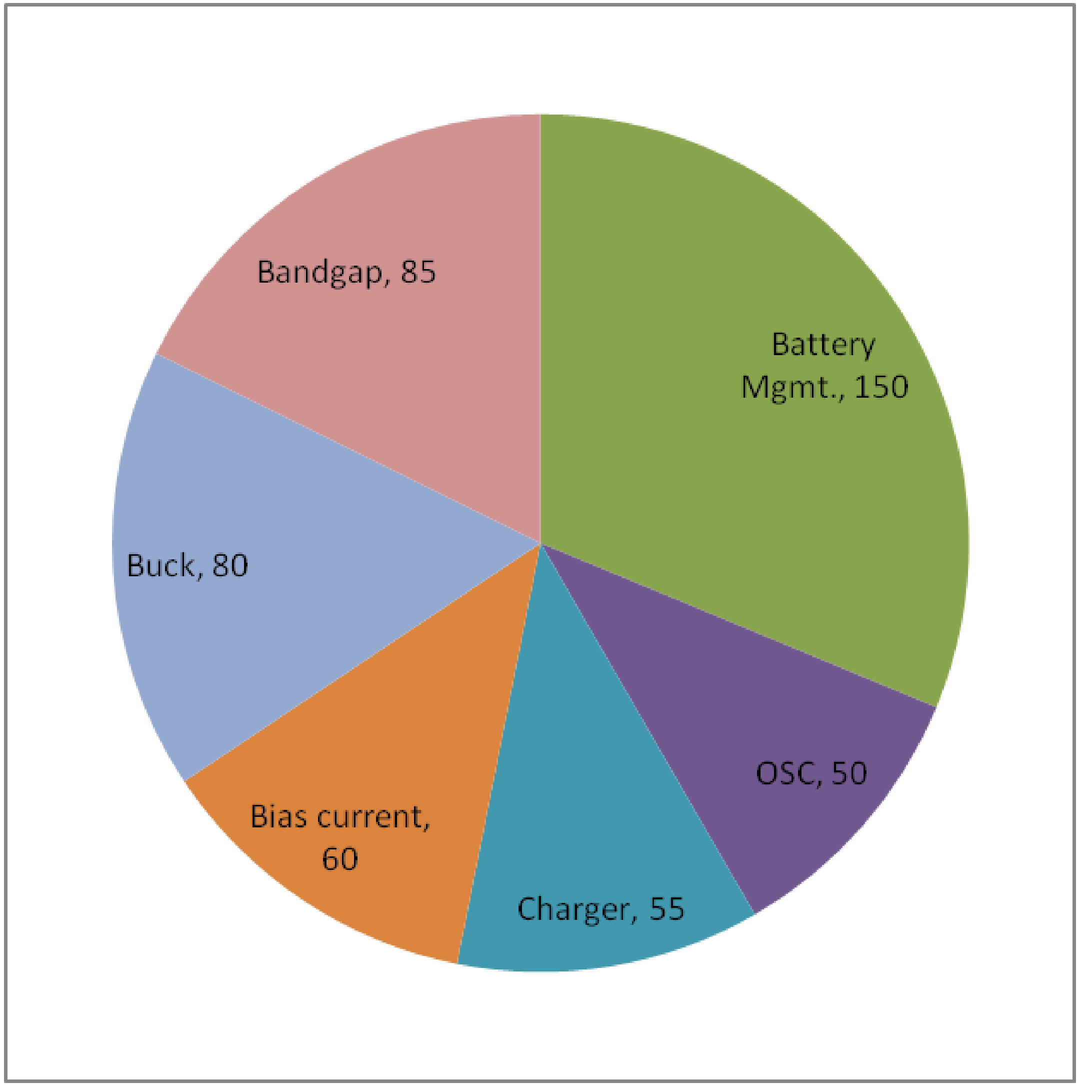
Protect the storage element, manage the IC and indicate level of stored energy

Battery Mgmt. Architecture



- Resistor programmable UV, OK, OV
- Cycle repeats every 64ms
- Duty cycled and sampled reference

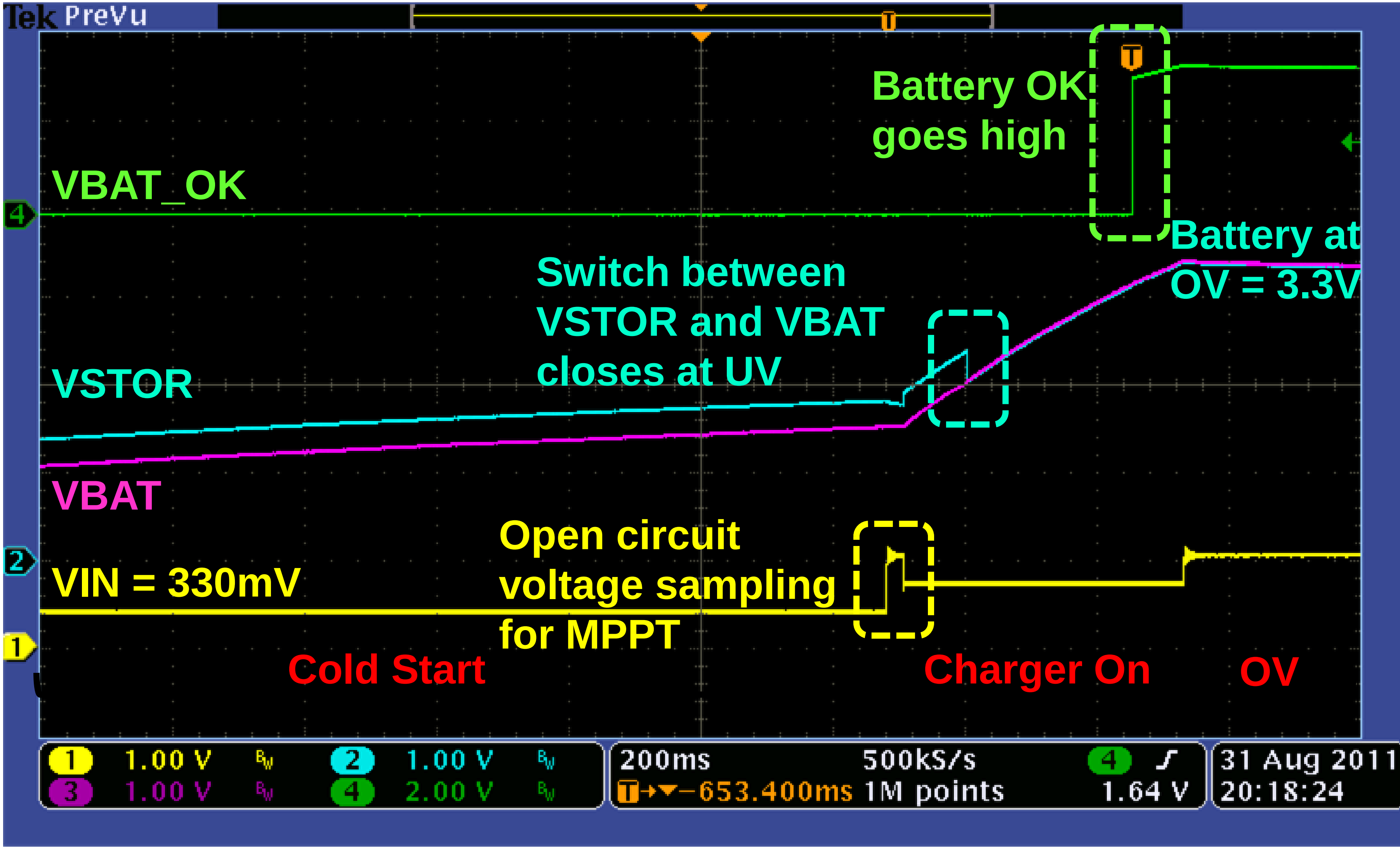
BQ25570 Quiescent Current



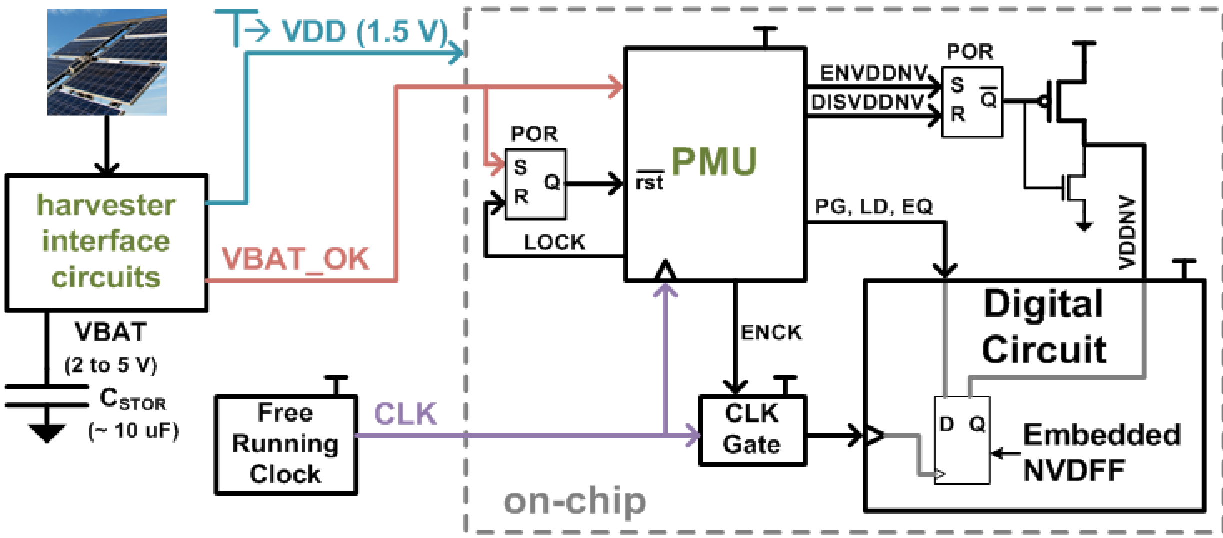
- VBAT = **3V**
- Overall Quiescent current : **480nA**
- Battery leakage below UV **= 1nA**

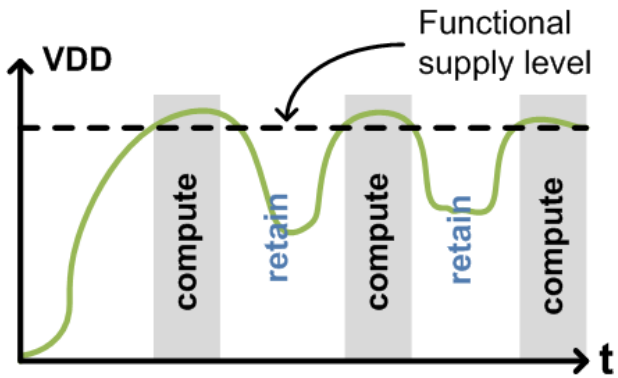
Currents in nA

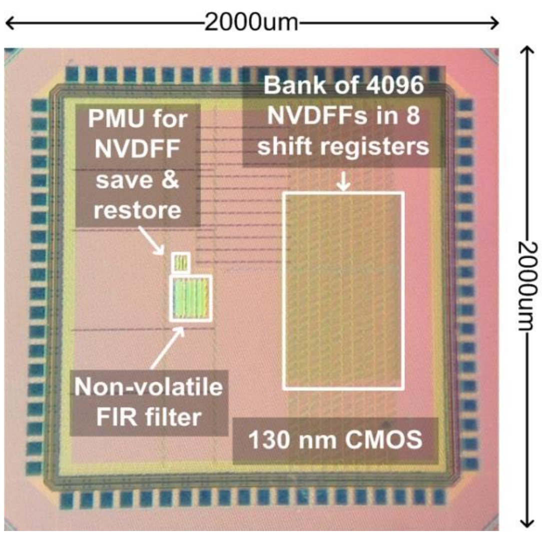
BQ25570 System Startup

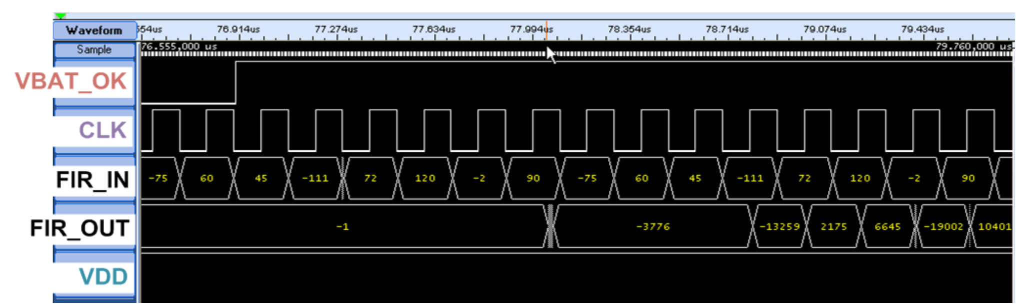


Computing Architecture with Energy Harvesting





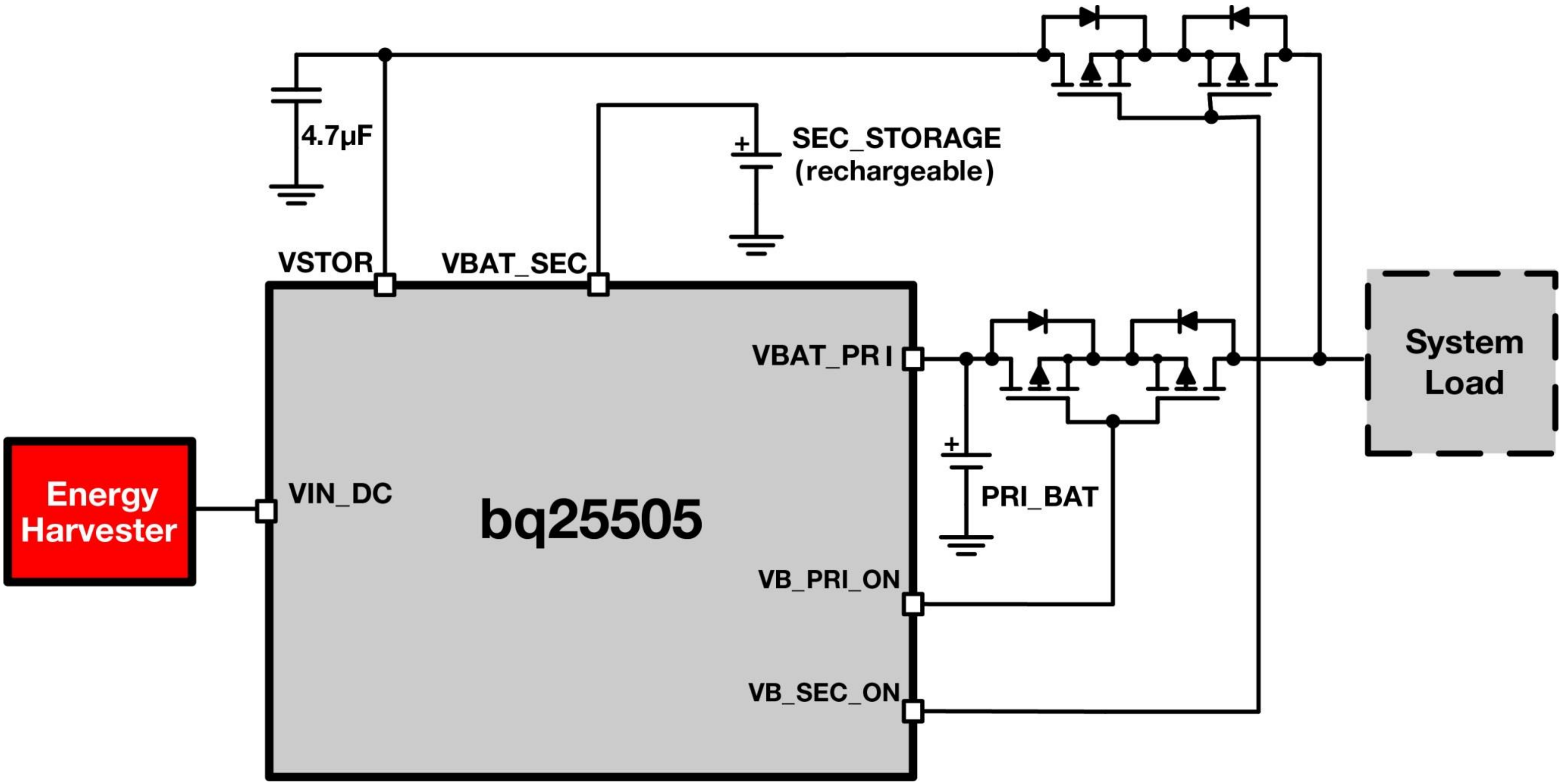




- Rapid transition from sleep to active

[M. Qazi, ISSCC 2013]

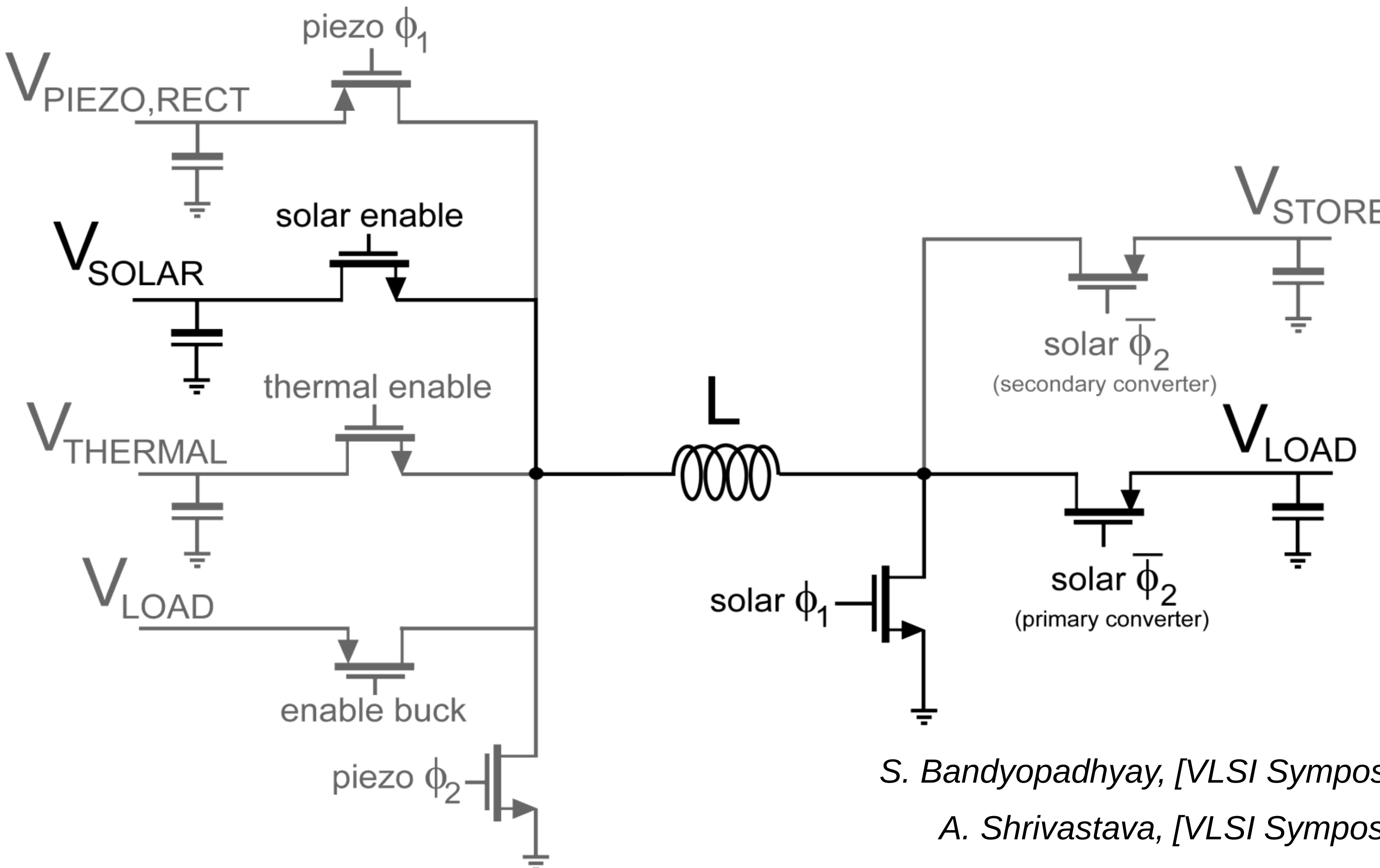
Energy Harvesting with Battery Backup



http://www.ti.com/product/bq25505

Autonomous handoff between primary and secondary storage

Energy Combining and Inductor Sharing



S. Bandyopadhyay, [VLSI Symposium 2013]

A. Shrivastava, [VLSI Symposium 2014]

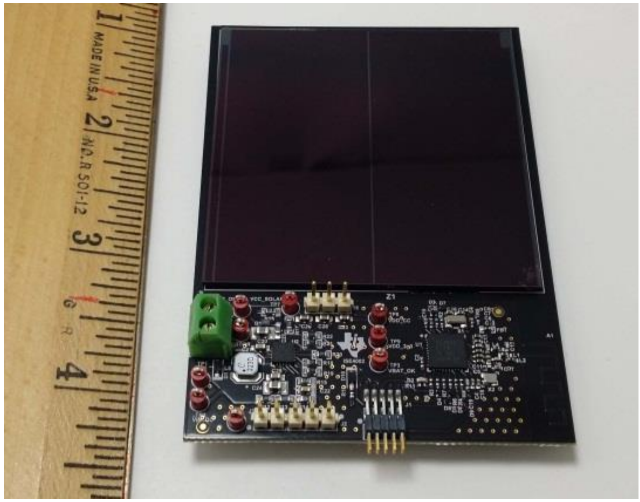
- A single inductor is shared between multiple harvesters and output voltage regulators

Indoor Light Harvesting for Bluetooth LE (BLE) Beacons

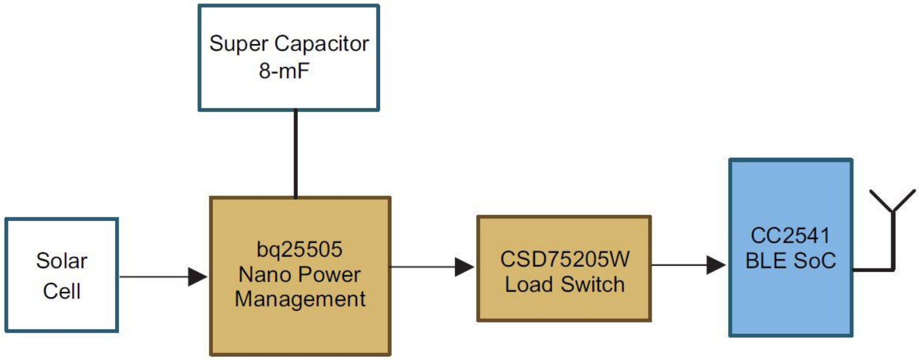
Required Energy Budget Calculation

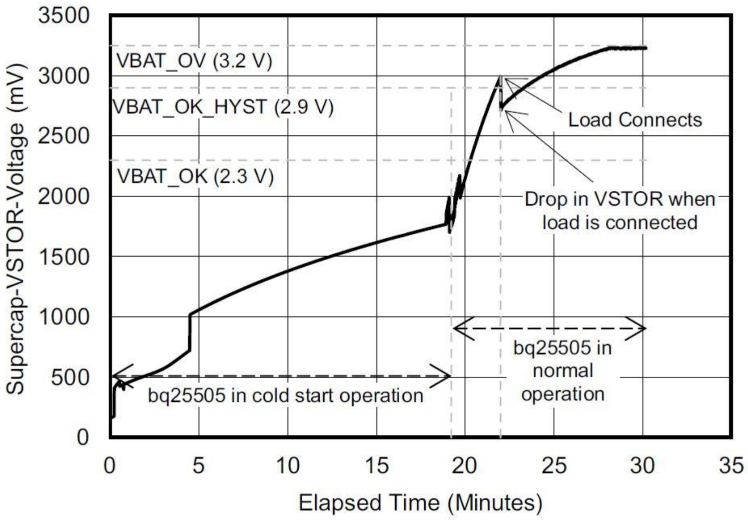
	CURRENT	VOLTAGE	POWER	TIME	ENERGY	ENERGY (RMS)
Event	mA	V	mA.V	ms	uW.s	uW.s
BLE Beacon Region 1	32	3.1	99.2	0.2	19.84 [(1)]	14.03
BLE Beacon Region 2	7.5	3.1	23.25	0.6	13.95	13.95
BLE Beacon Region 3	7.5	3.1	23.25	0.4	9.30	9.30
BLE Beacon Region 4	20	3.1	62	0.6	37.20	37.20
BLE Beacon Region 5	7.5	3.1	23.25	1.4	32.55	32.55
LED Blinking	0.45	3.1	1.395	50	69.75	69.75
CC2541 Sleep	0.001	3.1	0.0031	946.8	2.94	2.94
		Total Energy Budget				179.71 uW.s

(1) Note that for the BLE Beacon Region 1, which is a high energy current pulse at the beginning, an RMS value has been used to realistically reflect the energy usage.



Solar cell provides 400µW at 450Lux





Summary

- Advances in circuit design techniques and architectures have made it possible for electronic systems to be completely self-powered
- Energy harvesting sources differ in characteristics from conventional batteries requiring specialized interface circuits
- Optimized energy processing circuits are crucial to manage the ultra-low power levels output by energy harvesters
- Holistic optimization of the complete system from the energy sources to the load circuits is key to building and powering a successful IoT system