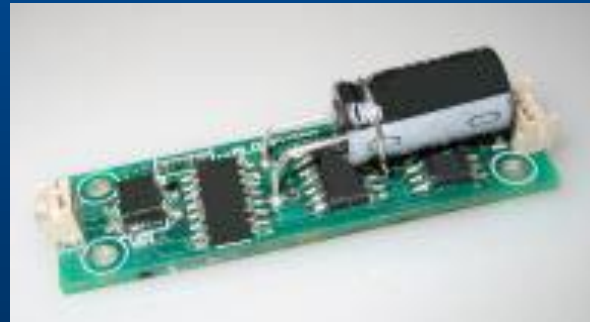




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Energy Harvesting Electronics for TEG, PV and EM Micro-Power Generators





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Energy Harvesting Sources

Common Energy Harvesting Sources

- Mechanical Energy (PZT)
 - Vibration, Stress
- Thermal Energy (TEG)
 - Furnaces, Heaters, Friction
- Light Energy (PV)
 - Photo-sensor, Photo-diode
- Electro-Magnetic (EM)
 - Inductors, Coils, Transformers
- Natural Resources
 - Wind, Water, Solar, Human
- Other
 - Chemical, Biological



Thermoelectric Energy Generator (TEG)

- Capture from small thermal differentials from 1°K to 10°K
- Ambient/Natural Environmental
- Human Body heat
- Higher thermal differentials from 10°K to 100°K
- Waste heat/ exhaust from machinery and motors



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Low Voltage EH Sources

Photovoltaic Energy Generators (PV)

- Photo-sensor, Photo-diode
- Single-Cell Photovoltaic Cell tapping ambient indoor lights
- Infrared and UV sensors



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Low Voltage EH Sources

Electro-Magnetic Energy Generators (EM)

- Inductors, Coils, Transformers
- Transducers that tap ambient dynamic/RF energy sources
- Micro-turbines, low-friction coils, antennas



Design Challenges

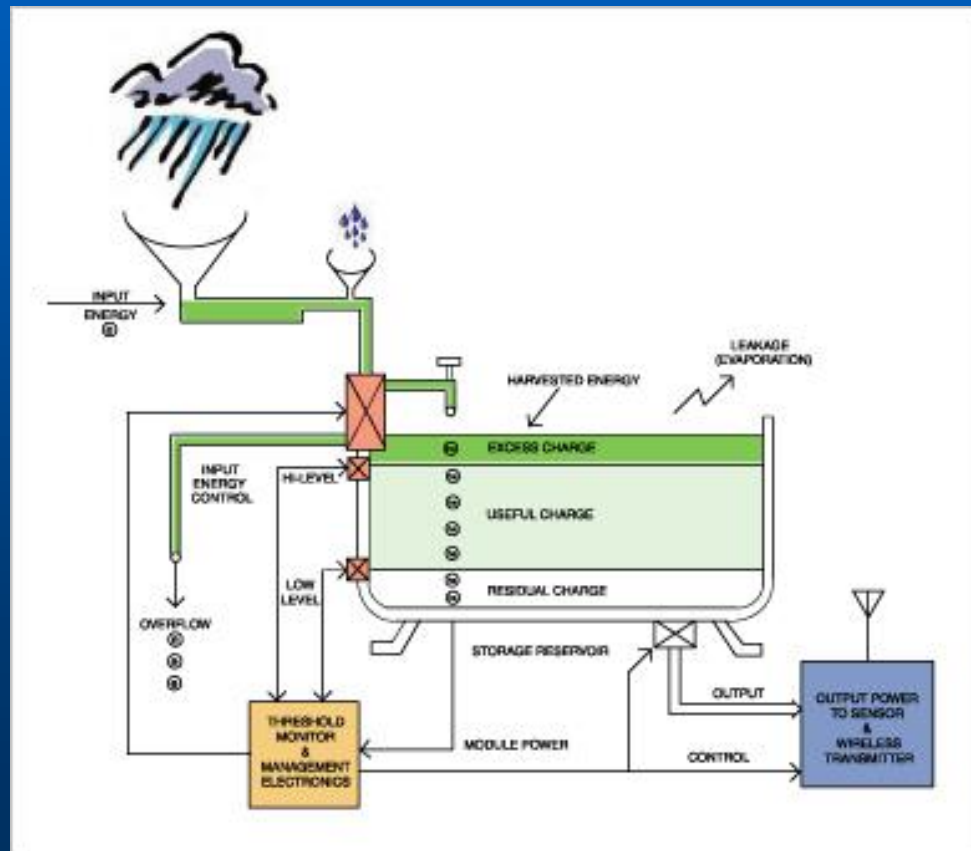
Key Design Challenges of LV EH Modules

- Accept Input Voltages Compatible to EH Generators
- Powers Electronic Circuits between 1.8V and 5V
- Perpetually self-powered and always active
- Begins charging from power generators at $<+/-0.1V$ to capture miniscule electrical impulses
- Micro-power – energy spent on its own circuit operation
- Power conversion efficiency depends on large number of variables
- Stores and manages energy for extended periods
- Long Operating Life enhances system reliability



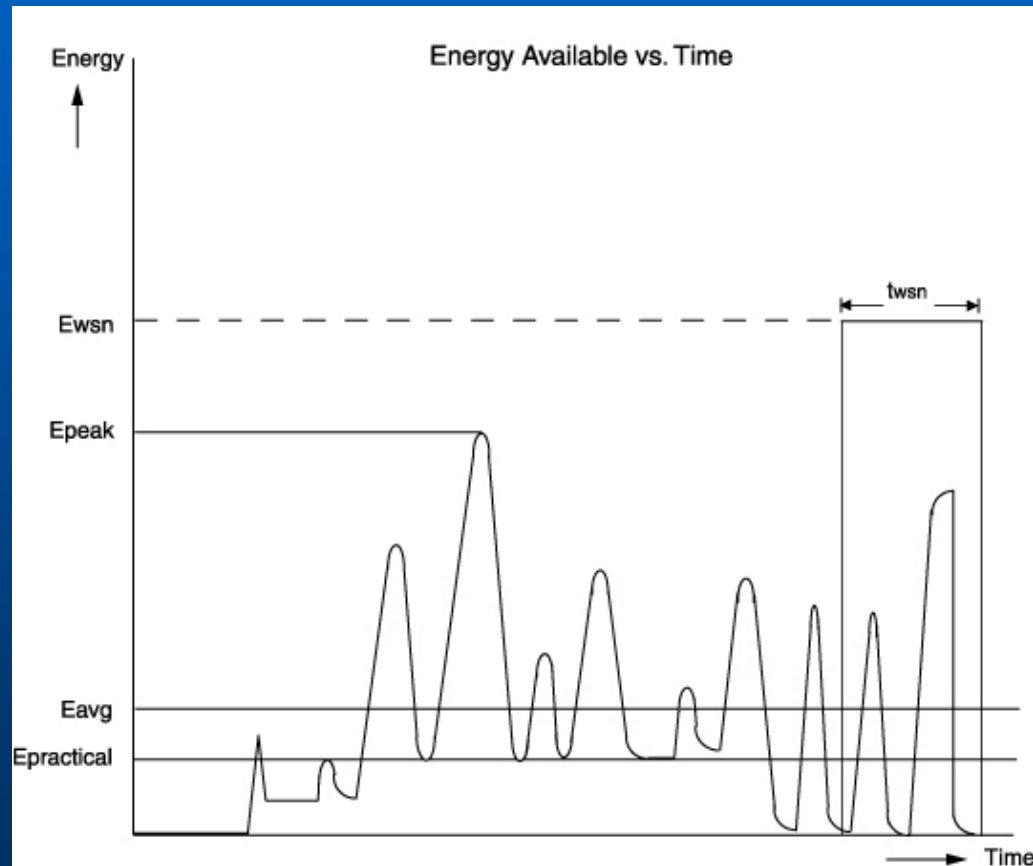
EH Concept Analogy

Capture, Accumulate, Store & Manage Energy





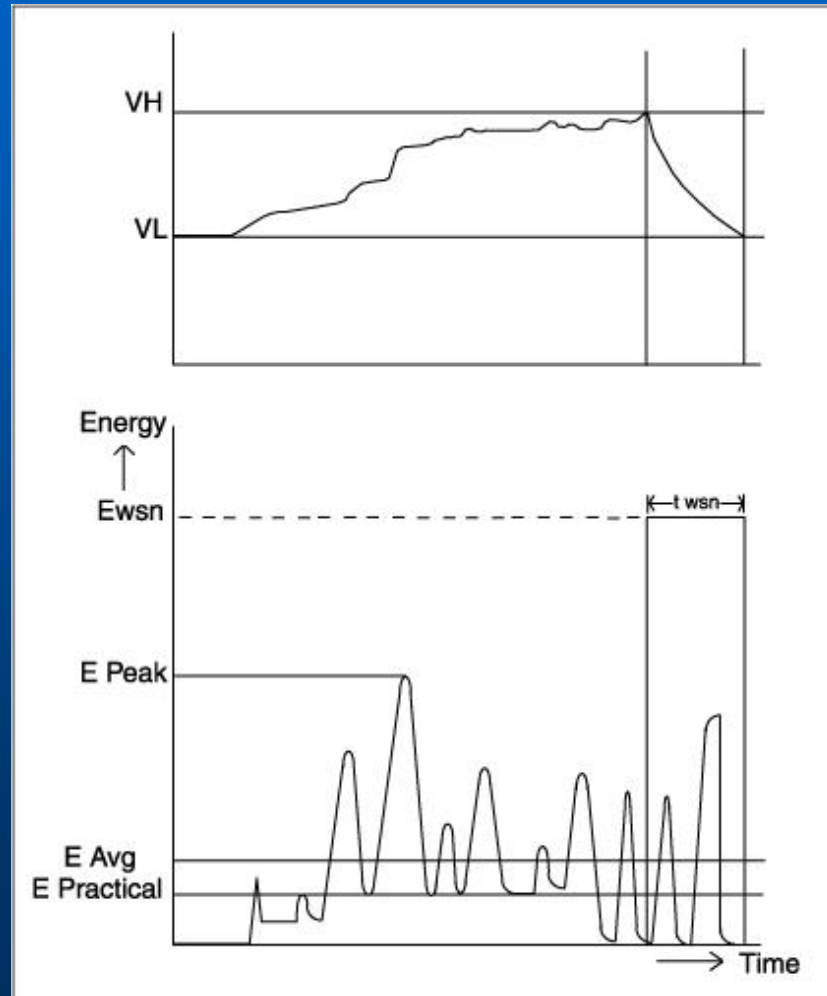
Energy Available vs. Time





Energy Available vs. Time

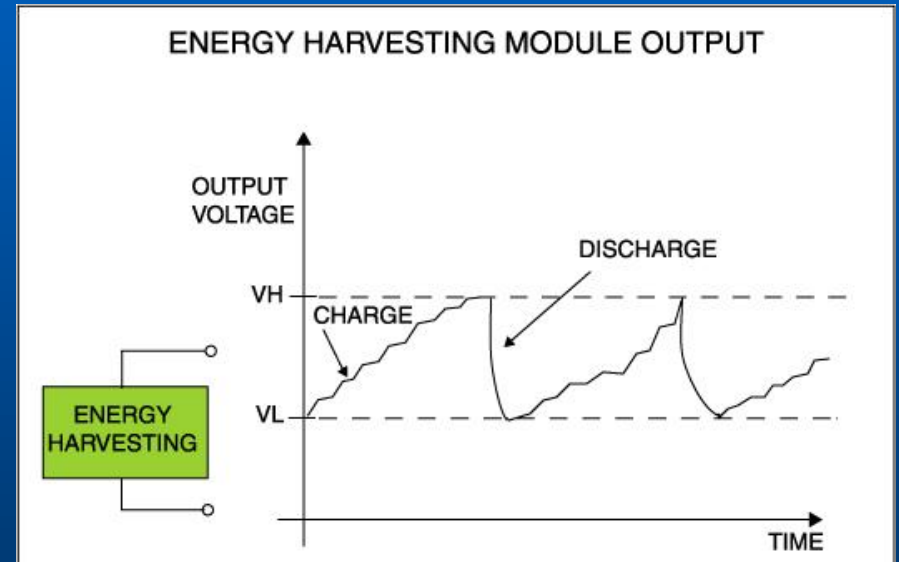
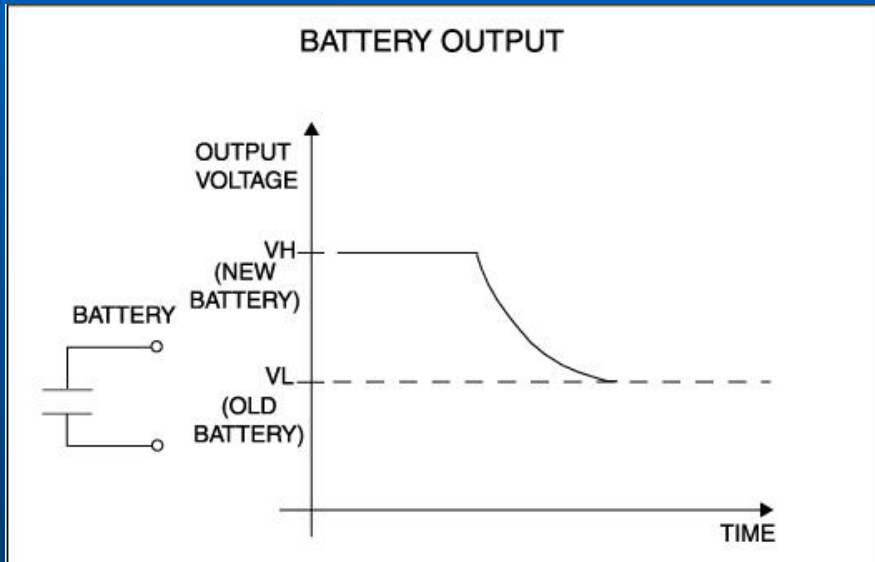
EH Module Voltage vs. Time





Energy Harvesting Modules

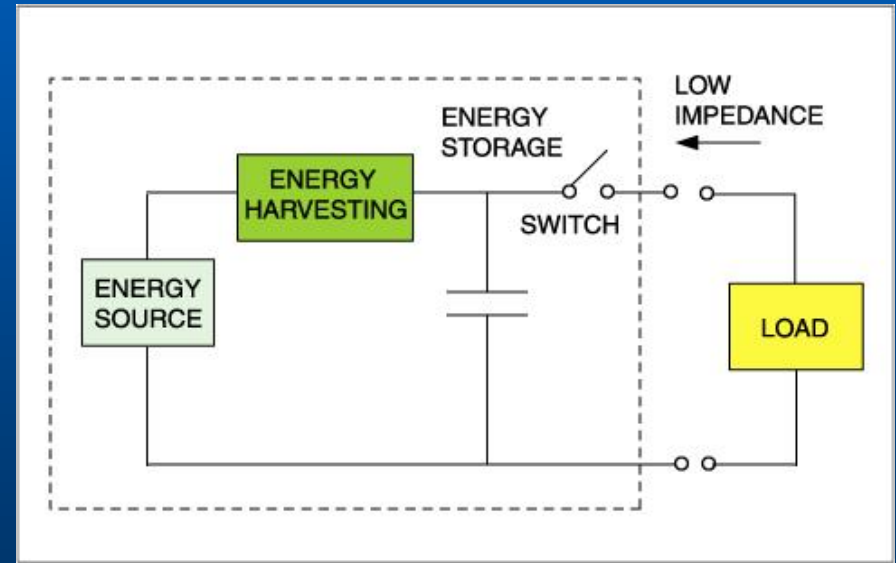
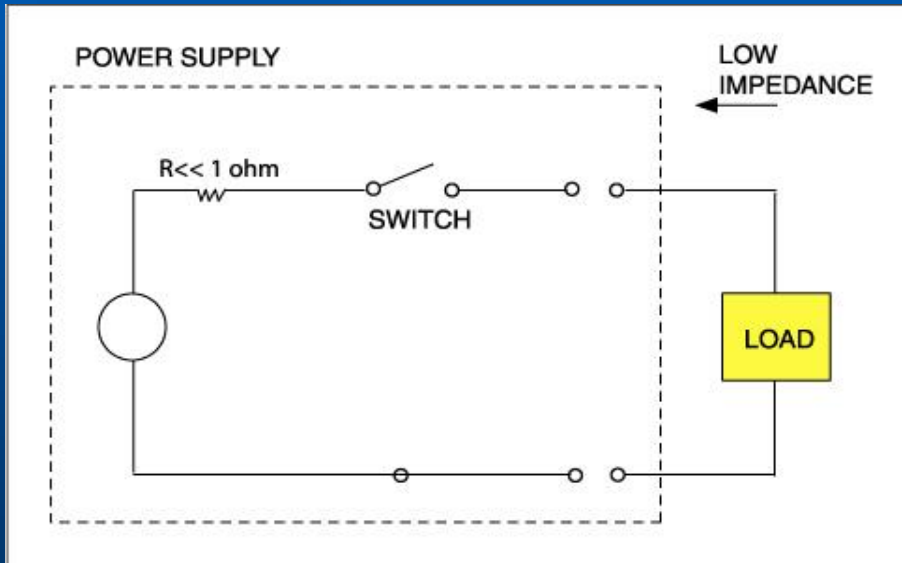
Battery Output vs. EH Module Output





Energy Harvesting Modules

Most Electronic Loads Require
a Low Impedance Power Source





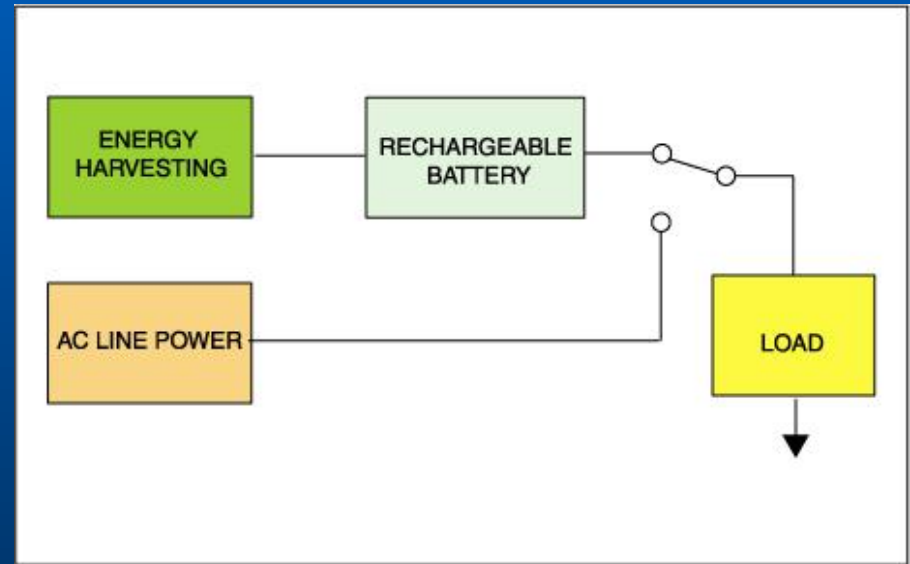
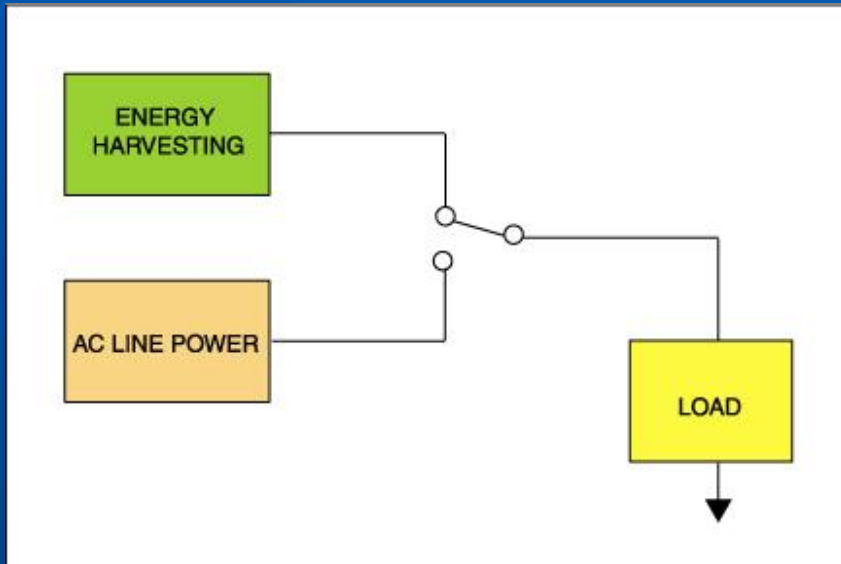
Typical EH Applications

- Extreme Life-Span Power Source
- Battery Eliminator
- Condition Based Monitoring system
- High Reliability Wireless Sensor Networks
- Battery Charger for maintenance-free applications
- Super-Capacitor charging replacing battery-based (chemical) charging
- Redundant Power Systems



Long Life & Reliability

Redundant Power Systems Improve Reliability





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Energy Harvesting Module

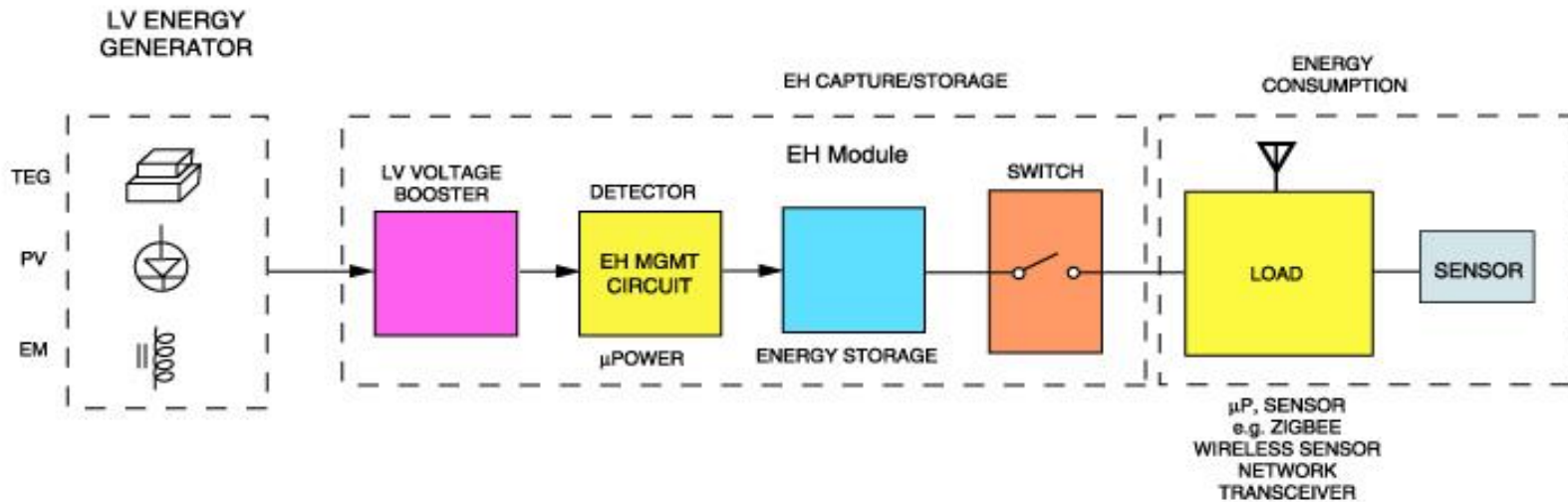
Key Functional requirements

- Energy from ultra-low-voltage ambient energy sources
- Capture, Accumulate, Store and Manage Energy
- Produce usable Energy from low cost energy generators
- Perpetually internal self-powered self-starting circuitry
- High Energy Retention
- Always active in energy capture mode
- Output directly drive CMOS ICs, μ P, WSN, ZIGBEEs
- Outlasts system deployment lifetime
- Distributed energy sources enhances system reliability
- Virtually unlimited charge/discharge cycles



Low Voltage EH System

LOW VOLTAGE ENERGY HARVESTING SYSTEM





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Low Voltage Booster Circuit

Low Voltage Booster EH Circuitry

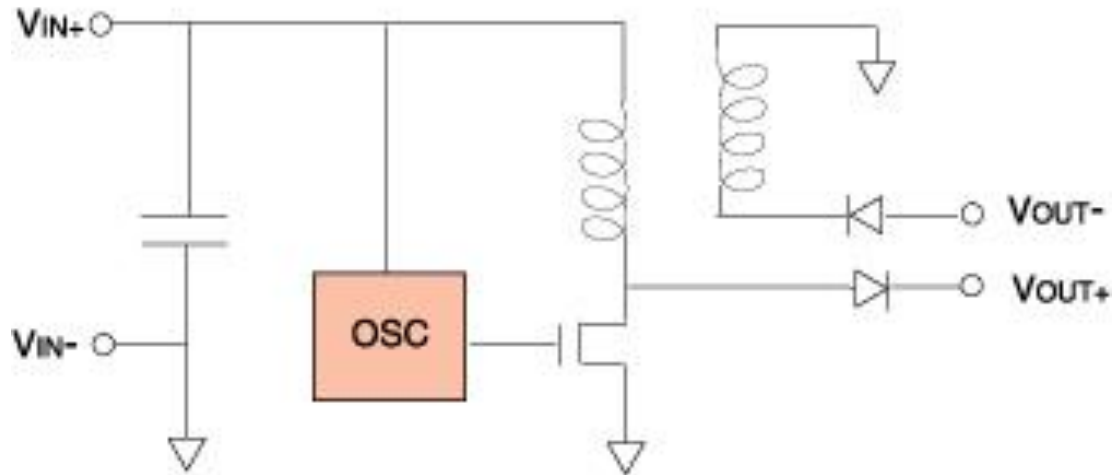
- Accepts energy from low-voltage energy sources that cannot supply adequate power for any useful purpose directly
- Accepts Intermittent Input Energy
- Accepts Steady-State Input Energy
- Provides Intermittent Low Duty-Cycle Output
- Efficiently and effectively manage harvested energy to power wireless sensor networks and other applications
- Expands range of power source beyond AC lines and batteries



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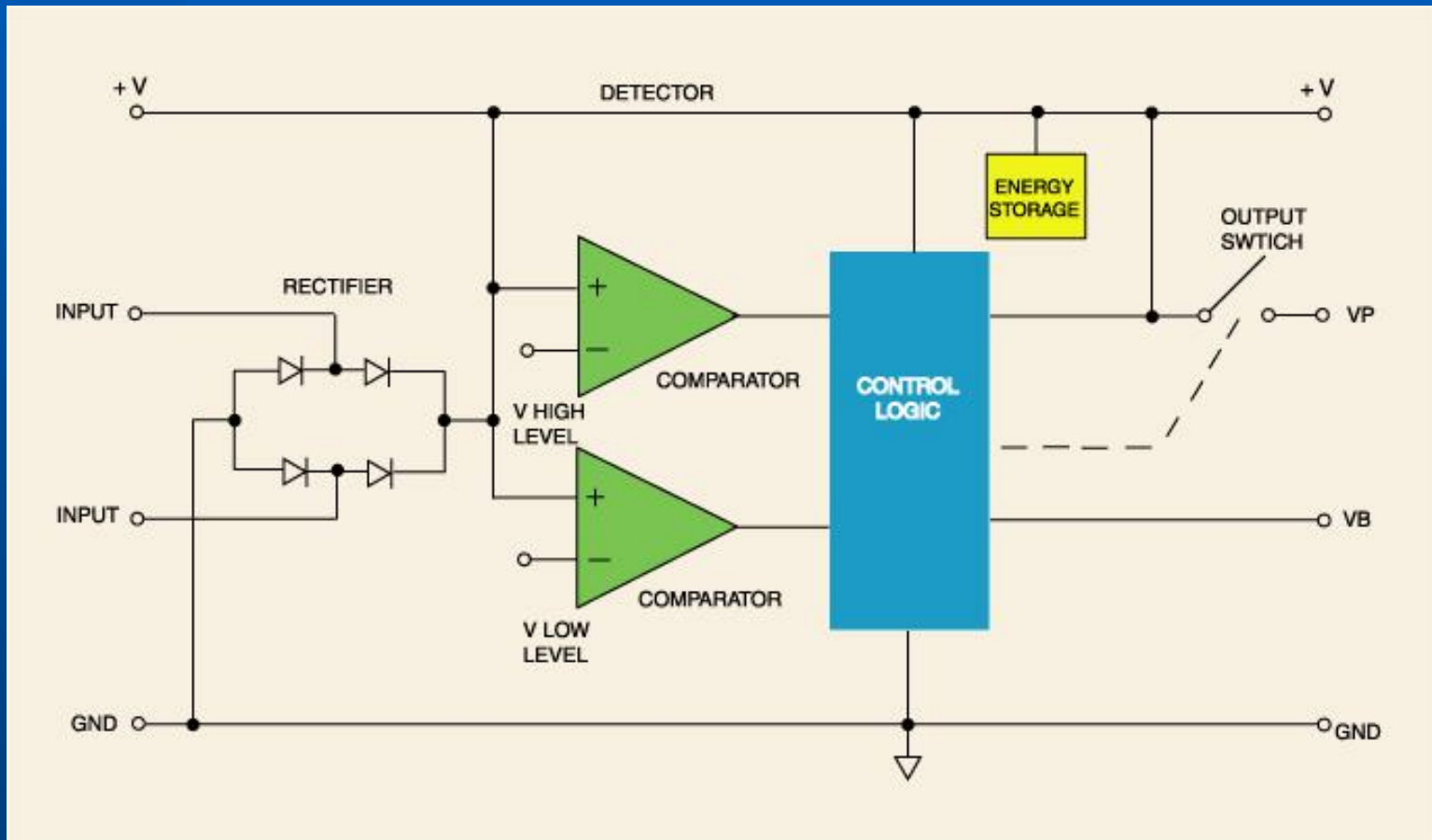
Low Voltage Booster Circuit

LOW-POWER
LOW-VOLTAGE VOLTAGE BOOSTER





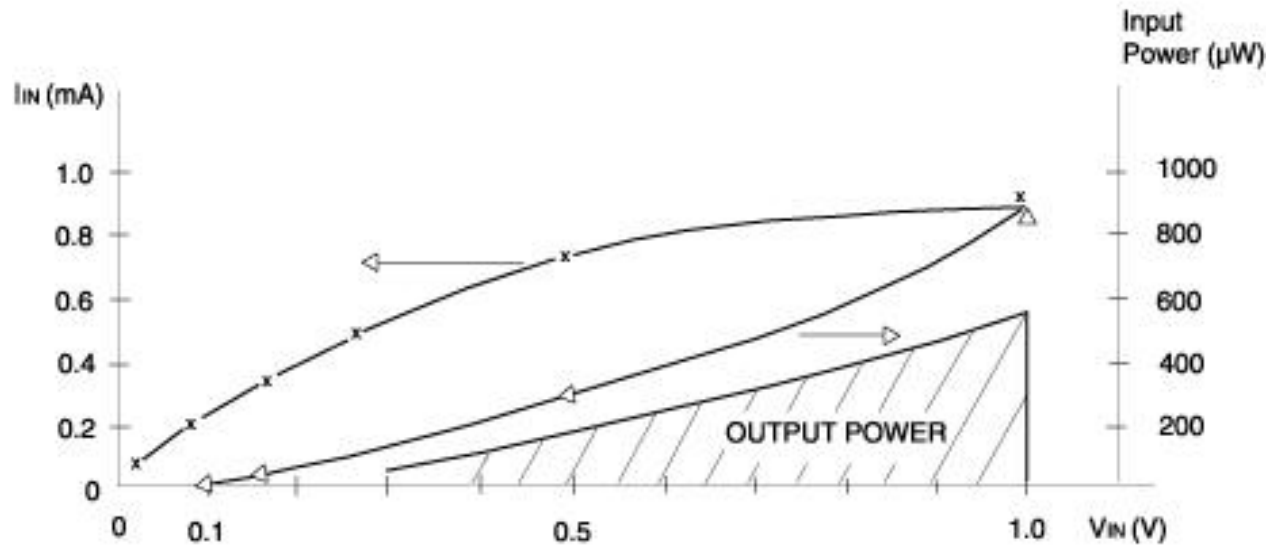
Detector Switch & Storage Module





Low Voltage Booster

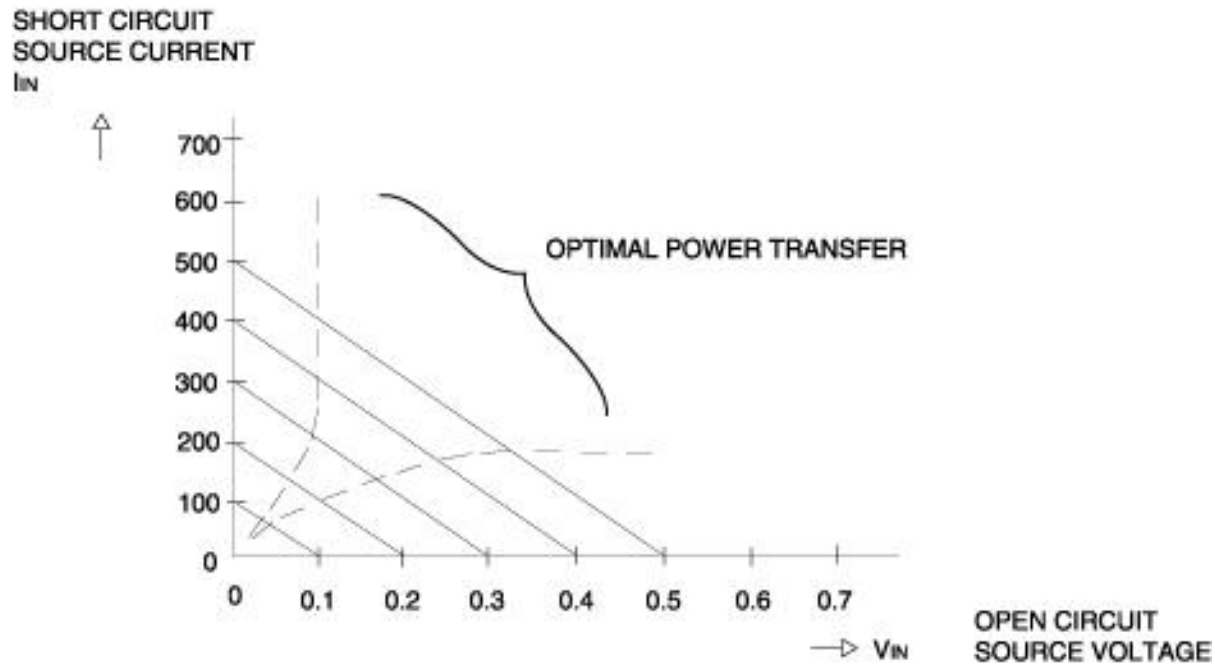
**INPUT CURRENT vs. INPUT VOLTAGE
FOR FIXED 4V OUTPUT**





Low Voltage Booster

**TYPICAL LOW VOLTAGE ENERGY GENERATOR
ELECTRICAL CHARACTERISTICS**





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Energy Harvesting Modules

Key Operating Input Parameters

EH4205/EH4295

- Input Voltage Range $< + 0.1V$ to $+ 4.0V$
- Input Current Range $100\mu A$ to $50.0mA$
- Min. Energy harvesting starts at $50mV$ and $100\mu A$
- Minimum Input Power $\sim 5 \mu W$
- Maximum Input Power $\sim 250 mW$
- Power Conversion Efficiency optimized at $\sim 0.25V$
- Energy Generator specific input designs



Key Output Electrical Parameters

EH300

- 1.8V to 3.6V operation @ Output of 4.6mJ
- Output on-time rating 68 msec@25mA

EH300A

- 1.8V to 3.6V operation @ Output of 30mJ
- Output on-time rating 75 msec@150mA

EH301

- 3.1V to 5.2V operation @ Output of 8.3mJ
- Output on-time rating 80msec@25mA

EH301A

- 3.1V to 5.2V operation @ Output of 55mJ
- Output on-time rating 88msec@150mA



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Technology Inside

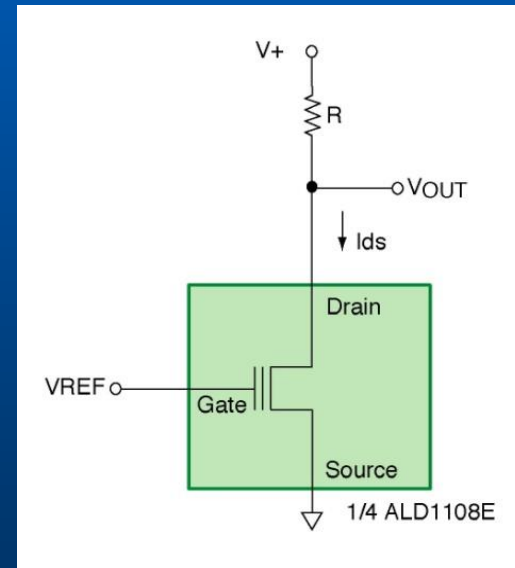
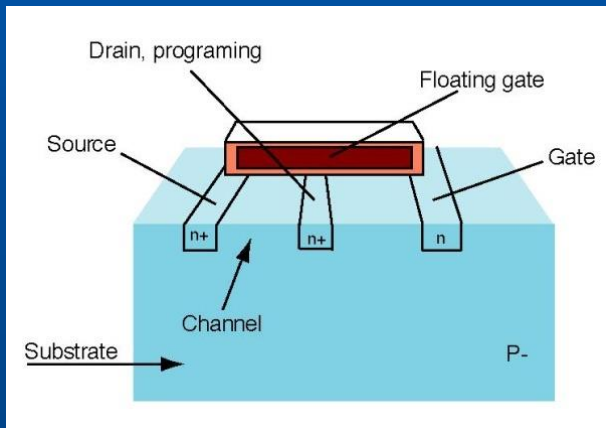
ALD EPAD® Technology



- Patented and Trademarked
- On-chip trimming and calibration
- Floating-gate MOSFET transistors
- Precision and ultra low operating voltages
- Proven EPAD® manufacturing
- 20+ Years evolution in technology and manufacturing
- Millions of circuits shipped to date



- Zero Threshold[™] MOSFETs and NanoPower[™] MOSFETs



- silicon cross section

equivalent circuit symbol



Summary

- LV low-power EH Electronics charging at $\leq \pm 0.1V$ to capture miniscule electrical impulses
- Ambient TEG, PV and EM energy sources become practical energy sources
- Paradigm change on how EH power sources operate
- EH circuits are crucial link between energy source and system load
- Intermittent duty cycle and high energy retention rate
- EH requires unique, specialized electronics technology
- Many self-powered applications with low-voltage and low-power energy generators