

TFE4188 - Lecture X

Energy Sources

Goal

Why do we need energy sources?

Introduction to **Energy Harvesting**

Why

Lithium Battery

1 year $\Rightarrow 45 \mu\text{W}/\text{cm}^3$

10 year $\Rightarrow 3.5 \mu\text{W}/\text{cm}^3$

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Towards a Green and Self-Powered Internet of Things Using Piezoelectric Energy Harvesting

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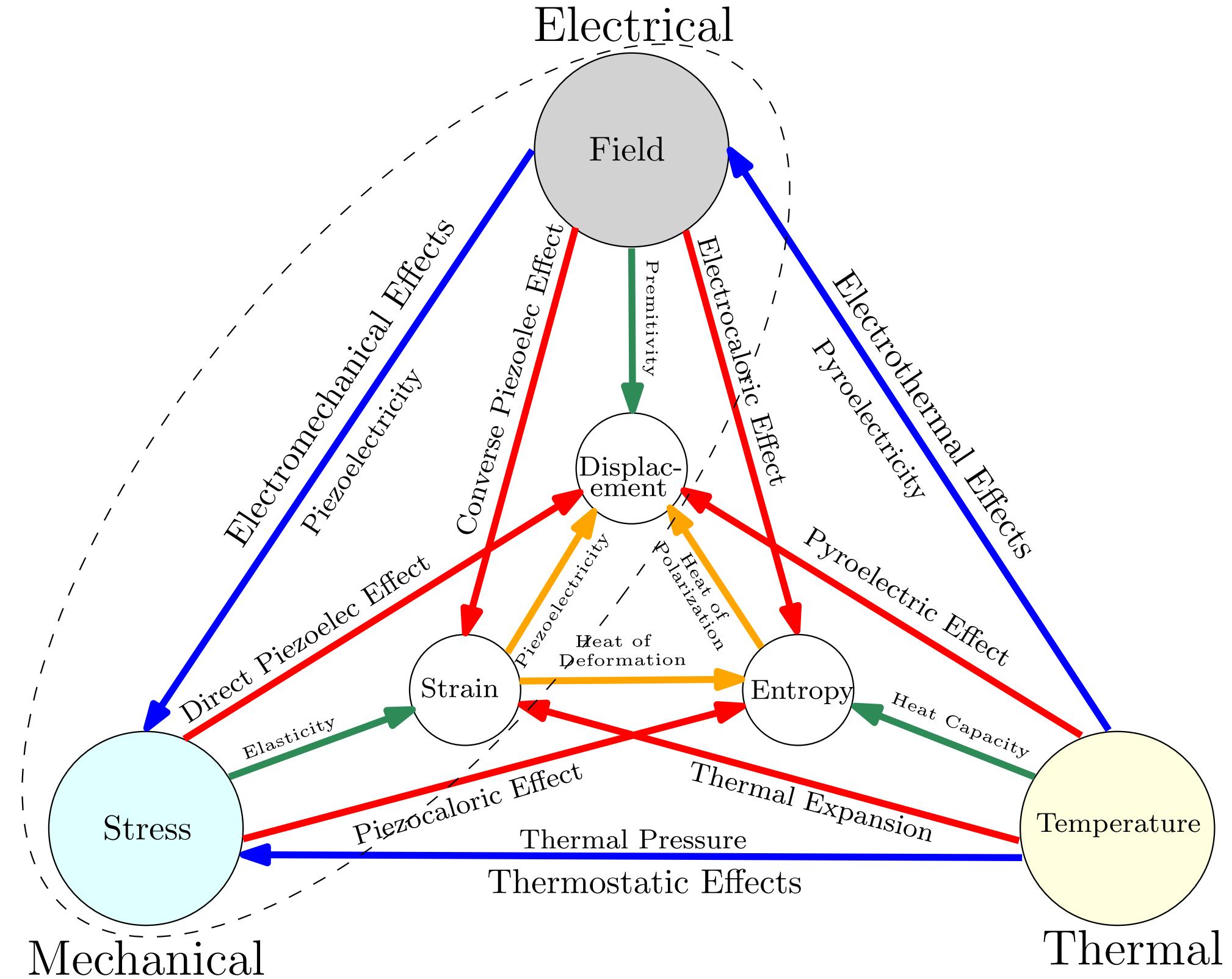


FIGURE 5. A Heckman diagram representing the interrelationship between mechanical, thermal and electrical properties of materials [41].

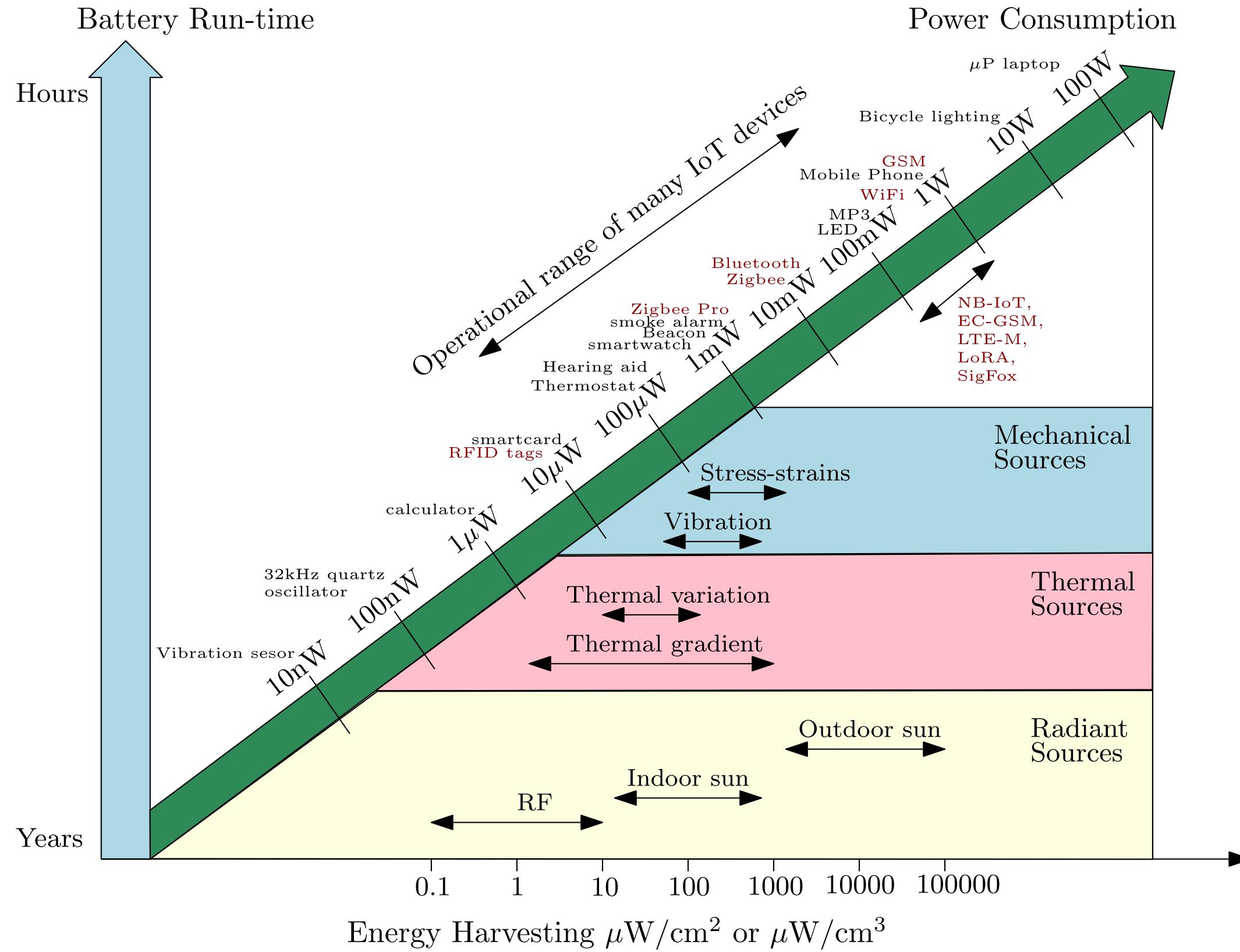


FIGURE 6. Power consumption for various applications and power densities for various energy sources (data obtained from [85]).

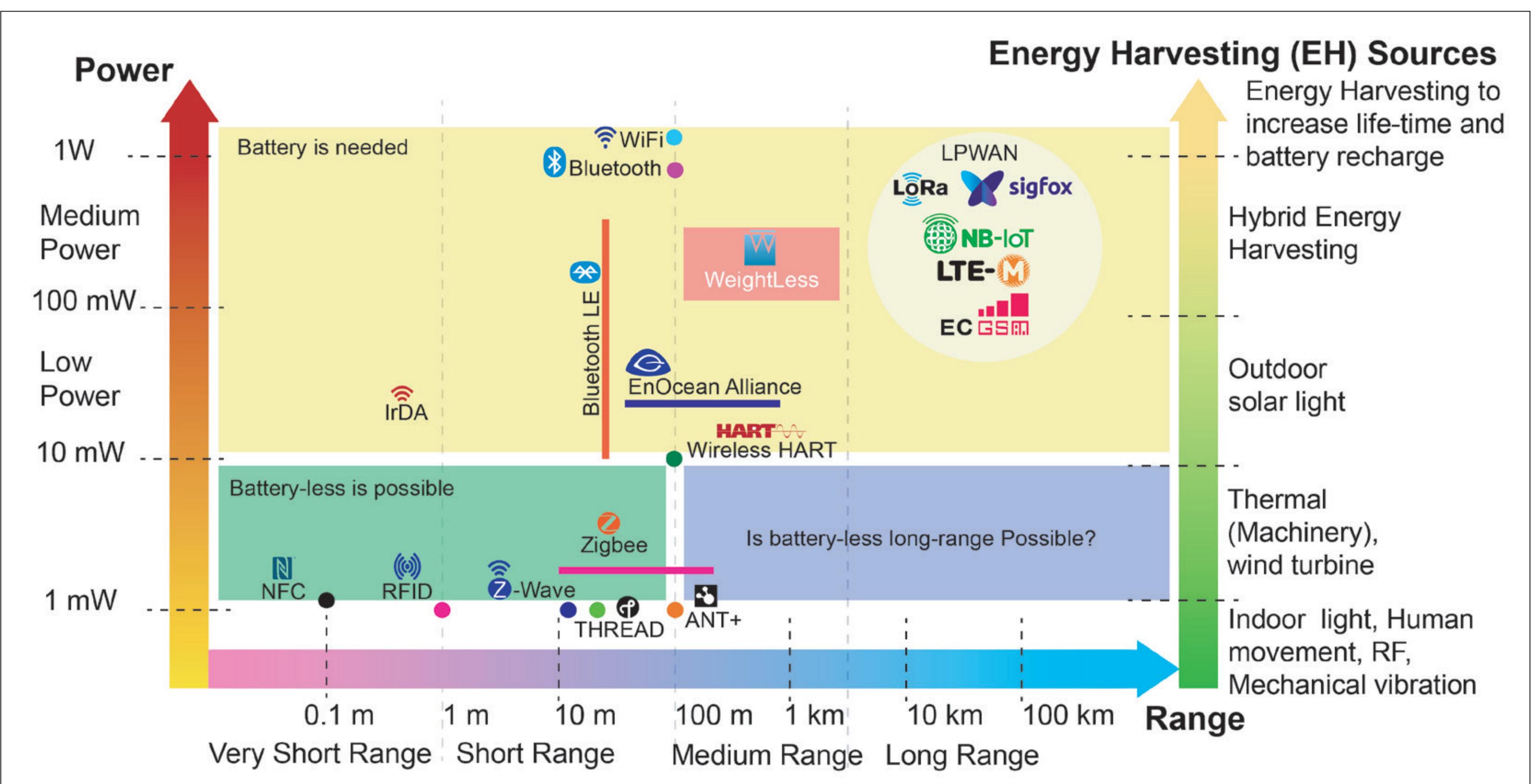


FIGURE 2. Consumed peak power vs. coverage applicable for wireless systems. Low-range wireless technologies operating over extremely low power, which is acceptable for IoT applications, may not be viable in long-range systems. Long-range wireless technologies such as LPWAN require substantial transmit power; therefore, batteries will stay basic parts for IoT devices.

Thermoelectric

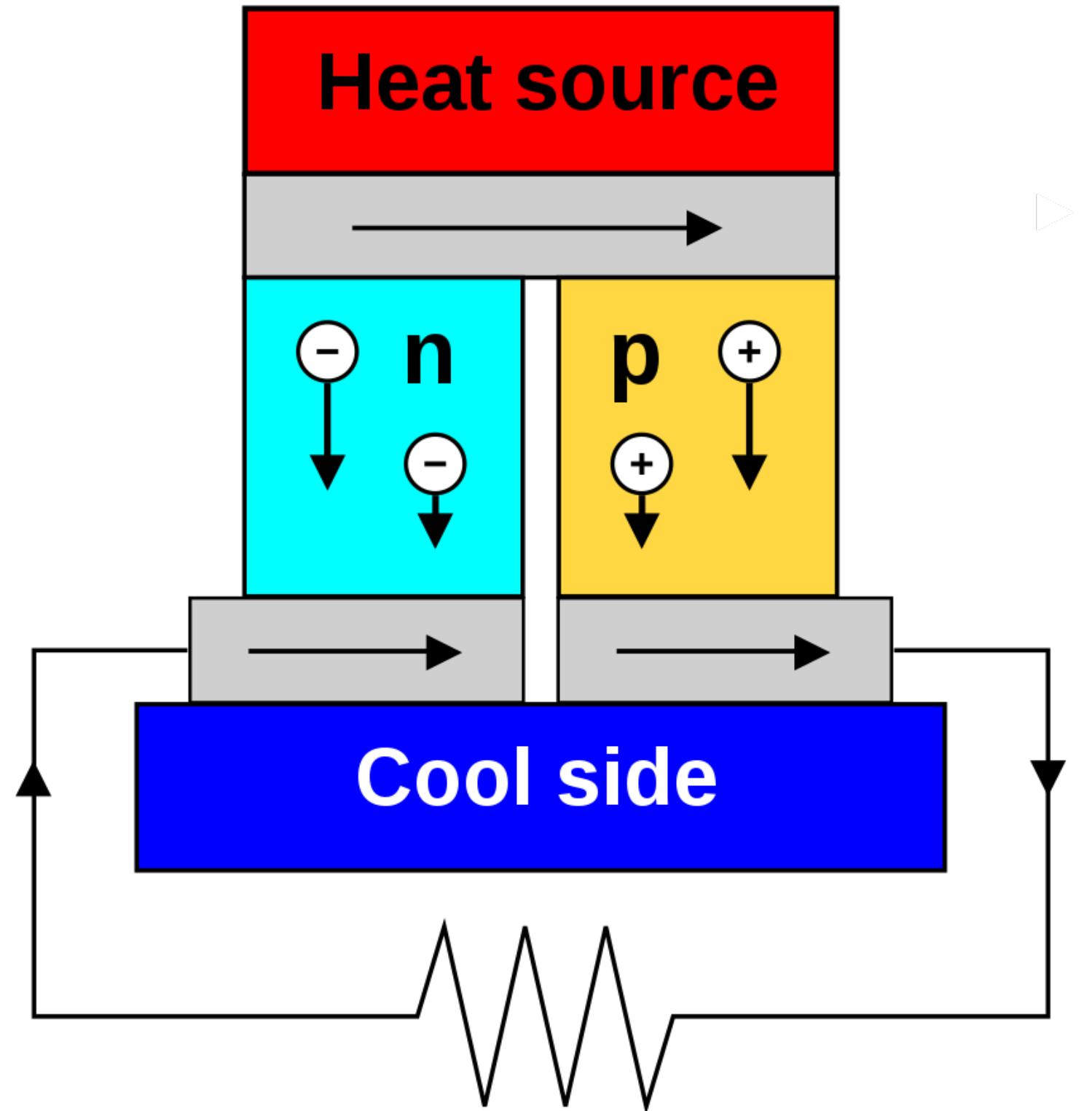
Photovoltaic

Piezoelectric

Ambient RF

Triboelectric

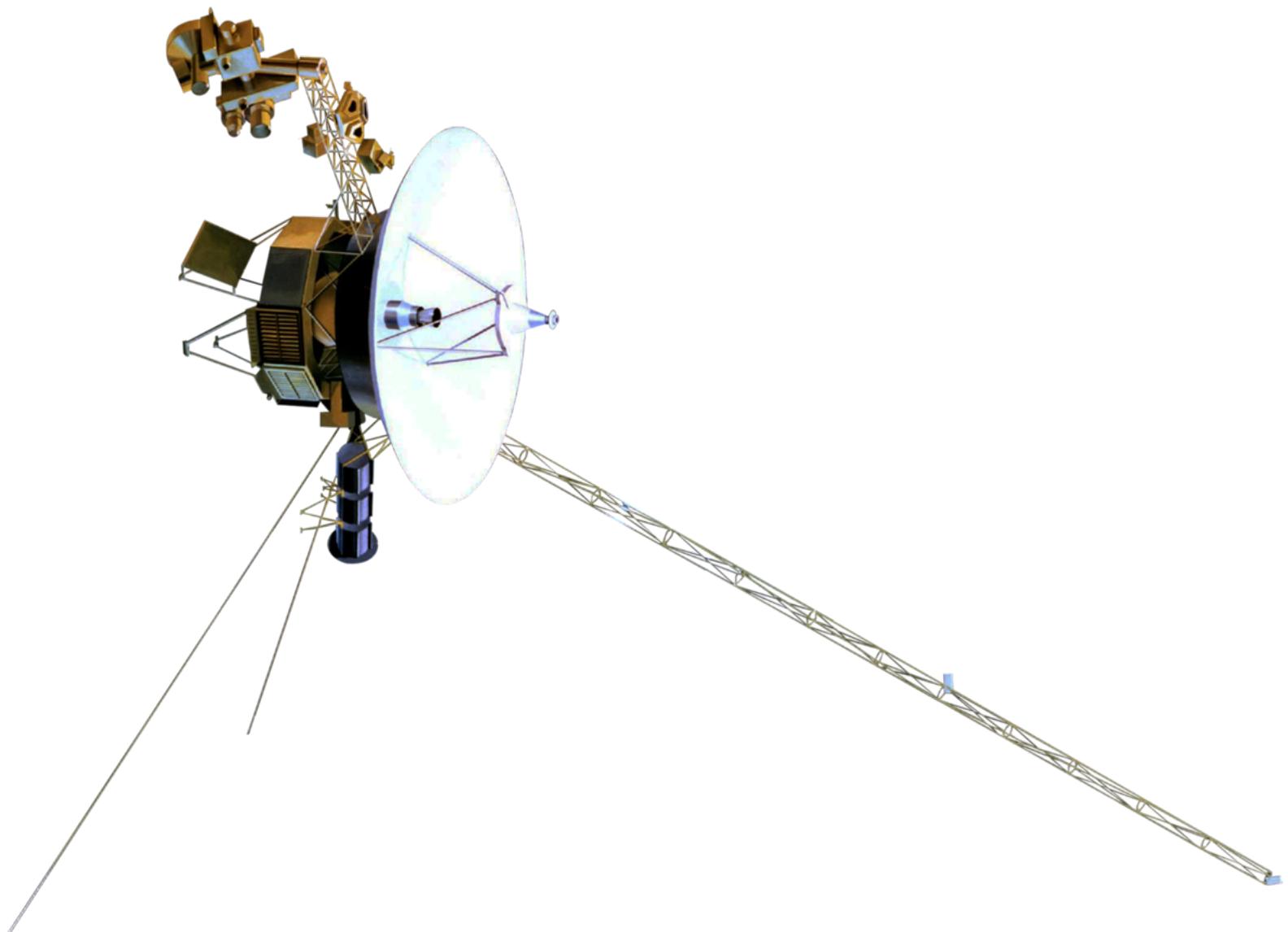
Thermoelectric

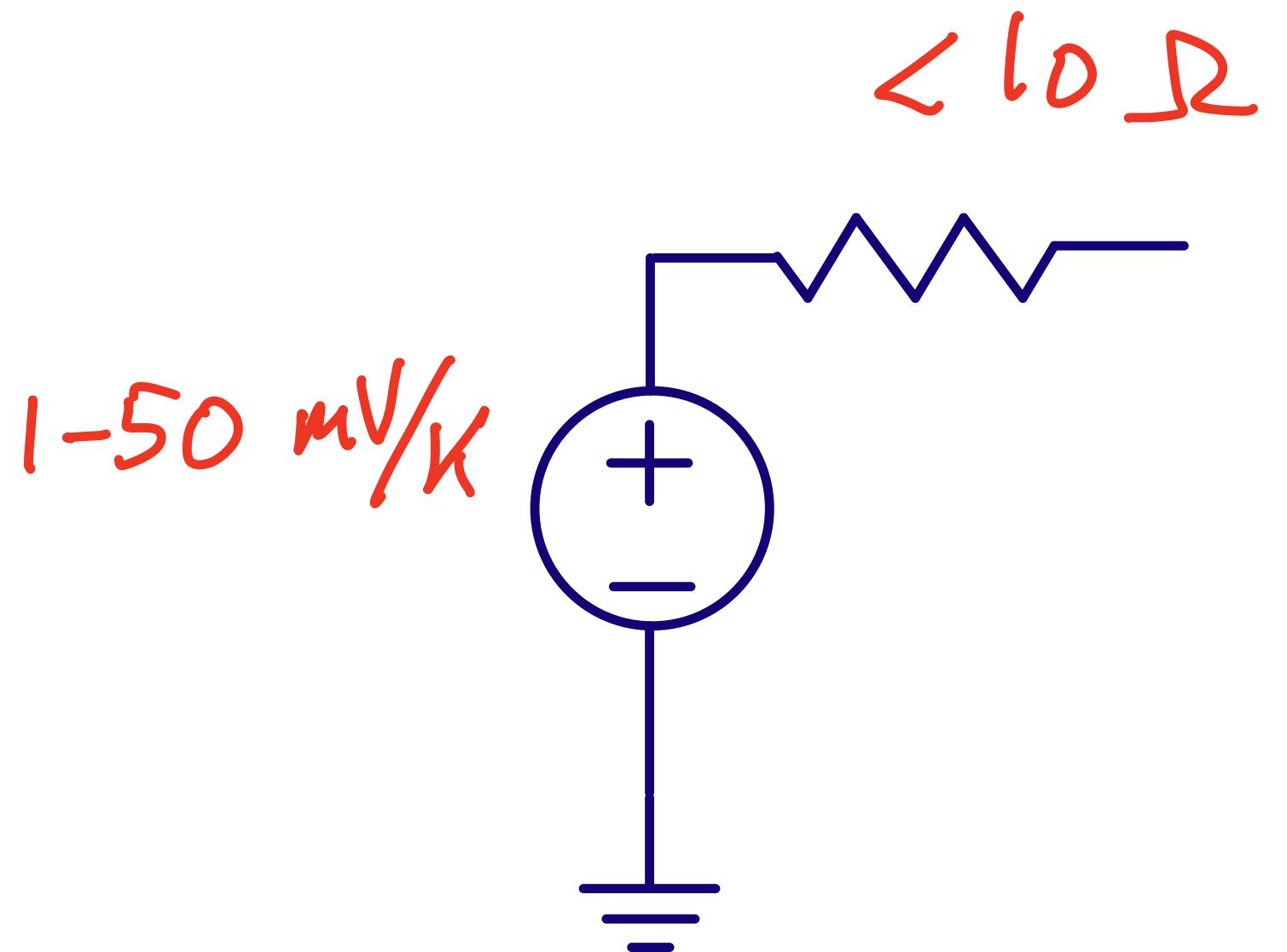


Thermoelectric_effect

- Seebeck effect
- Peltier effect
- Thomson effect

Radioisotope Thermoelectric generator





Thermoelectric generators

A 3.5-mV Input Single-Inductor Self-Starting Boost Converter With Loss-Aware MPPT for Efficient Autonomous Body-Heat Energy Harvesting

Soumya Bose^{ID}, *Member, IEEE*, Tejasvi Anand, *Member, IEEE*, and Matthew L. Johnston^{ID}, *Member, IEEE*

Abstract—A single-inductor self-starting boost converter is presented, which is suitable for thermoelectric energy harvesting from human body heat. In order to extract maximum energy from a thermoelectric generator (TEG) at small temperature gradients, a loss-aware maximum power point tracking (MPPT) scheme was developed, which enables the harvester to achieve high end-to-end efficiency at low input voltages. The boost converter is implemented in a $0.18\text{-}\mu\text{m}$ CMOS technology and is more than 75% efficient for a matched input voltage range of 15–100 mV, with a peak efficiency of 82%. Enhanced power extraction enables the converter to sustain operation at an input voltage as low as 3.5 mV. In addition, the boost converter self-starts with a minimum TEG voltage of 50 mV leveraging a dual-path architecture without using additional off-chip components.

Index Terms—Battery-less, body heat, cold-start, dc–dc boost converter, energy harvesting, thermoelectric generator (TEG).

for fully autonomous applications, the converter must also self-start at this low input voltage.

In recent years, a variety of dc–dc boost converter architectures have been reported to address the challenges posed by low input voltage. One such boost converter designed for thermoelectric energy harvesting can operate with an input voltage as low as 20 mV [3]. However, this architecture lacks maximum power point tracking (MPPT), reducing the total extracted output power of the harvester despite high converter efficiency; the design also requires an additional source of energy for initial start-up of the converter. Boost converter architectures sustaining operation with an input voltage as low as 10 mV have also been demonstrated [4], [5], but these approaches also fail to self-start at low input voltage, making them unsuitable for fully battery-less energy harvesting.

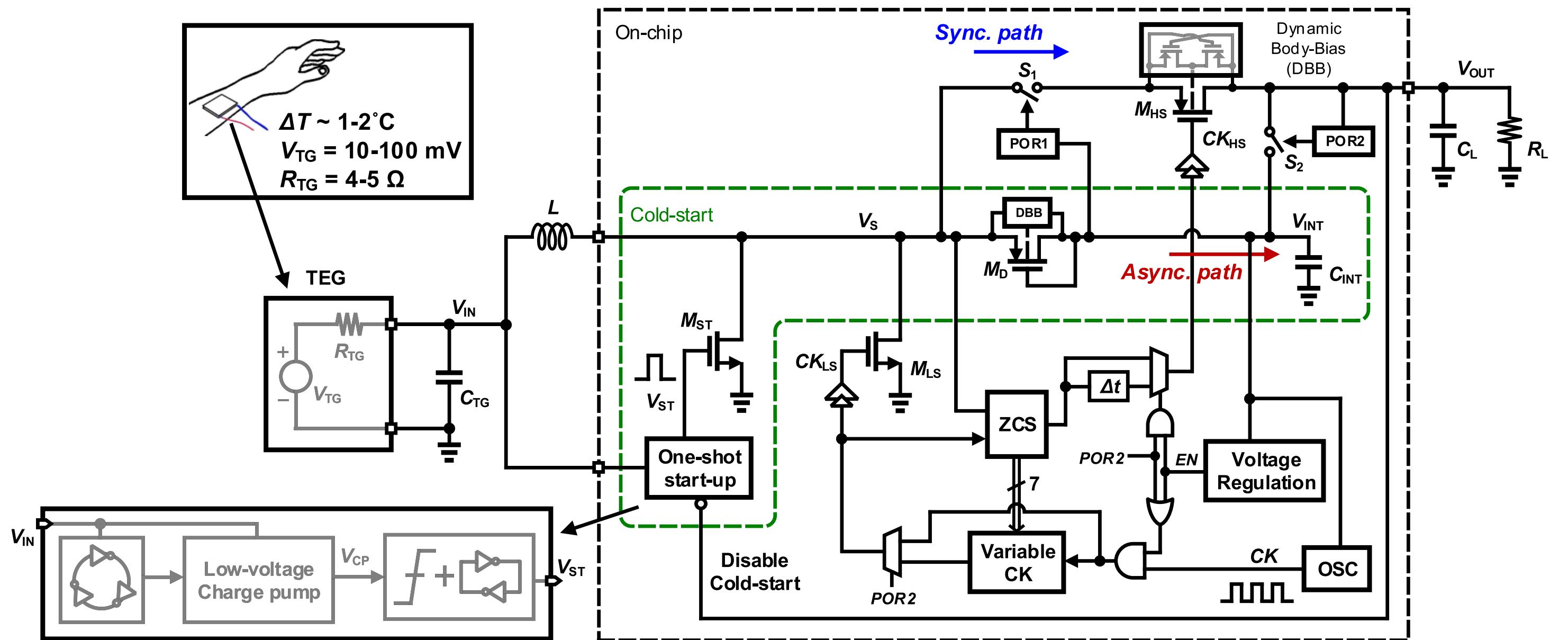
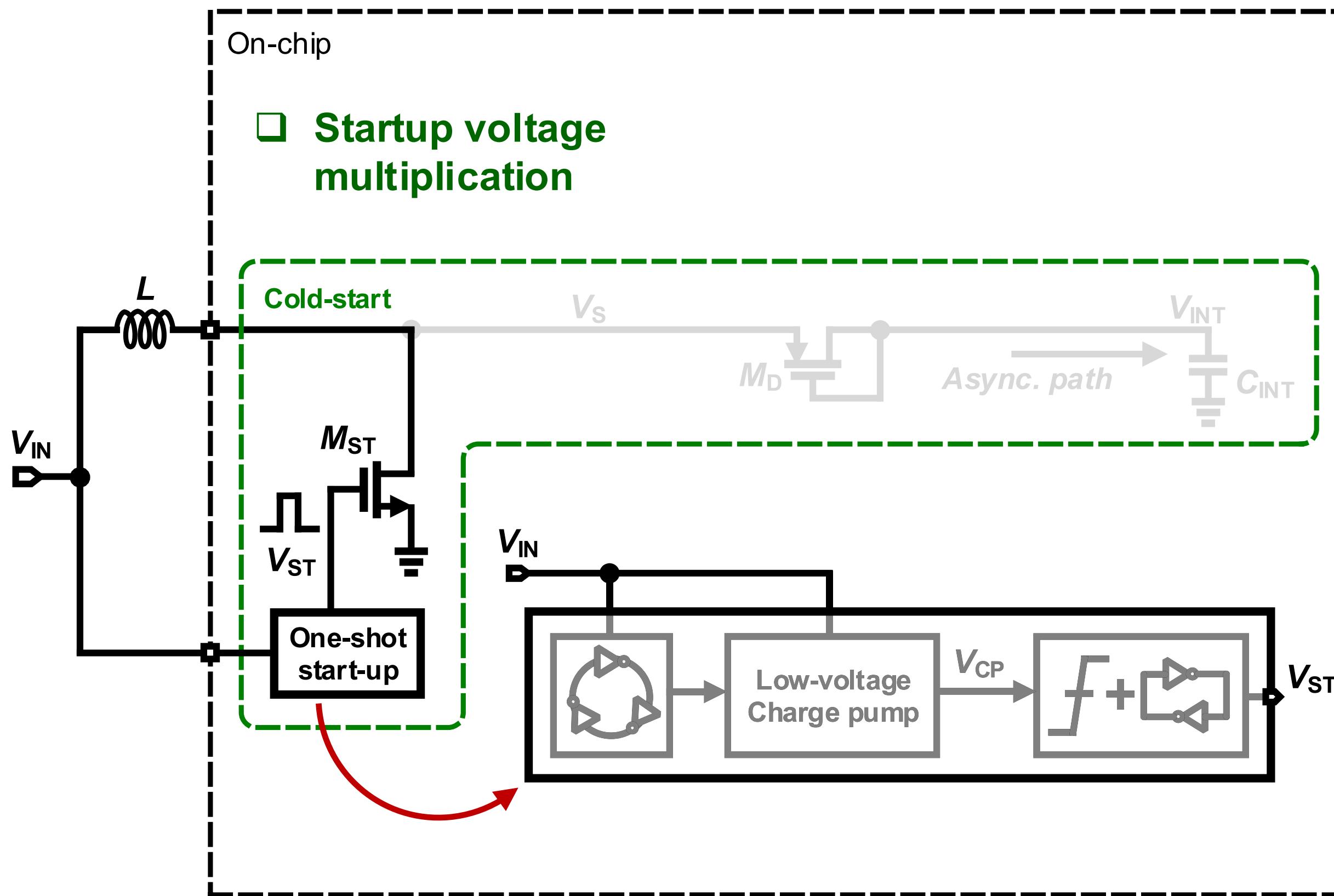
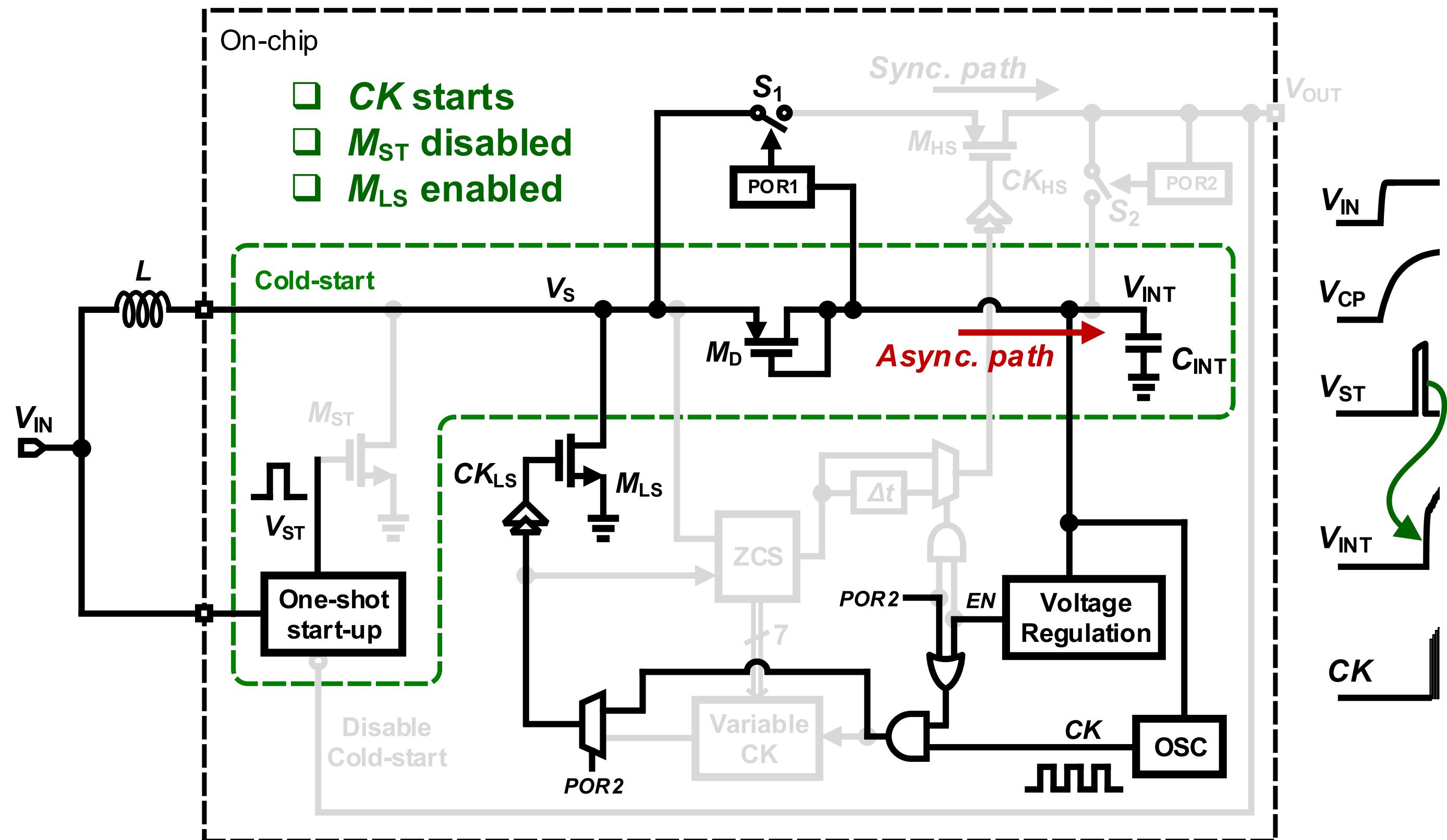


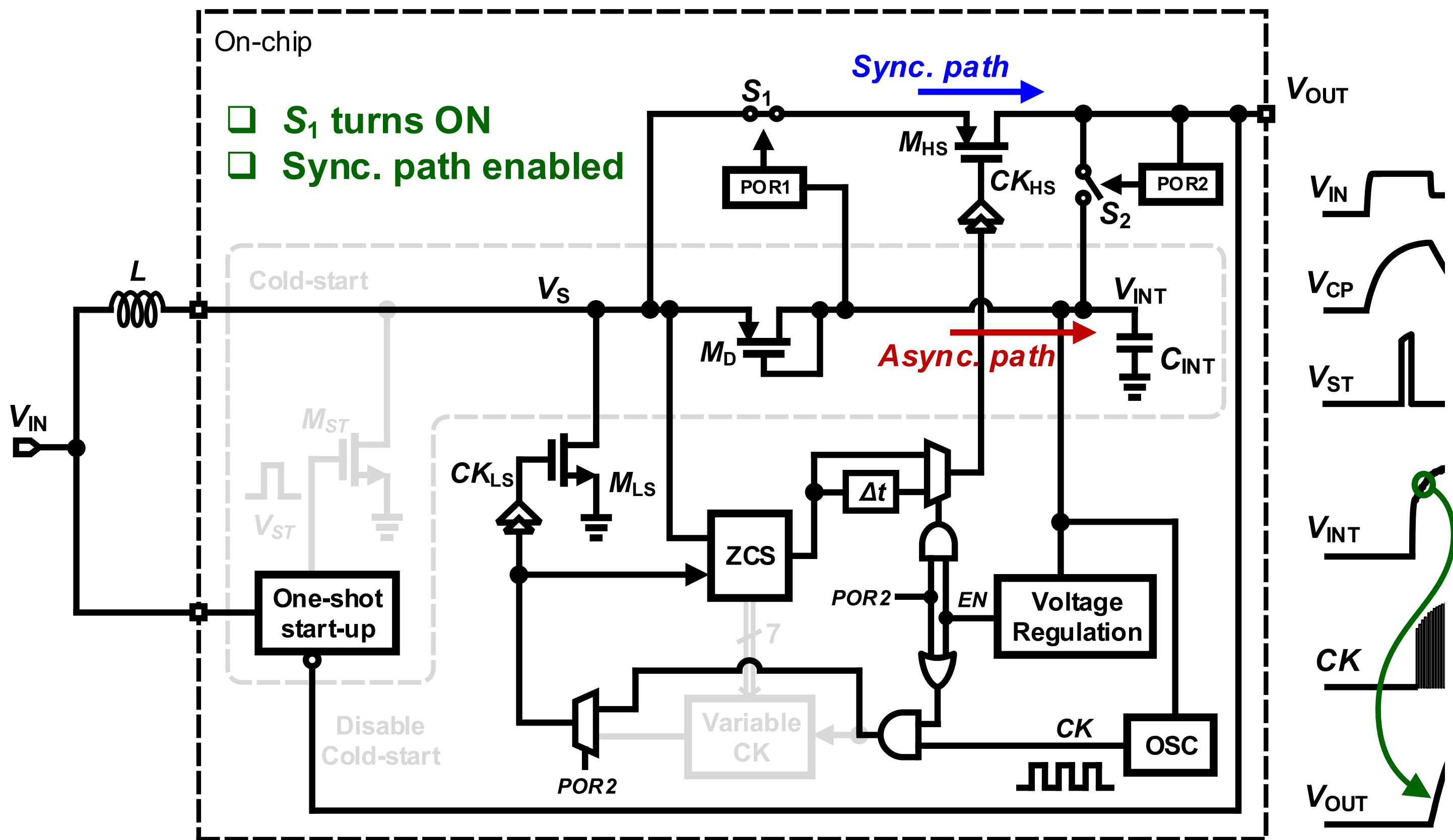
Fig. 1. Self-starting single-inductor boost converter architecture for low-voltage thermoelectric energy harvesting utilizing human body heat.

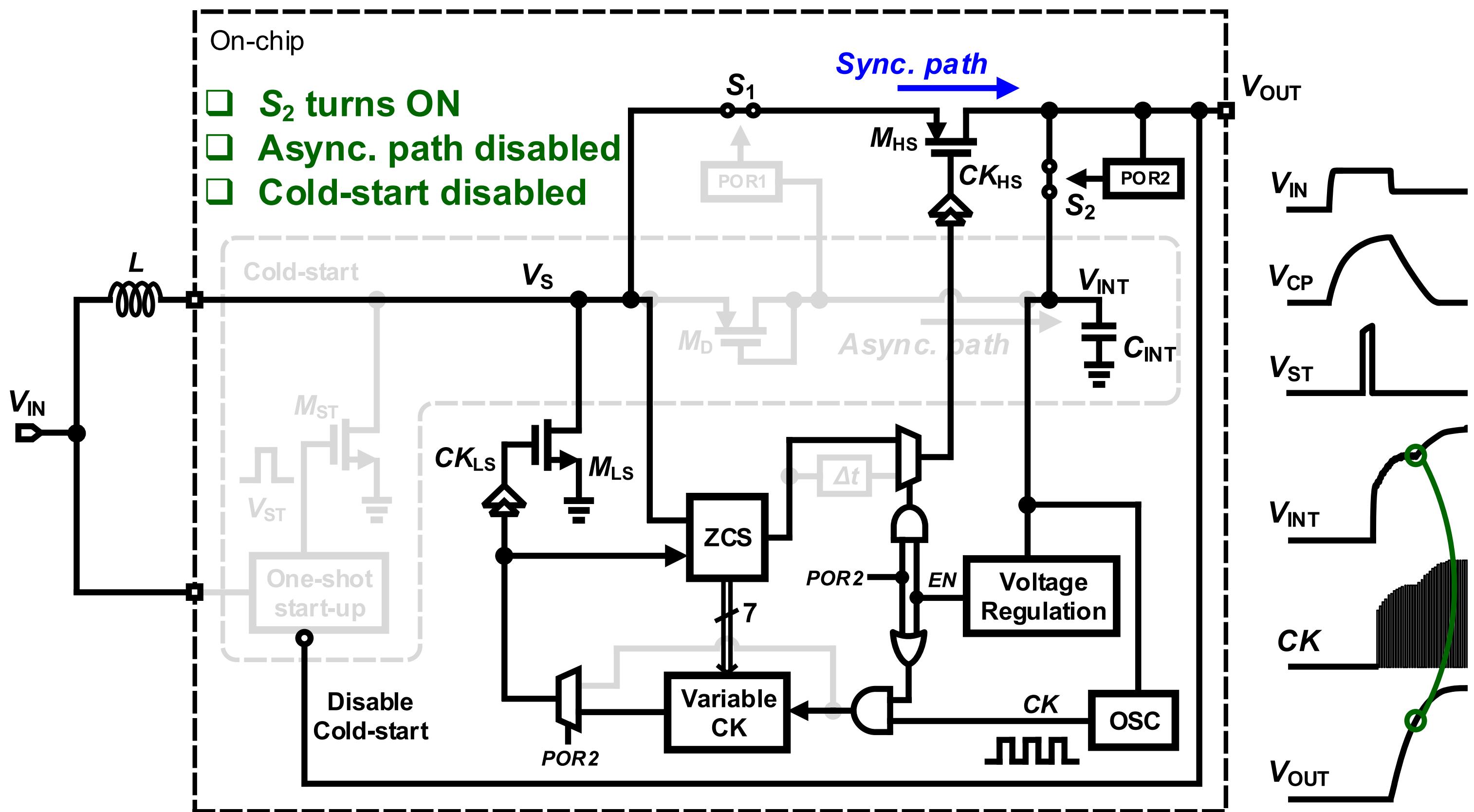




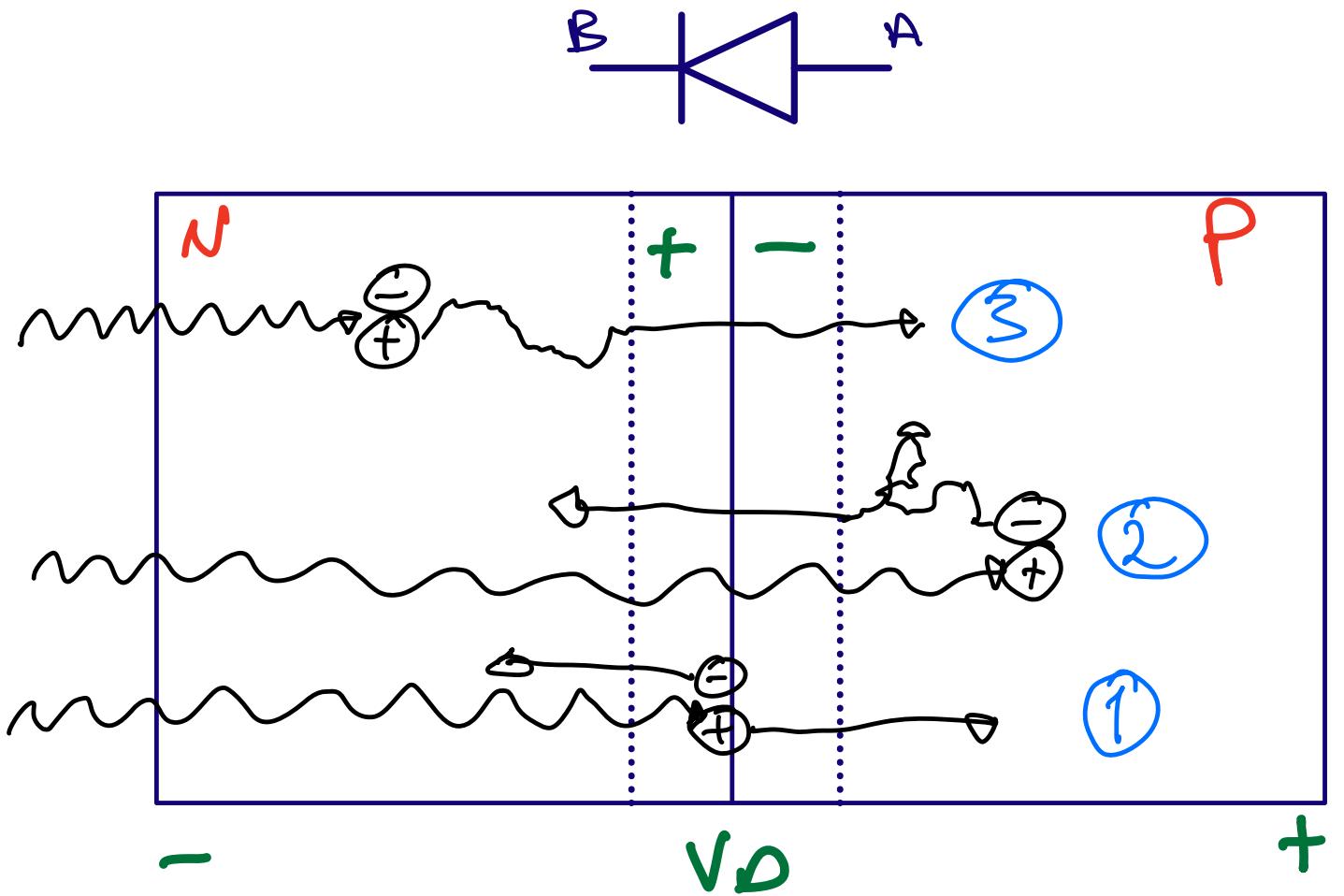
(b)

(c)

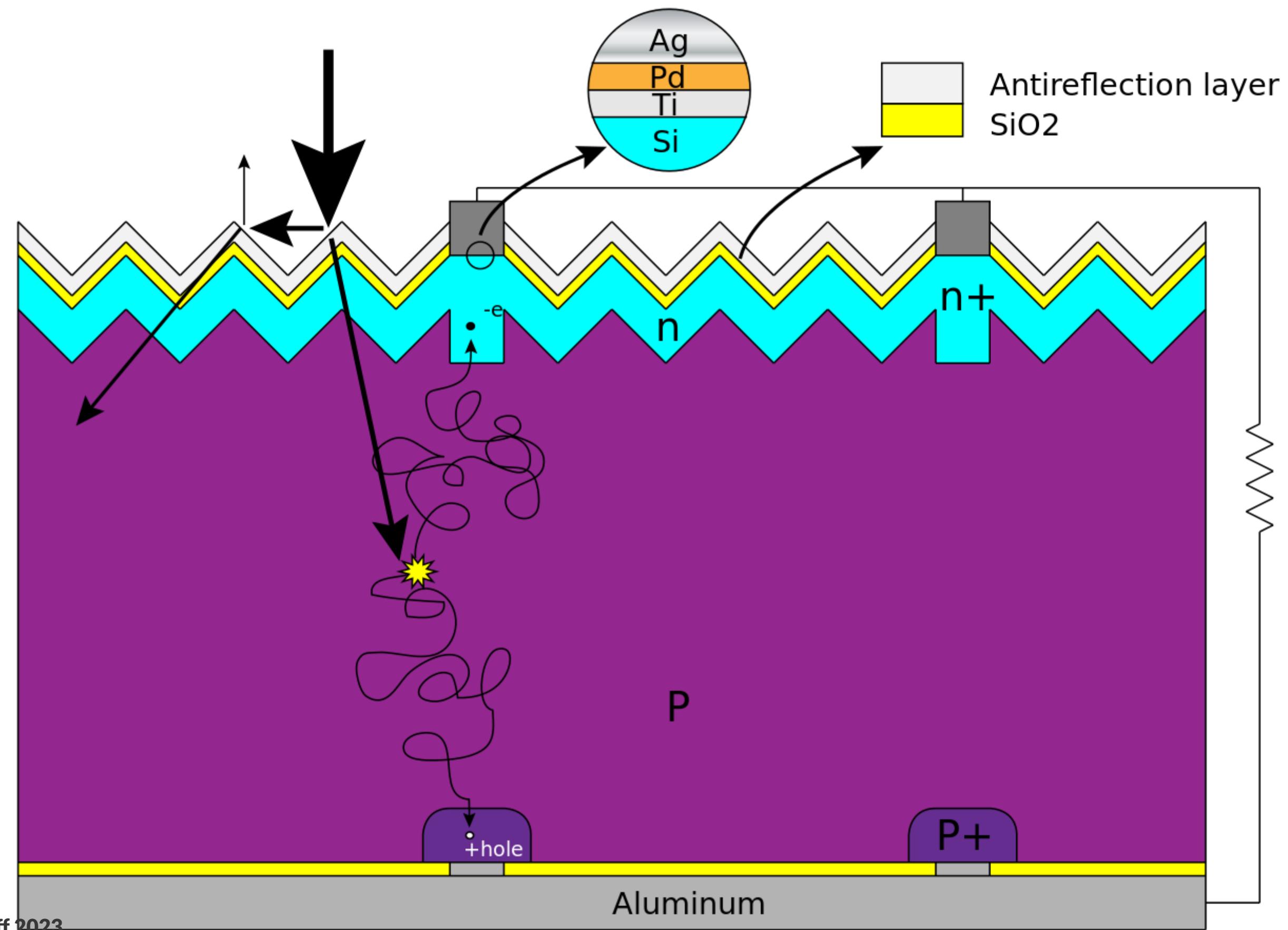


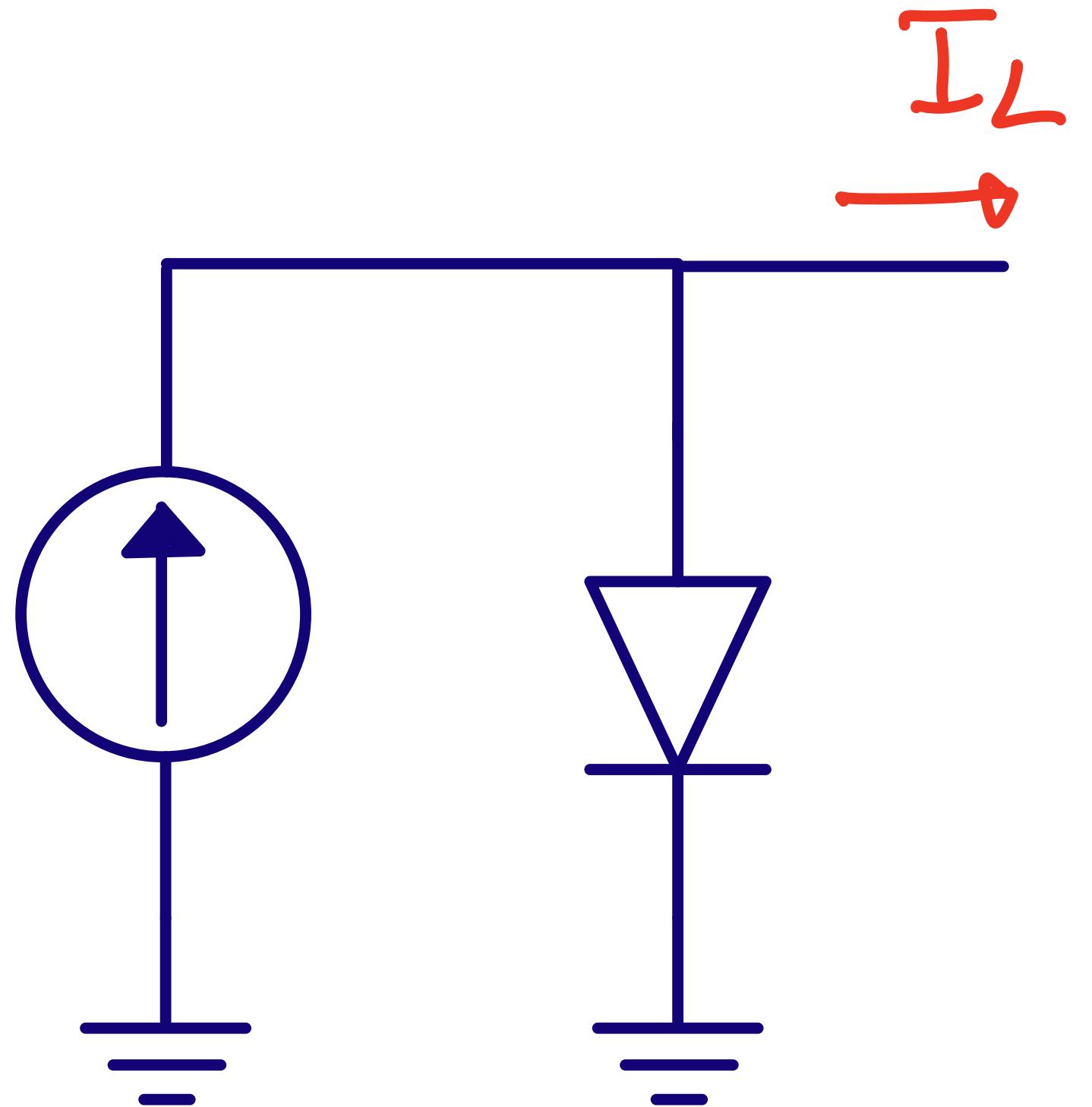


Photovoltaic



Photovoltaic effect





$$I_D = I_S \left(e^{\frac{V_D}{V_T}} - 1 \right)$$

$$I_D = I_{Photo} - I_{Load}$$

$$V_D = V_T \ln \left(\frac{I_{Photo} - I_{Load}}{I_S} + 1 \right)$$

$$P_{Load} = V_D I_{Load}$$

```

#!/usr/bin/env python3

import numpy as np
import matplotlib.pyplot as plt

m = 1e-3
i_load = np.linspace(1e-5,1e-3,200)

i_s = 1e-12

i_ph = 1e-3

V_T = 1.38e-23*300/1.6e-19

V_D = V_T*np.log((i_ph - i_load)/(i_s) + 1)

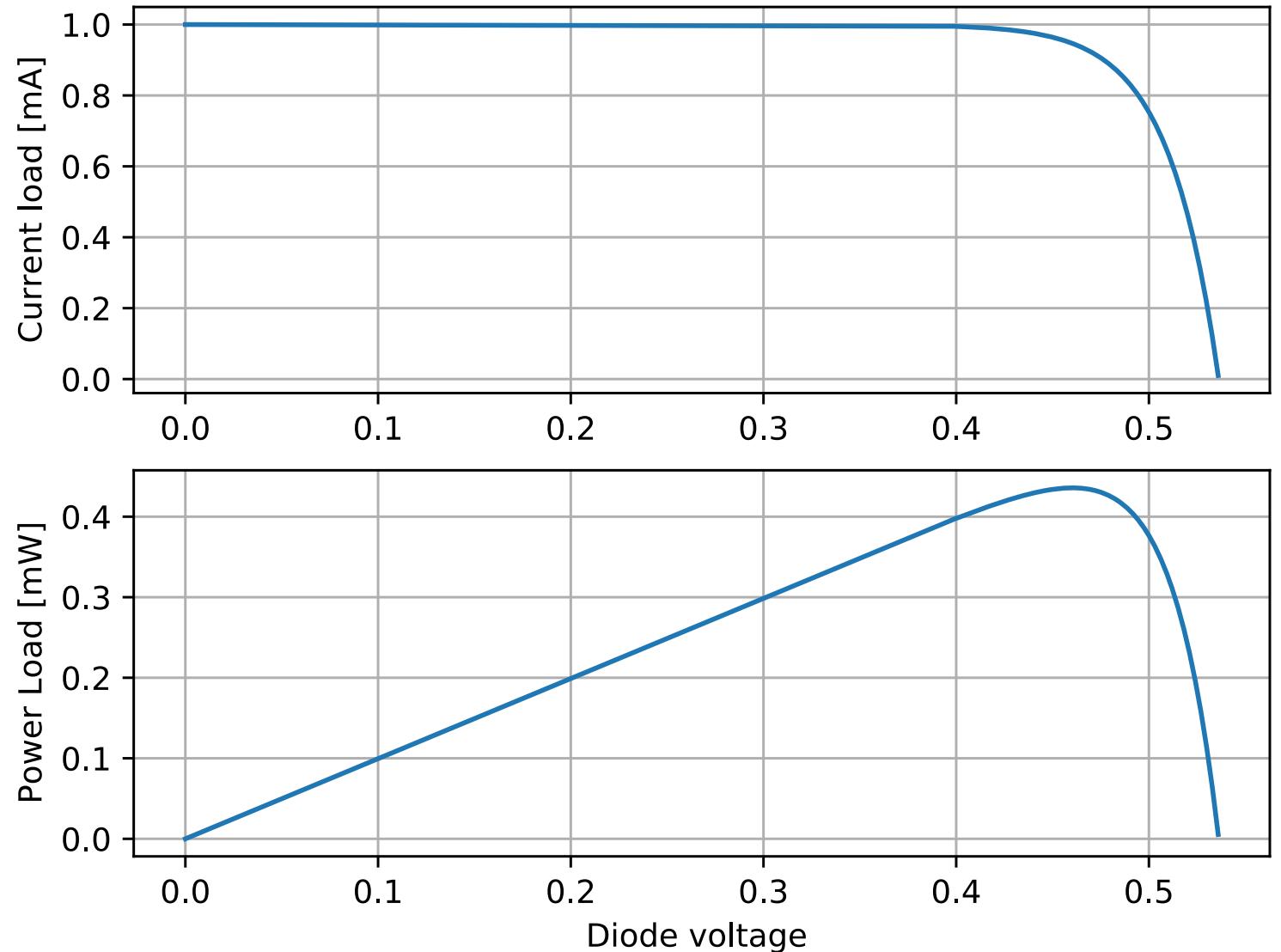
P_load = V_D*i_load

plt.subplot(2,1,1)
plt.plot(i_load/m,V_D)
plt.ylabel("Diode voltage [mA]")
plt.grid()

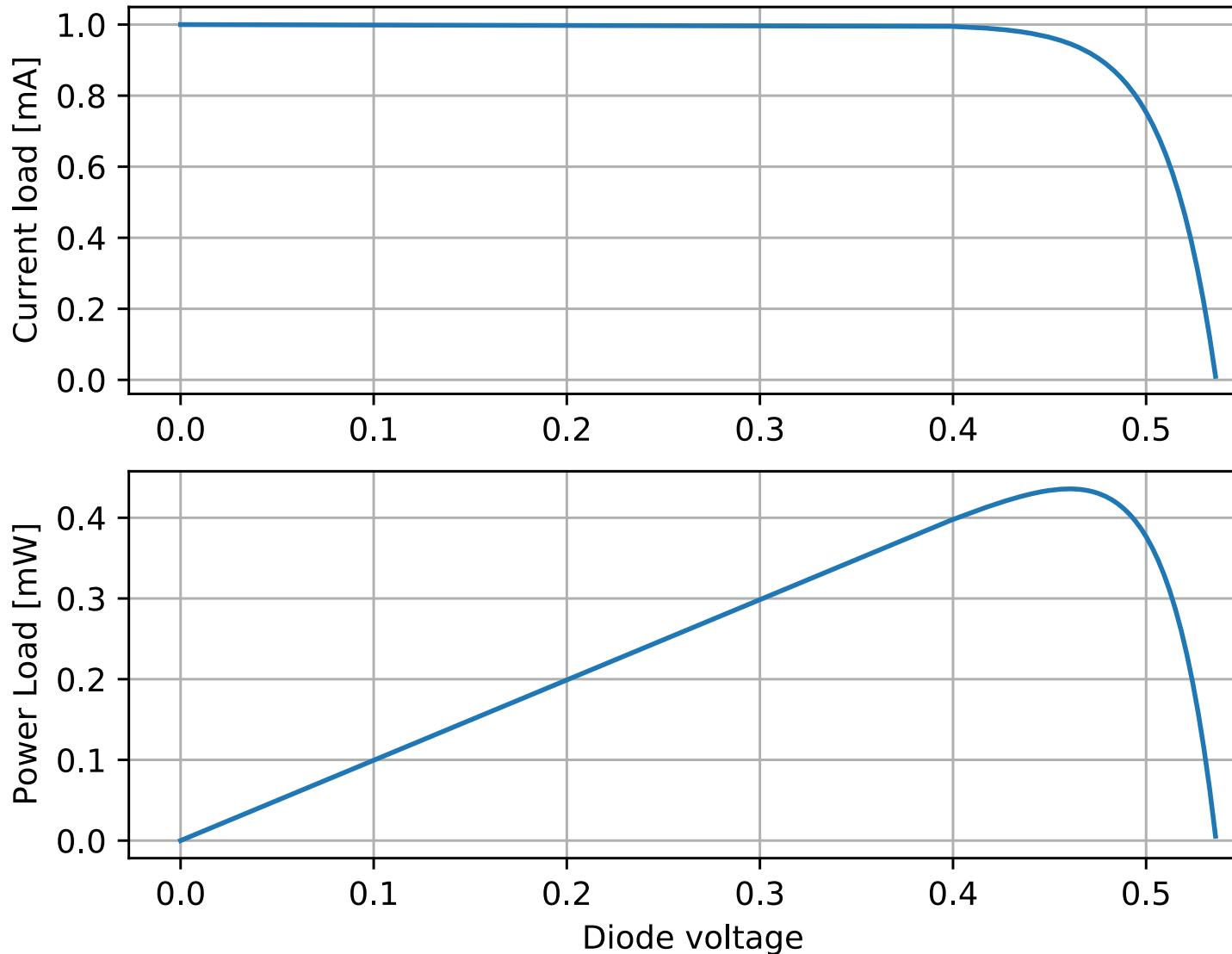
plt.subplot(2,1,2)
plt.plot(i_load/m,P_load/m)
plt.xlabel("Current load [mA]")
plt.ylabel("Power Load [mW]")
plt.grid()

plt.savefig("pv.pdf")
plt.show()

```

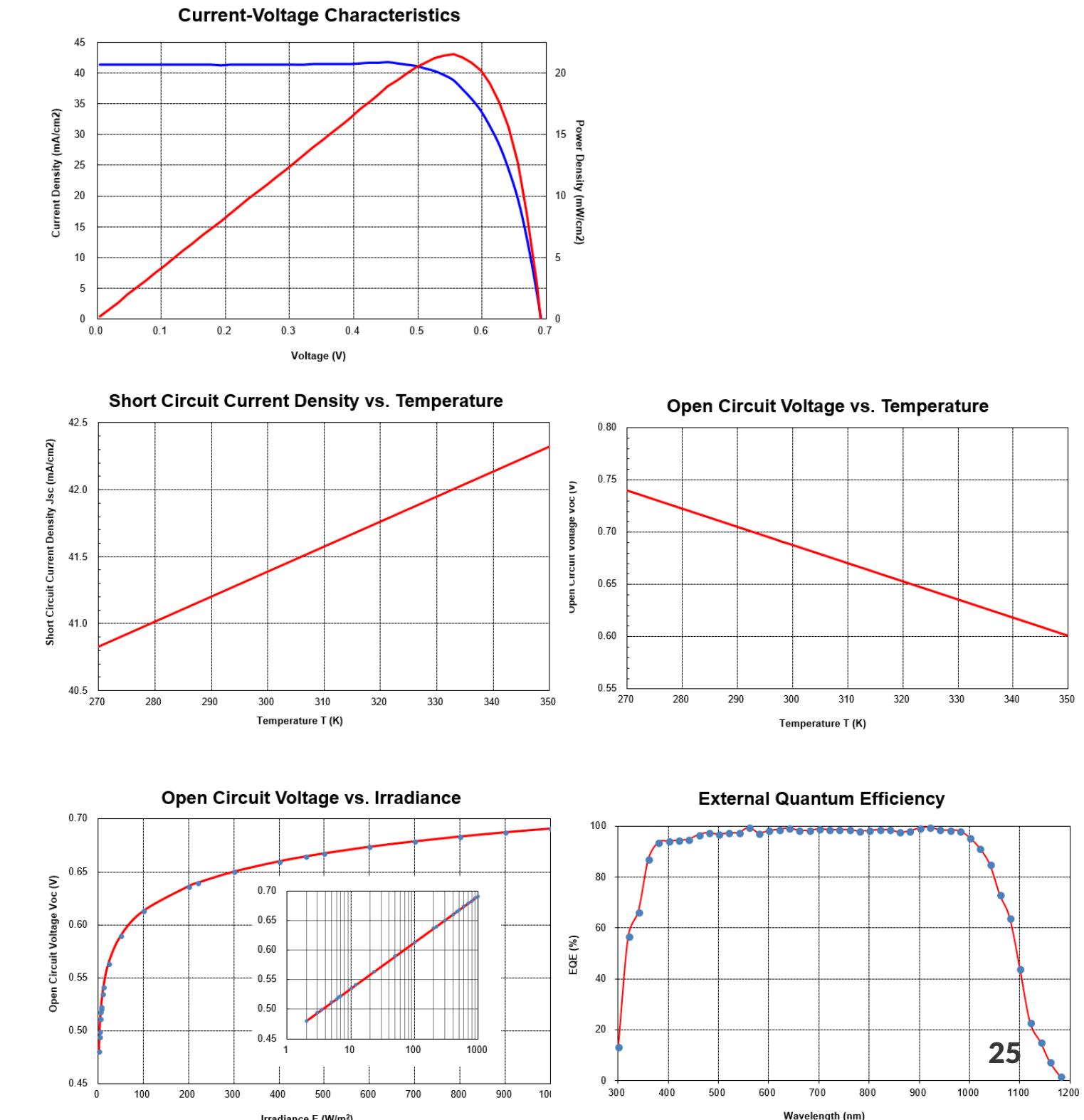


ANY SOLAR



Carsten Wulff 2023

Typical SolarMD Performance Data



25

A Reconfigurable Capacitive Power Converter With Capacitance Redistribution for Indoor Light-Powered Batteryless Internet-of-Things Devices

Hao-Chung Cheng^{ID}, *Graduate Student Member, IEEE*, Po-Han Chen^{ID}, *Student Member, IEEE*, Yu-Tong Su, and Po-Hung Chen^{ID}, *Senior Member, IEEE*

Abstract—In this article, a reconfigurable capacitive power converter with capacitance redistribution for indoor light-powered batteryless Internet-of-Things (IoT) devices is presented. The proposed converter is capable of redistributing the capacitance among two charge pump stages to efficiently utilize the harvested energy and further powering milliwatt-powered

amplifier for data transmission. However, with the rising number of IoT sensing nodes, replacing the batteries requires extra cost and effort, thus limiting possible applications. Recently, batteryless IoT devices have been considered as a promising solution to extend the range of applications. The use of energy

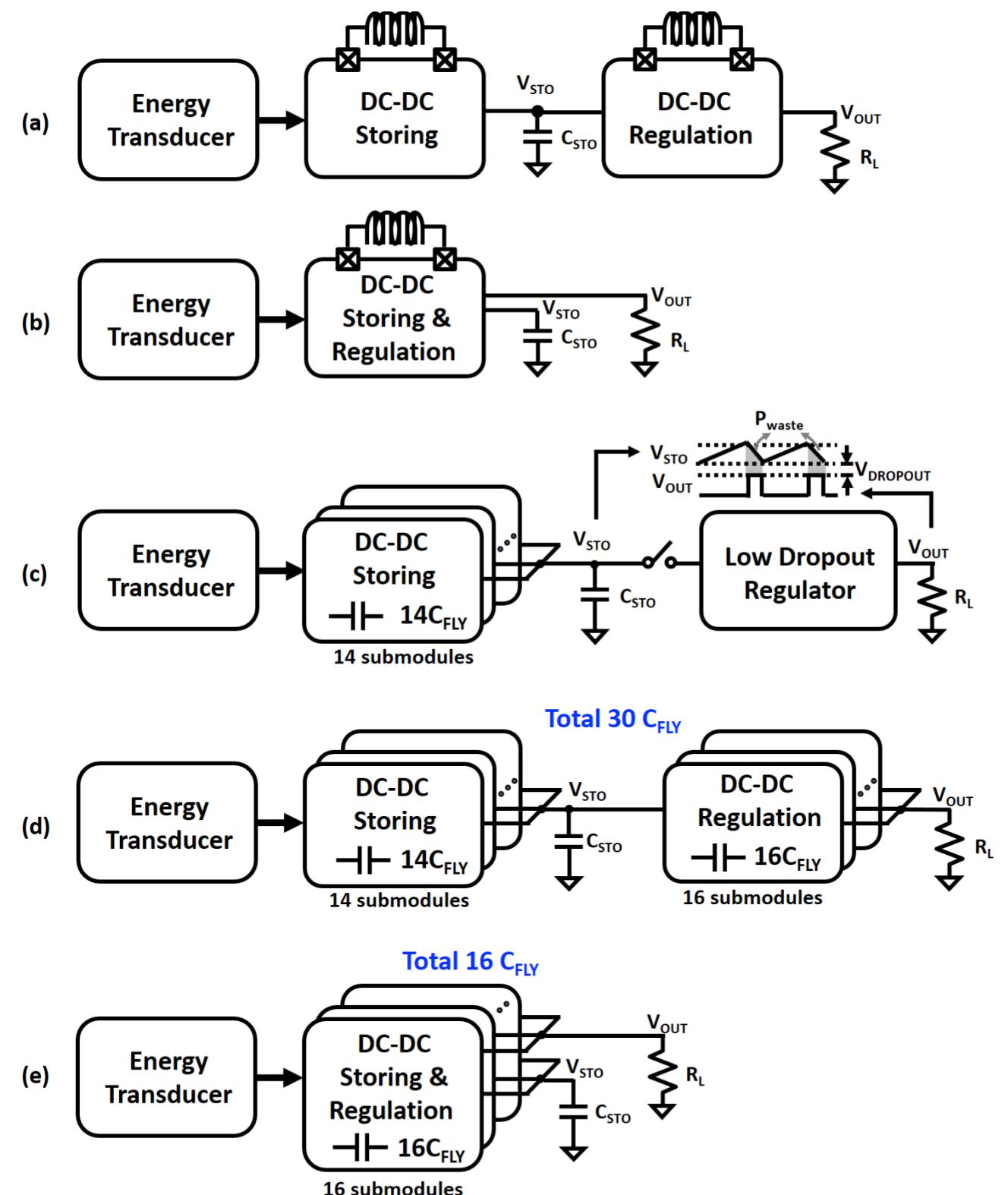


Fig. 1. Possible approaches for batteryless IoT devices: (a) inductive converter with two inductors, (b) SIMO inductive converter [5], (c) capacitive converter with hysteresis control [6], (d) two-stage capacitive converter, and (e) proposed redistributable capacitive converter.

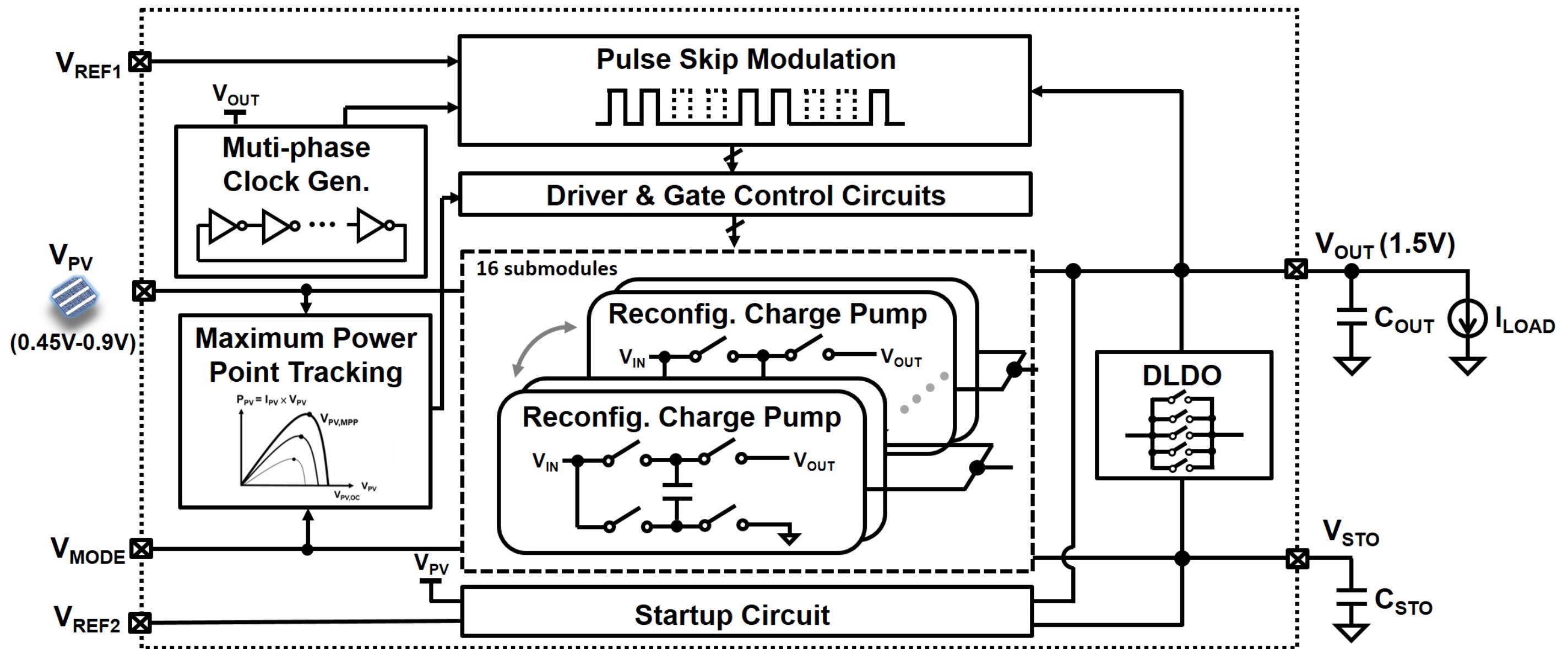
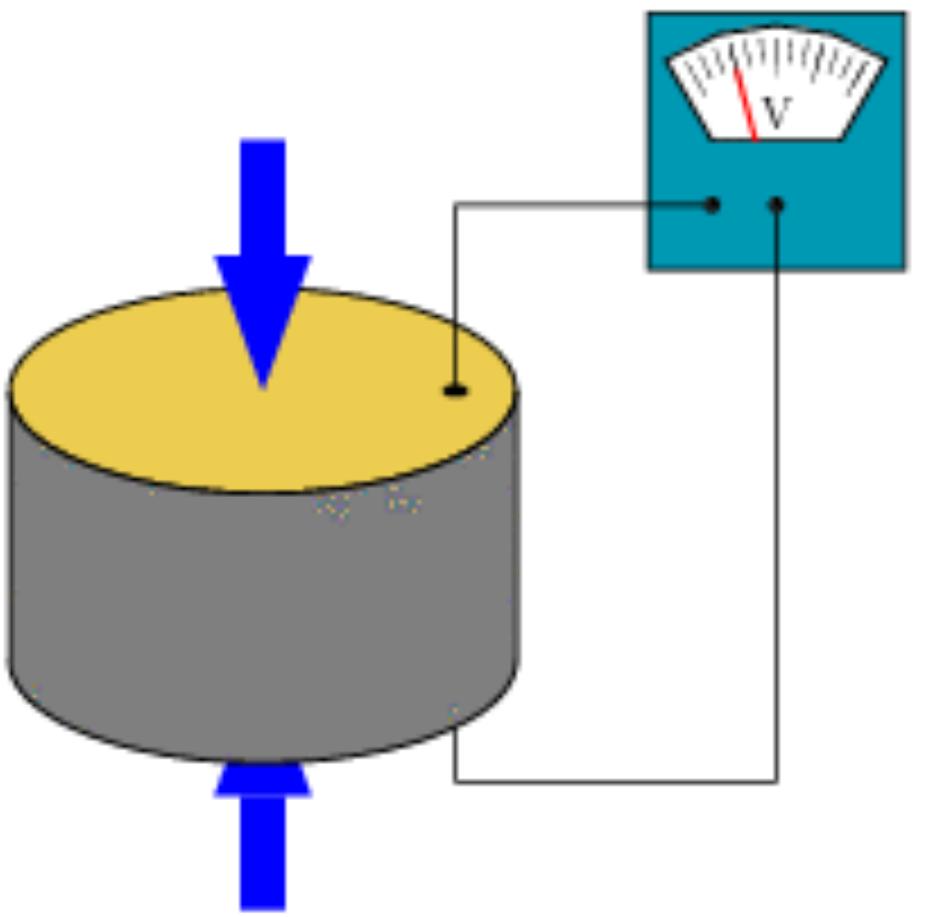


Fig. 2. System architecture of the proposed redistributable capacitive converter.

Piezoelectric



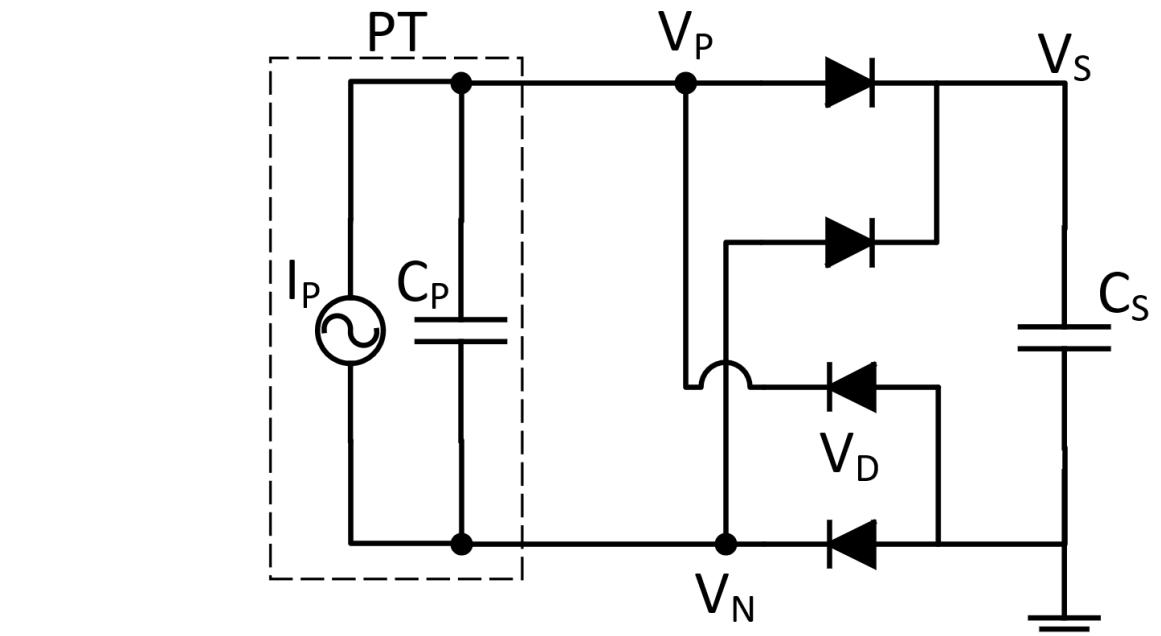
Piezoelectric effect

A Fully Integrated Split-Electrode SSHC Rectifier for Piezoelectric Energy Harvesting

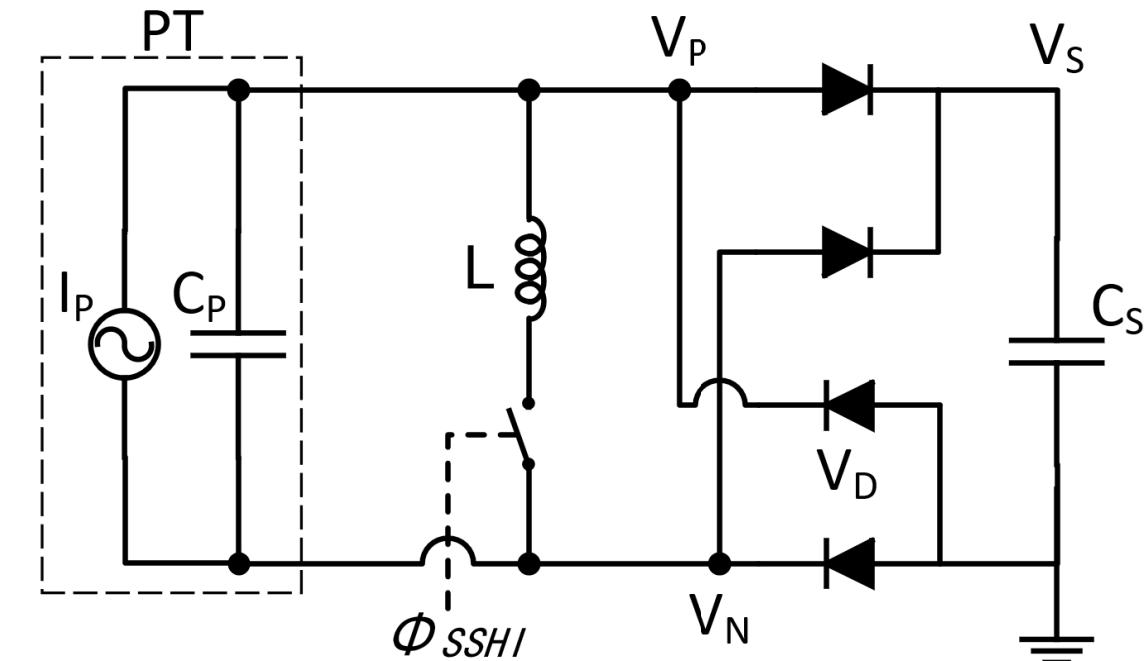
Sijun Du^{ID}, *Member, IEEE*, Yu Jia, *Member, IEEE*, Chun Zhao^{ID}, *Member, IEEE*, Gehan A. J. Amaratunga, and Ashwin A. Seshia^{ID}, *Senior Member, IEEE*

Abstract—In order to efficiently extract power from piezoelectric vibration energy harvesters, various active rectifiers have been proposed in the past decade, which include synchronized switch harvesting on inductor (SSHI), synchronous electric charge extraction (SECE), and so on. Although reported active rectifiers show good performance improvements compared to full-bridge rectifiers (FBRs), large off-chip inductors are typically required and the system volume is inevitably increased as a result, counter to the requirement for system miniaturization. In this paper, a fully integrated split-electrode synchronized switch

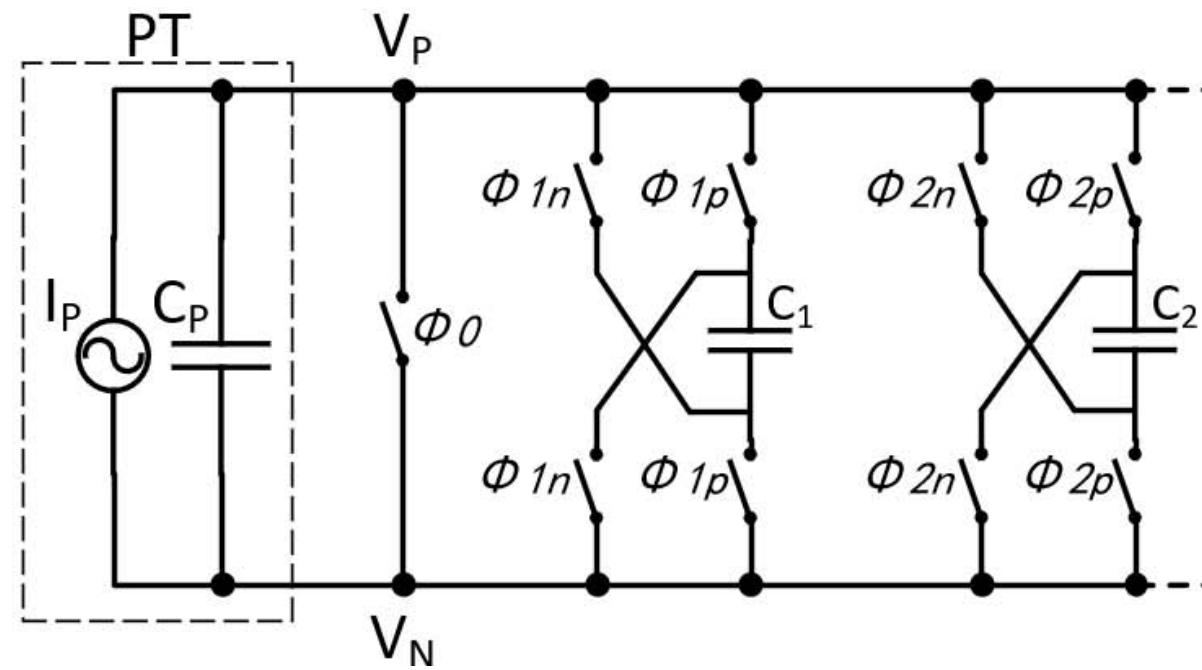
environmental vibration is periodic and highly unpredictable, the energy generated by a piezoelectric transducer (PT) cannot be directly used and an interface circuit is needed to rectify the generated power and provide a stable dc supply to the loads. Full-bridge rectifiers (FBRs) are widely employed in most commercially available power management units (PMU) due to their simplicity and stability; however, the low power-extraction efficiency of FBRs limits the usable output power for loads, especially under low ambient exci-



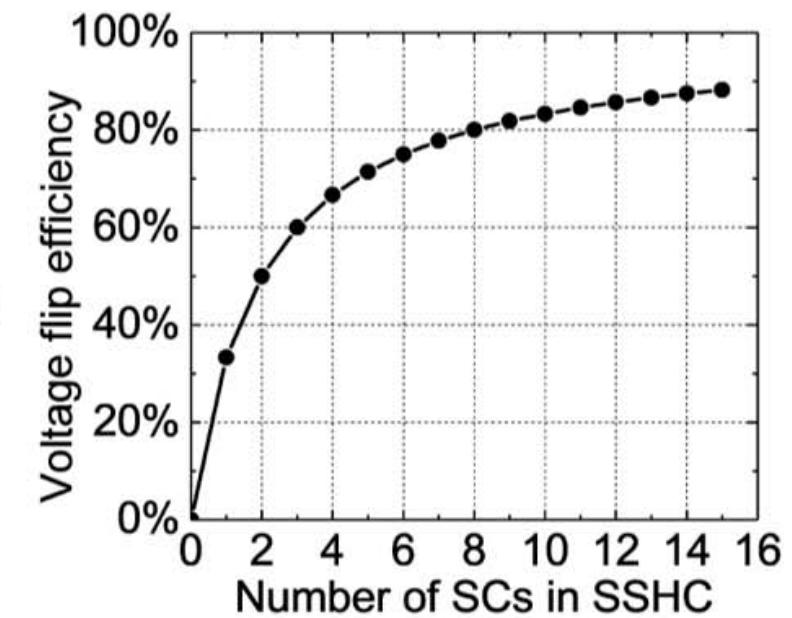
(a)



(b)



(c)

Fig. 1. Circuit diagrams of (a) FBR, (b) SSHI rectifier, and (c) SSHC rectifier with k SCs.

Ambient RF

Ambient RF Harvesting

Extremely inefficient idea, but may find special use-cases at short-distance

Will get better with beamforming and directive antennas

AirFuel

dBm	w
30	1
0	1 m
-30	1 u
-60	1 n
-90	1 p

Assume $P_{TX} = 1 \text{ W (30 dBm)}$ and $P_{RX} = 10 \mu\text{W (-20 dBm)}$

$$D = 10^{\frac{P_{TX}-P_{RX}+20\log_{10}\left(\frac{c}{4\pi f}\right)}{20}}$$

Freq [dB]	D [m]
915M	-31.7
2.45G	-40.2
5.80G	-47.7

Triboelectric generator

Current progress on power management systems for triboelectric nanogenerators¹

Tingshu Hu, *Senior Member, IEEE*, Haifeng Wang, *Member, IEEE*, William Harmon,
David Bamgoje, *Member, IEEE*, Zhong-Lin Wang

Abstract—This paper presents a review on the development of power management systems (PMS) for triboelectric nanogenerators (TENGs). The TENG is a most recent technology to harvest ambient mechanical energy from the environment and human activities. Its invention was motivated by the prospect of building self-powered systems. The TENG has several appealing advantages, such as, high power density, high voltage output, high efficiency at low frequency and low cost. However, due to the TENG’s unique nonlinear electrical property and capacitive behavior, the development of its PMS has presented great challenges as compared to other energy harvesters. The objective of PMS design has evolved from boosting the peak output power, to increasing the energy stored in a capacitor, and to increasing the steady-state output power of a resistive load by using a power converter. Driven by the need to build self-powered systems, the

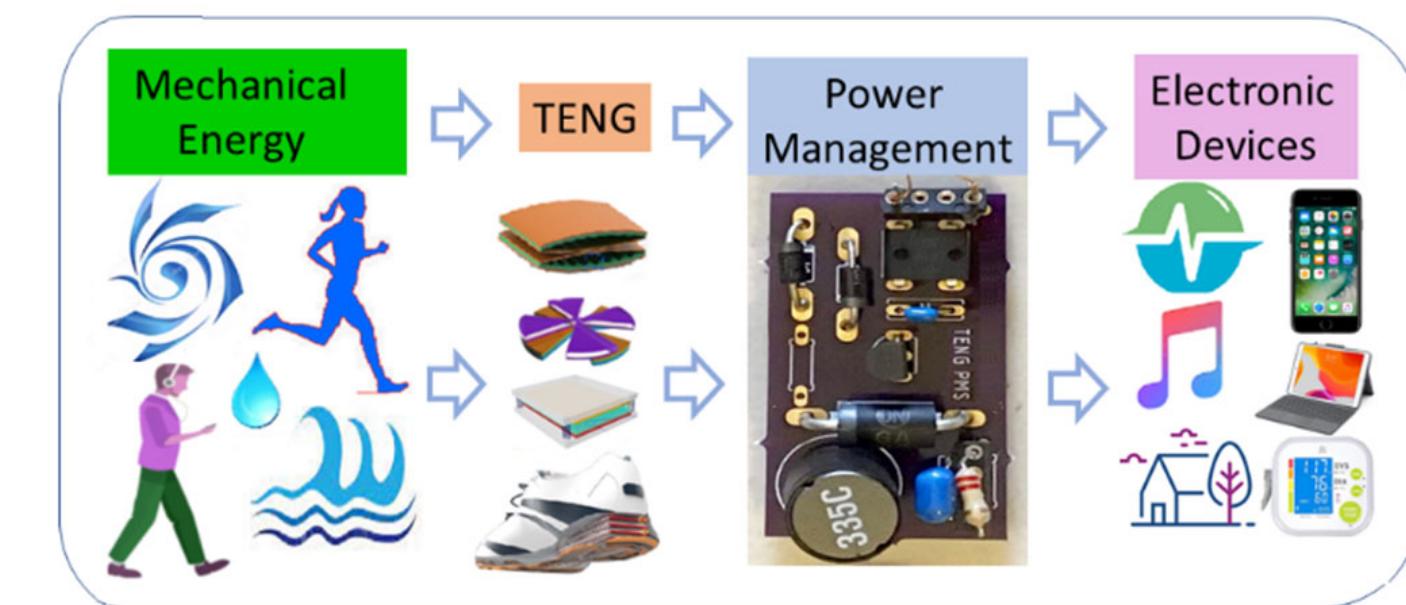
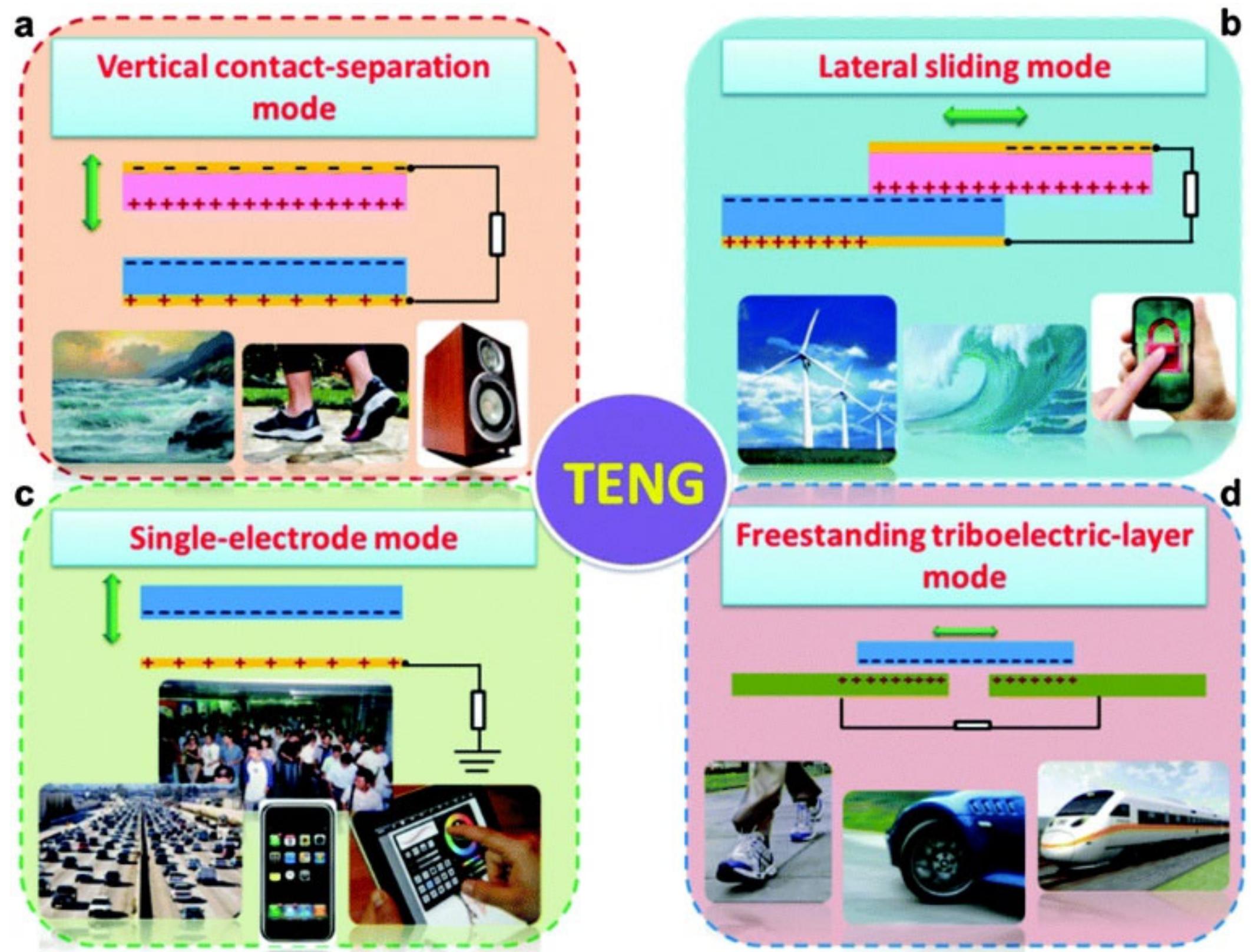


Fig. 1. Illustration of a self-powered system using energy harvested with TENGs. A power management system is needed to convert the TENG’s output into a regulated form suitable for electronic devices.



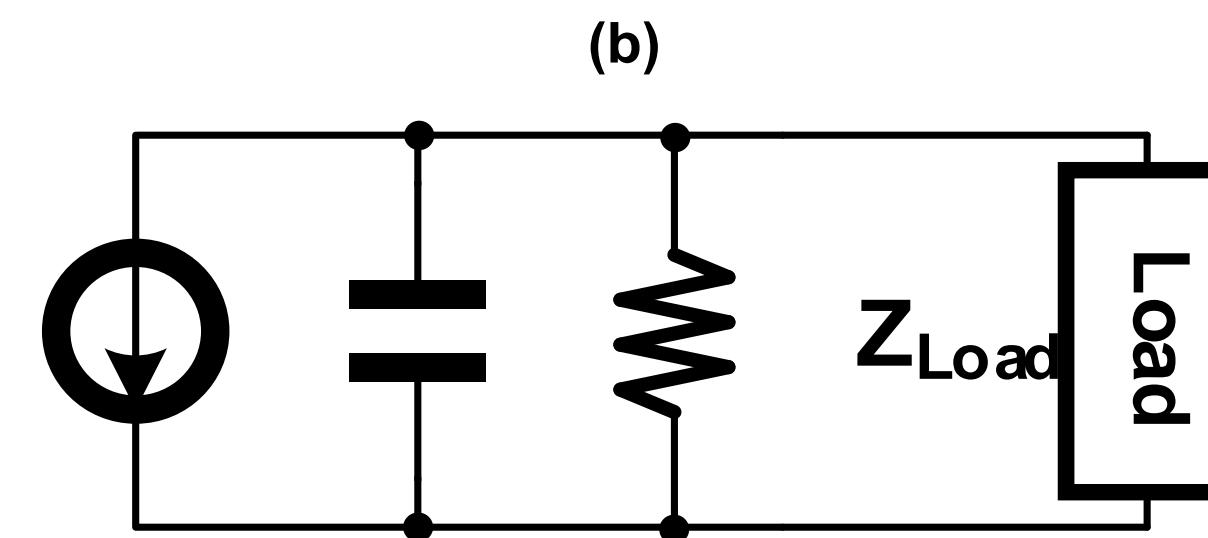
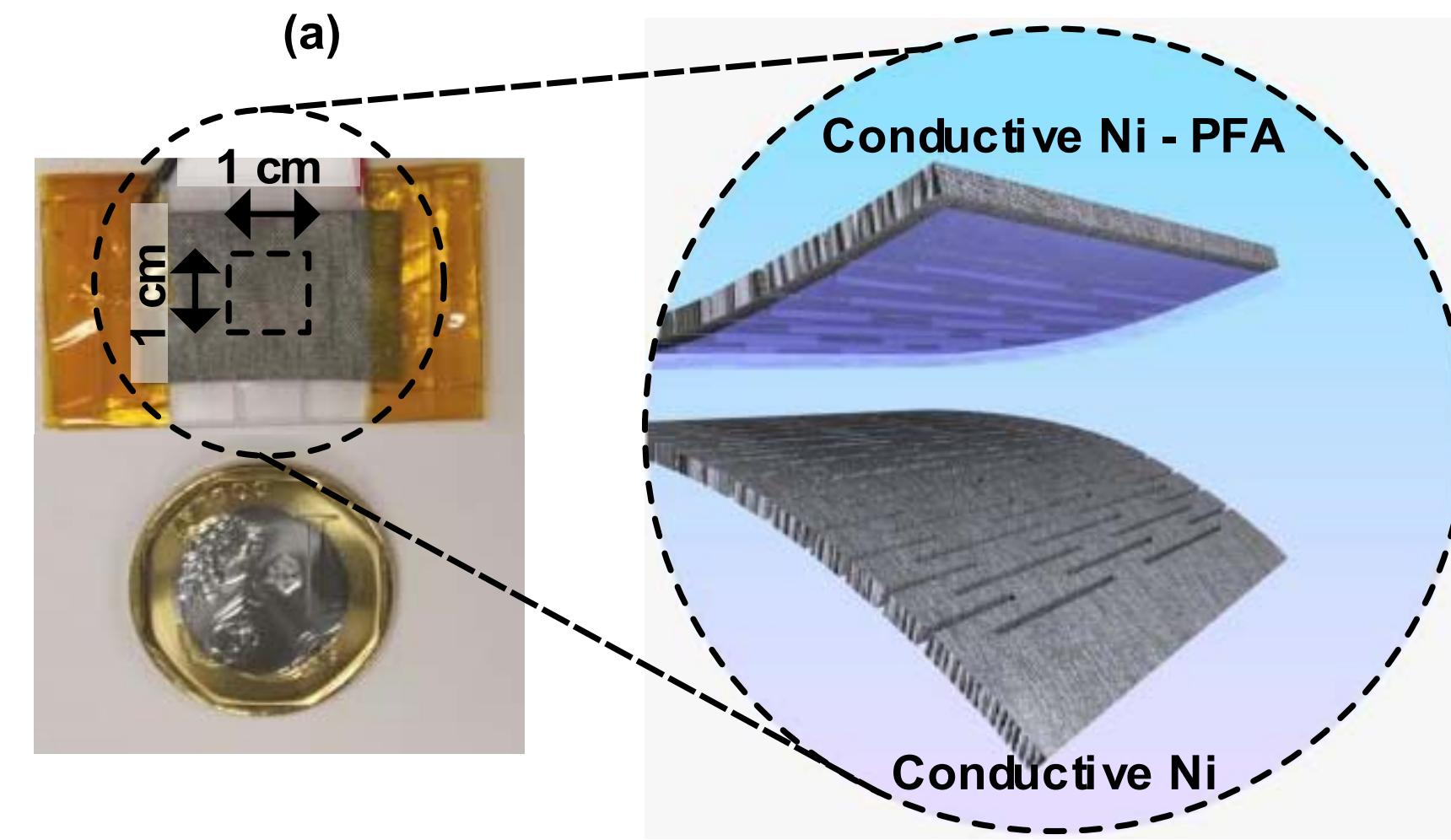
A Fully Energy-Autonomous Temperature-to-Time Converter Powered by a Triboelectric Energy Harvester for Biomedical Applications

Joanne Si Ying Tan^{ID}, *Student Member, IEEE*, Jeong Hoan Park, *Member, IEEE*,
Jiamin Li, *Student Member, IEEE*, Yilong Dong, *Student Member, IEEE*, Kwok Hoe Chan,
Ghim Wei Ho, and Jerald Yoo^{ID}, *Senior Member, IEEE*

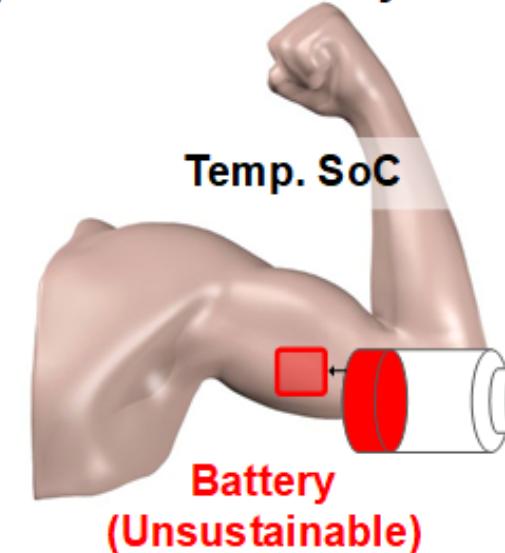
Abstract—This article presents a fully energy-autonomous temperature-to-time converter (TTC), entirely powered up by a triboelectric nanogenerator (TENG) for biomedical applications. Existing sensing systems either consume too much power to be sustained by energy harvesting or have poor accuracy. Also, the harvesting of low-frequency energy input has been challenging due to high reverse leakage of a rectifier. The proposed dynamic leakage suppression full-bridge rectifier (DLS-FBR) reduces the reverse leakage current by more than $1000\times$, enabling harvesting from sparse and sporadic energy sources; this enables the TTC to function with a TENG as the sole power source operating at <1-Hz human motion. Upon harvesting 0.6 V in the storage capacitor, the power management unit (PMU) activates the low-power TTC, which performs one-shot conversion of temperature to pulsedwidth. Designed for biomedical applications, the TTC enables a temperature measurement range from 25°C to 45°C . The energy-autonomous TTC is fabricated in 0.18- μm 1P6M CMOS technology, consuming 0.14 pJ/conversion with 0.014-ms conversion time.

overheating becomes detrimental to not only device performance but more importantly for tissues that suffer from thermal damage when exposed to high temperatures above 43°C [1]. Therefore, implanted systems, such as [2] and [3], require temperature data to ensure patients' safety. Conversely, detection of temperatures below meaningful range detectable on body ($<36^{\circ}\text{C}$) could signal a potential detachment in need of prompt discovery and adjustment. Hence, the collection of temperature data is vital in biomedical devices for the safety of the patients and effectiveness of the monitoring devices.

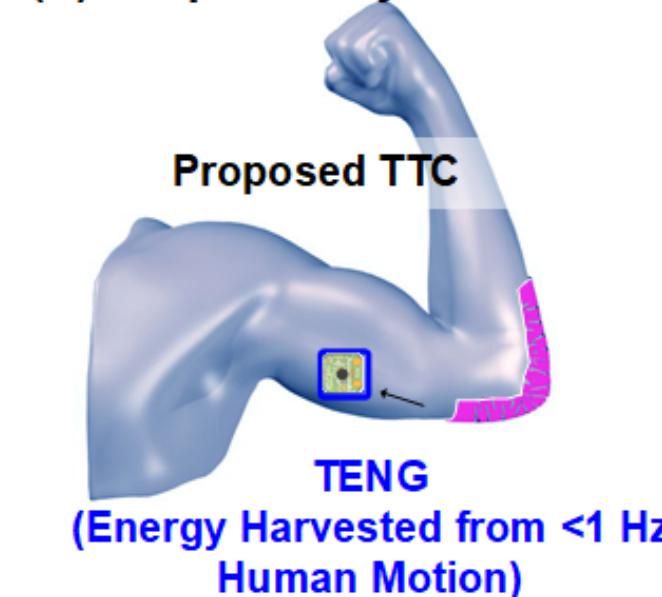
Sensor nodes for biomedical IoT are numerous and widely distributed. For long-term monitoring, it is imperative to have sustainable and maintenance-free capabilities. One of the greatest limitations is the heavy reliance on batteries, an unsustainable source of power that requires replacement or cumbersome recharging [4]. Hence, it is essential for energy



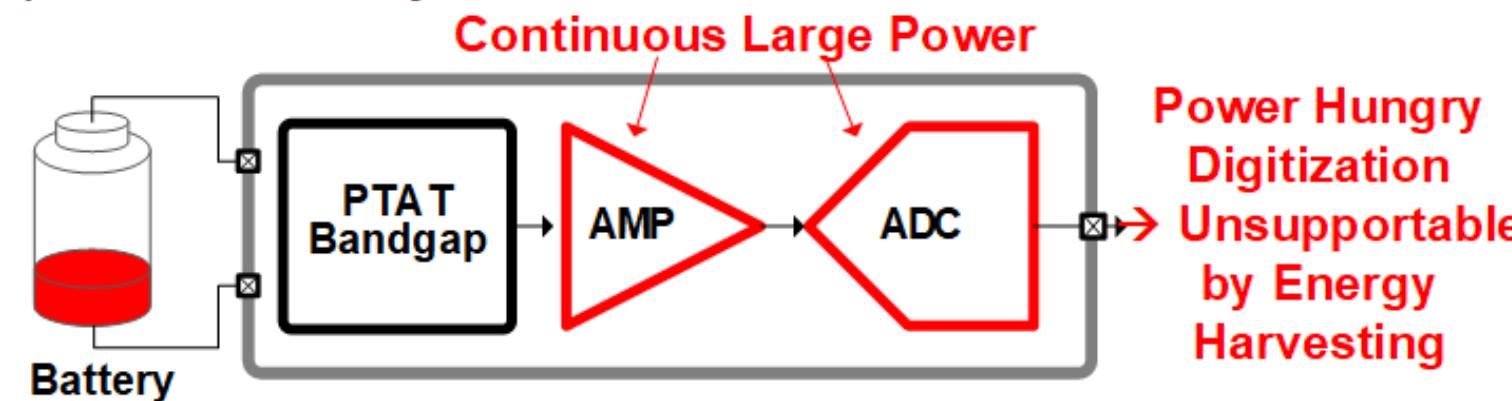
(a) Conventional System



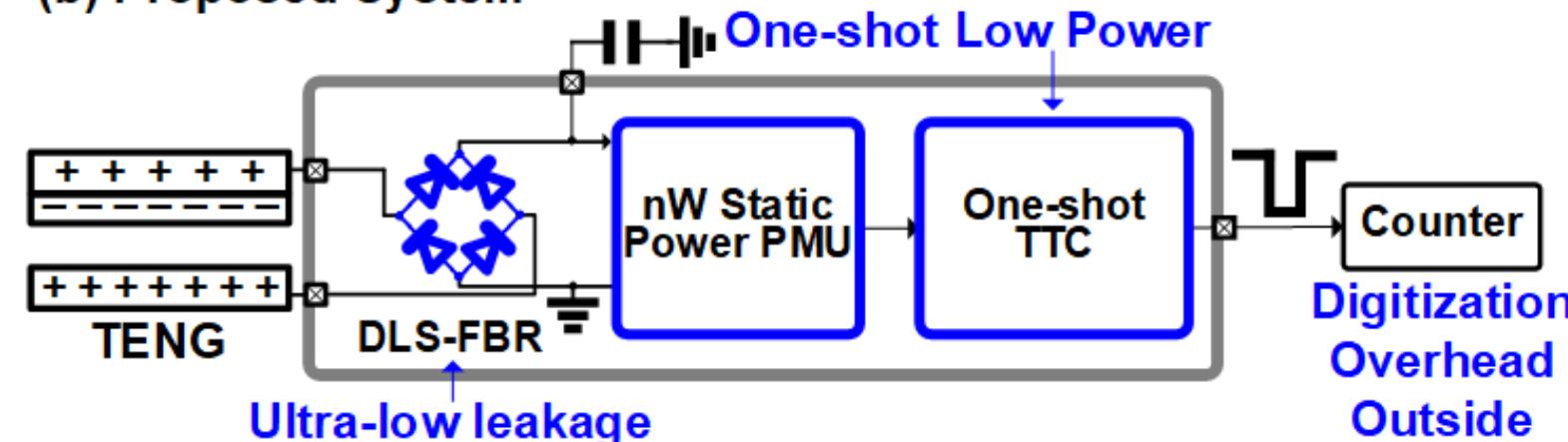
(b) Proposed System



(a) Conventional System



(b) Proposed System



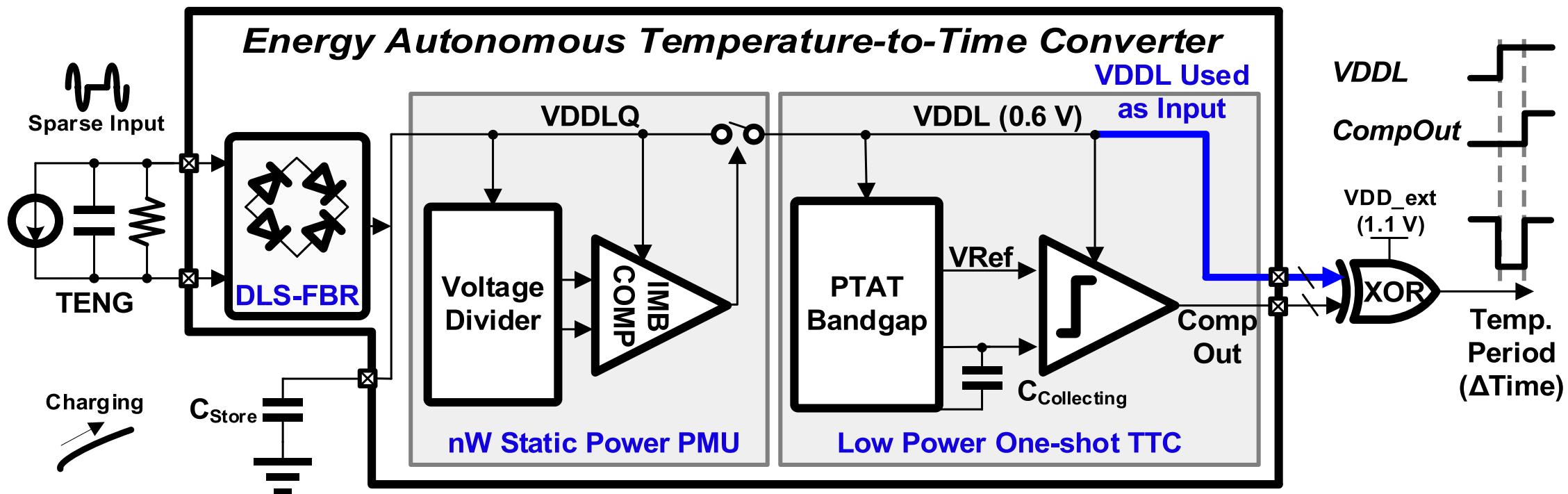
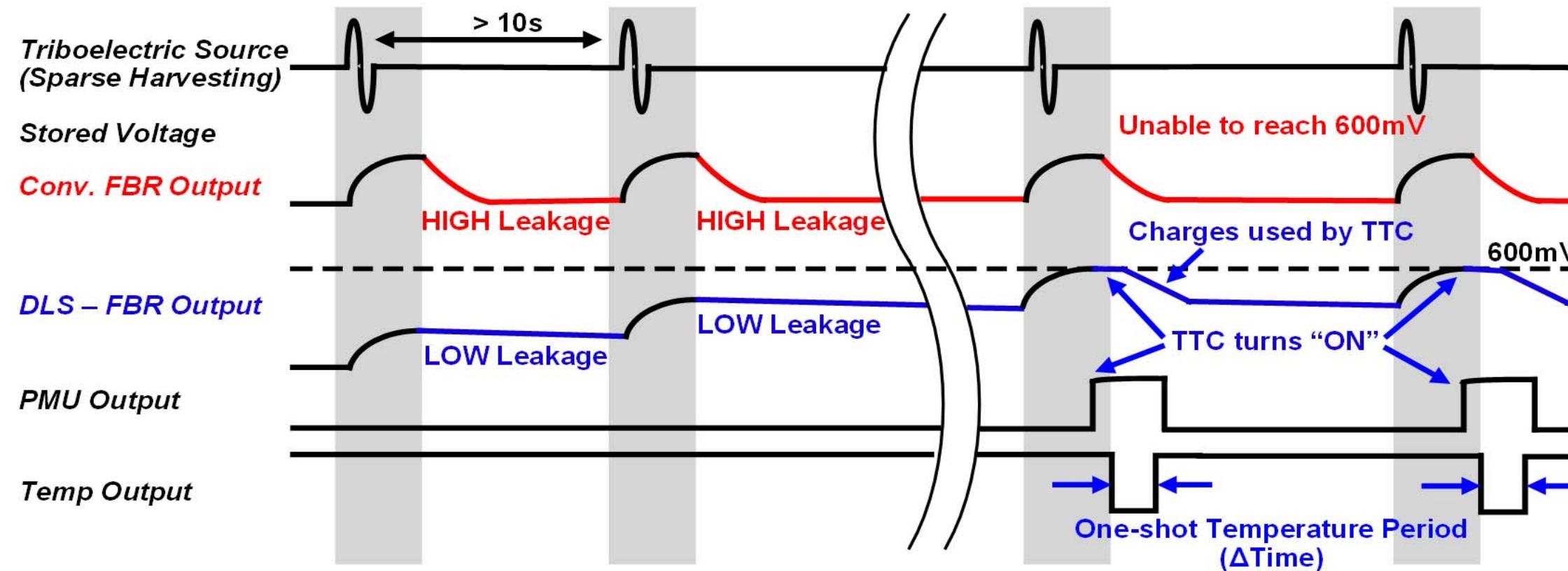


Fig. 2. Overall architecture of the proposed energy-autonomous TTC.



Comparison

Energy Source	Power Density	Frequency	Characteristics
Solar/PV	10μW/cm²(indoor) 15mW/cm²(outdoor)	DC	Requires exposure to light
RF Energy	0.1μW/cm²(GSM) 0.01μW/cm²(WiFi)	380M ~ 5 Hz	Low efficiency for indoor and out of line-of-sight
Thermal – body heat	40μW/cm²	DC	Requires high temperature differences
Piezoelectric	4μW/cm²	> 30 Hz	Not limited by indoors or outdoors
Triboelectric (TENG)	1μW/cm²	1 Hz	Not limited by indoors or outdoors

Fig. 4. Comparison of energy harvesters [4].

References

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Thanks!