# TFE4188 - Lecture X

# Energy Sources

# Goal

**Why** do we need energy sources?

Introduction to **Energy Harvesting**

# Why

# Lithium Battery

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

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

Received June 23, 2019, accepted July 3, 2019, date of publication July 15, 2019, date of current version July 31, 2019.

*Digital Object Identifier 10.1109/ACCESS.2019.2928523*

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

**MAHYAR SHIRVANIMOGHADDAM[1], (Member, IEEE), KAMYAR SHIRVANIMOGHADDAM[2], MOHAMMAD MAHDI ABOLHASANI[3], MAJID FARHANGI[4], VAHID ZAHIRI BARSARI[4], HANGYUE LIU[4], (Student Member, IEEE), MISCHA DOHLER[5], (Fellow, IEEE), AND MINOO NAEBE[2]**

[1]Centre for IoT and Telecommunications, School of Electrical and Information Engineering, The University of Sydney, Sydney, NSW 2006, Australia
[2]The Institute for Frontier Materials, Deakin University, Geelong, VIC 3216, Australia
[3]Chemical Engineering Department, University of Kashan, Kashan, Iran
[4]School of Electrical and Information Engineering, The University of Sydney, Sydney, NSW 2006, Australia
[5]Centre for Telecommunications Research, Department of Informatics, King's College London, London WC2B 4BG, U.K.

Corresponding authors: Mahyar Shirvanimoghaddam (mahyar.shm@sydney.edu.au) and Minoo Naebe (minoo.naebe@deakin.edu.au)

This work was supported in part by the Australian Research Council under the Discovery Project Grant DP180100606, in part by the Australian Research Council World Class Future Fiber Industry Transformation Research Hub under Grant H140100018, and in part by the Australian Research Council Training Centre for Light Weight Automotive Structures (ATLAS).

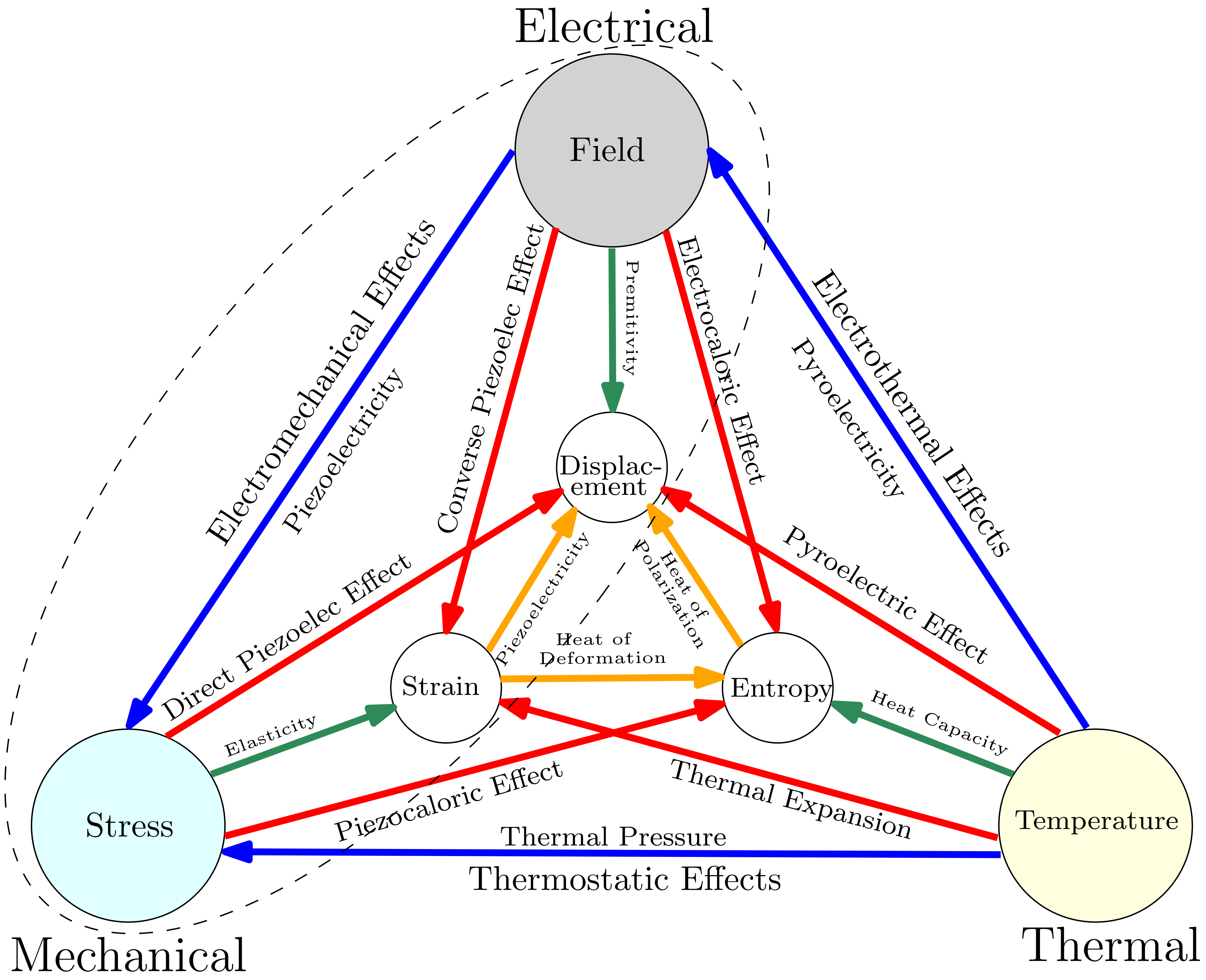
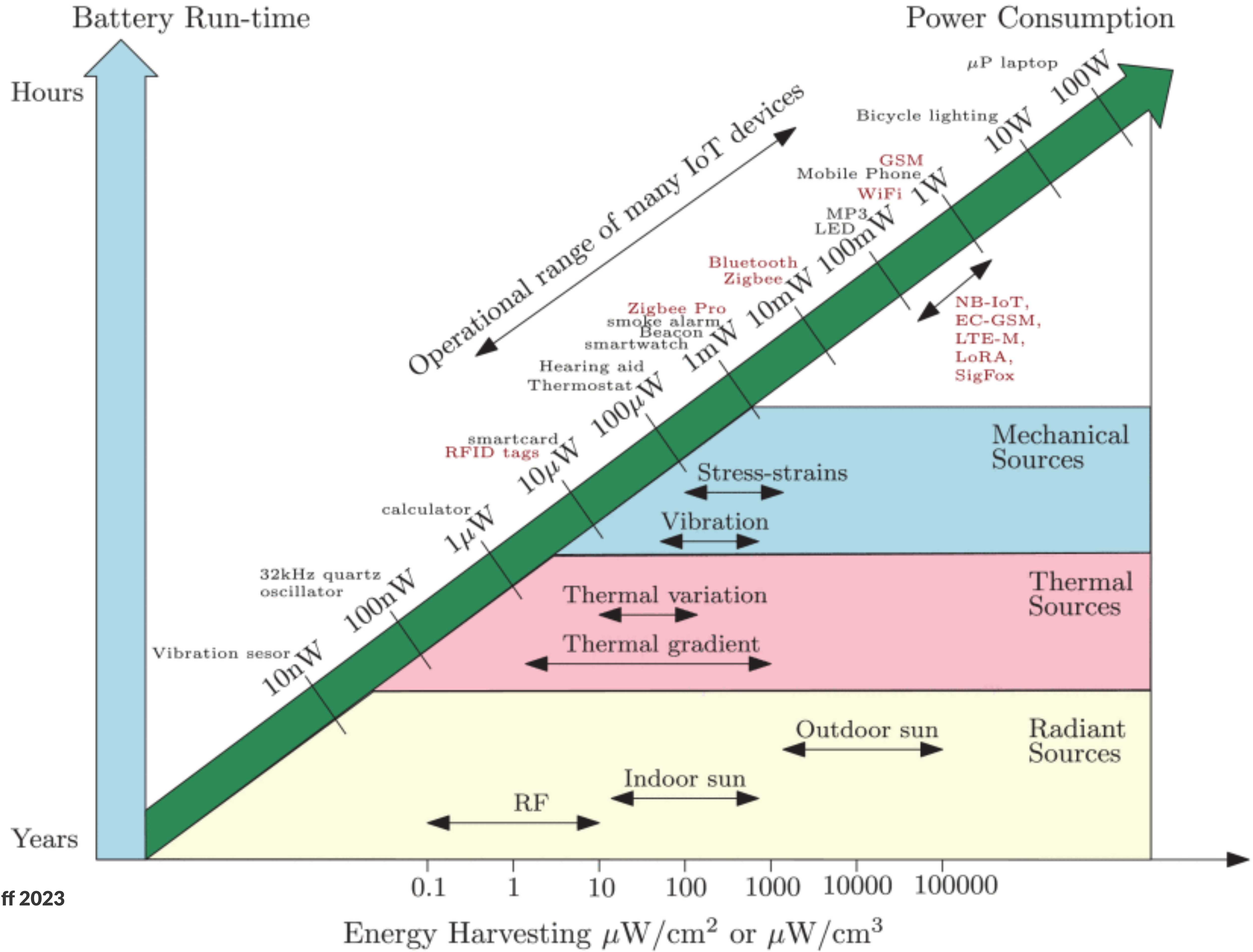


**FIGURE 5. A Heckman diagram representing the interrelationship between mechanical, thermal and electrical properties of materials [41].**


Battery Run-time
Hours
Years
Power Consumption
Operational range of many IoT devices
10nW
100nW
1µW
10µW
100µW
1mW
10mW
100mW
1W
10W
100W
Vibration sesor
32kHz quartz oscillator
calculator
smartcard
RFID tags
Hearing aid
Thermostat
smartwatch
Beacon
smoke alarm
Zigbee Pro
Bluetooth
Zigbee
LED
MP3
WiFi
Mobile Phone
GSM
Bicycle lighting
µP laptop
NB-IoT,
EC-GSM,
LTE-M,
LoRA,
SigFox
Mechanical Sources
Stress-strains
Vibration
Thermal Sources
Thermal variation
Thermal gradient
Radiant Sources
Outdoor sun
Indoor sun
RF
0.1
1
10
100
1000
10000
100000
Energy Harvesting µW/cm² or µW/cm³

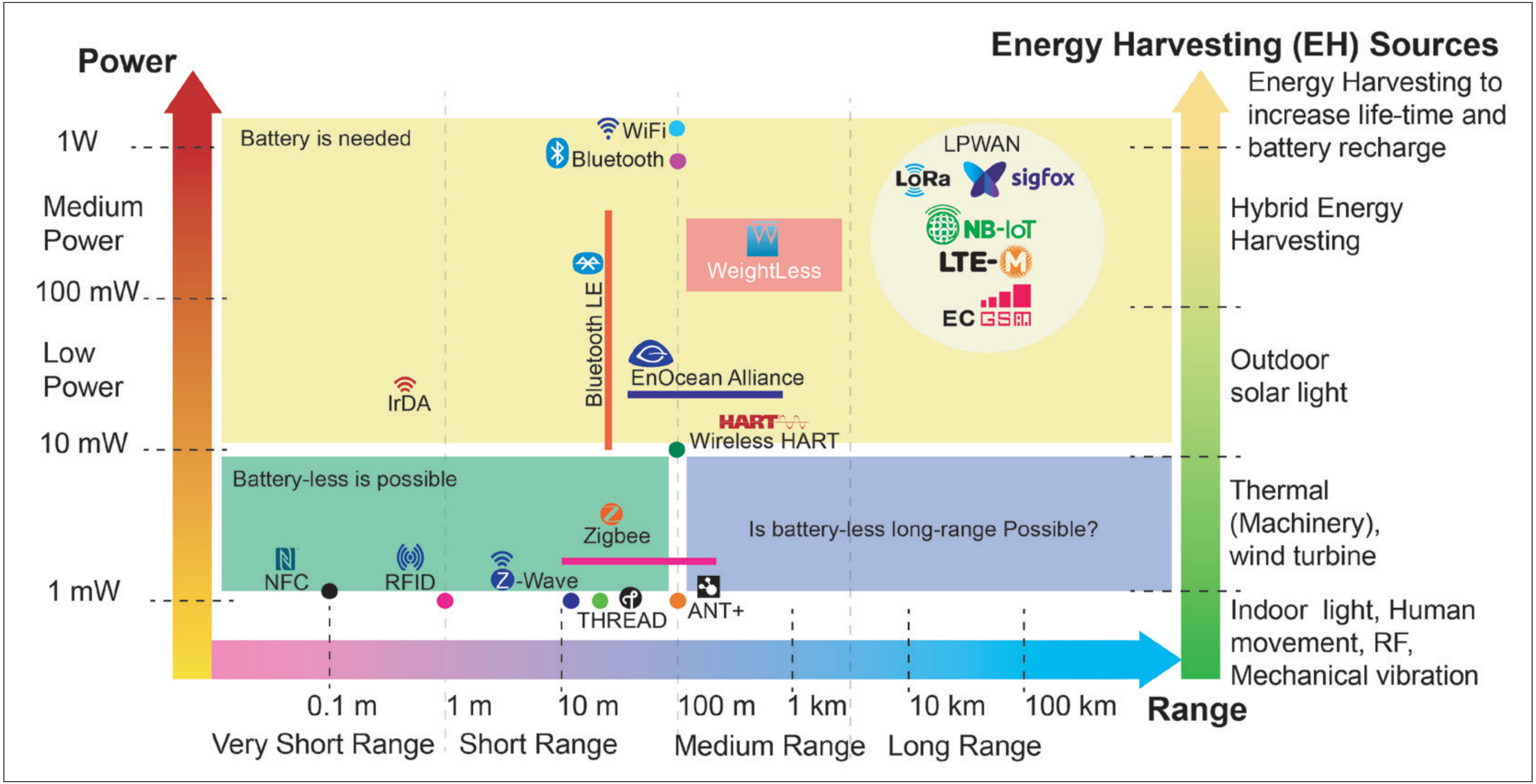


FIGURE 2. Consumed peak power vs. coverage applicable for wireless systems. Low-range wireless technologies operating over extremely low power, which is acceptable for IoT applications, may not be viable in long-range systems. Long-range wireless technologies such as LPWAN require substantial transmit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

Thermoelectric

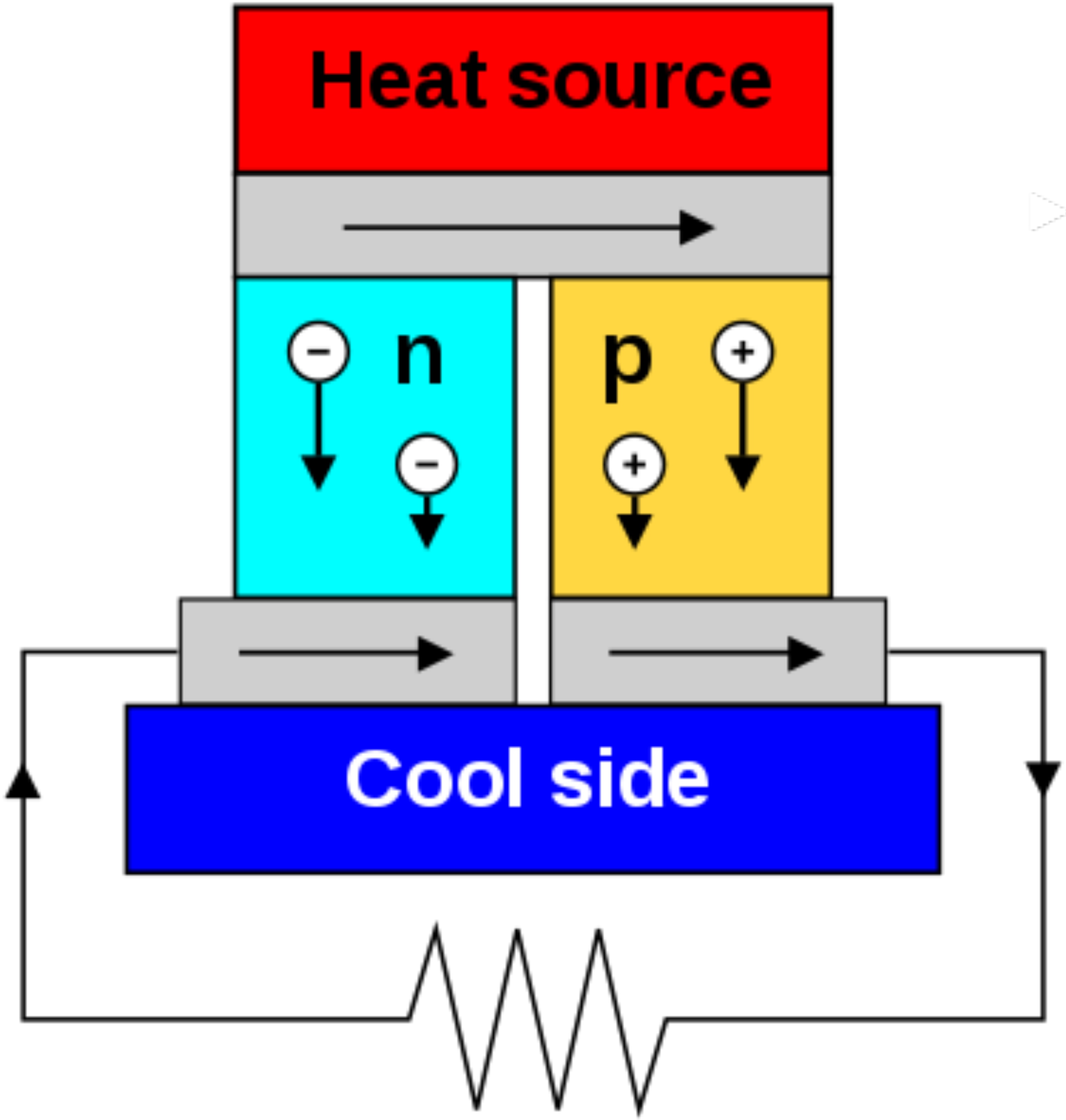
Photovoltaic

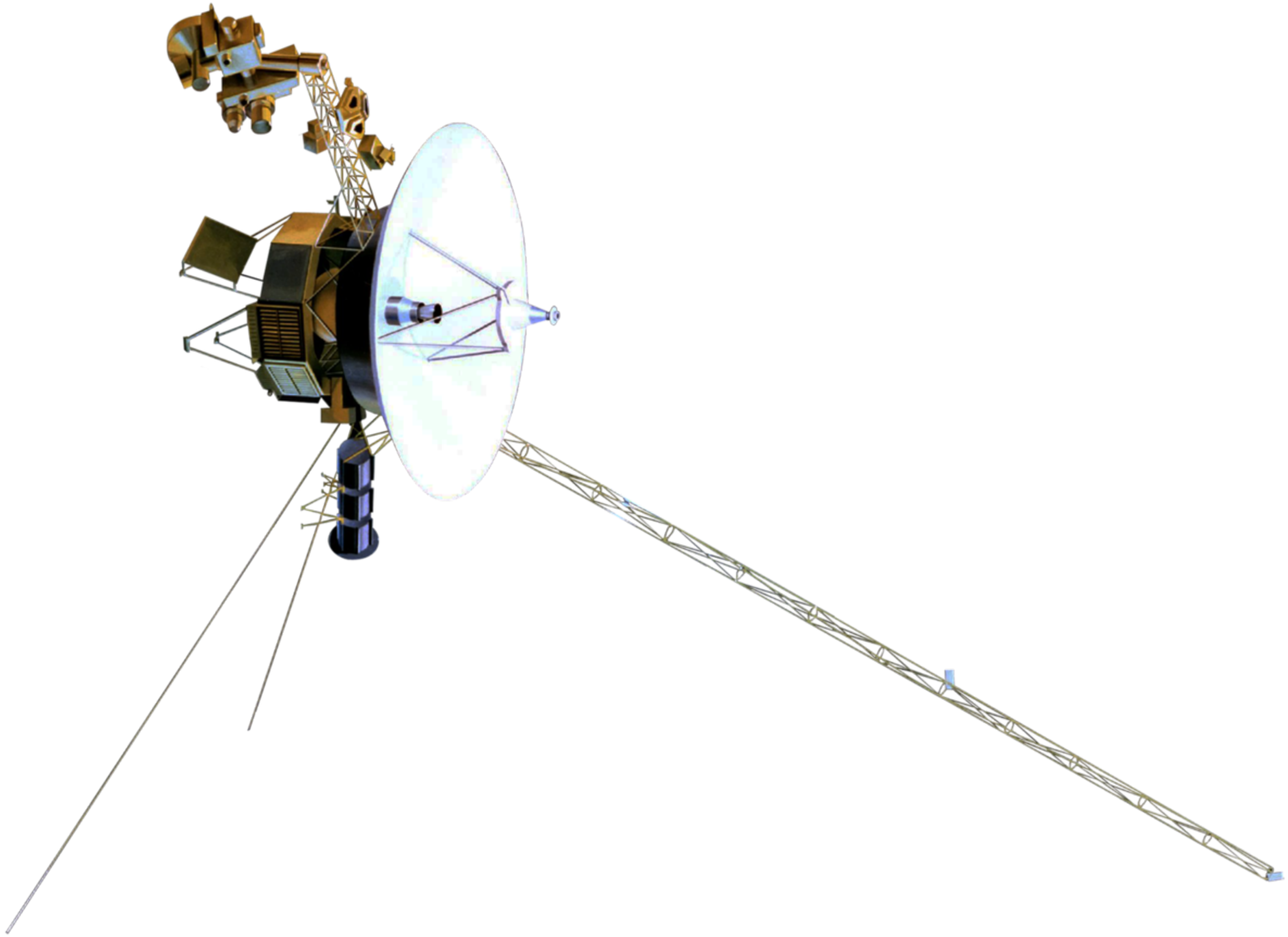
Piezoelectric

Ambient RF

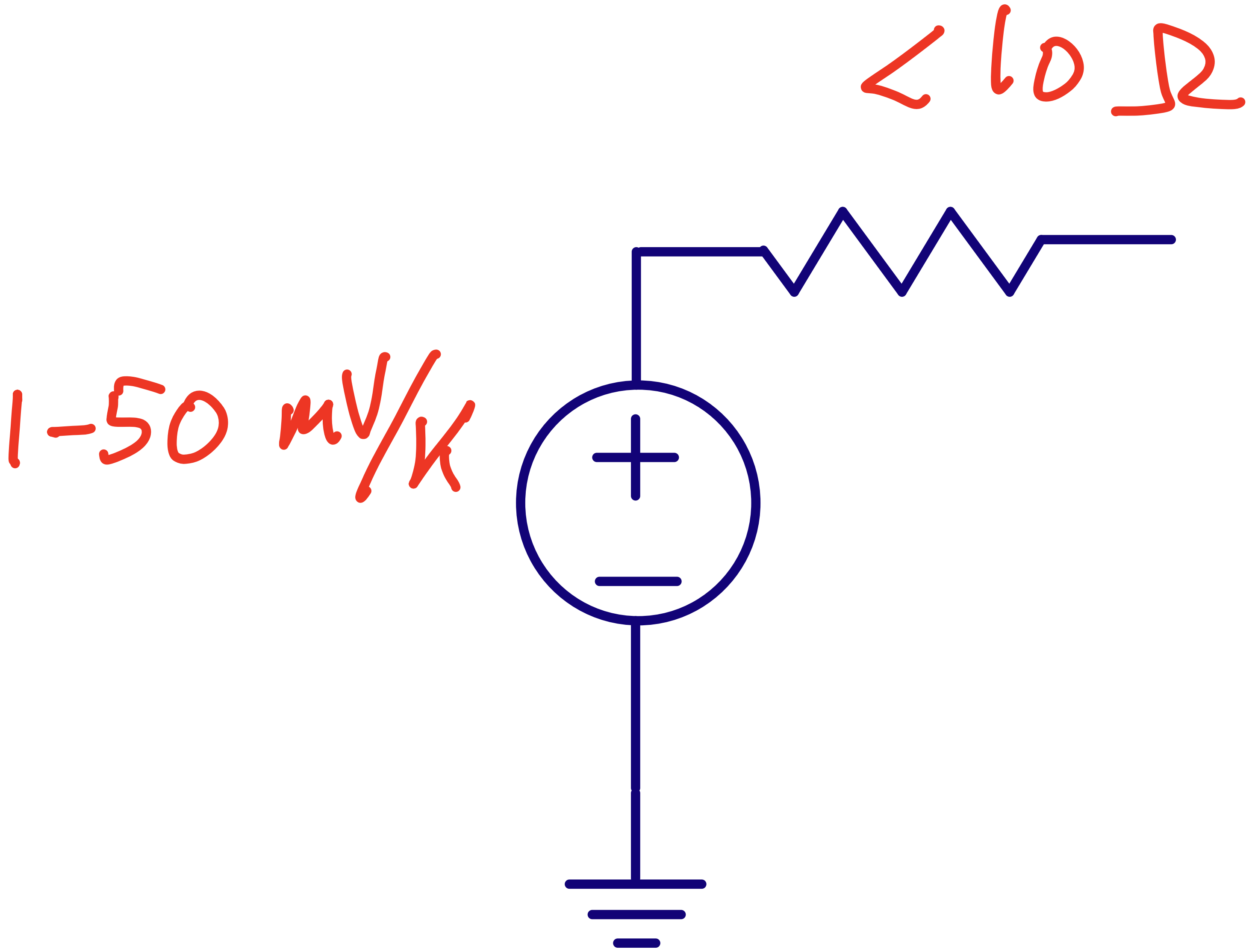
Triboelectric

# Thermoelectric

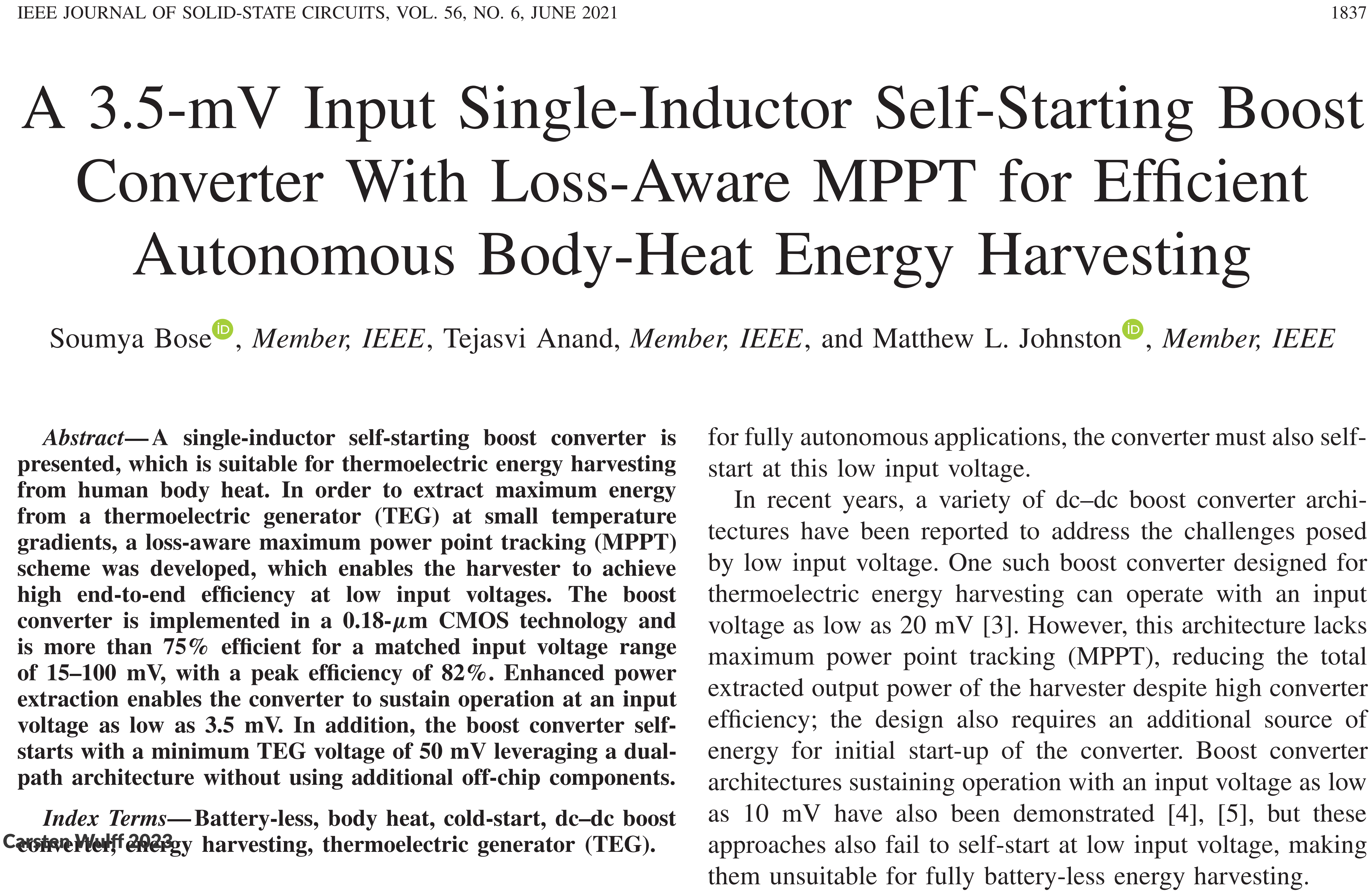

Heat source
n
p
Cool side



# Radioisotope Thermoelectric generator



# Thermoelectric generators



IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 56, NO. 6, JUNE 2021 1837

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

Soumya Bose, *Member, IEEE*, Tejasvi Anand, *Member, IEEE*, and Matthew L. Johnston, *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-$\mu$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.

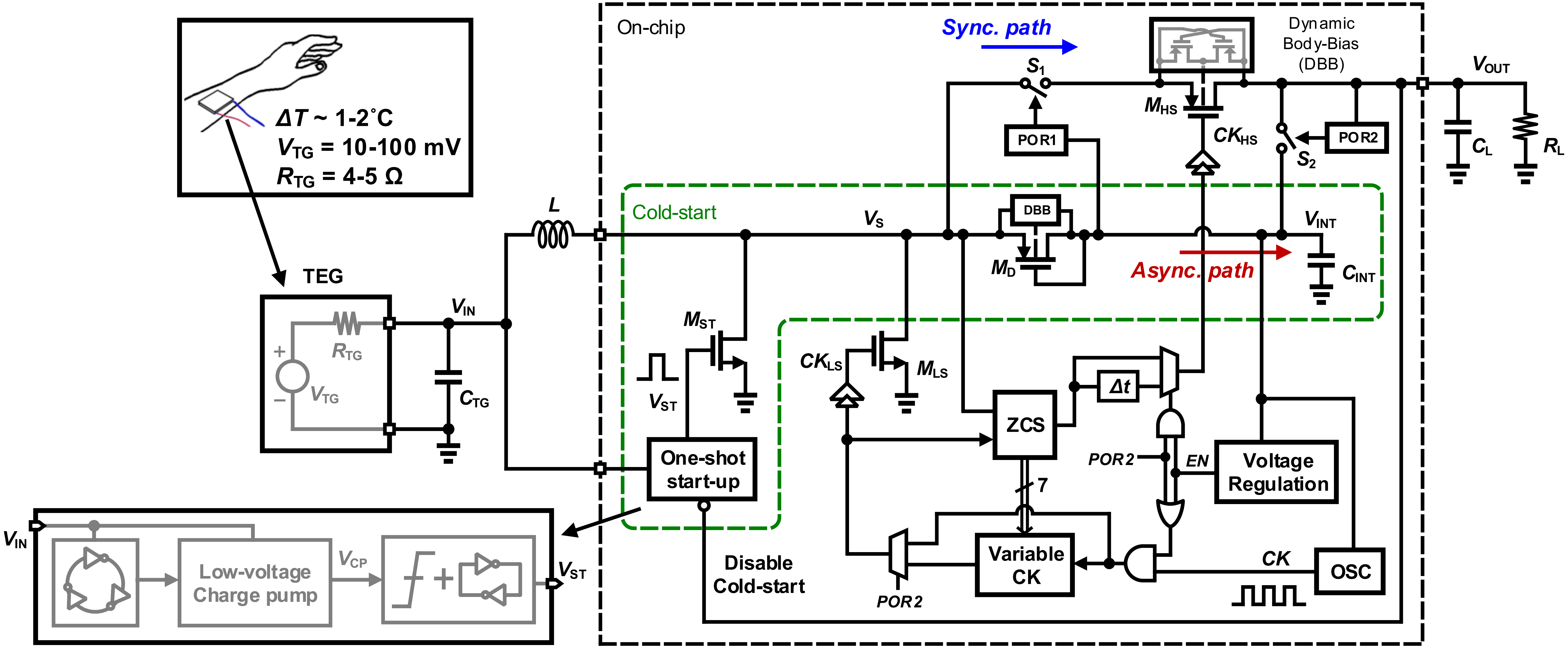
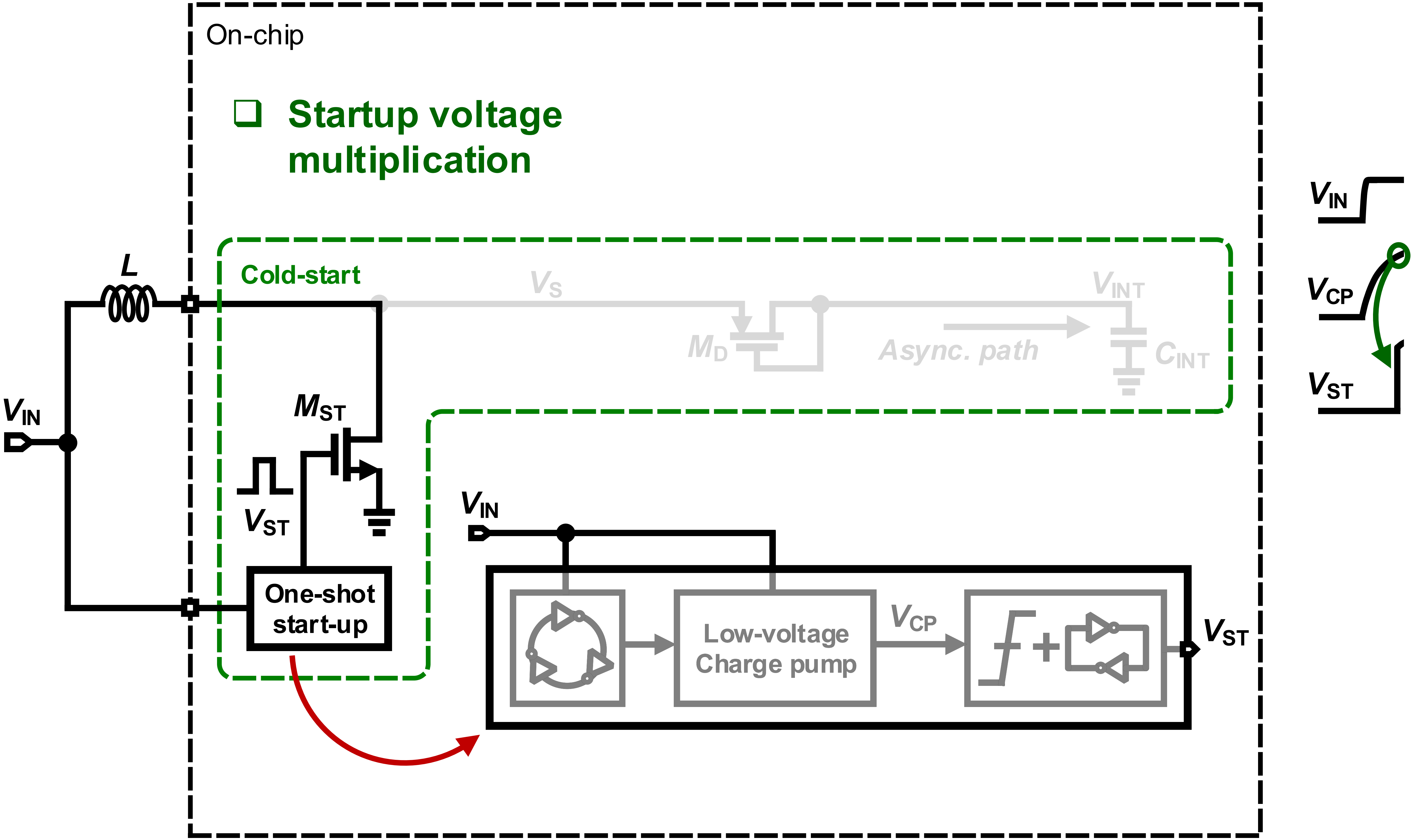
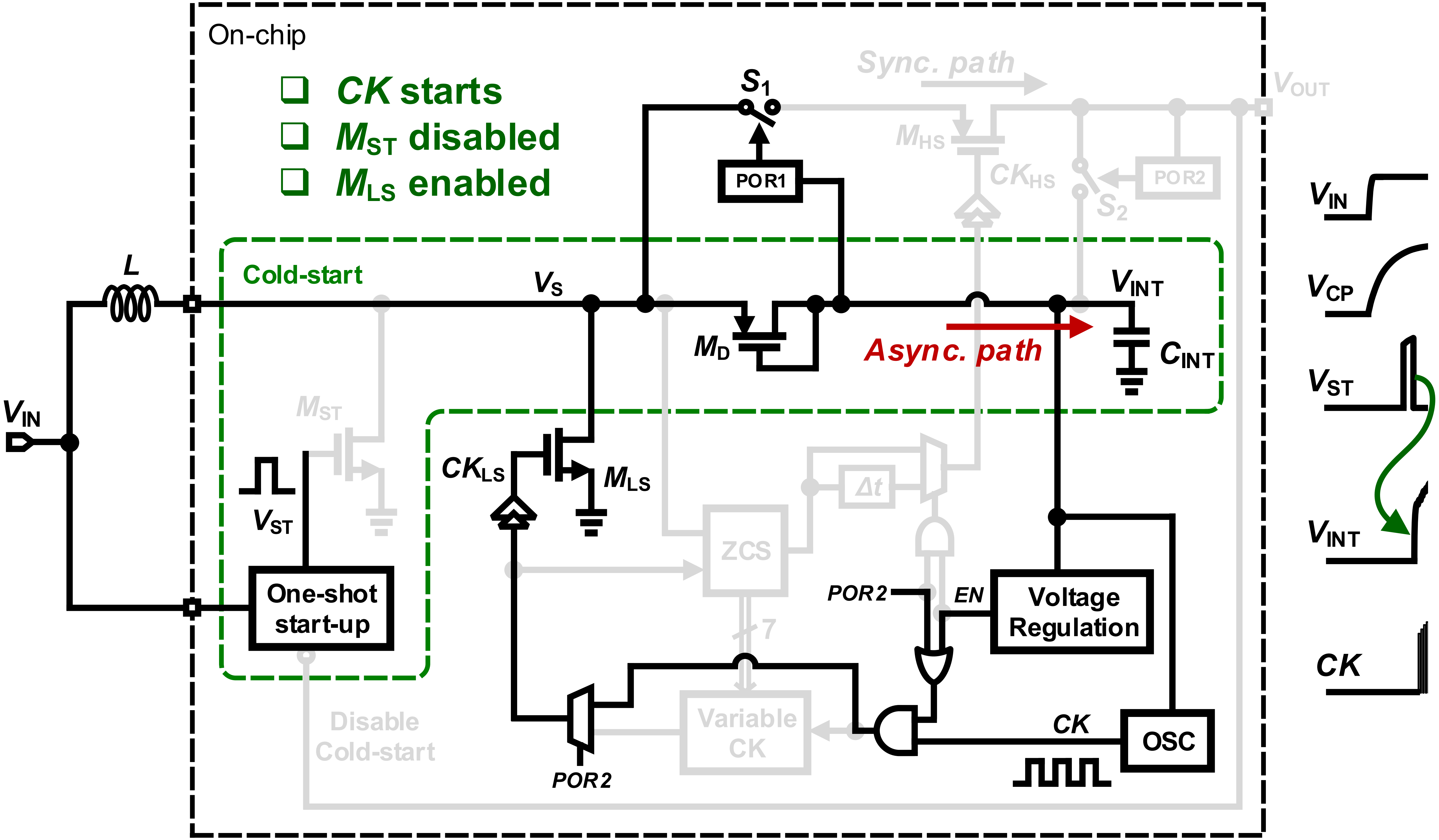


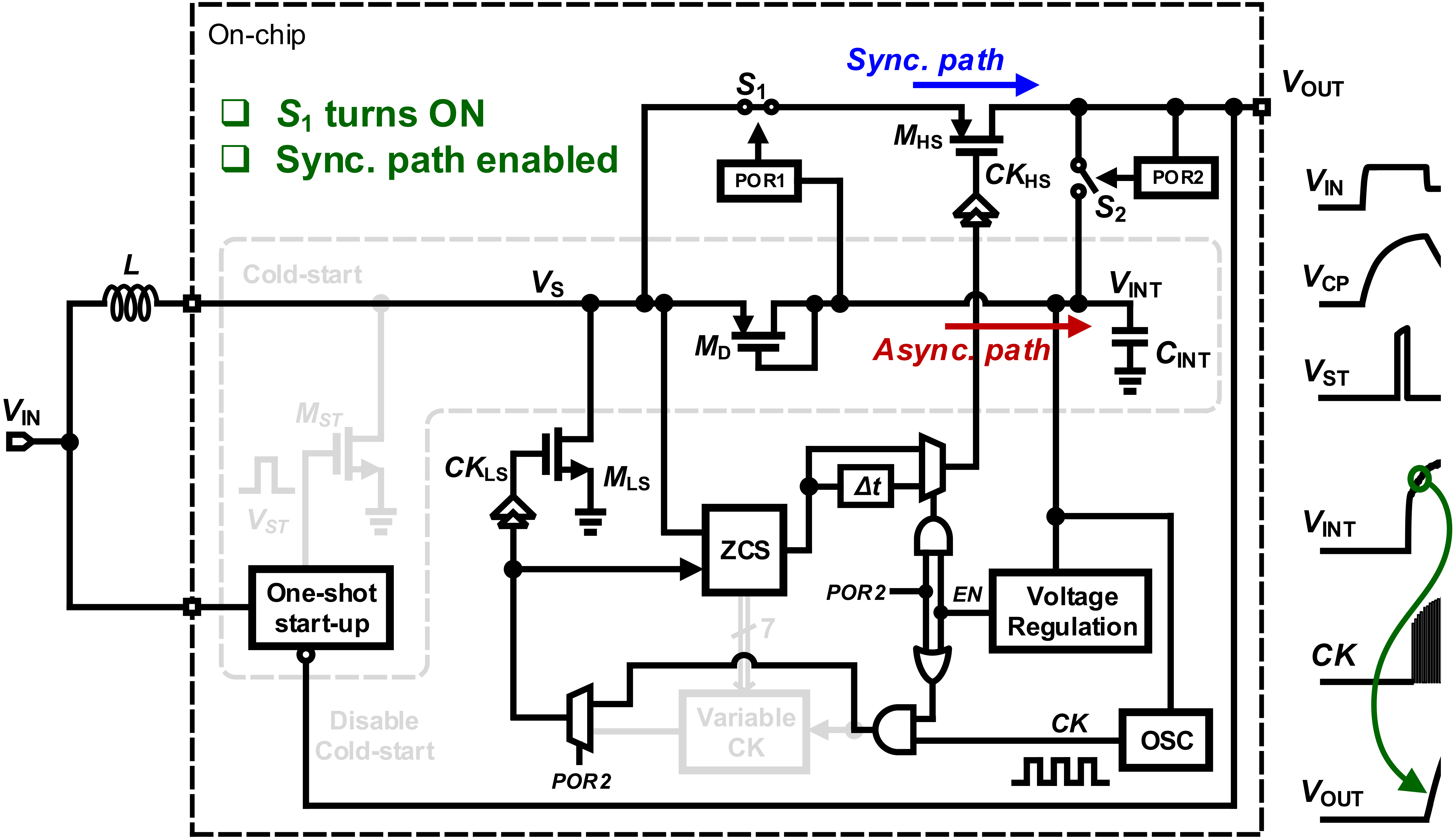
Fig. 1. Self-starting single-inductor boost converter architecture for low-voltage thermoelectric energy harvesting utilizing human body heat.


On-chip
Startup voltage multiplication
Cold-start
L
$V_{IN}$
$V_S$
$V_{INT}$
$M_D$
Async. path
$C_{INT}$
$M_{ST}$
$V_{ST}$
One-shot start-up
$V_{IN}$
Low-voltage Charge pump
$V_{CP}$
$V_{ST}$
$V_{IN}$
$V_{CP}$
$V_{ST}$

(a)

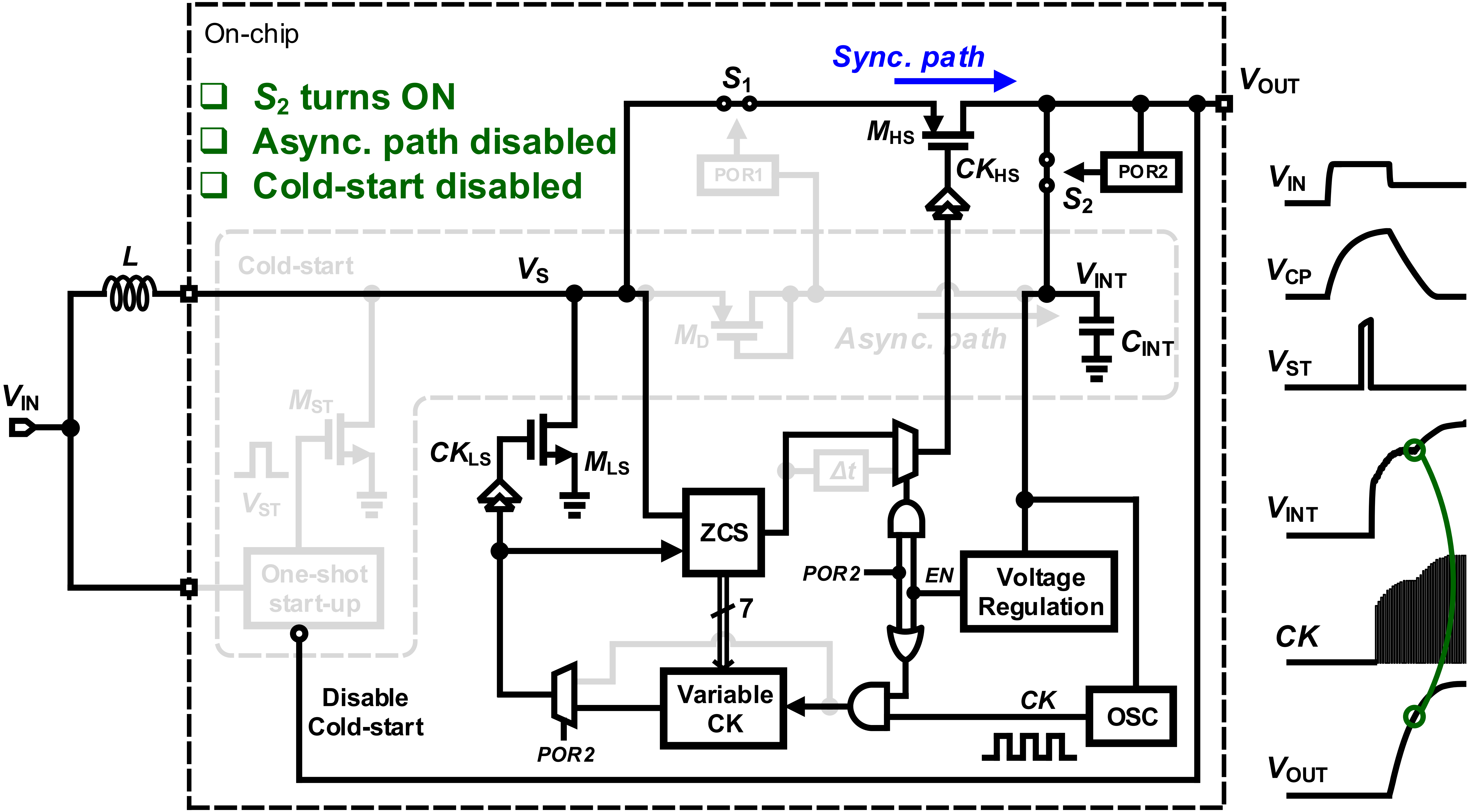

On-chip
☐ CK starts
☐ M_ST disabled
☐ M_LS enabled
Sync. path
S_1
V_OUT
M_HS
CK_HS
POR1
POR2
S_2
Cold-start
V_S
V_INT
L
M_D
Async. path
C_INT
V_IN
M_ST
V_ST
CK_LS
M_LS
Δt
ZCS
7
POR2
EN
Voltage Regulation
One-shot start-up
Disable Cold-start
Variable CK
POR2
CK
OSC
V_IN
V_CP
V_ST
V_INT
CK

(b)



- ☐ $S_1$ turns ON
- ☐ Sync. path enabled

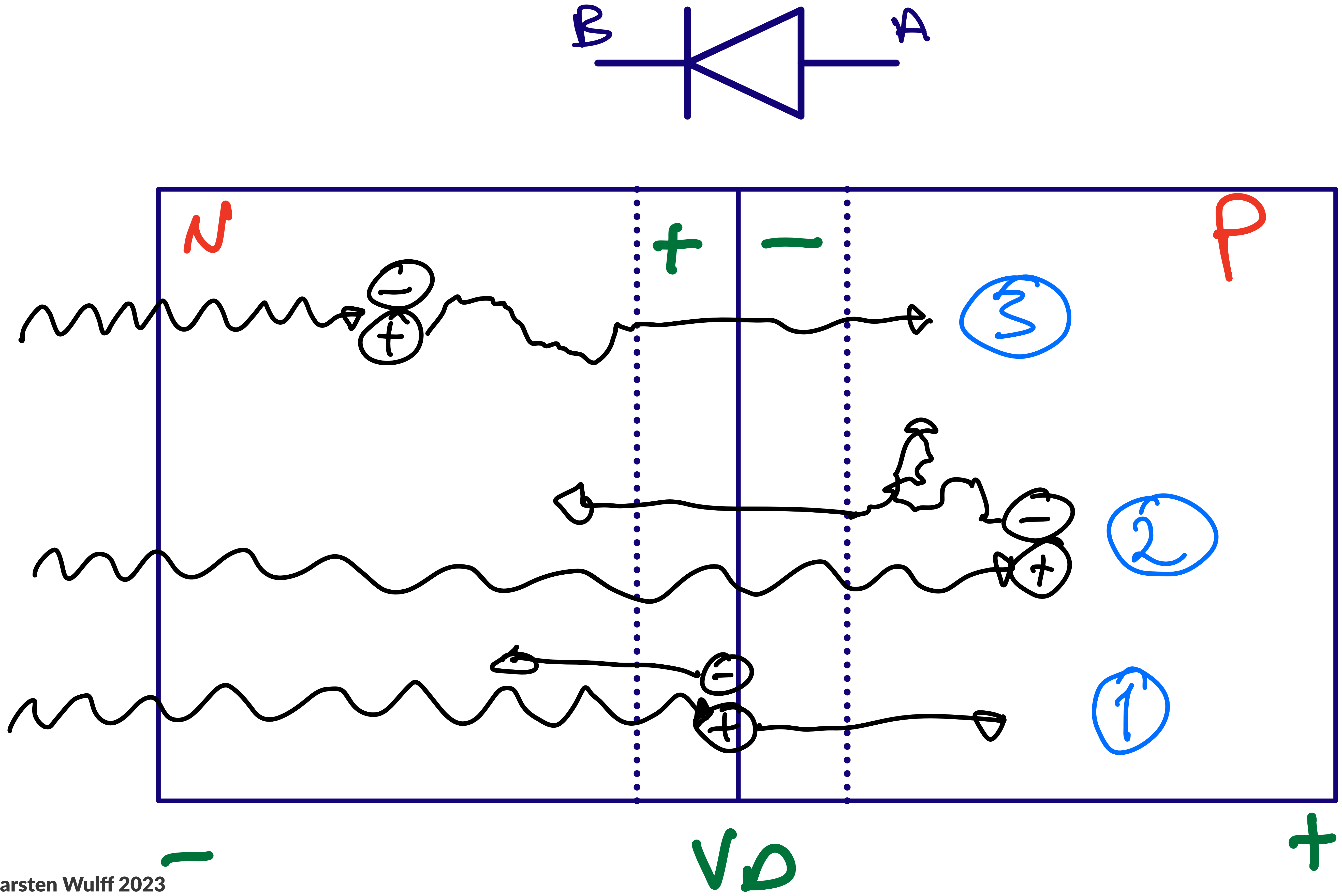
(c)

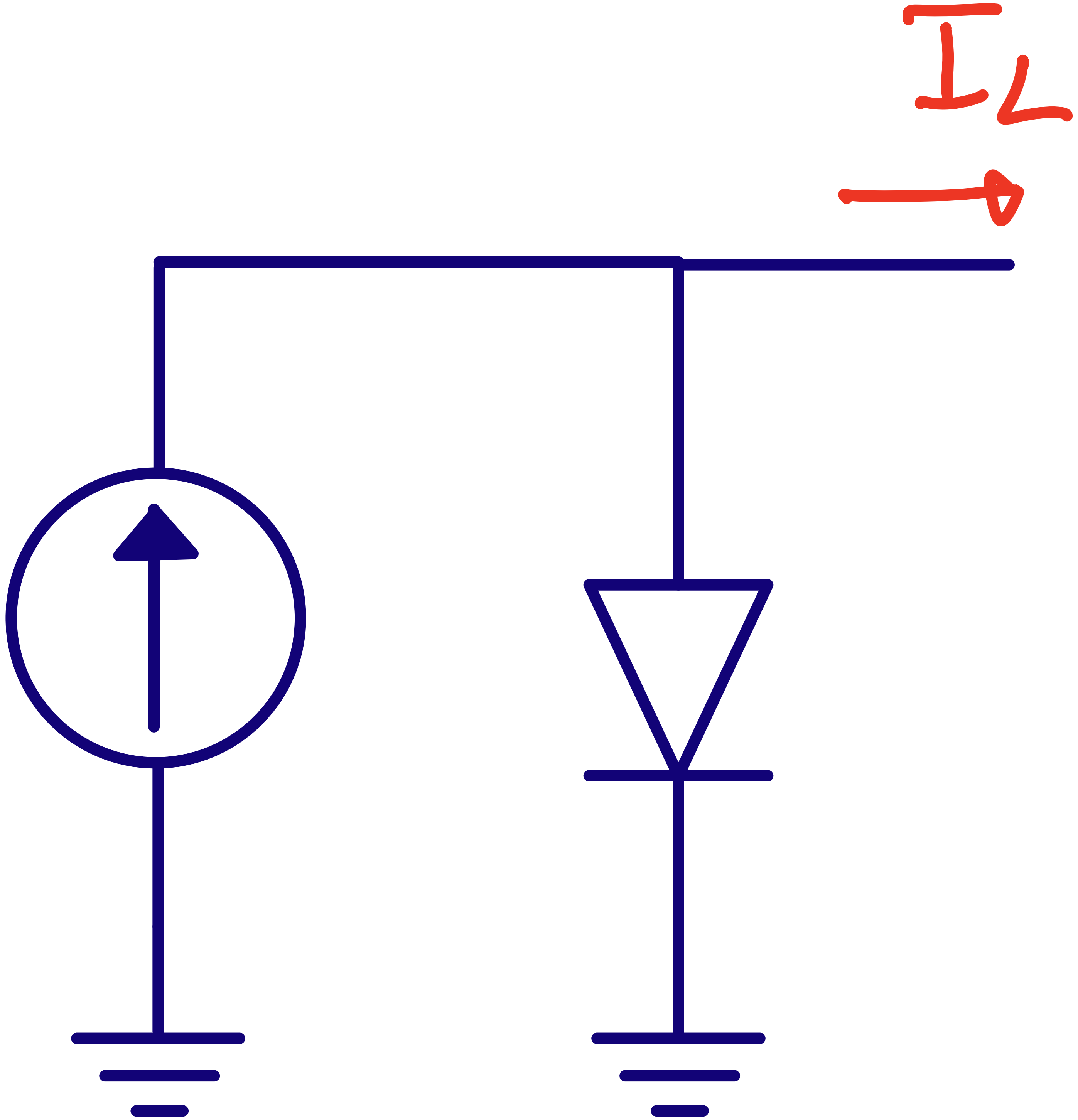


- ☐ $S_2$ turns ON
- ☐ Async. path disabled
- ☐ Cold-start disabled

(d)

# Photovoltaic


B
A
N
P
+
−
③
②
①
−
VD
+



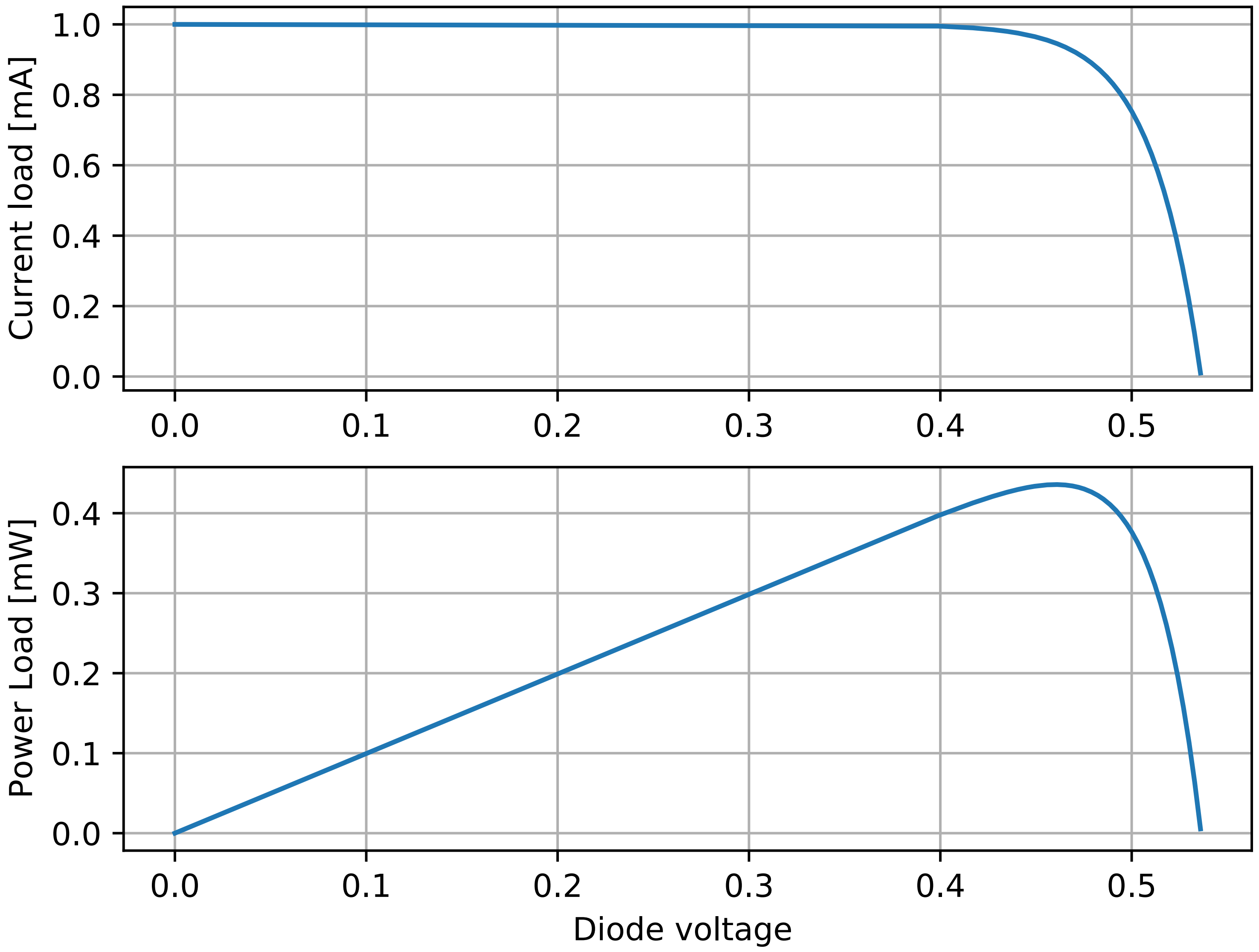
$$I_D = I_S \left( e^{\frac{V_D}{V_T}} - 1 \right)$$

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

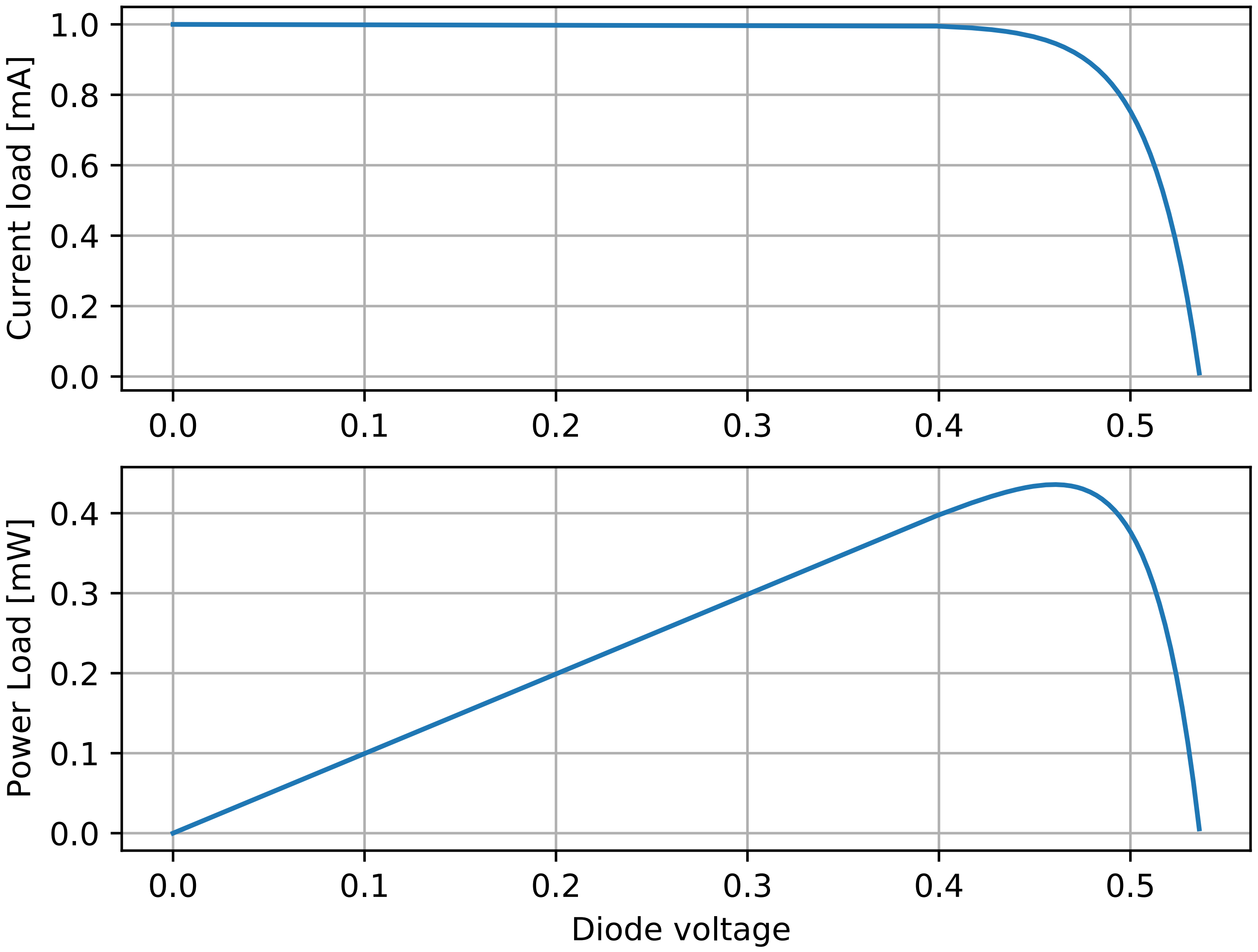
$$V_D = V_T ln \left( \frac{I_{Photo} - I_{Load}}{I_S} + 1 \right)$$

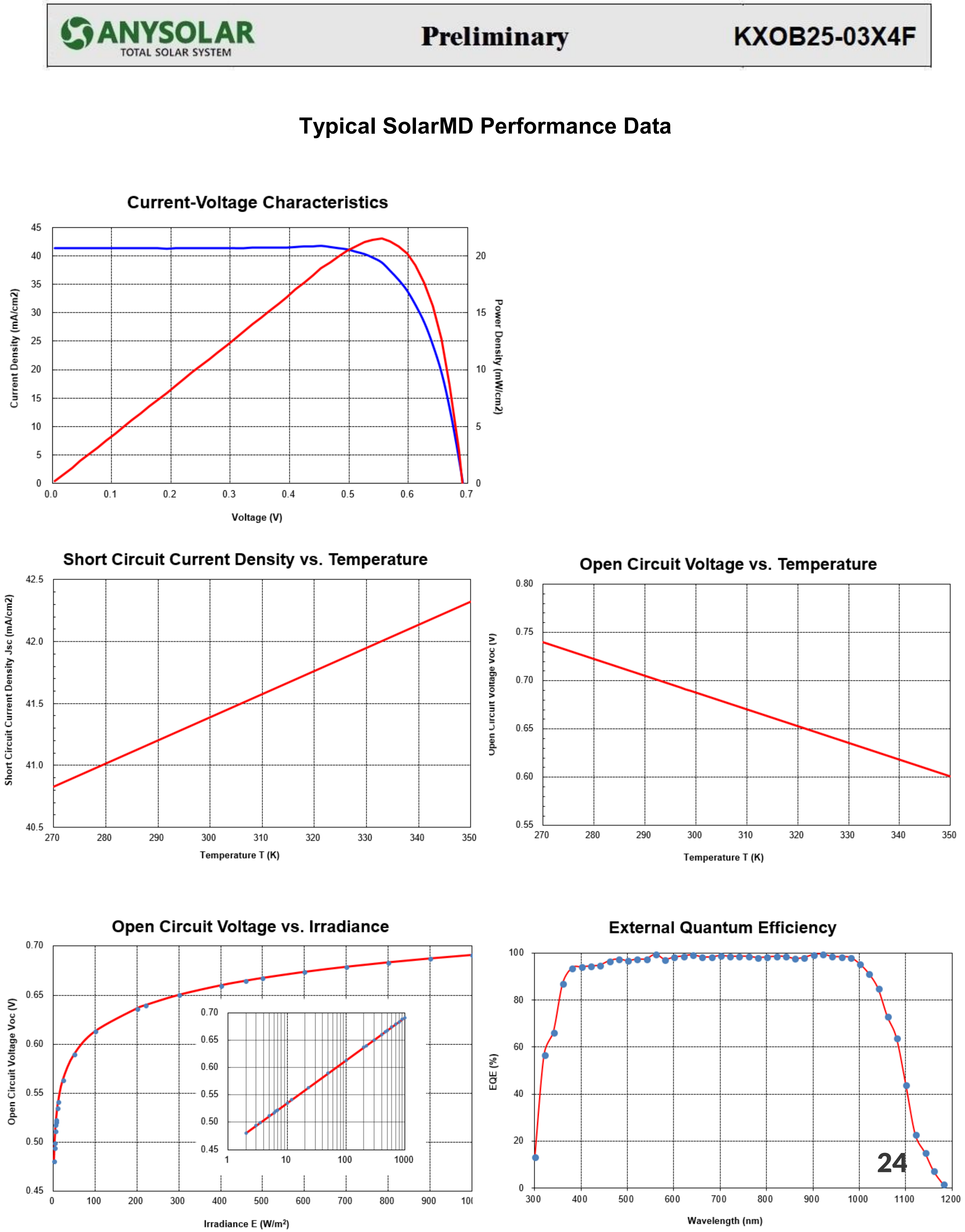
$$P_{Load} = V_D I_{Load}$$

```
#!/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  # saturation current
i_ph = 1e-3  # Photocurrent

V_T = 1.38e-23*300/1.6e-19  #Thermal voltage

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()
```



# ANYSOLAR





ANYSOLAR TOTAL SOLAR SYSTEM **Preliminary** **KXOB25-03X4F**

**Typical SolarMD Performance Data**

**Current-Voltage Characteristics**

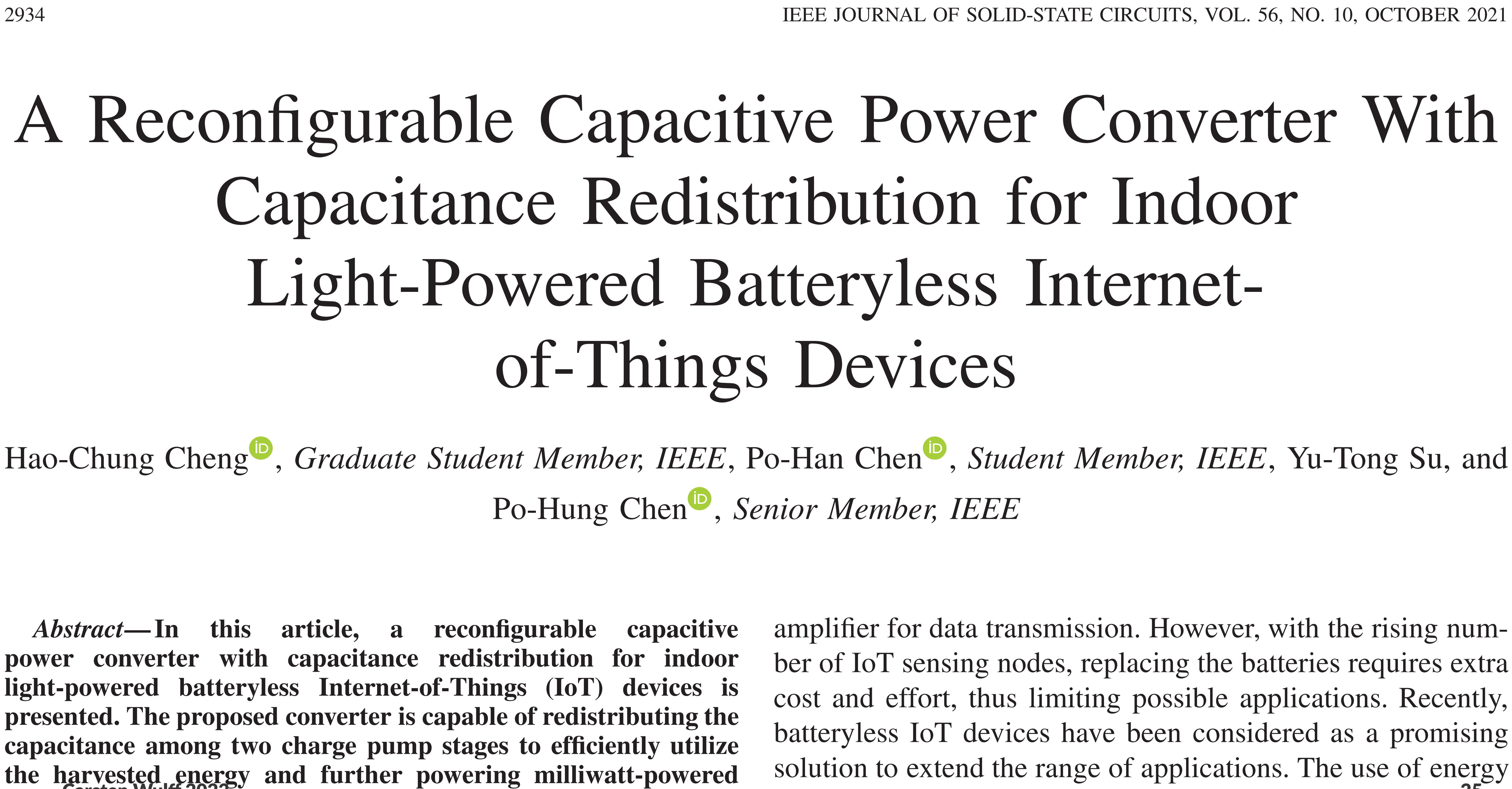
**Short Circuit Current Density vs. Temperature**

**Open Circuit Voltage vs. Temperature**

**Open Circuit Voltage vs. Irradiance**

**External Quantum Efficiency**

**Carsten Wulff 2023**



2934 IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 56, NO. 10, OCTOBER 2021

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

Hao-Chung Cheng, *Graduate Student Member, IEEE*, Po-Han Chen, *Student Member, IEEE*, Yu-Tong Su, and
Po-Hung Chen, *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

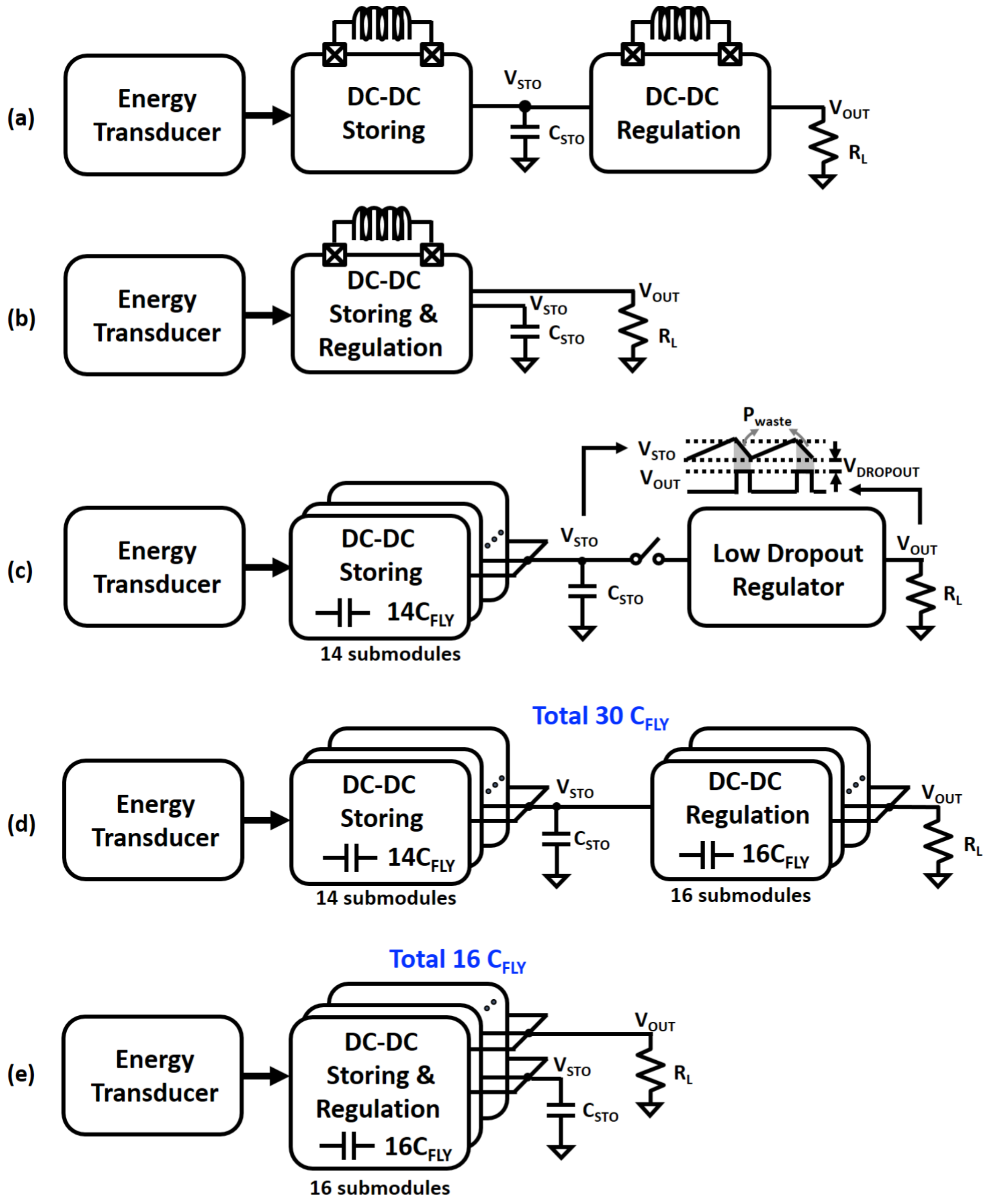


Fig. 1. Possible approaches for batteryless IoT devices: (a) inductive converter with two inductors, (b) SIMO inductive converter [5], (c) capacitive converter with hysteresis control [6], (d) two-stage capacitive converter, and (e) proposed redistributable capacitive converter.

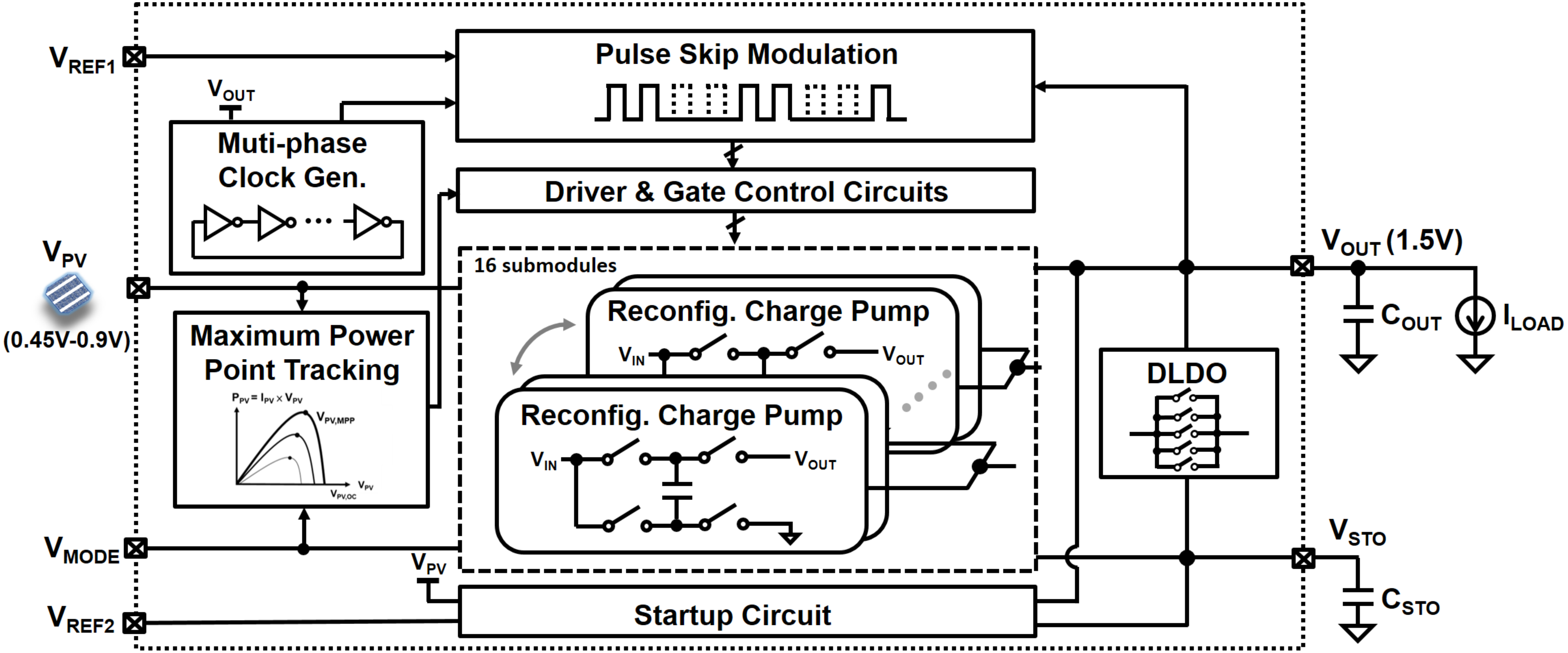
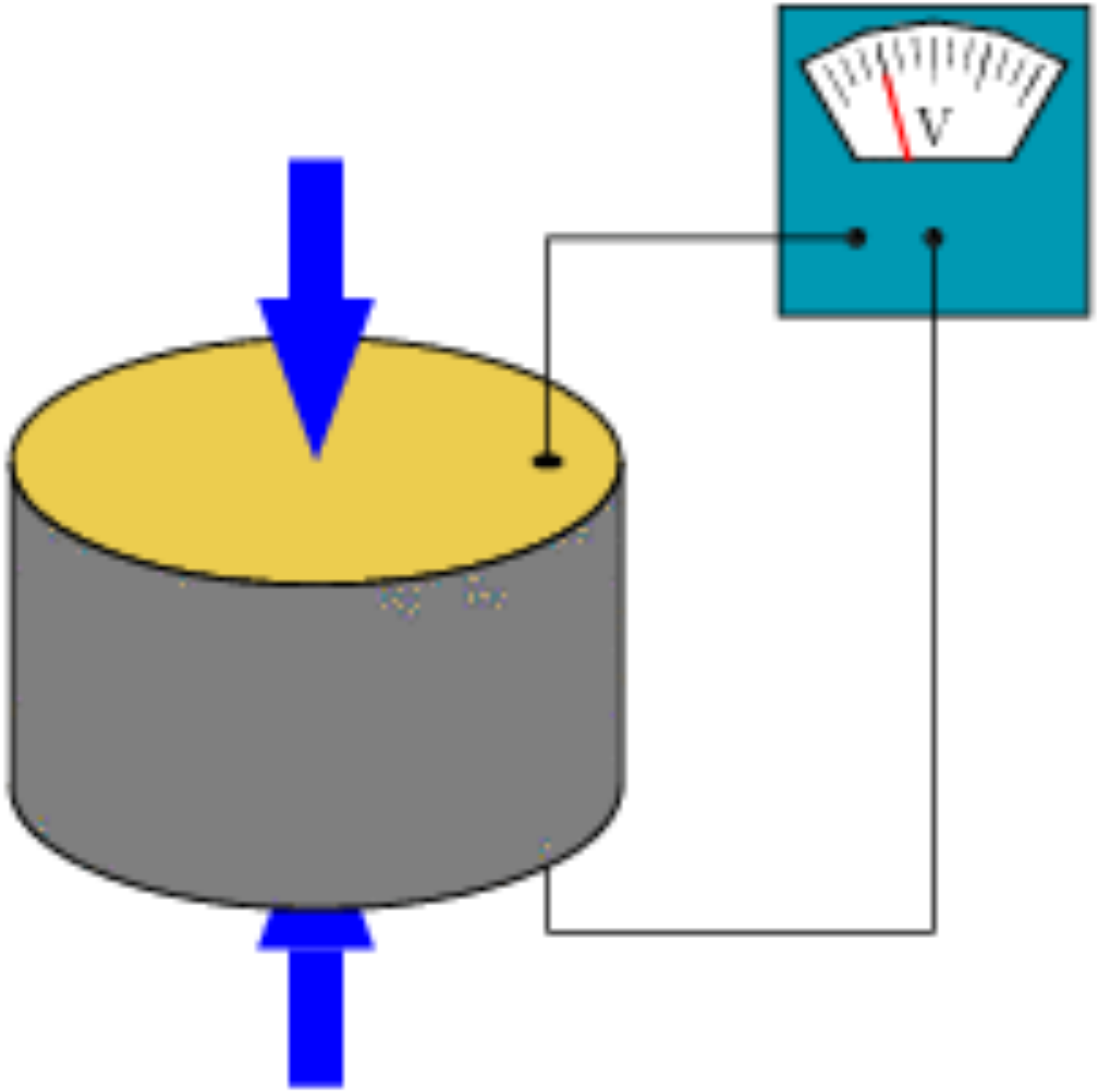
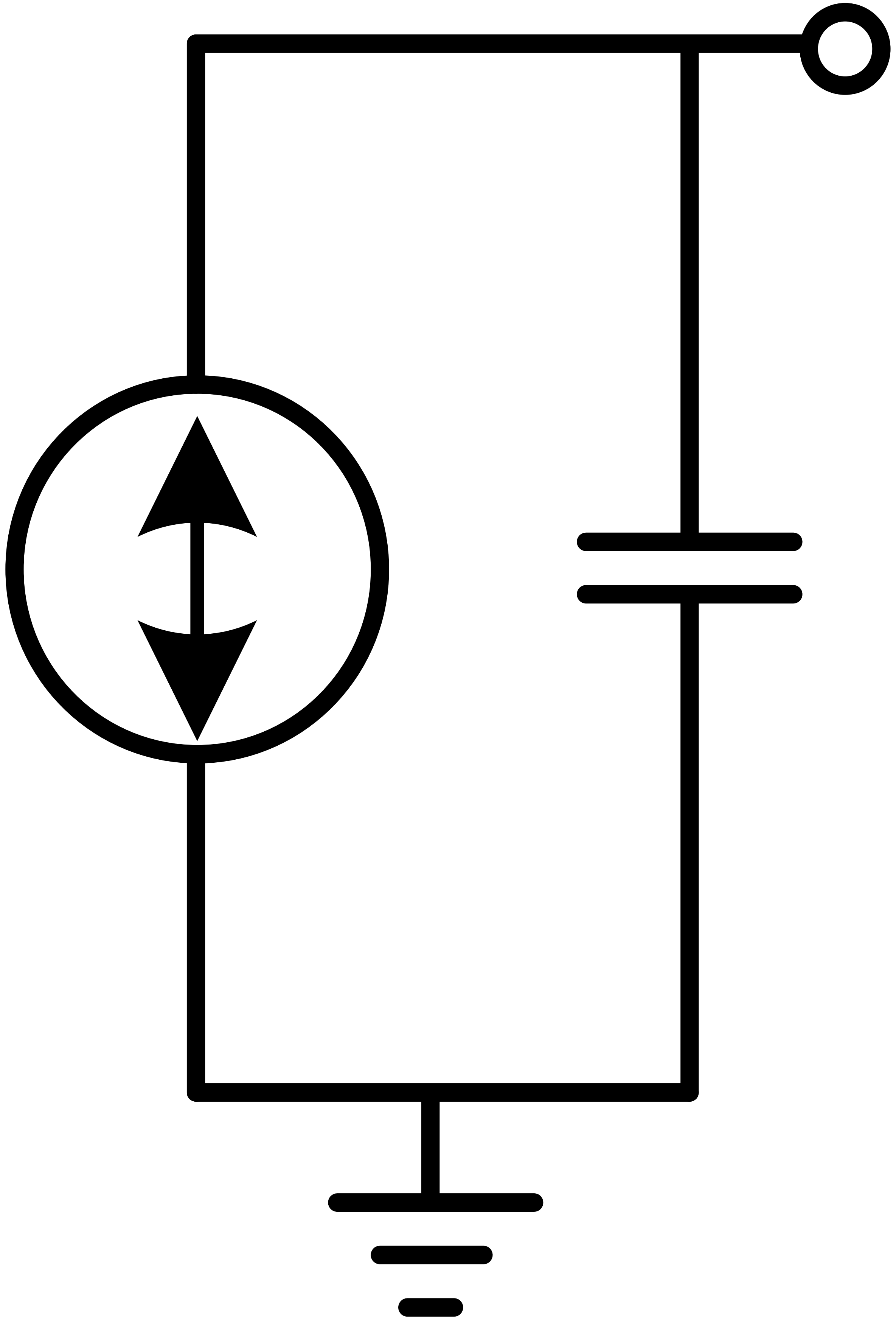
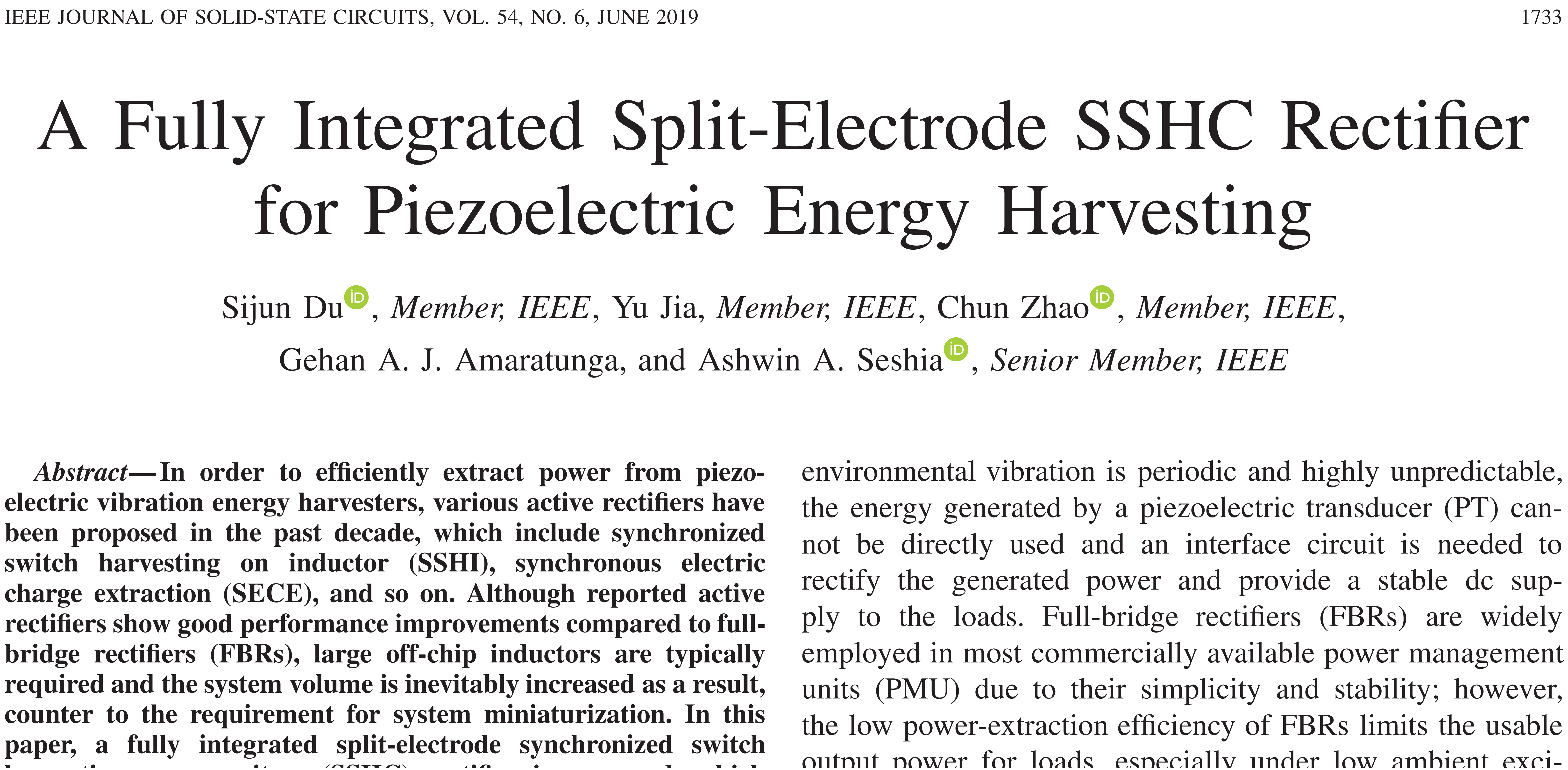


Fig. 2. System architecture of the proposed redistributable capacitive converter.

# Piezoelectric


V





IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 54, NO. 6, JUNE 2019 1733

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

Sijun Du, *Member, IEEE*, Yu Jia, *Member, IEEE*, Chun Zhao, *Member, IEEE*,
Gehan A. J. Amaratunga, and Ashwin A. Seshia, *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-

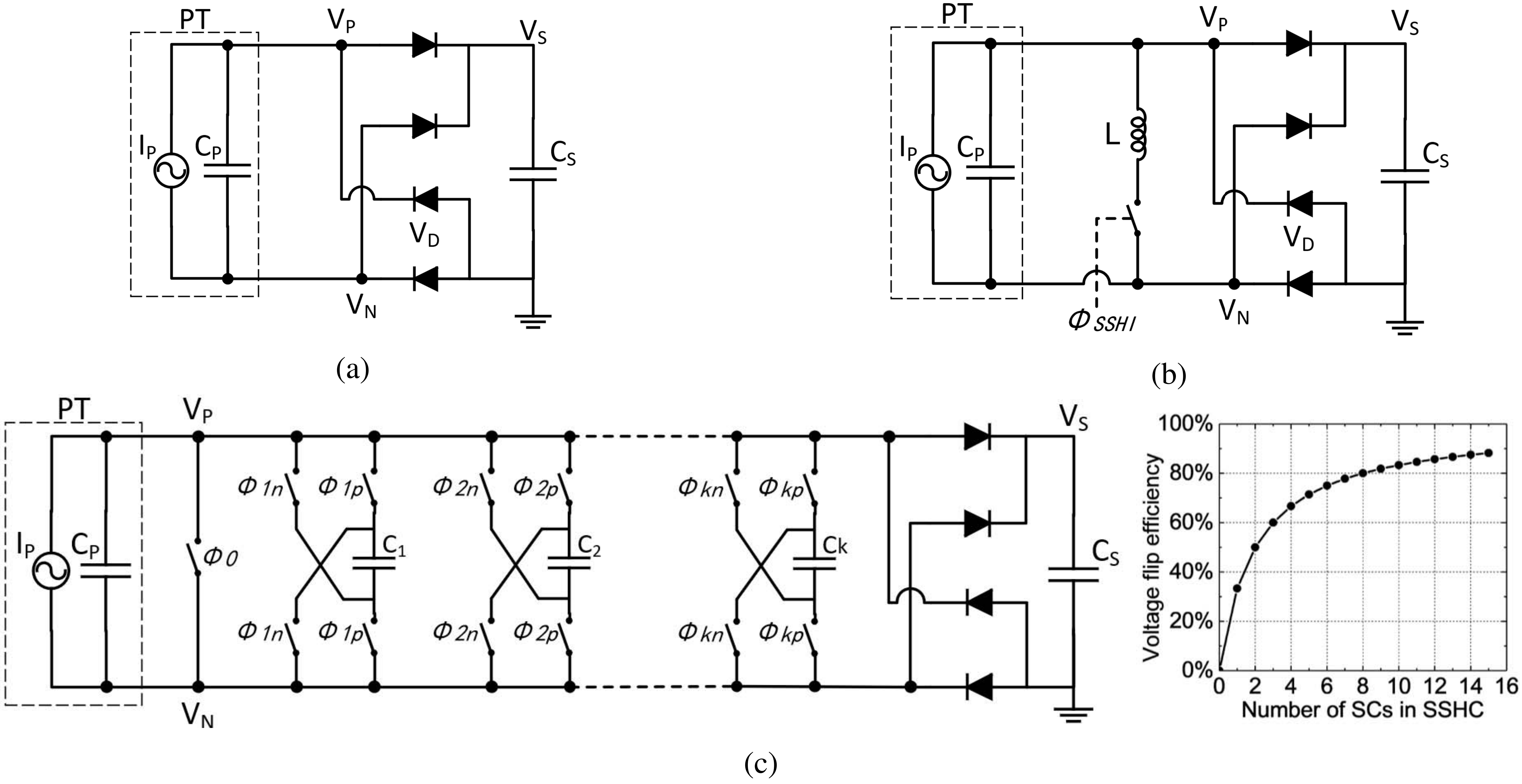


Fig. 1. Circuit diagrams of (a) FBR, (b) SSHI rectifier, and (c) SSHC rectifier with *k* SCs.

# Ambient RF

# Ambient RF Harvesting

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

Will get better with beam-forming and directive antennas

AirFuel

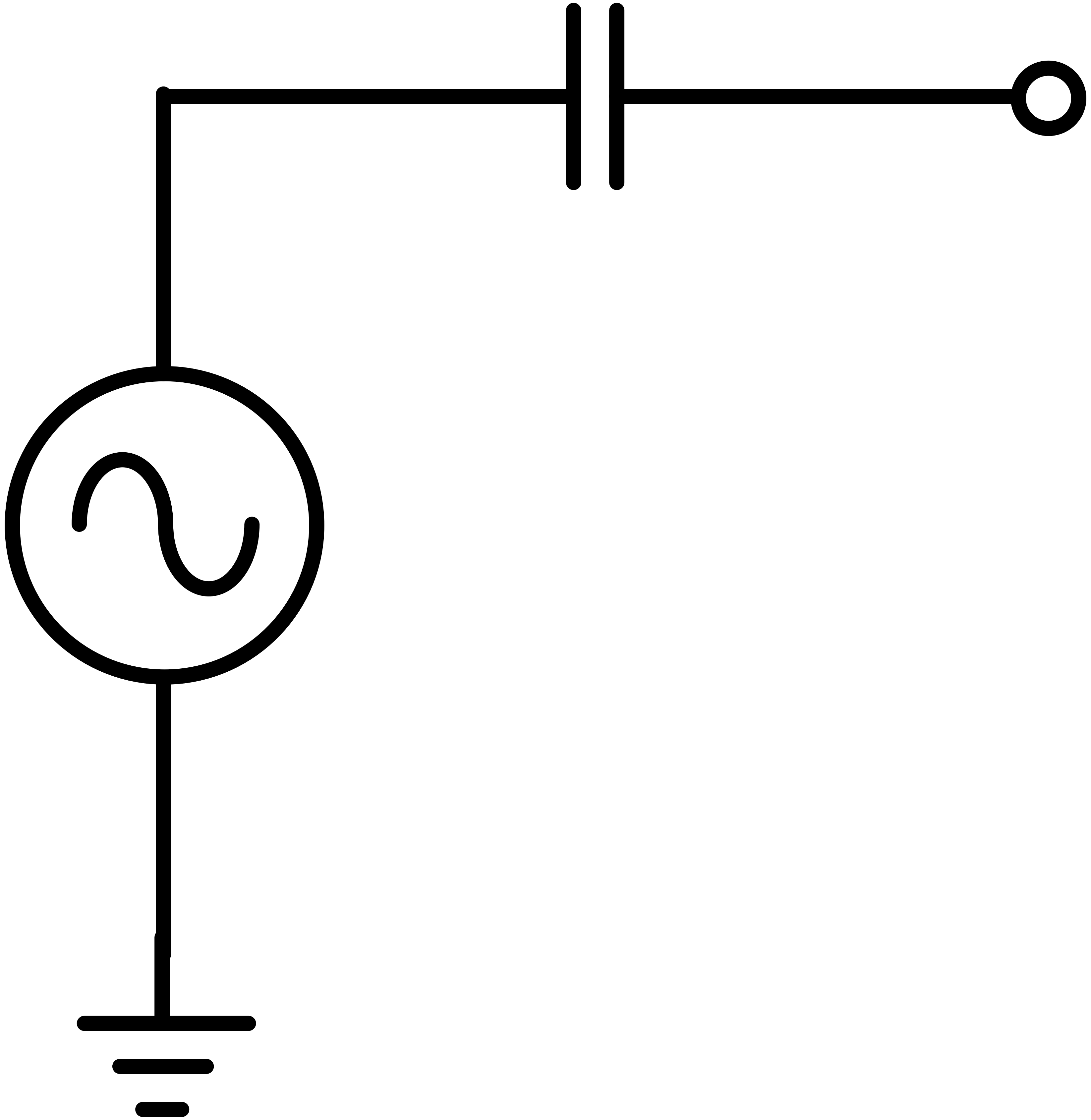
| dBm | W |
|---|---|
| 30 | 1 |
| 0 | 1 m |
| -30 | 1 u |
| -60 | 1 n |
| -90 | 1 p |

# Assume $P_{TX}$ = 1 W (30 dBm) and $P_{RX}$ = 10 uW (-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 | 8.2 |
| 2.45G | -40.2 | 3.1 |
| 5.80G | -47.7 | 1.3 |

# Triboelectric generator



This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2022.3156871, IEEE Transactions on Power Electronics

# Current progress on power management systems for triboelectric nanogenerators[1]

Tingshu Hu, *Senior Member, IEEE,* Haifeng Wang, *Member, IEEE,* William Harmon, David Bamgboje, *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**

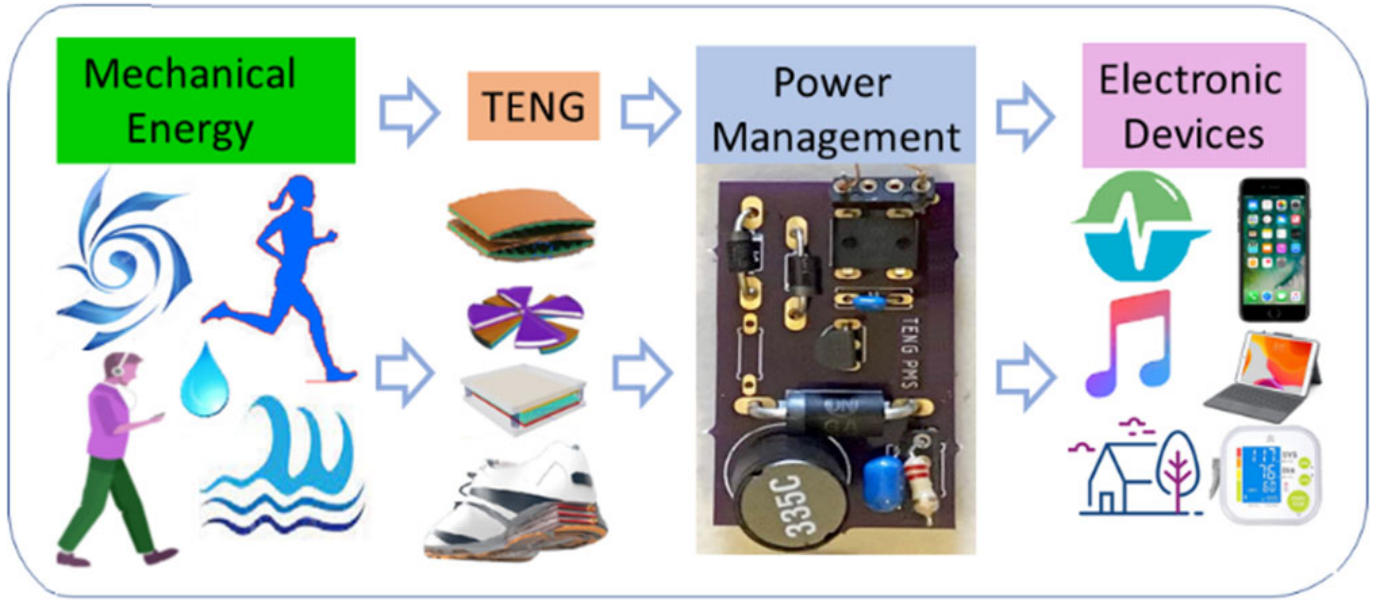


Fig. 1. Illustration of a self-powered system using energy harvested with TENGs. A power management system is needed to convert the TENG's output into a regulated form suitable for electronic devices.

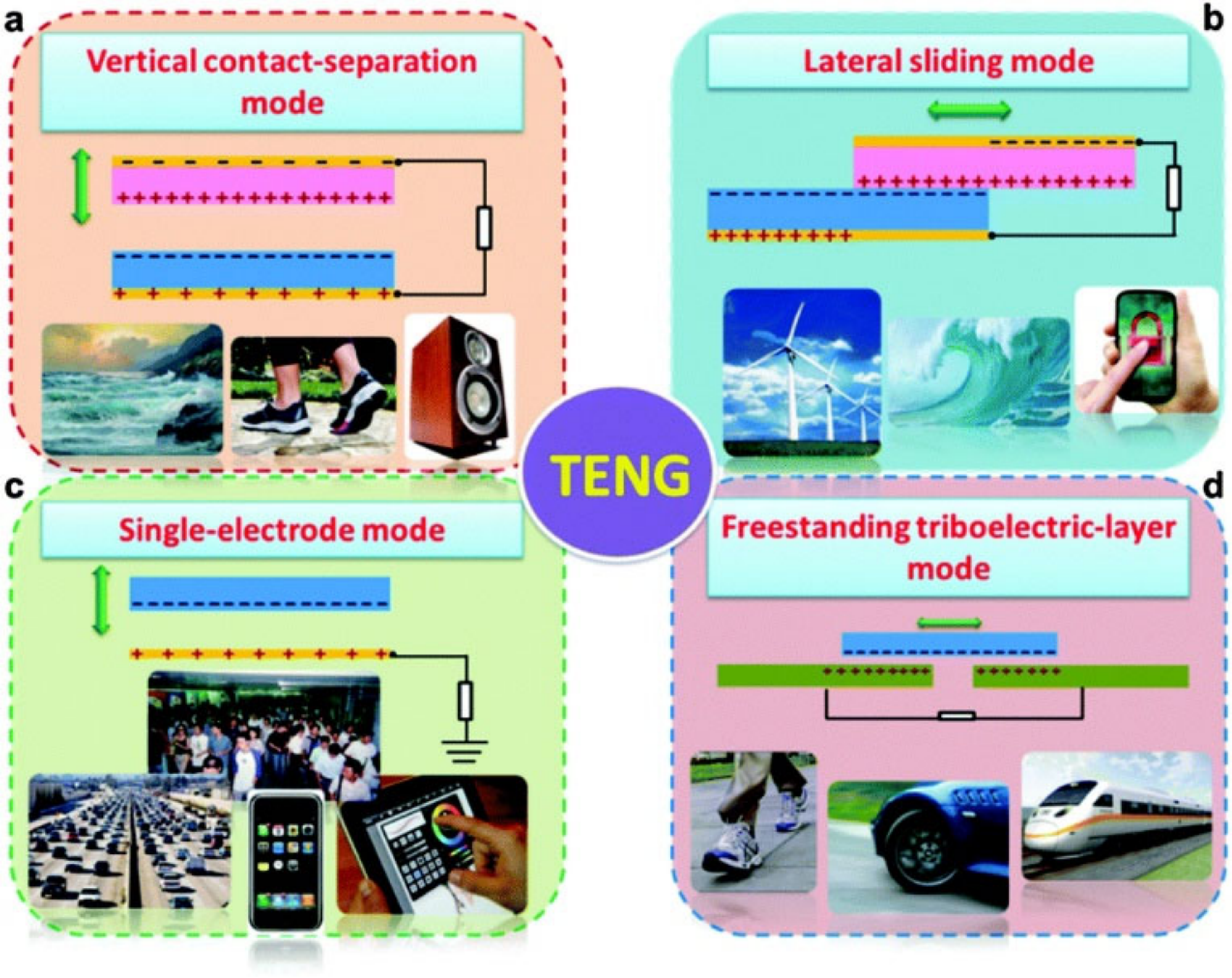
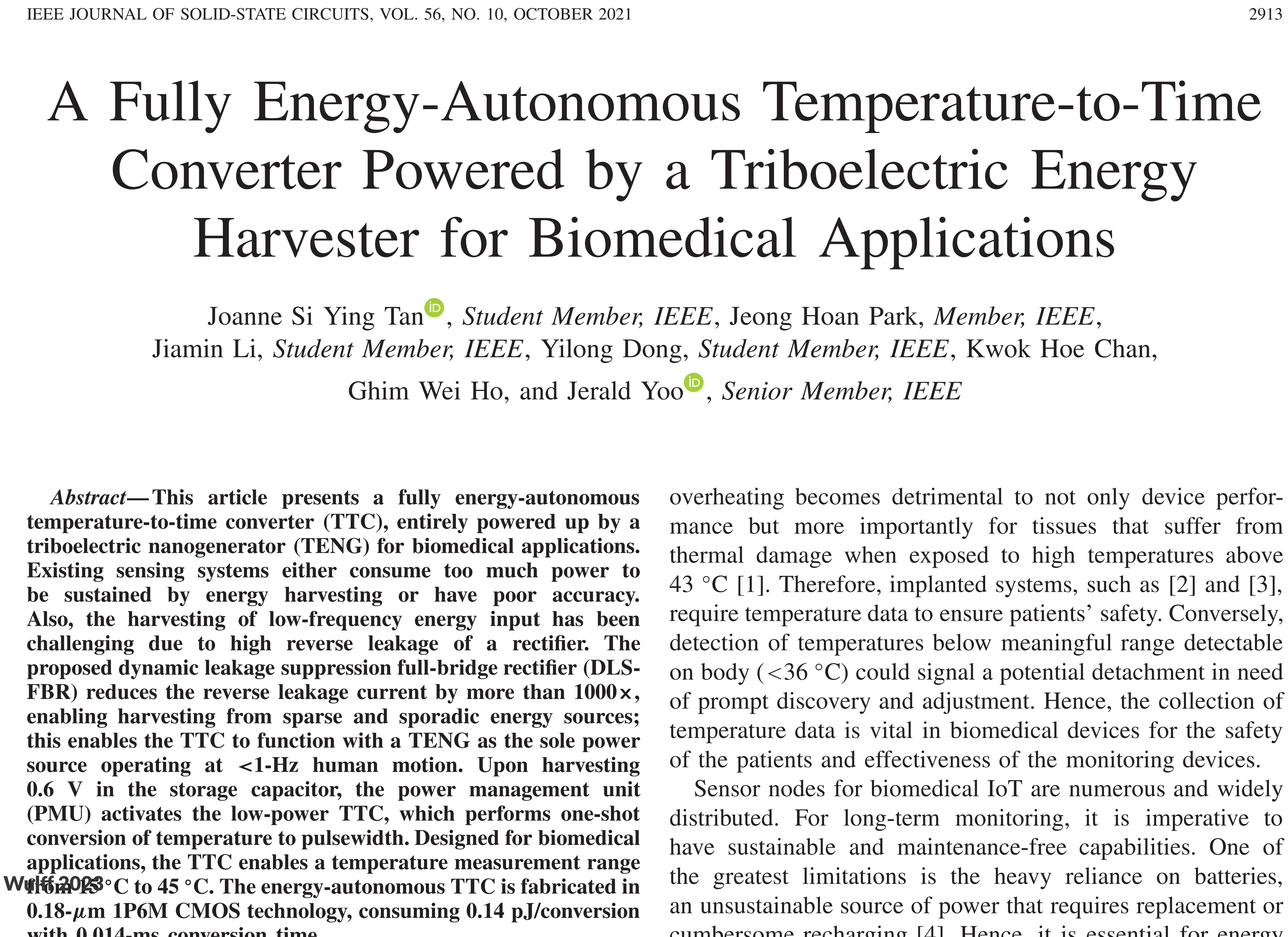


Fig. 3. 4 modes of TENG operation [5]



IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 56, NO. 10, OCTOBER 2021 2913

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

Joanne Si Ying Tan, *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, *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×, 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 pulsewidth. Designed for biomedical applications, the TTC enables a temperature measurement range from 15 °C to 45 °C. The energy-autonomous TTC is fabricated in 0.18-$\mu$m 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 °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

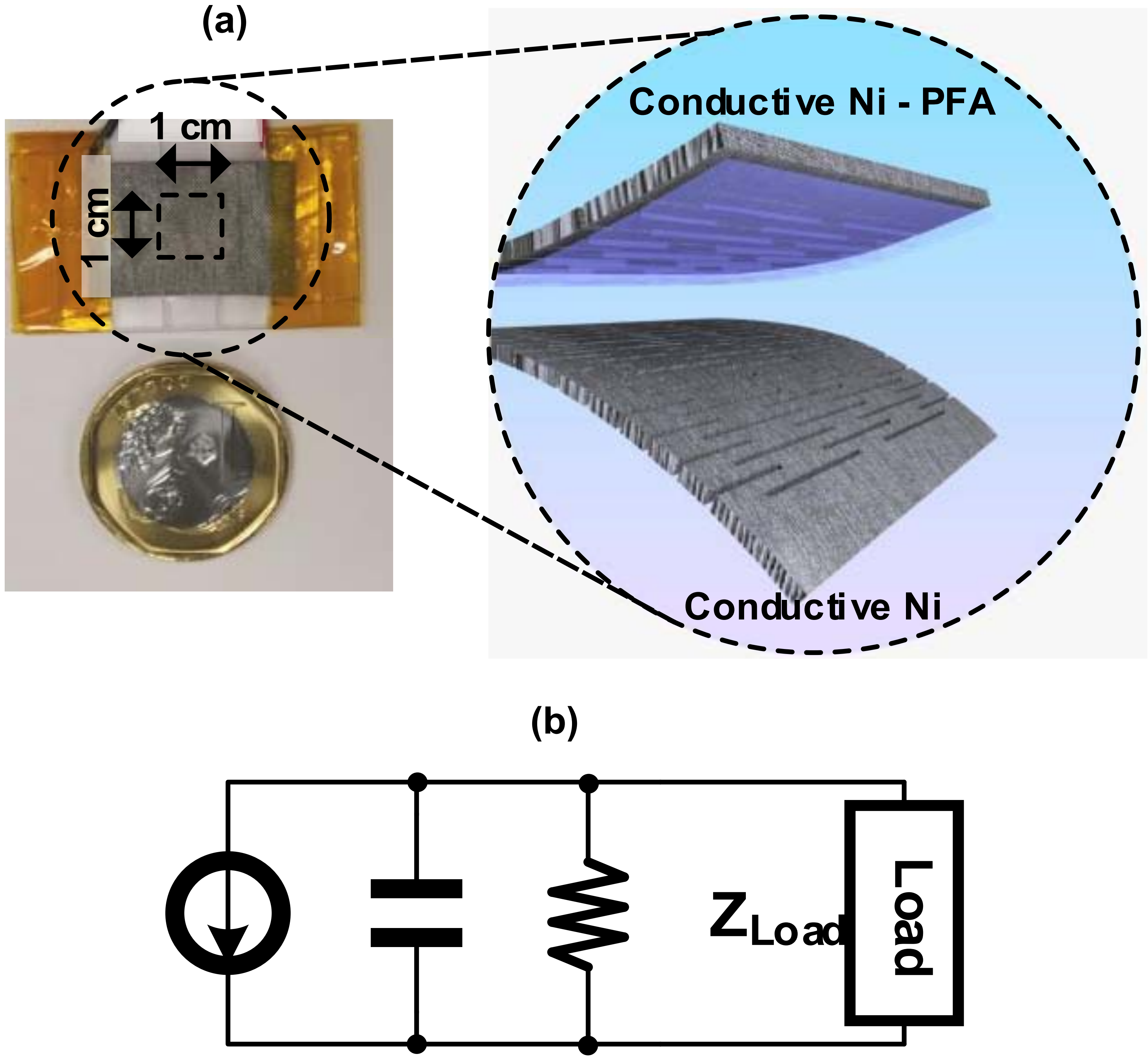


Fig. 6. (a) Photograph and (b) model of the TENG.

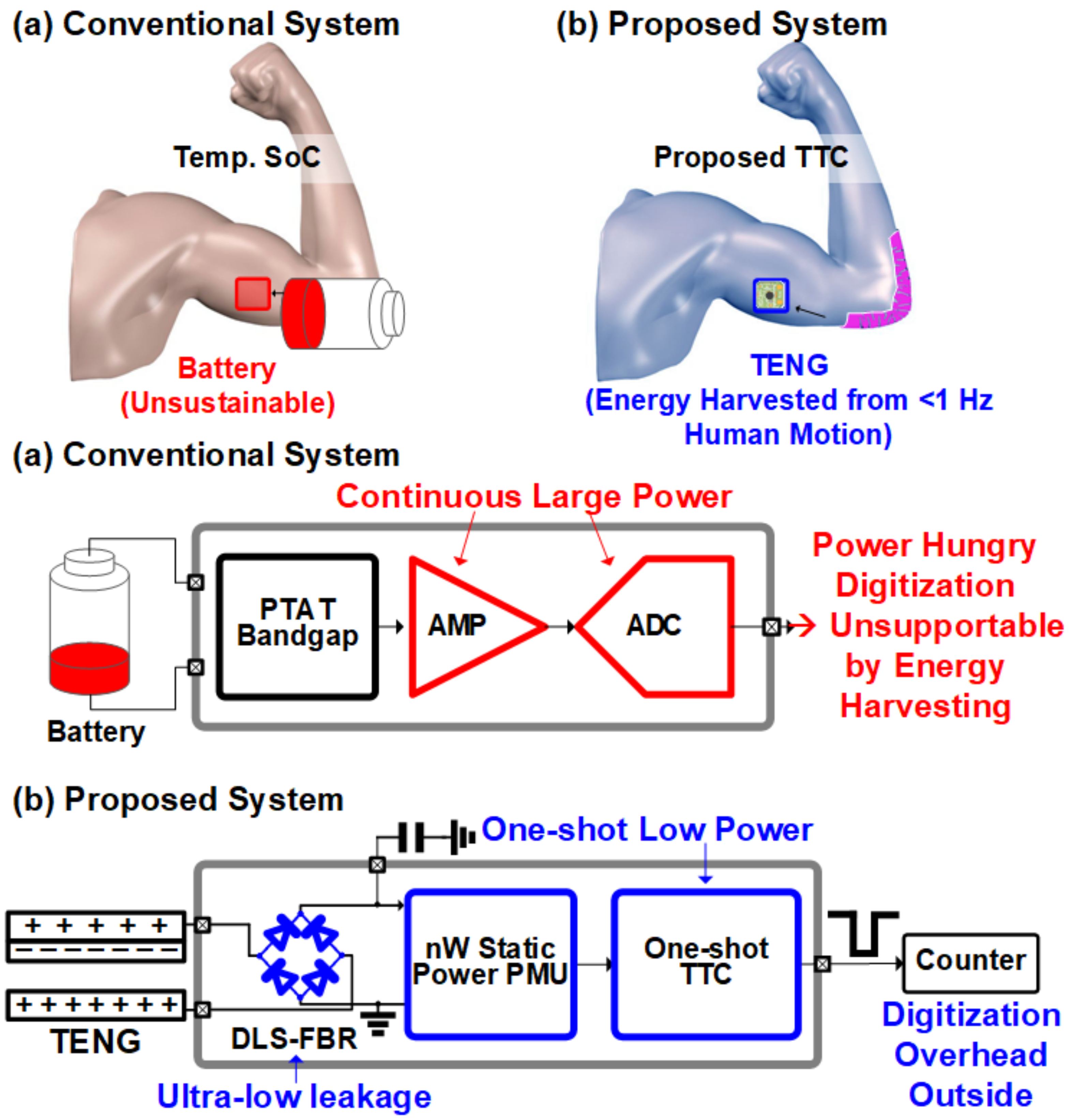


Fig. 1. System architecture of (a) conventional temperature sensing system and (b) proposed energy-autonomous system.

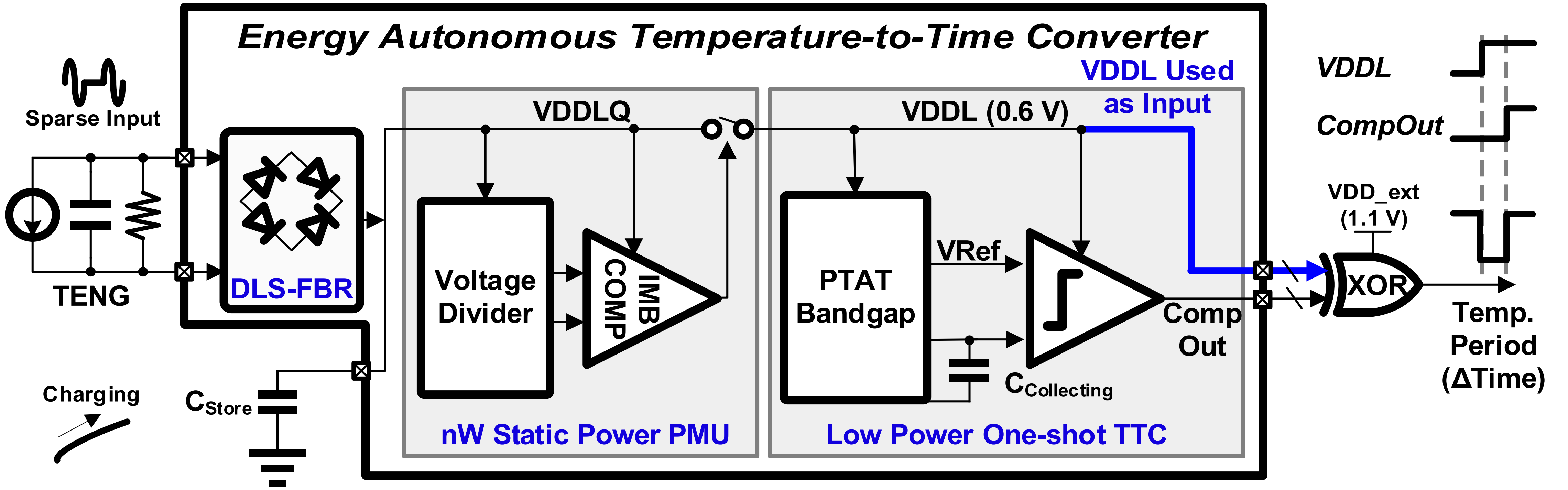


Fig. 2. Overall architecture of the proposed energy-autonomous TTC.

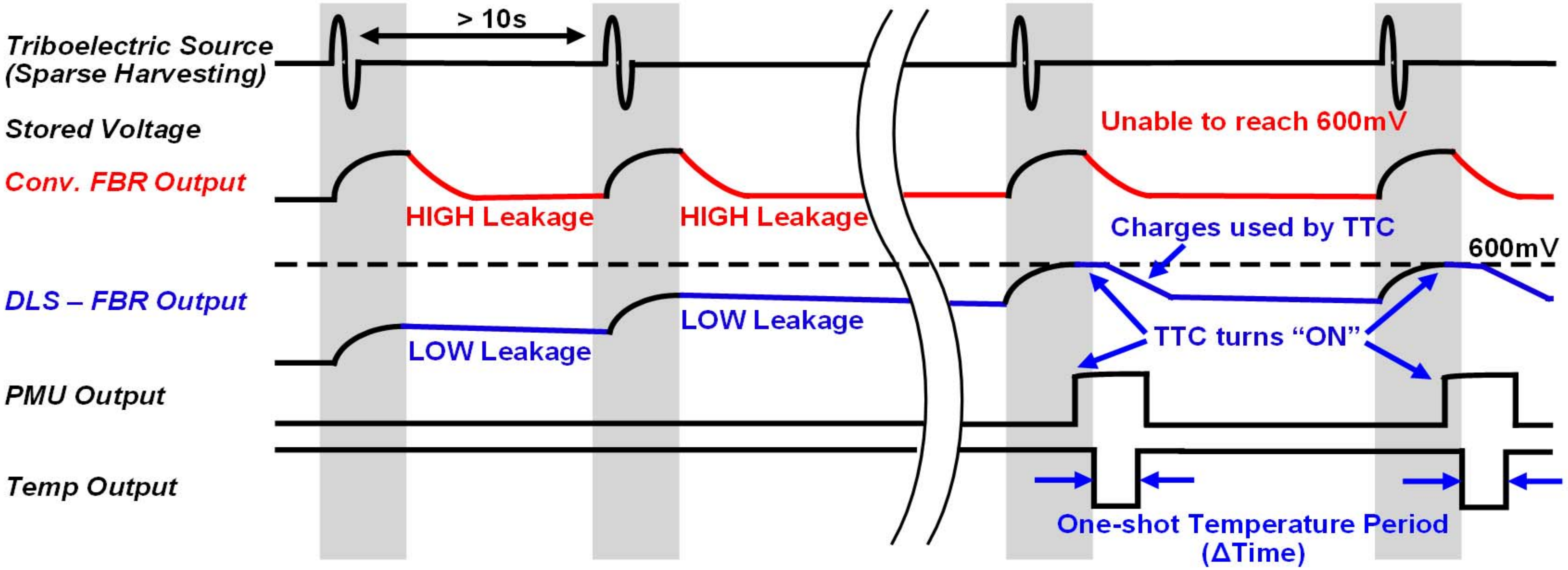
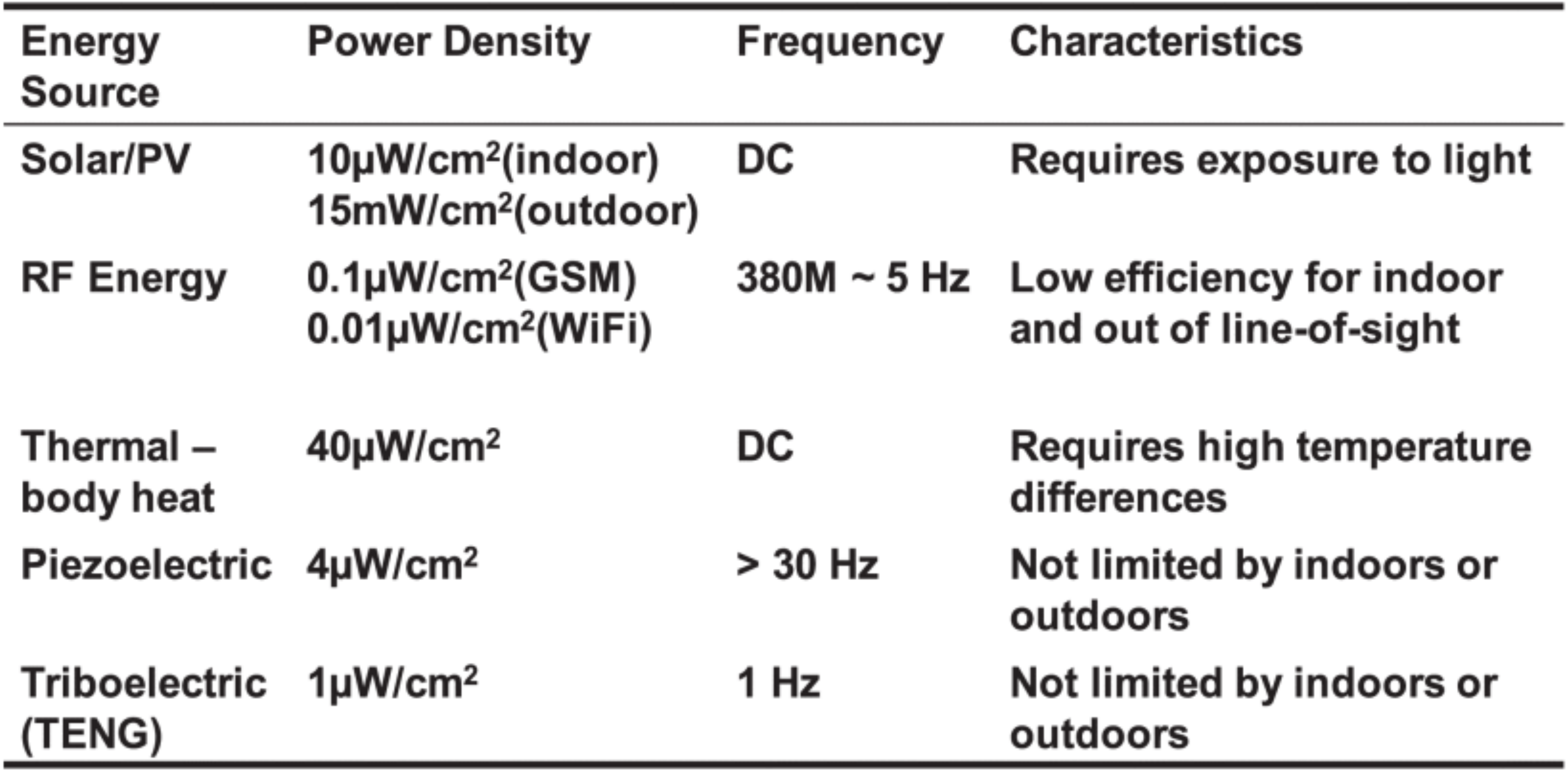


Fig. 3. Concept of the proposed energy-autonomous TTC.

# Comparison



| Energy Source | Power Density | Frequency | Characteristics |
|---|---|---|---|
| Solar/PV | 10μW/cm$^2$(indoor)<br>15mW/cm$^2$(outdoor) | DC | Requires exposure to light |
| RF Energy | 0.1μW/cm$^2$(GSM)<br>0.01μW/cm$^2$(WiFi) | 380M ~ 5 Hz | Low efficiency for indoor and out of line-of-sight |
| Thermal – body heat | 40μW/cm$^2$ | DC | Requires high temperature differences |
| Piezoelectric | 4μW/cm$^2$ | > 30 Hz | Not limited by indoors or outdoors |
| Triboelectric (TENG) | 1μW/cm$^2$ | 1 Hz | Not limited by indoors or outdoors |

# References

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

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

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

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

Current progress on power management systems for triboelectric nanogenerators

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

# Thanks!