date: 2024-04-12

TFE4188 - Lecture X

Energy Sources

Goal

Why do we need energy sources?

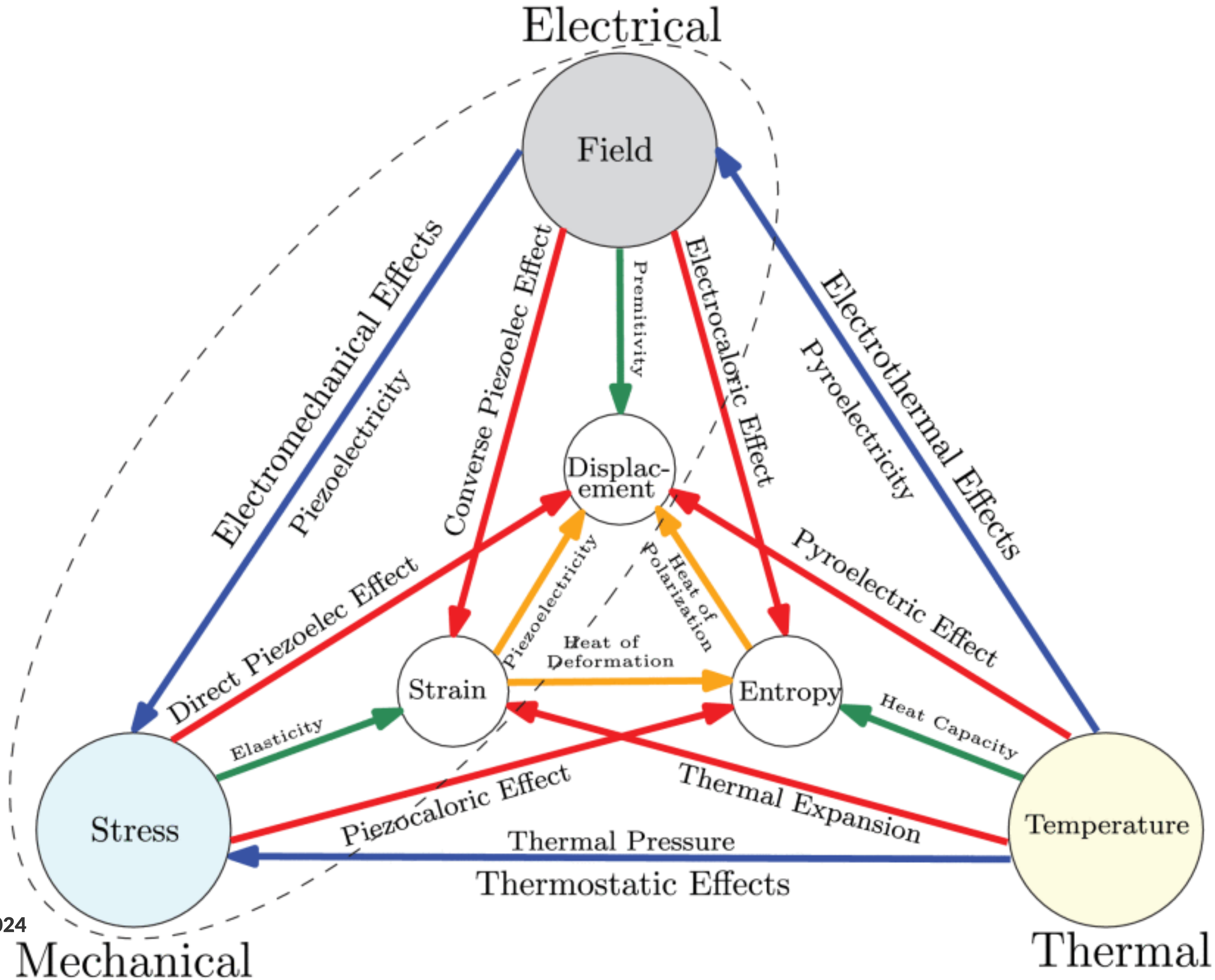
Introduction to **Energy Harvesting**

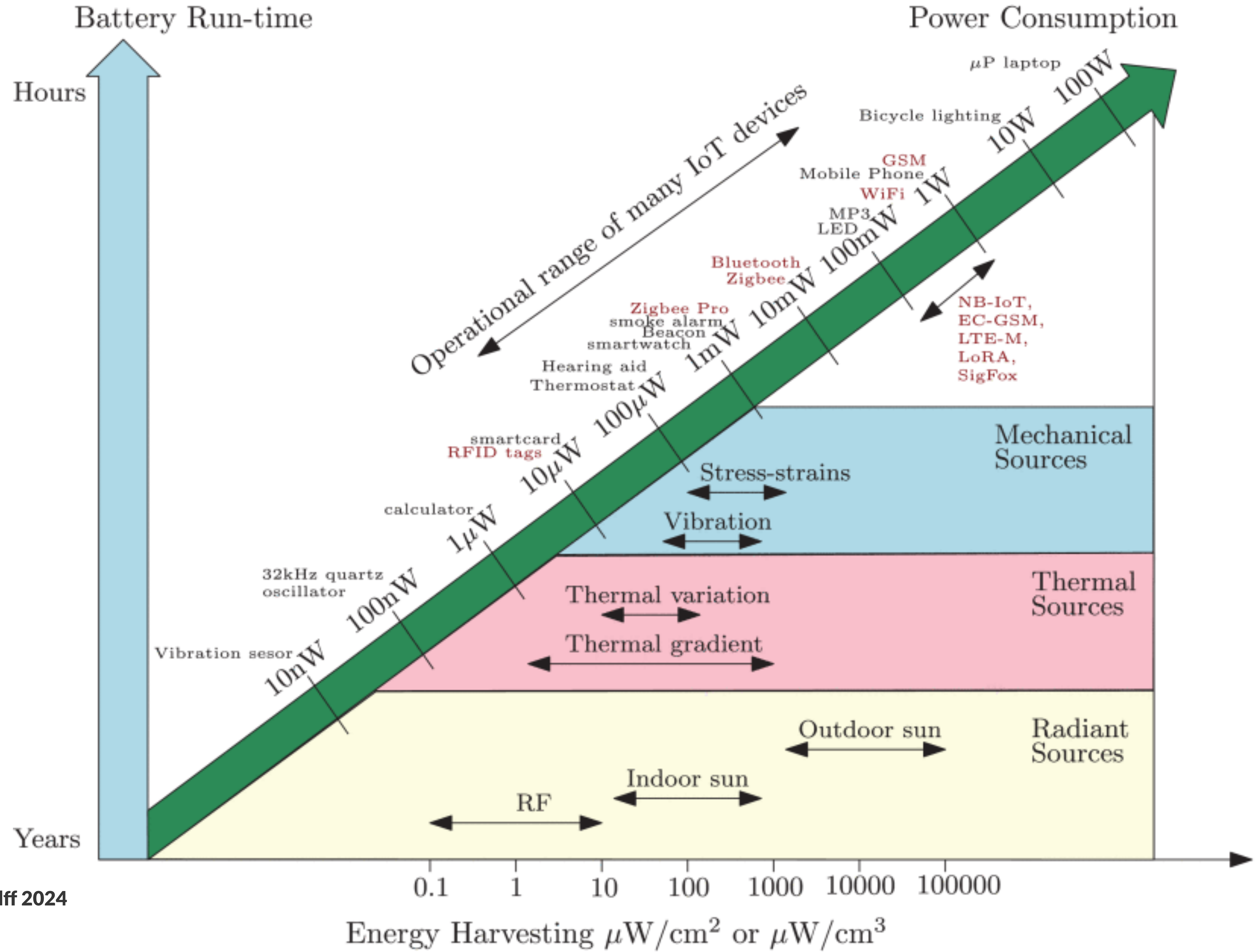
Why

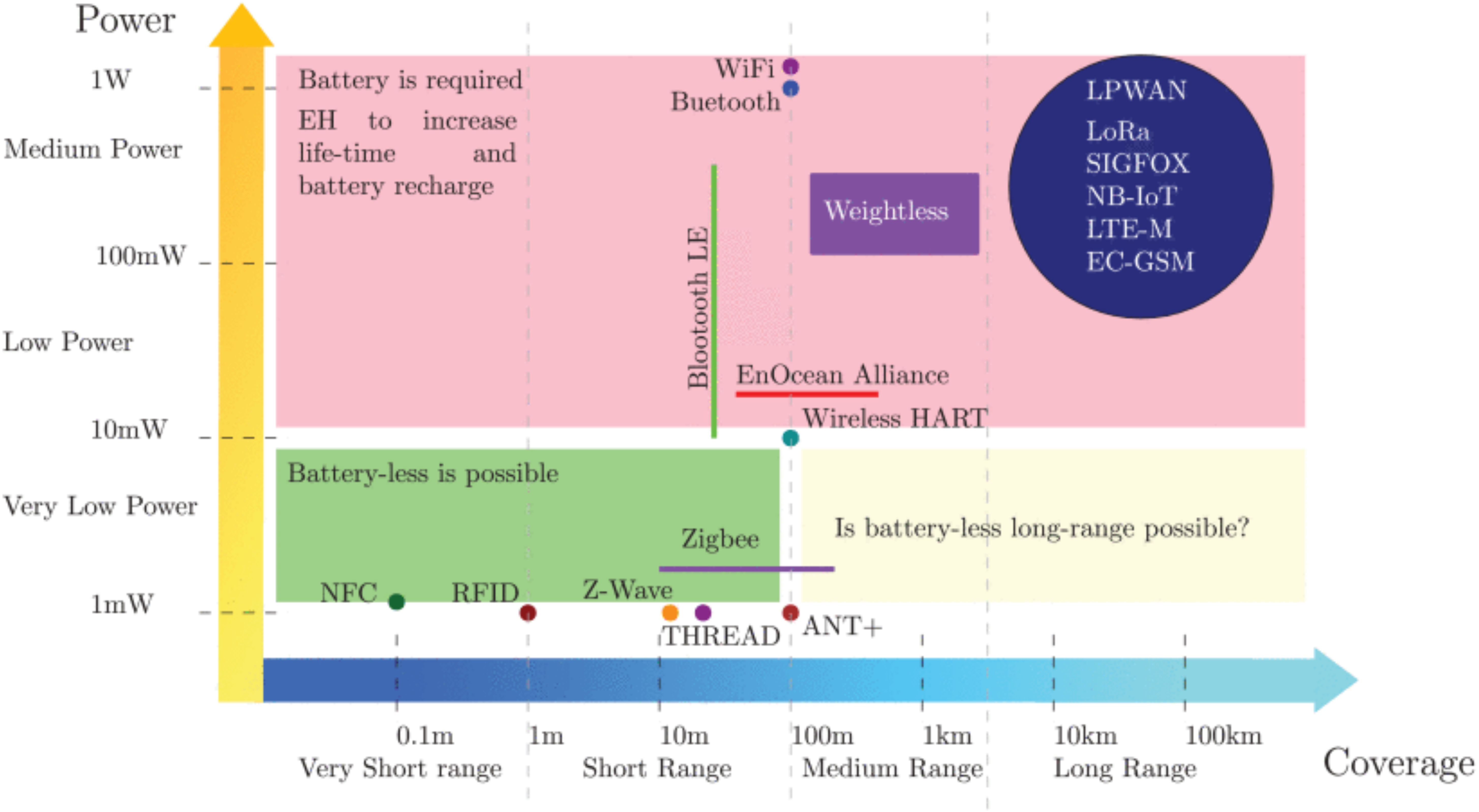
Lithium Battery

1 year $\Rightarrow$ 45 μW/cm^3

10 year $\Rightarrow$ 3.5 μW/cm^3


Electrical
Field
Electromechanical Effects
Piezoelectricity
Converse Piezoelec Effect
Premitivity
Electrocaloric Effect
Pyroelectricity
Electrothermal Effects
Displac-
ement
Direct Piezoelec Effect
Piezoelectricity
Heat of
Polarization
Pyroelectric Effect
Heat of
Deformation
Strain
Entropy
Elasticity
Heat Capacity
Piezocaloric Effect
Thermal Expansion
Stress
Thermal Pressure
Temperature
Thermostatic Effects
Mechanical
Thermal


Battery Run-time
Power Consumption
Hours
Years
Operational range of many IoT devices
µP laptop
Bicycle lighting
GSM
Mobile Phone
WiFi
MP3
LED
Bluetooth
Zigbee
Zigbee Pro
smoke alarm
Beacon
smartwatch
Hearing aid
Thermostat
smartcard
RFID tags
calculator
32kHz quartz oscillator
Vibration sesor
10nW
100nW
1µW
10µW
100µW
1mW
10mW
100mW
1W
10W
100W
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


Power
1W
Medium Power
100mW
Low Power
10mW
Very Low Power
1mW
Battery is required
EH to increase life-time and battery recharge
WiFi
Buetooth
Blootooth LE
Weightless
LPWAN
LoRa
SIGFOX
NB-IoT
LTE-M
EC-GSM
EnOcean Alliance
Wireless HART
Battery-less is possible
Is battery-less long-range possible?
Zigbee
NFC
RFID
Z-Wave
THREAD
ANT+
0.1m
1m
10m
100m
1km
10km
100km
Very Short range
Short Range
Medium Range
Long Range
Coverage

Thermoelectric

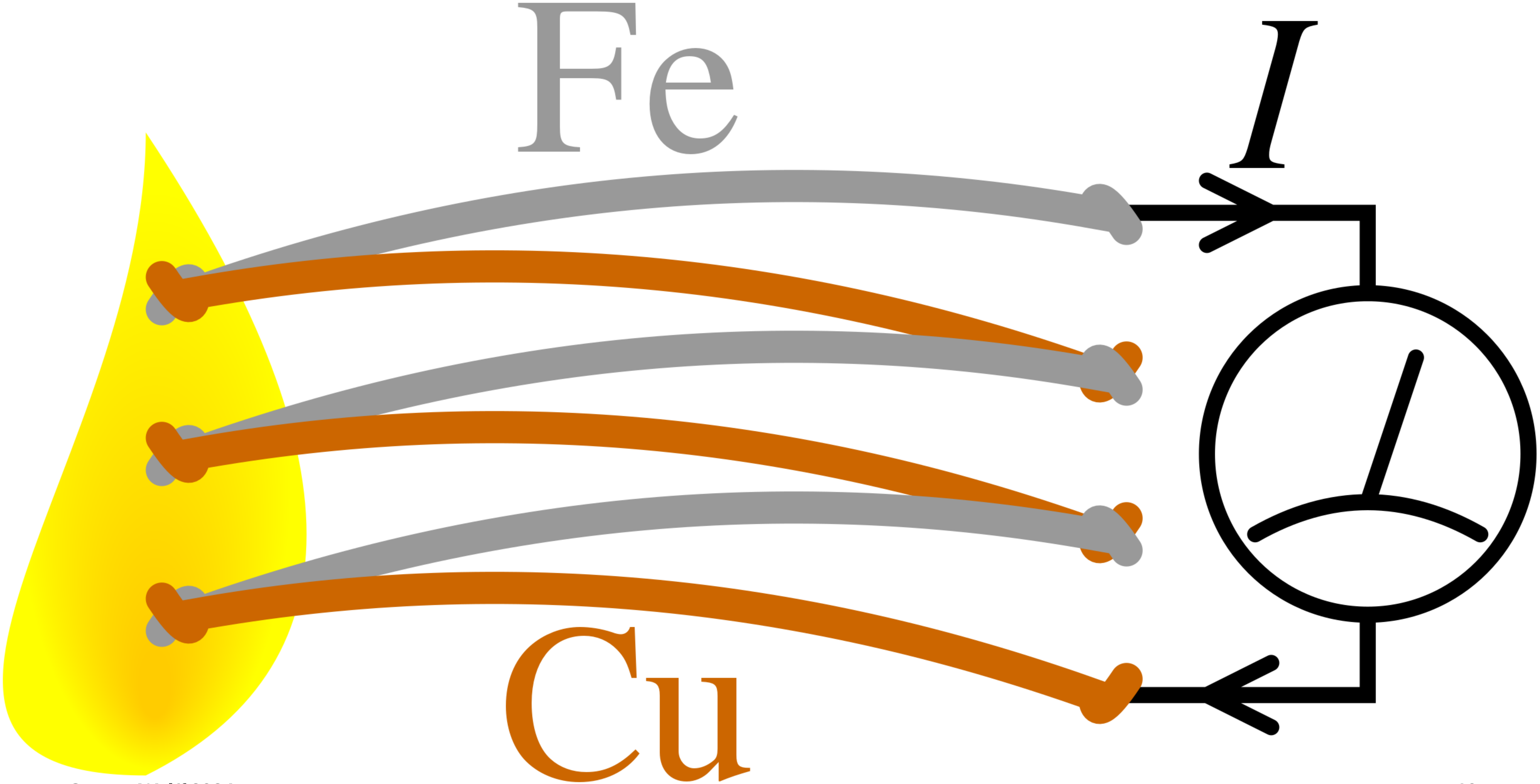
Photovoltaic

Piezoelectric

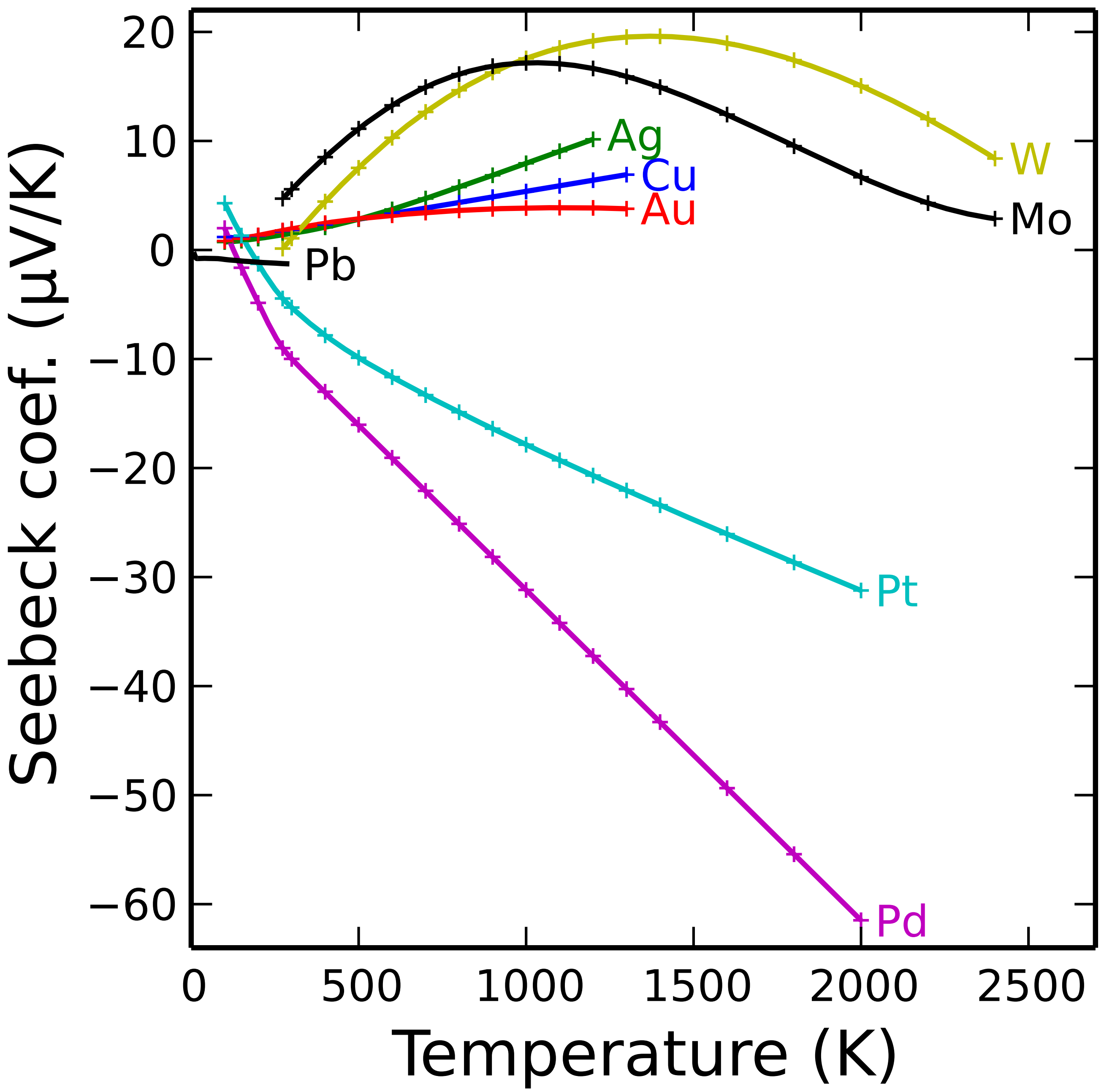
Electromagnetic

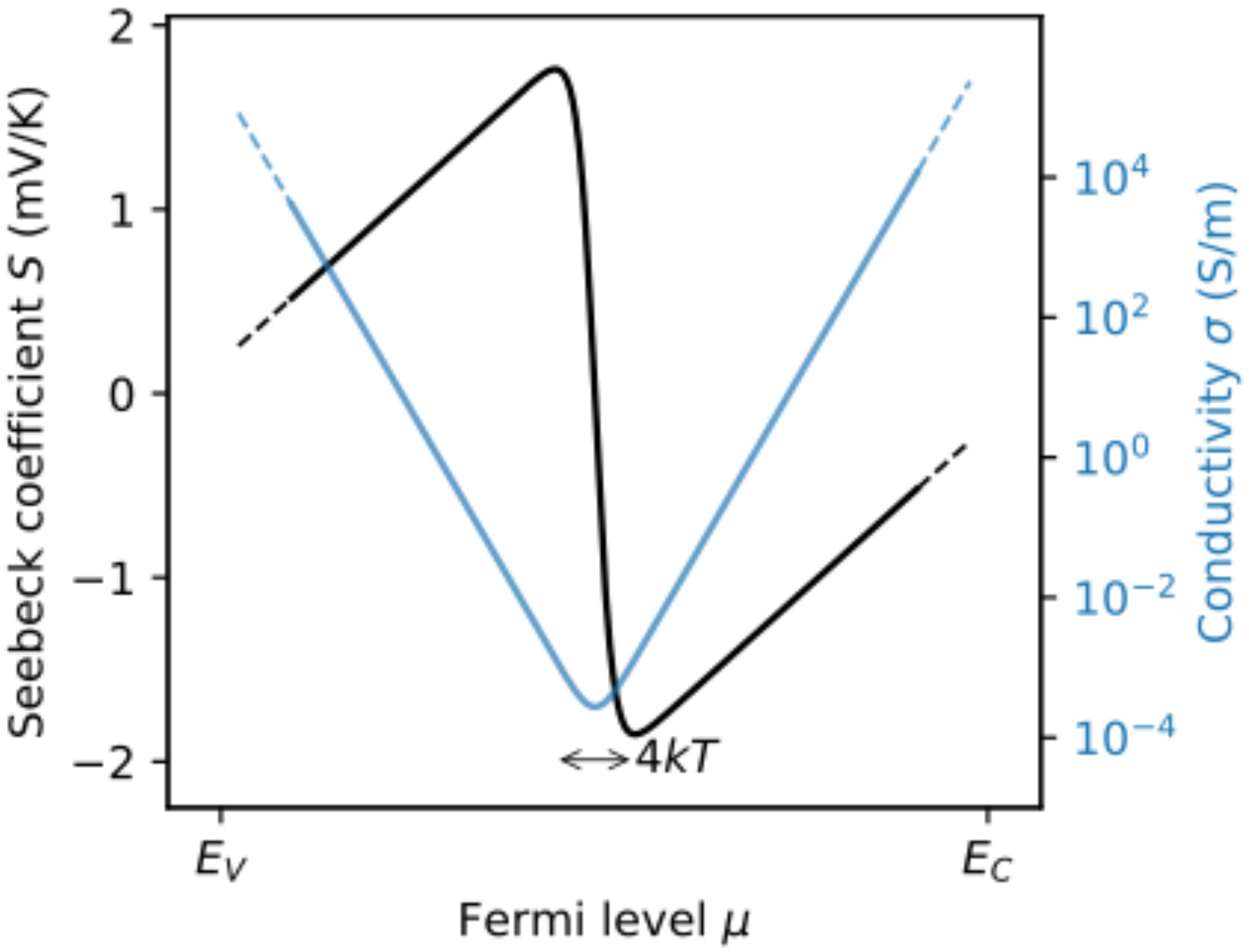
Triboelectric

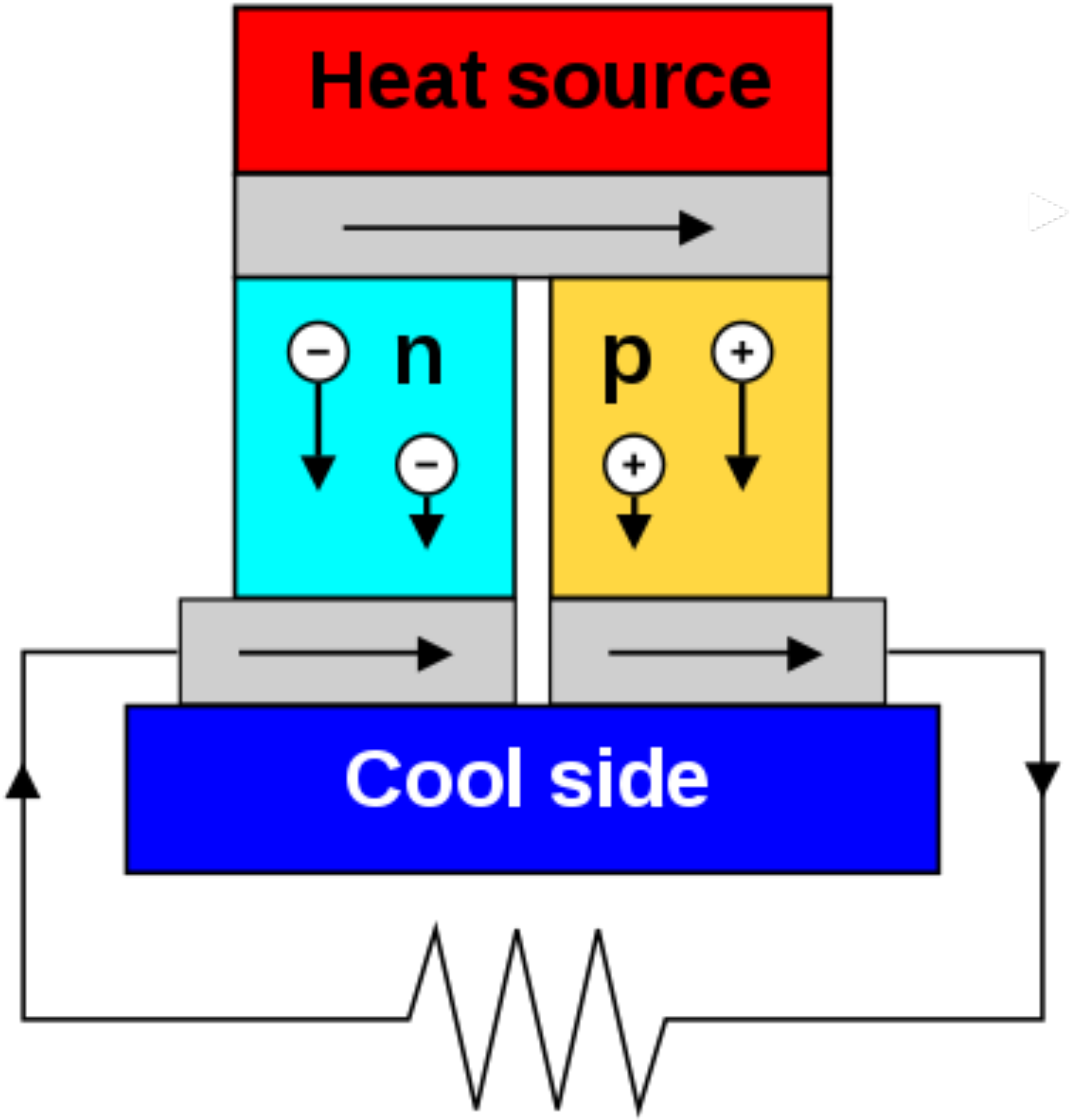
Thermoelectric

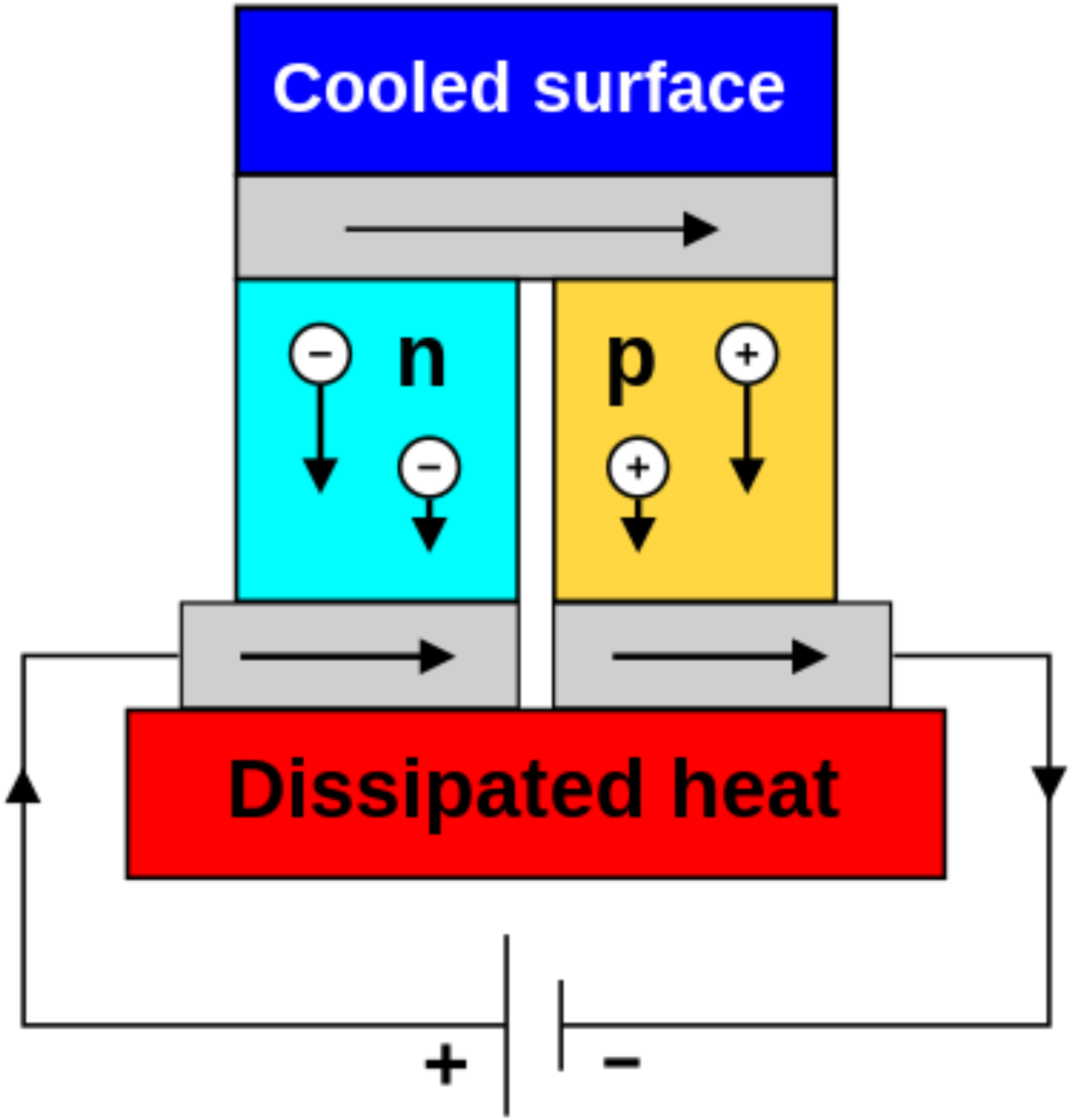

Fe
I
Cu

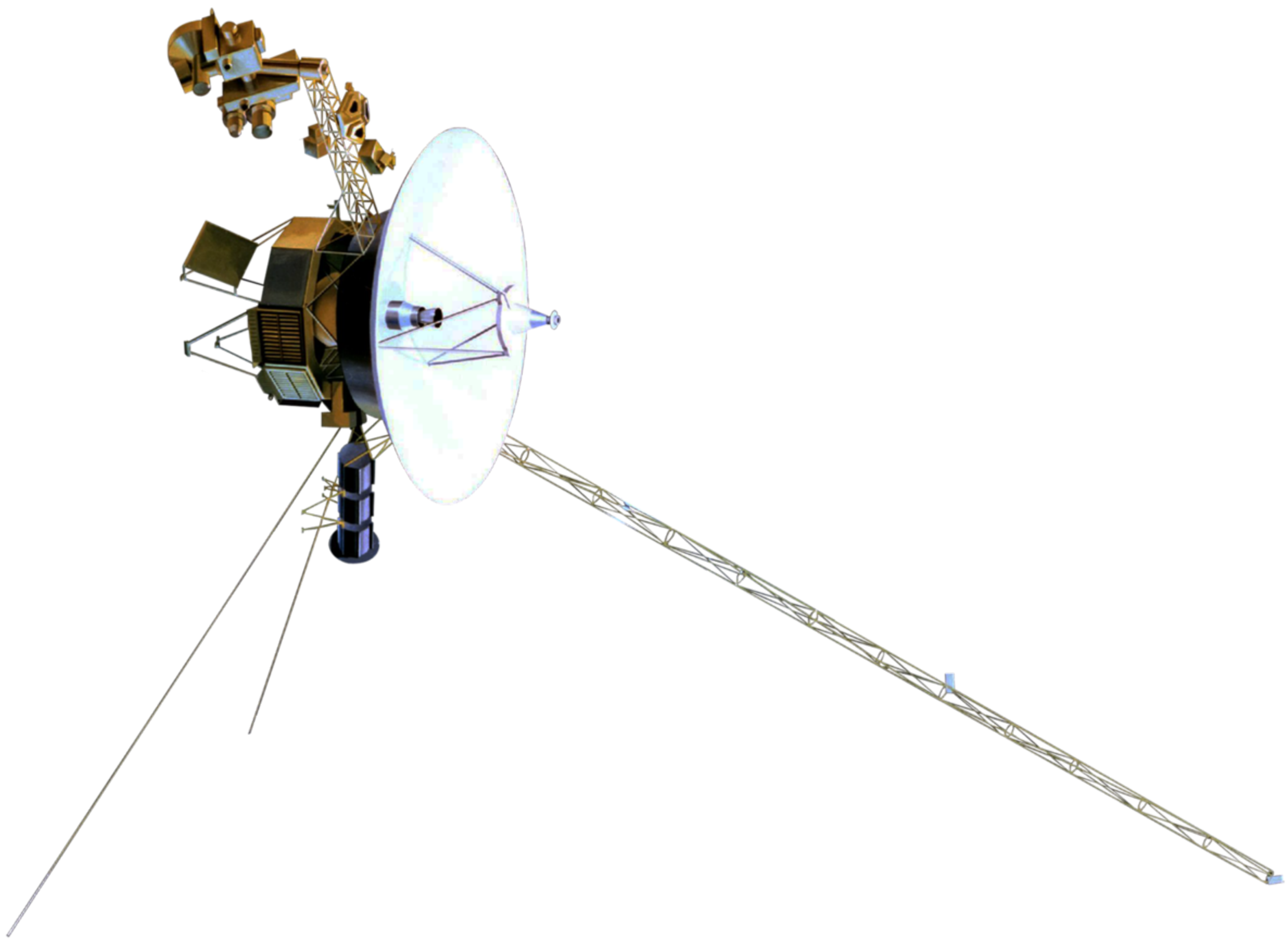
Seebeck coefficient





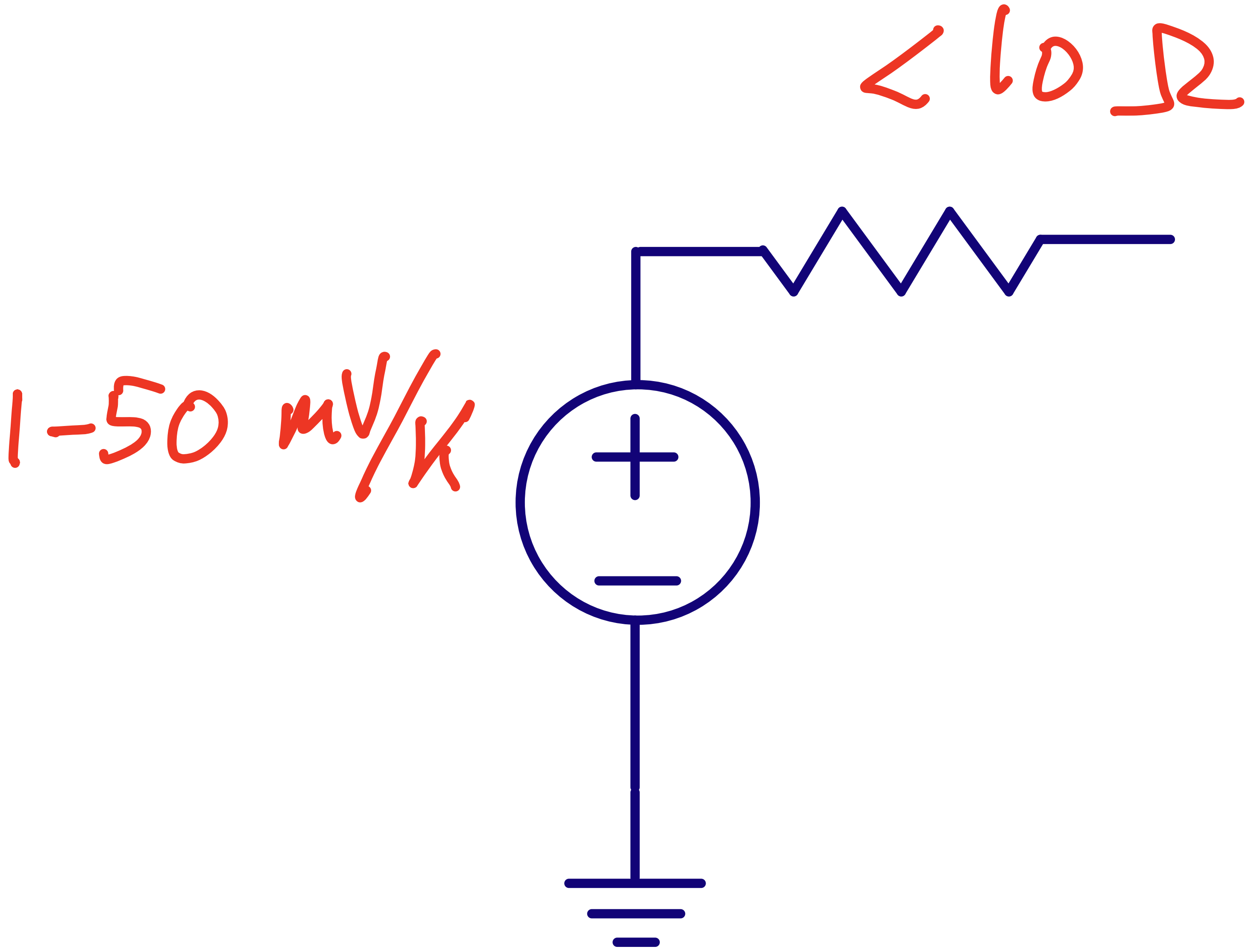

Heat source
n
p
Cool side


Cooled surface
n
p
Dissipated heat
+
−



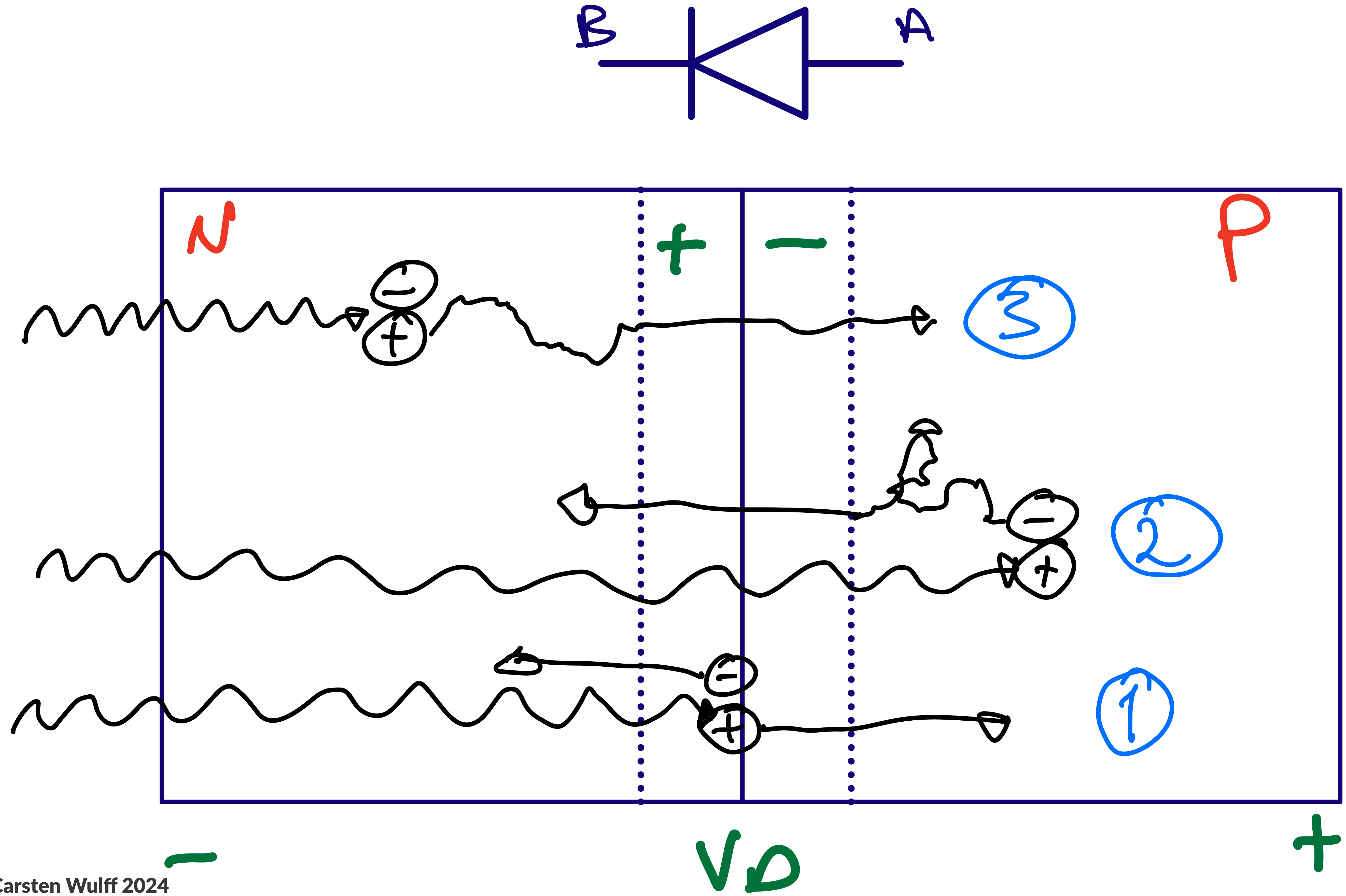
Radioisotope Thermoelectric generator

Thermoelectric generators

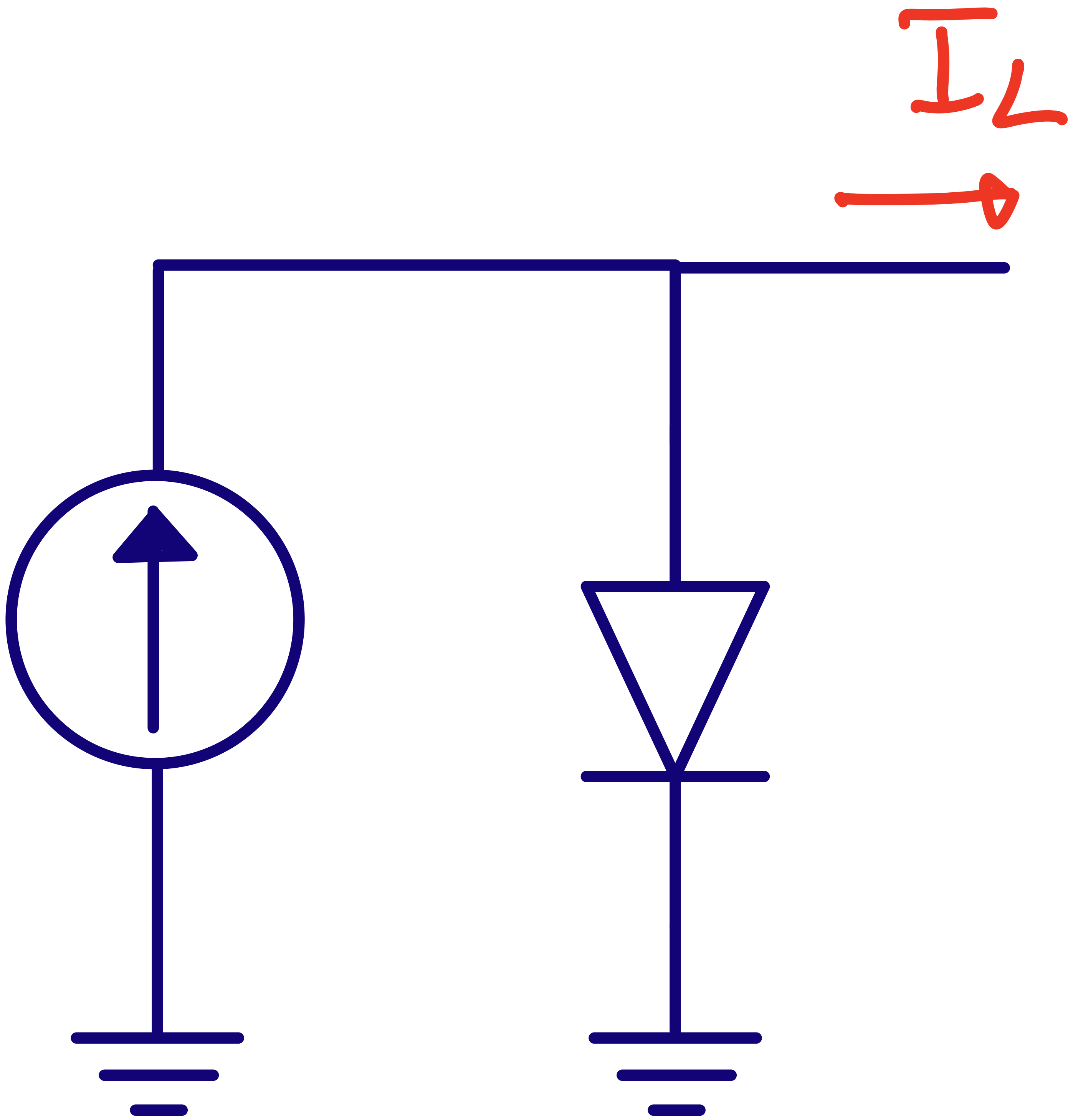


In A 3.5-mV Input Single-Inductor Self-Starting Boost Converter With Loss-Aware MPPT for Efficient Autonomous Body-Heat Energy Harvesting they use a combination of both switched capacitor and switched inductor boost.

Photovoltaic



B
A
N
P
+
−
3
2
1
−
VD
+



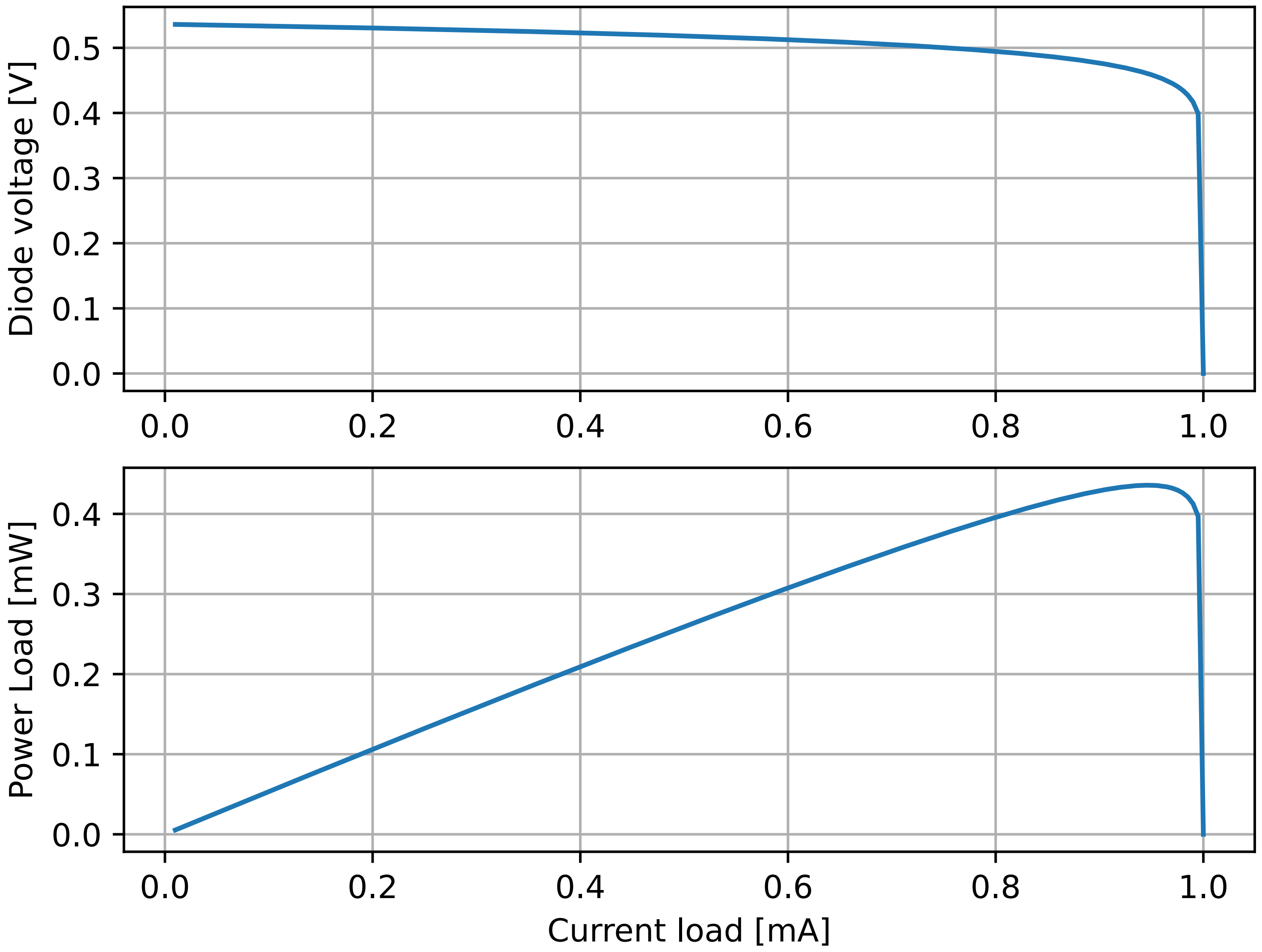
$$I_D = I_S\left(e^{\frac{V_D}{V_T}} - 1\right)$$

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

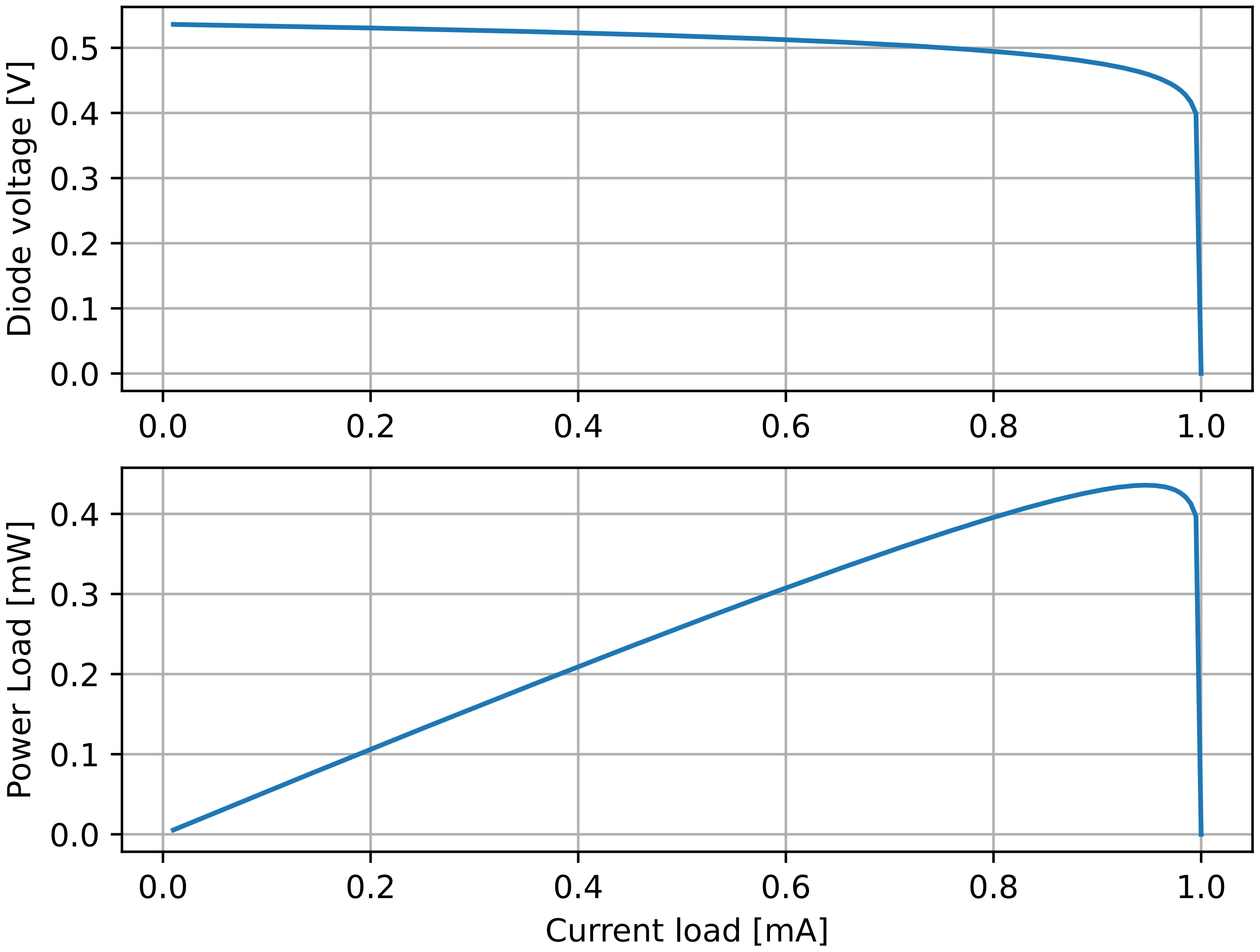
$$V_D = V_T ln\left(\frac{I_{Photo} - I_{Load}}{I_S} + 1\right)$$

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

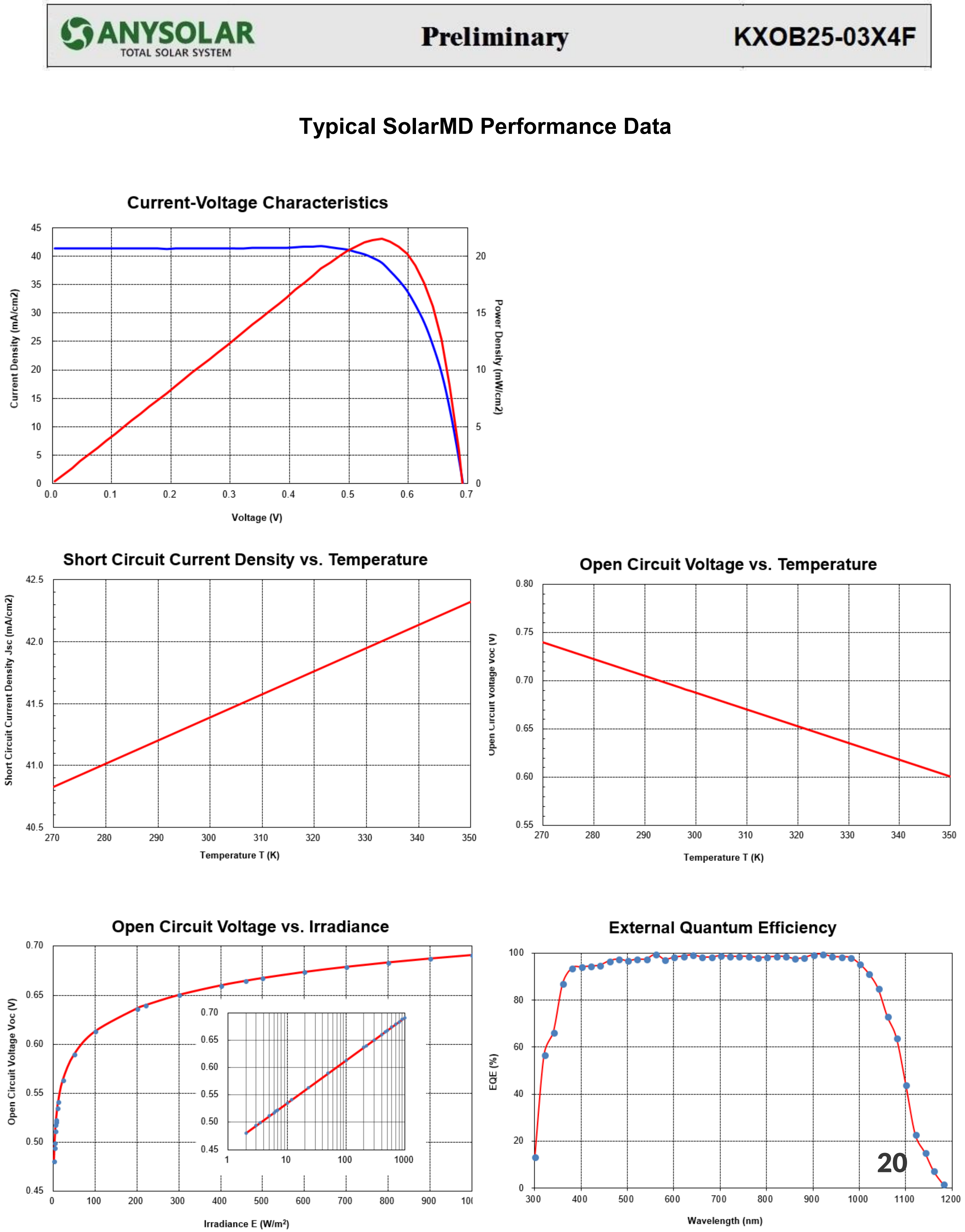
```python
#!/usr/bin/env python3
import numpy as np
import matplotlib.pyplot as plt

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



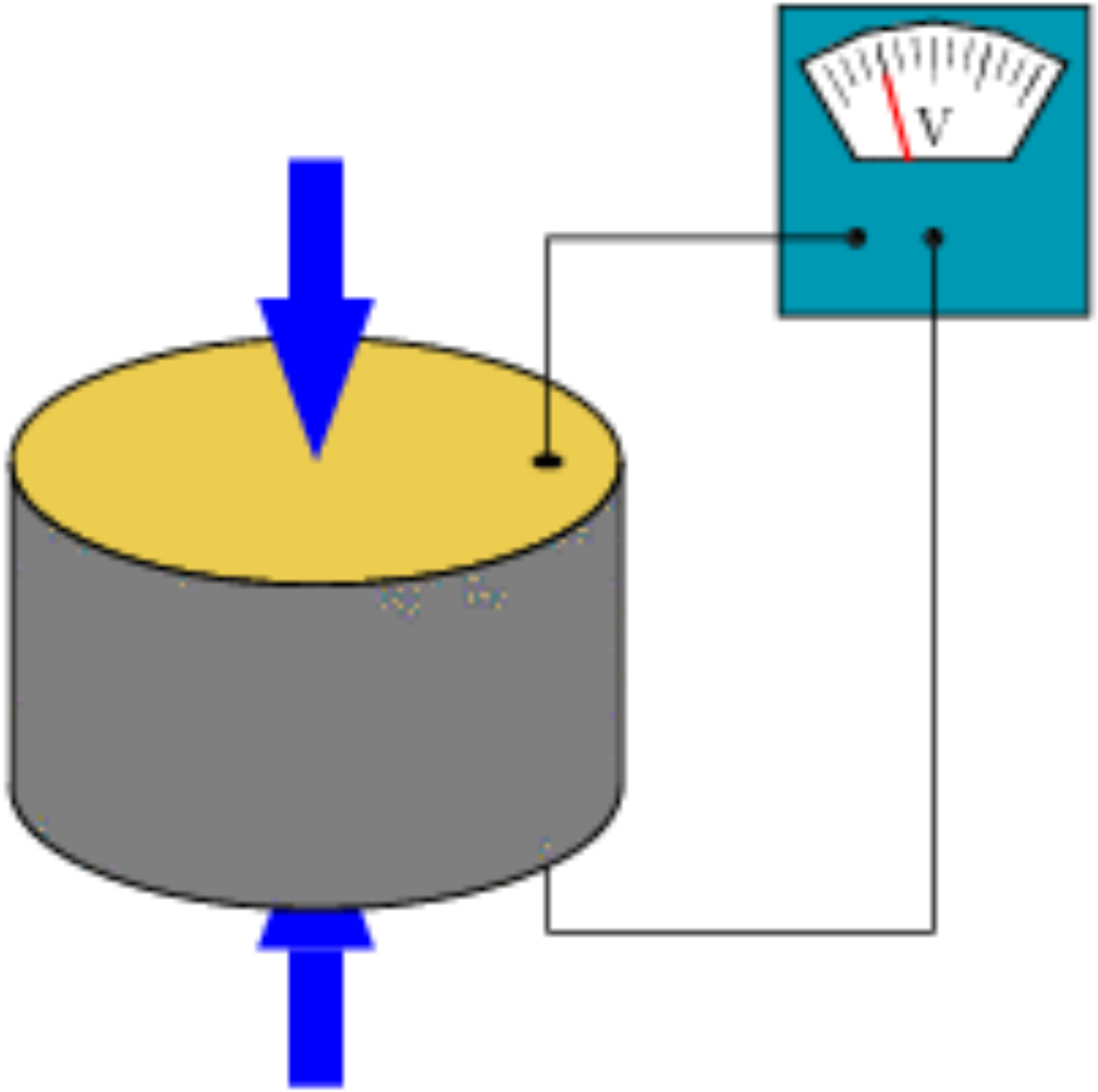
Diode voltage [V]
Power Load [mW]
Current load [mA]

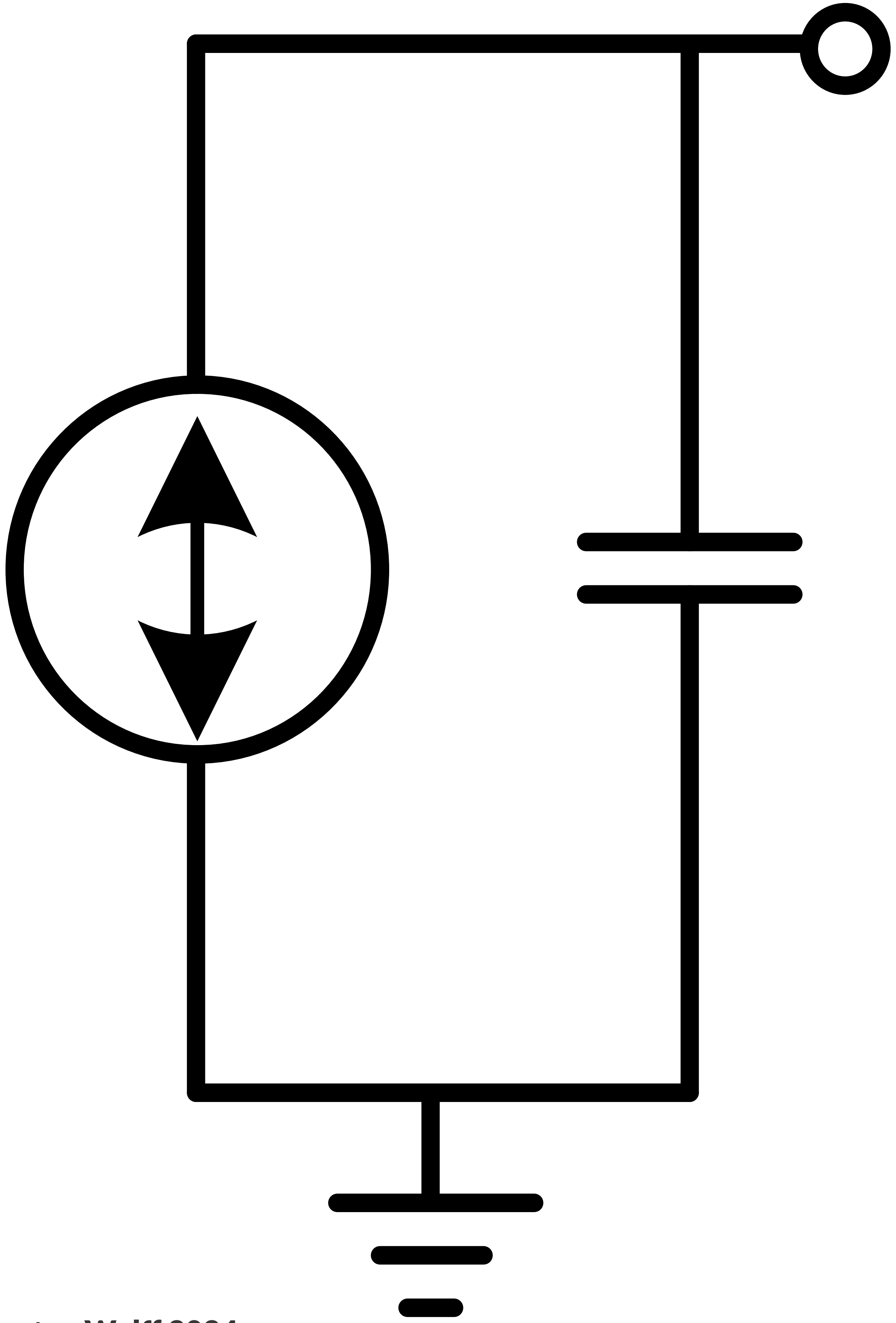


ANYSOLAR
TOTAL SOLAR SYSTEM
Preliminary
KXOB25-03X4F
Typical SolarMD Performance Data
Current-Voltage Characteristics
Current Density (mA/cm2)
Power Density (mW/cm2)
Voltage (V)
Short Circuit Current Density vs. Temperature
Short Circuit Current Density Jsc (mA/cm2)
Temperature T (K)
Open Circuit Voltage vs. Temperature
Open Circuit Voltage Voc (V)
Temperature T (K)
Open Circuit Voltage vs. Irradiance
Open Circuit Voltage Voc (V)
Irradiance E (W/m²)
External Quantum Efficiency
EQE (%)
Wavelength (nm)

In A Reconfigurable Capacitive Power Converter With Capacitance Redistribution for Indoor Light-Powered Batteryless Internet-of-Things Devices they include a maximum power point tracker and a reconfigurable charge pump to optimize efficiency.

Piezoelectric

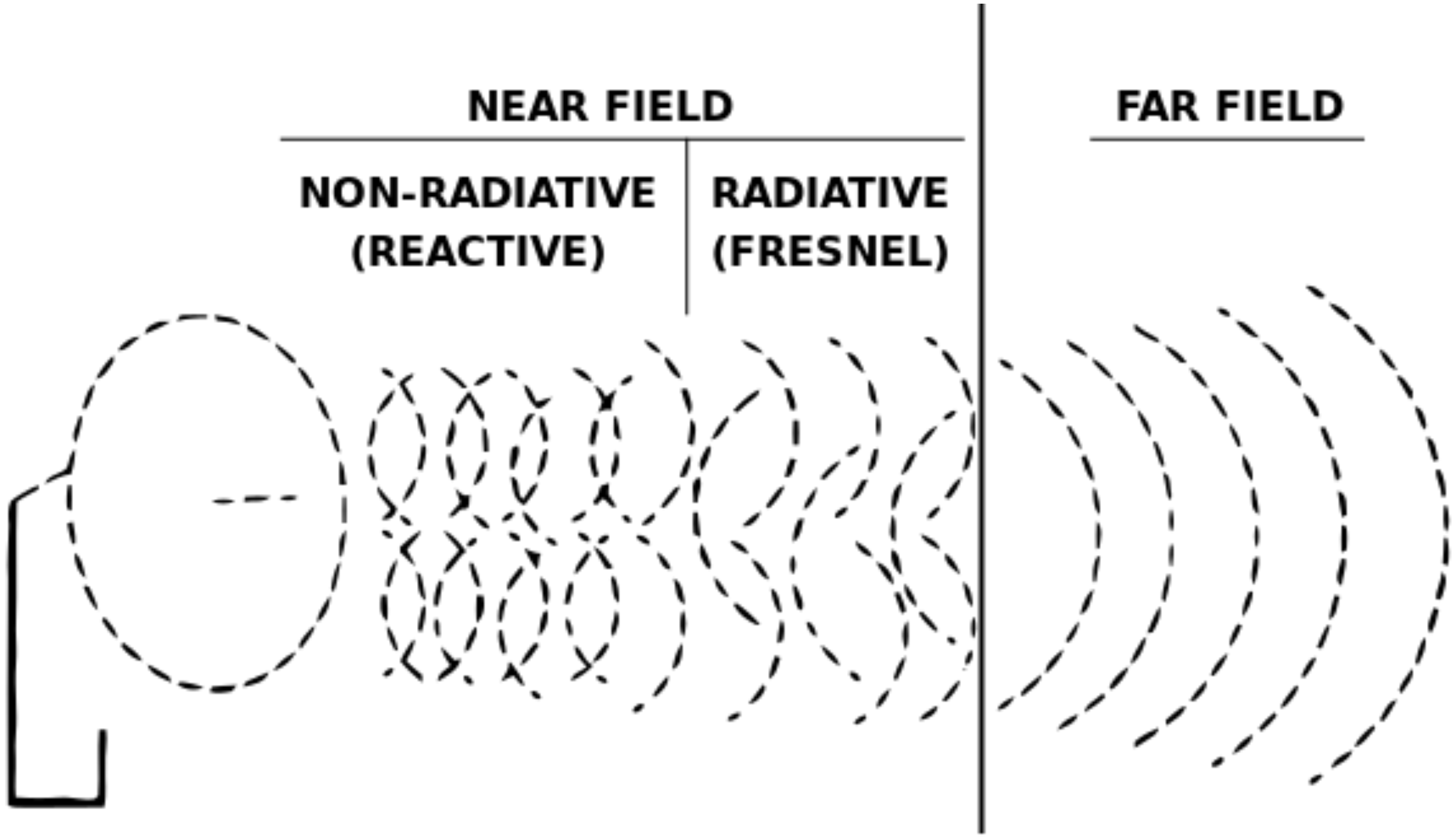

V



An example of piezoelectric energy harvester can be found in [A Fully Integrated Split-Electrode SSHC Rectifier for Piezoelectric Energy Harvesting]

Electromagnetic

"Near field" harvesting



Near Field Communcation (NFC) operates at close physical distances

Reactive near field or inductive near field

$$\text{Inductive} < \frac{\lambda}{2\pi}$$

Standard	Frequency [MHz]	Inductive [m]
AirFuel Resonant	6.78	7.03
NFC	13.56	3.52
Qi	0.205	232
Bluetooth	2400	0.02

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 RF

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

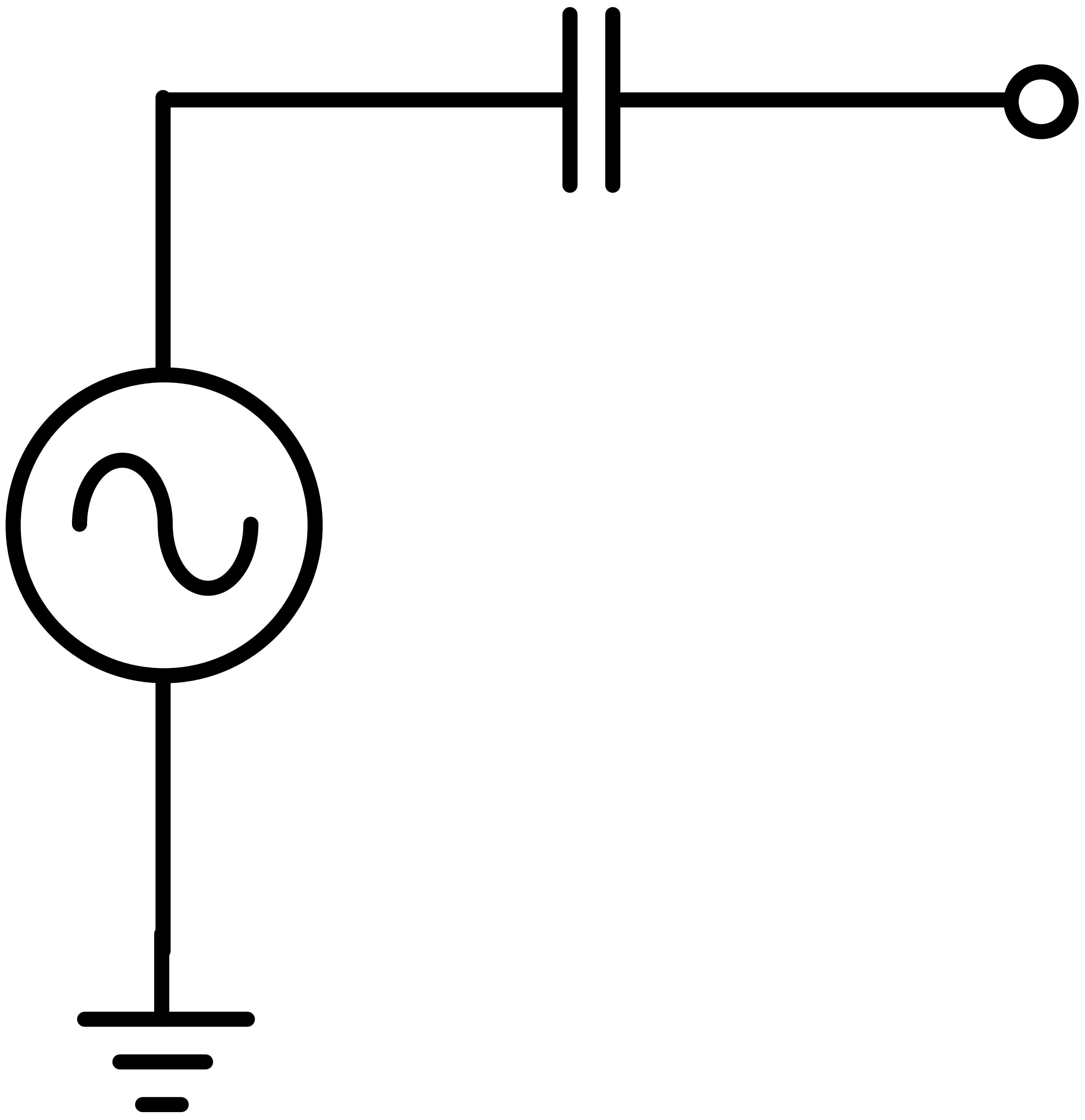
Assume P_{TX} = 1 W (30 dBm) and P_{RX} = 10 uW (-20 dBm)

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

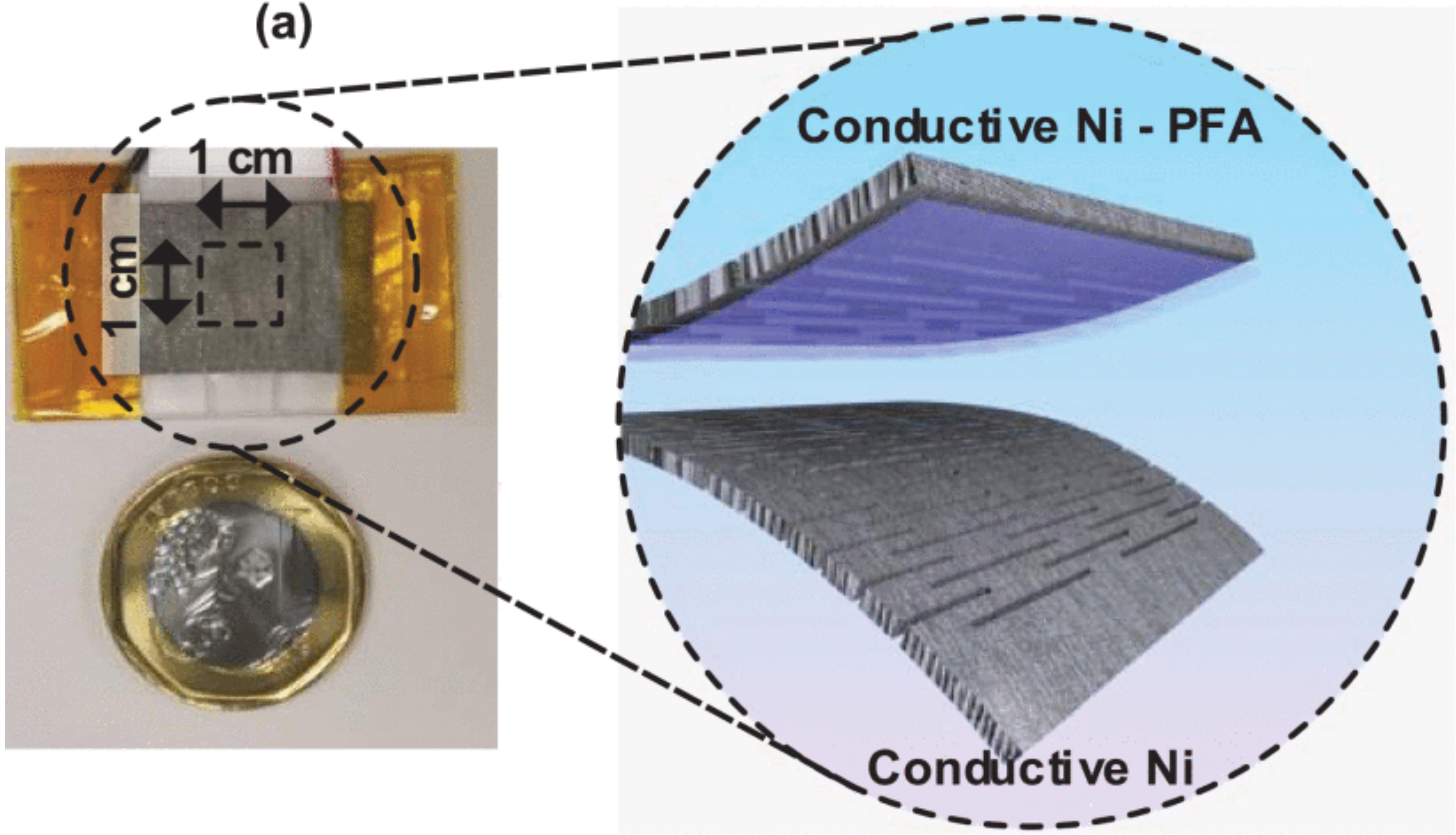
Freq	**[dB]**	**D [m]**
915M	-31.7	8.2
2.45G	-40.2	3.1
5.80G	-47.7	1.3

Triboelectric generator

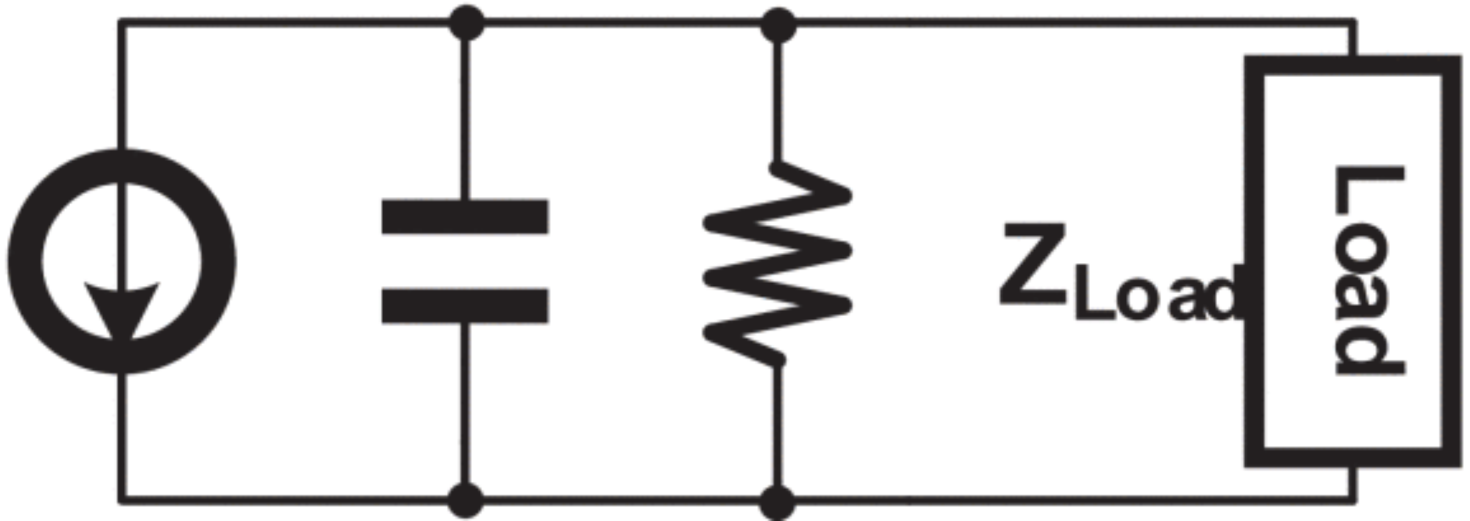
Take a look in A Fully Energy-Autonomous Temperature-to-Time Converter Powered by a Triboelectric Energy Harvester for Biomedical Applications
for more details.

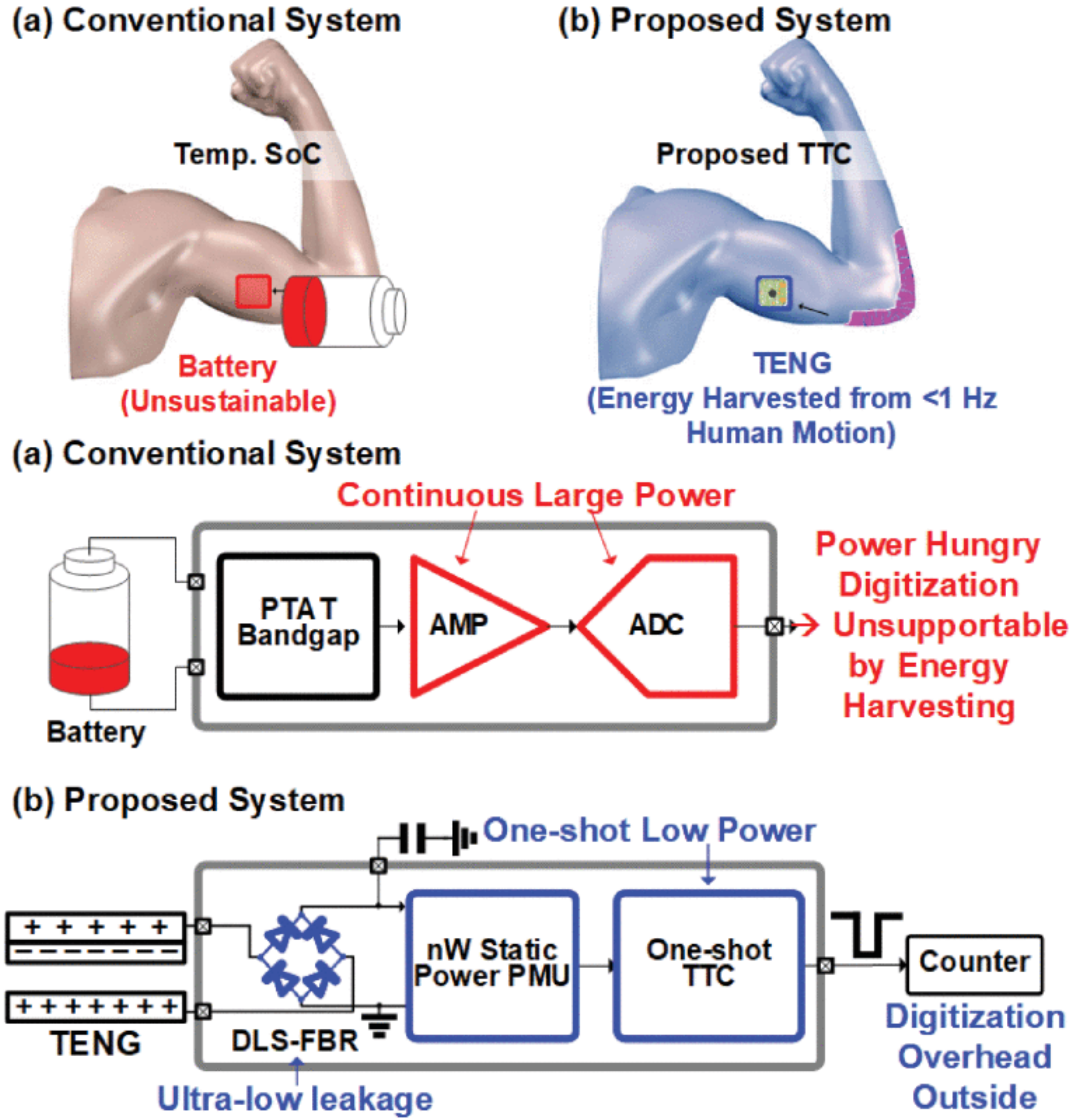


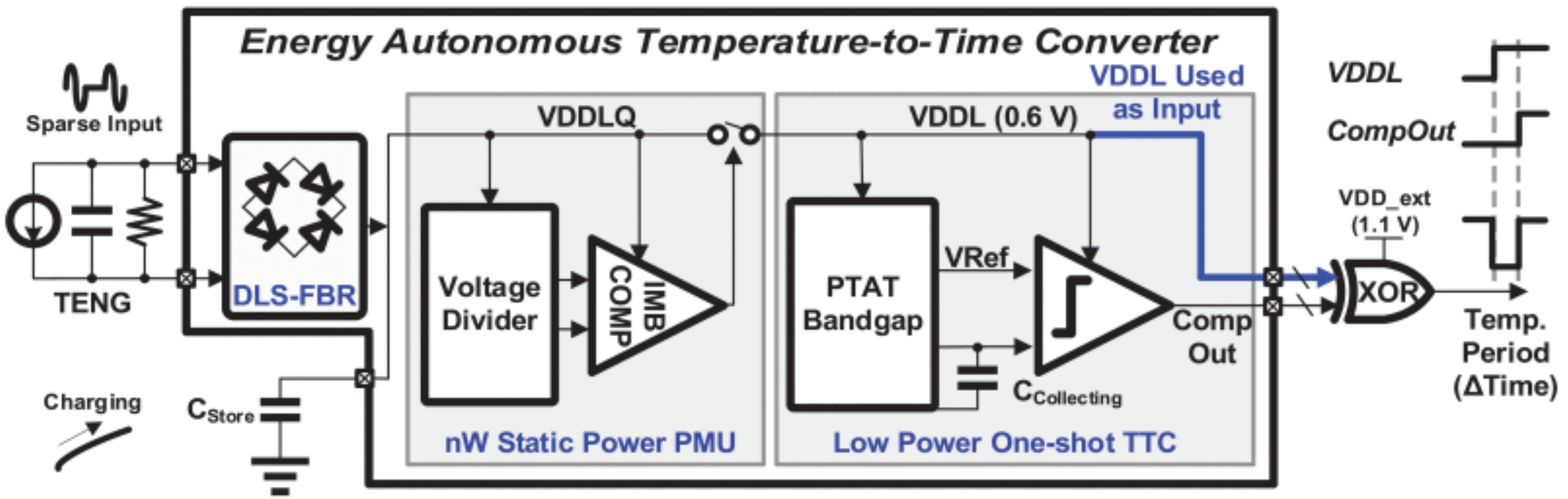
(a)

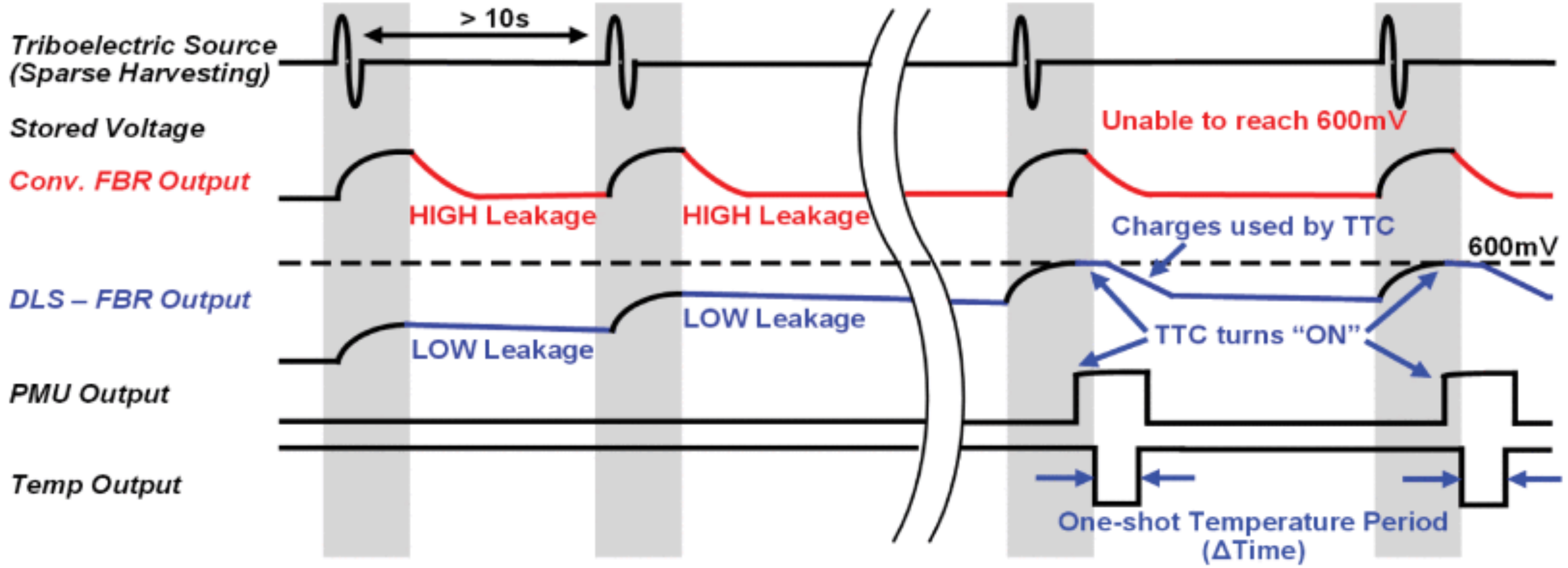


(b)




(a) Conventional System
Temp. SoC
Battery
(Unsustainable)
(b) Proposed System
Proposed TTC
TENG
(Energy Harvested from <1 Hz
Human Motion)
(a) Conventional System
Continuous Large Power
PTAT
Bandgap
AMP
ADC
Battery
Power Hungry
Digitization
Unsupportable
by Energy
Harvesting
(b) Proposed System
One-shot Low Power
nW Static
Power PMU
One-shot
TTC
Counter
TENG
DLS-FBR
Ultra-low leakage
Digitization
Overhead
Outside


Energy Autonomous Temperature-to-Time Converter
Sparse Input
TENG
DLS-FBR
Charging
CStore
VDDLQ
Voltage Divider
IMB COMP
nW Static Power PMU
VDDL (0.6 V)
VDDL Used as Input
PTAT Bandgap
VRef
CCollecting
Comp Out
Low Power One-shot TTC
VDDL
CompOut
VDD_ext (1.1 V)
XOR
Temp. Period (ΔTime)


Triboelectric Source (Sparse Harvesting)
> 10s
Stored Voltage
Conv. FBR Output
HIGH Leakage
HIGH Leakage
Unable to reach 600mV
Charges used by TTC
600mV
DLS – FBR Output
LOW Leakage
LOW Leakage
TTC turns "ON"
PMU Output
Temp Output
One-shot Temperature Period (ΔTime)

Comparison

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

References

[1] 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!