Concurrent Multi-Energy Harvesting IC for Self-Sustained Biomedical Applications

Zhuoyue Li[1,2], Joanne Si Ying Tan[2], Jia Yi Fong[2], Yingna Huang[2], Astrid Rusly[2], Jiaer Chen[1], Benjamin Ho Yin Lee[2], Jerald Yoo[1]
[1]Department of Electrical and Computer Engineering, Seoul National University, Korea
[2]Department of Electrical and Computer Engineering, National University of Singapore, Singapore
Email: jerald@snu.ac.kr

***Abstract*—We propose the first *Concurrent* Multi-Energy Harvesting (C-MEH) System that concurrently harvests energy from body-coupled 50/60 Hz electromagnetic waves, thermoelectric, and organic PV for robust-to-fluctuating-environment powering with boosted output level. So far, concurrent harvesting of multiple sources has been limited due to energy kickback. The Energy Kickback Prevention MIMO (EKP-MIMO) Buck-Boost converter suppresses this issue, increasing output power by 56.8%. Moreover, a low-power harvester-independent Self-Update Hybrid MPPT (SUH-MPPT) is implemented, which consumes 0.672 µW and saves area and power by 55.2% and 33.7%, respectively. In-vivo self-sustained EMG and ECG sensing are demonstrated under varying environmental conditions.**

Keywords—Concurrent multi-energy harvesting, energy kickback, self-sustained biomedical application

I. INTRODUCTION

As the healthcare industry increasingly adopts minimally invasive, long-term therapeutic and diagnostic solutions, biomedical monitoring platforms become essential. With an increasing number of wearable and implantable devices on and in the human body, continuous long-term biomedical monitoring places a high requirement on energy sources in terms of longevity, miniaturization, and capability. Traditional energy sources, such as batteries, are constrained by finite energy density and scalability, resulting in bulky size, increased motion artifacts, and frequent replacement. These challenges have promoted a shift towards exploring self-sustained biomedical devices.

Prior works in energy harvesting demonstrate transformative potential. Harvesting ambient environmental energy enables continuous biomedical monitoring and supports eco-friendly healthcare. Although it is a potential solution to tackle these problems caused by batteries [1]-[4], they still suffer from the instability of energy available from only one type of energy harvester (EH) in fluctuating environmental conditions. To increase the harvested energy across varying environmental conditions and maintain functionality sustainably, conventional MIMO works [5]-[8] demonstrate the utilization of multi-EHs that aggregate power from different sources. However, such MIMO PMU operates in a time division multiplexing fashion controlled by switches, allowing harvesting from only one source each time, and cannot fully maximize the available energy. Moreover, when multiple EHs operate simultaneously [9]-[11], the input harvesting sources are directly connected in parallel. The

This work is supported in part by the National Research Foundation, Korea (NRF) under grant no. RS-2024-00339998 funded by the Korea government (MSIT) and in part by the National Research Foundation, Singapore, under grant no. NRF-000214-00.

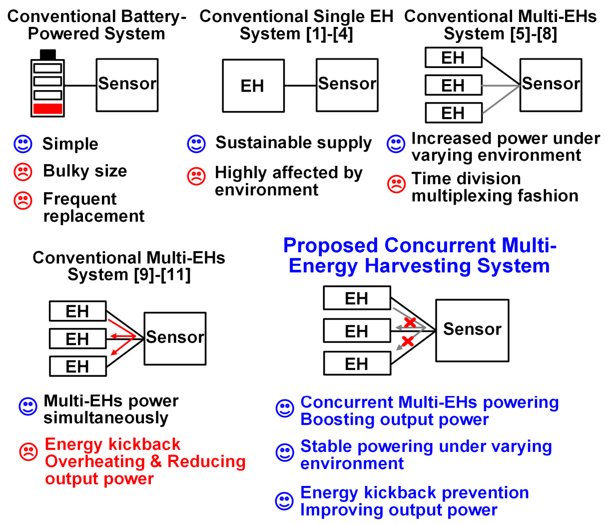

Fig. 1. Conventional powering system and proposed Concurrent Multi-Energy Harvesting system.

unbalanced currents between them may lead to energy flowing from one harvester to another (instead of to the load, ***energy kickback***), resulting in destructive harvesting and overheating of EHs, which will cause inefficiency and damage to EHs.

To prevent the energy kickback problem and allow self-sustained biomedical monitoring even under varying environmental conditions, this paper presents the Concurrent Multi-Energy Harvesting (C-MEH) system (Fig. 1) that ***concurrently*** harvests energy from multi-EHs and is robust to varying environmental conditions. The proposed C-MEH system features 1) concurrent multi-EHs harvesting to achieve output power boosting; 2) Energy Kickback Prevention MIMO (EKP-MIMO) Buck-Boost converter allows multi-EHs harvesting and prevents the energy kickback at the same time, which increases the output power by 56.8%; 3) Self-Update Hybrid Maximum Power Point Tracking (SUH-MPPT) is implemented for harvester-independent tracking while consuming 0.672 µW and saving area and power by 55.2% and 33.7%, respectively.

II. PROPOSED CONCURRENT MULTI-ENERGY HARVESTING (C-MEH) SYSTEM

A. System Architecture

Fig. 2 illustrates the proposed C-MEH system, powering a self-sustained ECG sensor. To exploit as much energy as possible, the C-MEH system adopts the organic PV (OPV), thermoelectric generator (TEG), and Body-Coupled Harvesting (BCH) (from 50/60 Hz EM waves) [12], [13] as the energy sources, ensuring concurrent power rather than employing a sequential or interleaving approach. While each EH has limited power under non-ideal environmental conditions, combining three of them by Multi-EHs PMU provides continuous and efficient power across indoor, outdoor, light, and dark conditions. The Multi-EHs PMU can combine energy from both AC and DC sources, ensuring stable output power for self-sustained ECG sensors. The EKP-MIMO Buck-Boost converter achieves concurrent harvesting and prevents the energy kickback phenomenon of multi-EHs functioning in different voltage domains. Meanwhile, the SUH-MPPT maximizes harvested power from the multi-EHs. There are two regulated output voltages, and the V_{DDL} is designed for an on-chip self-sustained sensor. The self-sustained ECG sensor shapes two ECG signals for QRS feature extraction and wirelessly transmits using Body-Coupled Communication (BCC) [14], [15]. To support the full body healthcare system, the C-MEH system can simultaneously power another biomedical sensor with V_{DDH}.

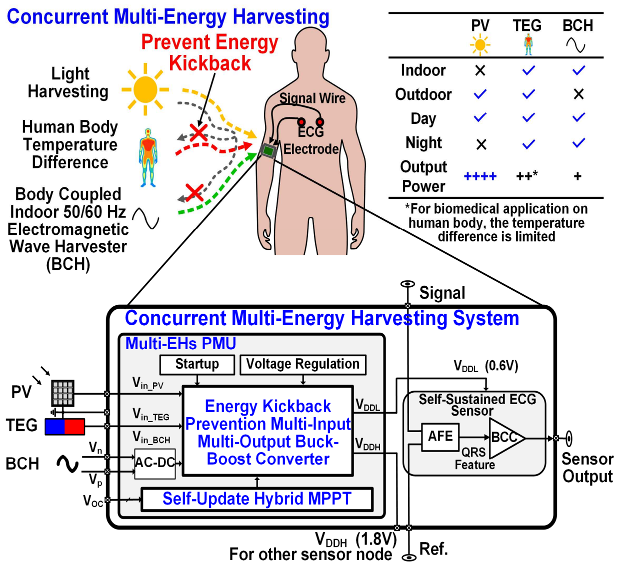

Fig. 2. The proposed Concurrent Multi-Energy Harvesting (C-MEH) system for self-sustained biomedical applications.

B. Energy Kickback Phenomenon

Different EHs exhibit significantly varying output voltage, which ranges from 10 mV to 5 V [7], [13]. Moreover, the operating voltage of an EH can fluctuate dramatically due to fluctuating environmental conditions. Under ideal environmental conditions for each EH, all EHs will deliver the current to the load as expected. However, in non-ideal conditions, when EHs operate concurrently, partial current flows back to other EHs (rather than to the load), a.k.a. ***energy kickback*** (Fig. 3), ultimately reducing the output power. The measurement with two commercial PVs is demonstrated to show that when two actively harvesting PVs are parallelly connected under an ideal environment, no energy kickback occurs, and the output power is combined (2.11 mW). However, if one of the PVs is covered, the energy kickback causes up to 23.4% power reduction compared to when it is working alone. Hence, contrary to enhancing the output power with multi-EHs, the energy kickback phenomenon, left unsolved, will cause the final output power to be lower than that of a single EH.

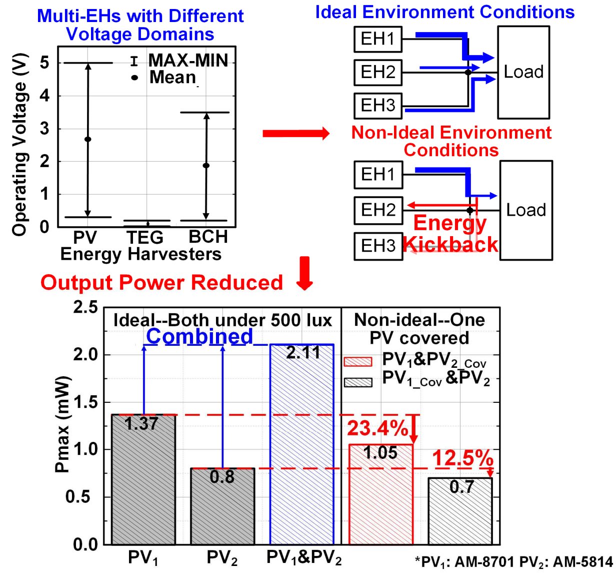

Fig. 3. The energy kickback (backflow) phenomenon.

C. Energy Kickback Prevention MIMO (EKP-MIMO) Buck-Boost Converter

To tackle the problem of energy kickback, the EKP-MIMO Buck-Boost converter with Alternate-On Complementary Switches (AOCS) is proposed (Fig. 4). If the input is not used or is connected but the power is almost zero (IN_SEL=0), the AOCS is fully turned off to block the leakage. Furthermore, based on voltage detection of V_{L+} and V_{IN} through a dynamic comparator, the energy kickback triggers AOCS to turn off, preventing the kickback current. As shown in Fig. 4, when the EH2 is under non-ideal environment conditions, the reversed current is blocked by the energy kickback prevention logic. Compared to [9]-[11] using a single transistor or complementary switches, the AOCS is alternately turned on based on input voltage. If the V_{IN} is smaller (larger) than V_{REF} (0.55 V), NMOS (PMOS) will be used to reduce the conductive loss, and the PMOS (NMOS) will be turned off to reduce the switch loss. Therefore, by selectively activating only one type of transistor, conductive loss is minimized, and switch loss is reduced by 50%

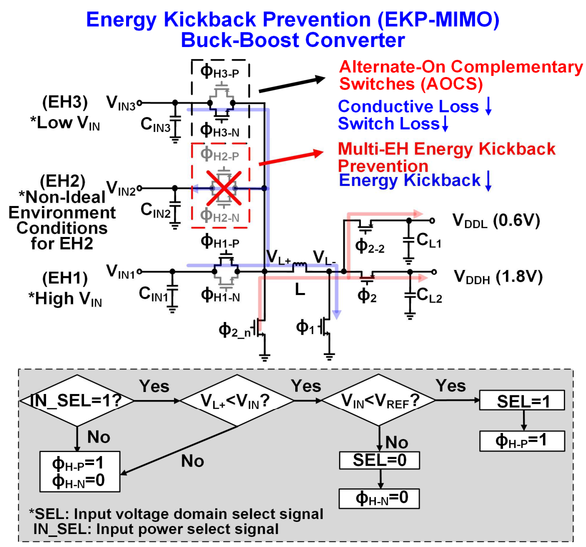

Fig. 4. The circuit details of Energy Kickback Prevention MIMO (EKP-MIMO) Buck-Boost converter.

theoretically compared to conventional complementary switches. As a result, the EKP-MIMO solves the energy kickback problem and allows concurrent harvesting that is adaptive to various conditions.

D. *Self-Update Hybrid Maximum Power Point Tracking (SUH-MPPT)*

Hill-climbing and fractional open-circuit MPPT (FOCV-MPPT) are two conventional MPPT methods for maximizing extracted power from EHs. Hill-climbing algorithm ensures continuous MPPT and can be used for various EHs. However, it requires complex hardware implementation and is power-hungry [7], [16]. Although fractional open-circuit MPPT (FOCV-MPPT) is more power-efficient, it is harvester-dependent, which is multi-EHs unfriendly, and the tracking efficiency is low [9]-[11]. To address this problem, we propose the harvester-independent SUH-MPPT. The harvester-independent SUH-MPPT, implemented on each input, integrates the benefits of FOCV-MPPT and hill-climbing, making it suitable for multi-EHs systems (Fig. 5).

The harvester voltage (V_{IN}) is regulated around the maximum power point voltage (V_{MPP}) within a hysteresis window (ΔV) determined by the hysteresis comparator. The power extracted from EH (P_{HAR}) can be simplified and is proportional to $V_{S2}/T_{\overline{\phi 1}}$. Therefore, the MPP tracking is achieved by comparing the value of $V_{S2}/T_{\overline{\phi 1}}$. The power monitor sampled V_{IN} by ϕ_1 to obtain V_{S2} and then converted it to time (T) by the voltage-to-time converter (VTC). Then the comparison of P_{HAR} is converted to compare the ratio of T and $T_{\overline{\phi 1}}$. Different from normal hill-climbing algorithms that return the $T_{\phi 1}$ [7], the self-update unit compares the current and previous power to decide the fraction (K) of open-circuit voltage (V_{OC}). The updated V_{mpp} that is closest to the required V_{mpp} is then obtained for maximum power. The K values are within 0.5-0.75 for most EHs [5], which reduces the sweep range of the self-update unit, allowing for faster tracking and lower power consumption. The proposed SUH-MPPT can self-update K under different environmental conditions while eliminating the low tracking efficiency of FOCV. The SUH-MPPT achieves low-power consumption through analog power monitoring and simplified calculation logic, operating at 0.672 µW. Compared with the hill-climbing algorithm, it achieves area and power saving by 55.2% and 33.7%, respectively.

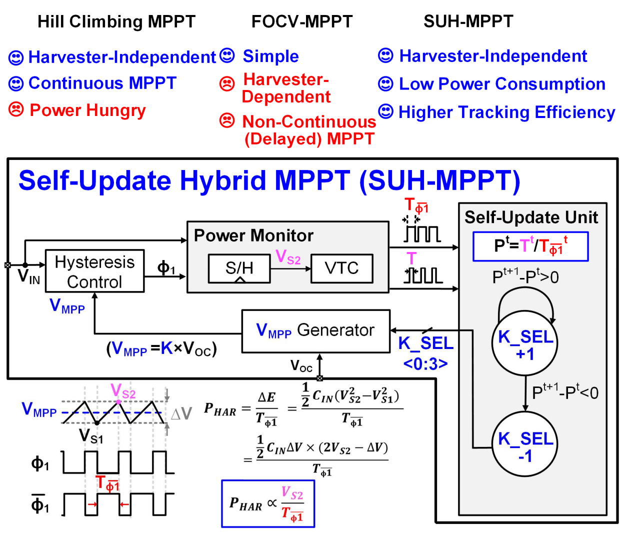

Fig. 5. The circuit details and mechanism of the proposed Self-Update Hybrid MPPT (SUH-MPPT) block.

III. Measurement Results

The design was fabricated in 0.18 µm 1P6M CMOS process, occupying an active area of 1.32 mm². Fig. 6 shows the IC micrograph.

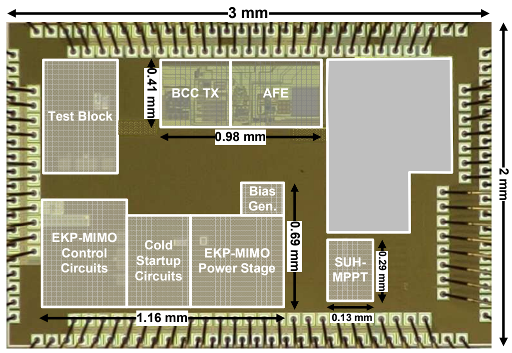

Fig. 6. Chip micrograph.

Fig. 7 shows the output power measurements and transient waveforms under fluctuating environmental conditions. Initially, the TEG is connected to the system without a temperature difference (ΔT); at 4.5 s, a 10 °C ΔT generated by the human body and room temperature is applied, then removed at 25 s. Despite varying the input voltage of TEG, the two output voltages remain unaffected (I_{Load} are 150 µA and 100 µA), indicating that the energy kickback phenomenon is prevented. Additionally, the two outputs remain stable even when the OPV is intentionally covered. Even under fluctuating environmental conditions, self-sustained sensing becomes possible. This system can achieve low-voltage cold startup by multi-EHs. The output power measurements show that the proposed concurrent Multi-EHs PMU effectively improves output power. Combining TEG results in a 1558× power boost compared to the sole BCH case. Furthermore, after integrating three EHs, the output power continuously increases by 2.36× compared with two EHs. We achieved an overall 56.8% power boost by EKP-MIMO with three EHs, illustrating that the energy kickback is prevented. Compared to the single transistor switch, the AOCS exhibits lower losses, resulting in a 20.8% power boost.

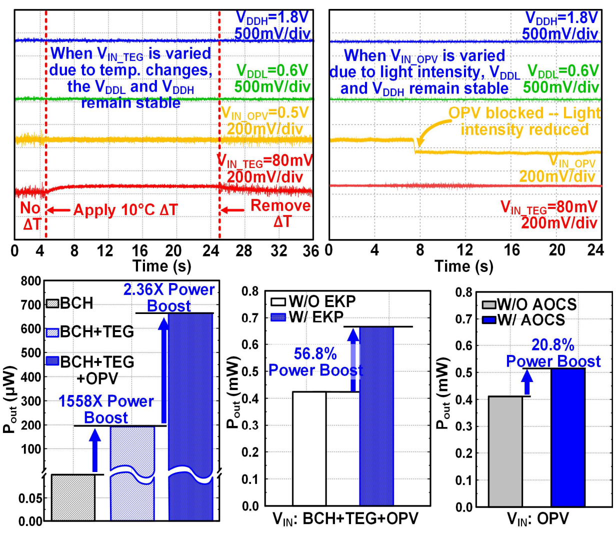

Fig. 7. Measurement results of output power and transient waveform under different environmental conditions.

Fig. 8 shows the measurement setup and in-vivo testing. Even when the OPV is covered (blocked), the quality of the ECG signal is unaffected. The QRS feature of the ECG signal is successfully transmitted by BCC under varying light conditions. The eye blinking signals are obtained to verify the self-sustained EMG monitoring. Compared to prior works (TABLE I), this work is the only system that ***concurrently*** harvests from OPV, TEG, and BCH with EKP-MIMO and SUH-MPPT, and is verified under fluctuating environments.

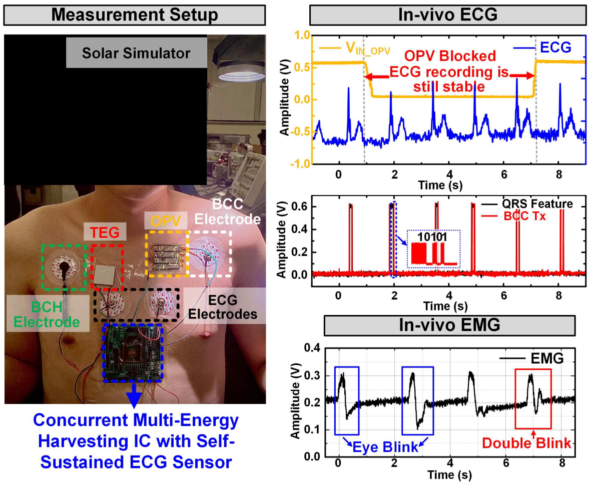

Fig. 8. Photograph of the measurement setup and measurement results of the in-vivo ECG signal and EMG waveform.

TABLE I Comparison table

	JSSC2021 [17]	ISSCC2022 [9]	VLSI2022 [2]	ISSCC2023 [1]	VLSI2024 [4]	This work
Technology (nm)	350	180	65	65	180 BCD	180
Application	NA	Env. Monitoring	Temperature	Temperature	NA	Biomedical
Area (mm^2)	4.67^	14.3^	3.1	0.516	NA	1.32
Concurrent Multi-Energy Harvesting	No	No	No	No	No	Yes (W/ EKP-MIMO)
Full System Demo	NA	Yes	Yes	No	No	Yes (In-vivo)
Converting Architecture	Boost	Buck-Boost	Boost	SC Boost+SC Buck-boost	Voltage Doubler (Rx)	Buck-Boost
No. Input	1	2	1	1	1	3
No. Output (DC-DC)	1	1	1	2	1	2
Energy Source	PV	MEC+PV	PV	PV	EM (Hill-strike)	PV+TEG+BCH
MPPT Algorithm	SRE-FOCV /AZ-PI MPPT	FOCV	FOCV	FOCV	MRPT	SUH-MPPT
MPPT Power (μW)	0.792/1.683	NA	NA	NA	NA	0.672
Output Power	0.7-1000 mW#	0.05-14 mW	NA	4 nW-5 W	NA	0.2 μW-1.1 mW
Output Voltage (V)	3.5	1.5	0.6/1.2(Doubler)/0.9(LDO)	0.58/1-1.2	2.7-4.3#	0.6/1.8
Peak Efficiency	92.6%	81.30%	70%	62.7%	12% (IBPT)	71.5%

^Chip/Die area #Estimated from figure

IV. Conclusion

In this paper, we proposed a C-MEH system, which is the first concurrent multi-energy harvesting system for self-sustained biomedical monitoring. It improves the output power and optimizes power stability and reliability. This is achieved by the proposed EKP-MIMO Buck-Boost converter, which prevents the energy kickback problem and increases the output power by 56.8%. Meanwhile, after combining the energy from BCH, TEG, and OPV, the output power is successfully boosted, even in fluctuating environments. The harvester-independent SUH-MPPT consumes 0.672 μW while achieving 55.2% area saving and 33.7% power saving. The in-vivo self-sustained ECG and EMG monitoring is demonstrated even under fluctuating environmental conditions.

Acknowledgment

The authors thank Dr. Kenjiro Fukuda and Prof. Takao Someya (RIKEN/The Univ. of Tokyo) for OPV fabrication.

References

[1] X. Liu *et al.*, "15.1 A Self-Powered SoC with Distributed Cooperative Energy Harvesting and Multi-Chip Power Management for System-in-Fiber," *IEEE Int. Solid-State Circ. Conf. (ISSCC) Dig. Tech. Papers, 2023*, pp. 236-238.

[2] D. S. Truesdel *et al.*, "NanoWattch: A Self-Powered 3-nW RISC-V SsC Operable from 160mV Photovoltaic Input with Integrated Temperature Sensing and Adaptive Performance Scaling" *Symp. on VLSI, 2022*, pp. 210-211.

[3] S. Bose, B. Shen, and M. L. Johnston, "26.5 A 20μ W Heartbeat Detection System-on-Chip Powered by Human Body Heat for Self-Sustaining Wearable Healthcare," *IEEE Int. Solid-State Circ. Conf. (ISSCC) Dig. Tech. Papers,* 2020, pp. 408-410.

[4] H. Cho *et al.*, "An Intra-Body-Power-Transfer System Energized by an Electromagnetic Energy Harvester for Powering Wearable Sensor Nodes," *Symp. on VLSI*, 2024, pp. 1-2.

[5] S. S. Amin and P. P. Mercier, "MISIMO: A multi-input single-inductor multi-output energy harvester employing event-driven MPPT control to achieve 89% peak efficiency and a 60,000x dynamic range in 28nm FDSOI," *IEEE Int. Solid-State Circ. Conf. (ISSCC) Dig. Tech. Papers,* 2018, pp. 144-146.

[6] C.-W. Liu *et al.*, "Dual-Source Energy-Harvesting Interface With Cycle-by-Cycle Source Tracking and Adaptive Peak-Inductor-Current Control," *IEEE J. Solid-State Circuits,* vol. 53, no. 10, pp. 2741-2750, 2018.

[7] S. Bandyopadhyay and A. P. Chandrakasan, "Platform Architecture for Solar, Thermal, and Vibration Energy Combining With MPPT and Single Inductor," *IEEE J. Solid-State Circuit,* vol. 47, no. 9, pp. 2199-2215, 2012.

[8] H. Kim *et al.*, "A 90.2% peak efficiency multi-input single-inductor multi-output energy harvesting interface with double-conversion rejection technique and buck-based dual-conversion mode", *IEEE J. Solid-State Circuits,* vol. 56, no. 3, pp. 961-971, 2021.

[9] C. -Y. Wu *et al.*, "A Self-powering Wireless Soil-pH and Electrical Conductance Monitoring IC with Hybrid Microbial Electrochemical and Photovoltaic Energy Harvesting," *IEEE Int. Solid-State Circ. Conf. (ISSCC) Dig. Tech. Papers,* 2022, pp. 198-200.

[10] X. Liu, A. Agrawal, A. Tanaka, and B. Calhoun, "A 6nA Fully-Autonomous Triple-Input Hybrid-Inductor-Capacitor Multi-Output Power Management System with Multi-Rail Energy Sharing, All-Rail Cold Startup, and Adaptive Conversion Control for mm-scale Distributed Systems," *IEEE Int. Solid-State Circ. Conf. (ISSCC) Dig. Tech. Papers,* 2024, pp. 152-154.

[11] S. Li, X. Liu, and B. H. Calhoun, "A 32nA Fully Autonomous Multi-Input Single-Inductor Multi-Output Energy-Harvesting and Power-Management Platform with 1.2× 105 Dynamic Range, Integrated MPPT, and Multi-Modal Cold Start-Up," *IEEE Int. Solid-State Circ. Conf. (ISSCC) Dig. Tech. Papers,* 2022, pp. 472-473.

[12] J. Li *et al.*, "34.5 Human-Body-Coupled Power-Delivery and Ambient-Energy Harvesting ICs for a Full-Body-Area Power Sustainability," *IEEE Int. Solid-State Circ. Conf. (ISSCC) Dig. Tech. Papers,* 2020, pp. 514-516.

[13] J. Li, Y. Dong, J. H. Park, and J. Yoo, "Body-coupled power transmission and energy harvesting," *Nat. Electronics* (4), no. 7, 2021.

[14] W. Saadeh, M. A. B. Altaf, H. Alsuradi and J. Yoo, "A Pseudo OFDM With Miniaturized FSK Demodulation Body-Coupled Communication Transceiver for Binaural Hearing Aids in 65 nm CMOS," *IEEE J. Solid-State Circuits,* vol. 52, no. 3, pp. 757-768, 2017.

[15] W. Saadeh, M. A. B. Altaf, H. Alsuradi and J. Yoo, "A 1.1-mW Ground Effect-Resilient Body-Coupled Communication Transceiver With Pseudo OFDM for Head and Body Area Network," *IEEE J. Solid-State Circuits,* vol. 52, no. 10, pp. 2690-2702, 2017.

[16] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. Energy Conversion*, vol. 22, no. 2, pp. 439-449, 2007.

[17] S. Uprety and H. Lee, "A 0.65-mW-to-1-W Photovoltaic Energy Harvester With Irradiance-Aware Auto-Configurable Hybrid MPPT Achieving >95% MPPT Efficiency and 2.9-ms FOCV Transient Time," *IEEE J. Solid-State Circuits,* vol. 56, no. 6, pp. 1827-1836, 2021.