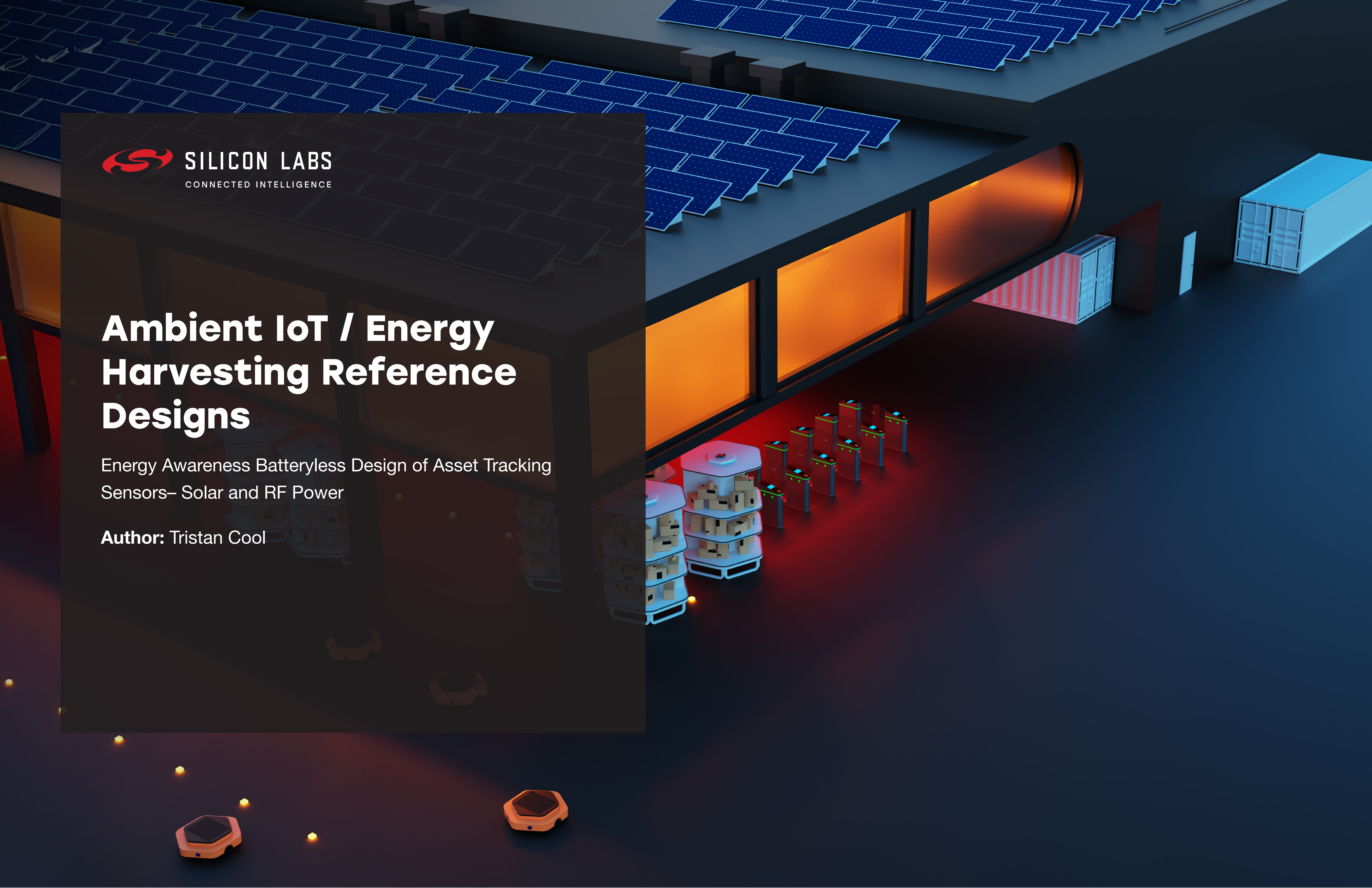

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Ambient IoT / Energy Harvesting Reference Designs

Energy Awareness Batteryless Design of Asset Tracking Sensors– Solar and RF Power

Author: Tristan Cool

INTRODUCTION

What is Ambient IoT?

Ambient IoT - often closely associated with ‘Energy Harvesting’ – refers to a class of connected devices that are powered by harvested ambient energy—such as light, RF, electromagnetic fields, thermal gradients, kinetic motion, and vibration—enabling batteryless or rechargeable operation. The aim is to reduce battery waste and extend device lifespan.

While Ambient IoT supports a wide range of applications, this whitepaper focuses on one of its most promising and fast-growing use cases: asset tracking. It presents several reference designs and explores key hardware and firmware considerations essential to enabling batteryless operation.

Quick Access Toolkit

Before you get started, click the links below to access the tools you’ll need to follow along with this whitepaper:

Access GitHub **Simplicity Connect App**

The Fundamentals of Energy-Harvesting Ambient Iot

Energy-harvesting-based IoT devices demand careful design considerations and tradeoffs in payload, power, and cost. Silicon Labs has advanced its Energy Friendly Radio (EFR) platform to be more energy-conscious, optimizing key functions like sleep mode transition, device cold-start, and IoT protocol algorithms essential to its operation. Additionally, Silicon Labs has partnered with industry leaders to simplify design processes, reduce design complexity, and facilitate broader mass-market adoption of new applications and customers.

This simplified block diagram highlights the importance of each design socket—from energy harvesting to storage and power management—all of which must be precisely aligned to the target application.

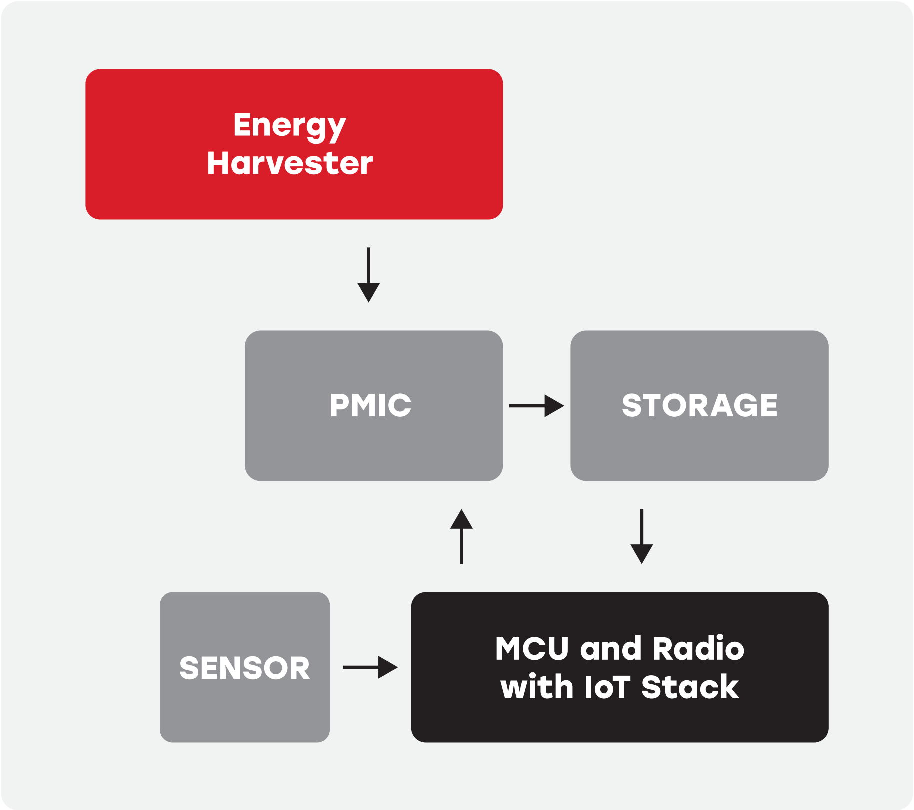


Figure 1: Energy Harvesting architecture (source: Works With 2024)

The power management IC (PMIC) must efficiently regulate energy flow, balancing charge and discharge cycles based on application-specific impedance and energy availability.

Storage elements—such as capacitor banks, supercapacitors, solid-state lithium capacitors, or conventional batteries—must be carefully designed to handle both average and peak current demands. Under-resourced storage can lead to brownouts or failed cold-starts, while overly resourced solutions, despite appearing advantageous, can increase cost, size, and start-up delays.

The MCU or IoT SoC plays a critical role in energy efficiency. A poorly optimized application can waste harvested energy, while overly conservative designs may limit radio range and data throughput. Achieving the right balance is central to effective Ambient IoT deployment, regardless of protocol or energy source.

Defining Attibutes	**Harvesting energy from any viable ambient power source**			
IoT Hardware Evolution	**New Device Feature Enablement** • Smaller device size and new form factors • Longer maintenance-free field life, including through battery-free device • Lower cost of hardware	**Function** • Tracking • Monitoring • Identity • Control	**Topologies** • Point-to-point • Mesh • Broadcast	**New Device Feature Enablement** • Smaller device size and new form factors • Longer maintenance-free field life, including through battery-free device • Lower cost of hardware
Applications	**Existing and new IoT use cases. Early examples include asset tracking, commercial building automation, condition based monitoring, cold chain monitoring control.**			

Figure 2: Ambient IoT definition (source: Bluetooth Special Interest Group - 2024)

Why Asset Tracking Needs Ambient IoT?

Asset tracking is one of the fastest-growing IoT applications, helping prevent the loss of billions of parcels, machines, and equipment transported globally each day. This application is supported by a diverse mix of short- and long-range wireless technologies, including cellular, GPS, Bluetooth, Sub-GHz, Wi-Fi, LoRa, and RFID.

According to the Bluetooth SIG and ABI Research, annual shipments of Bluetooth-based real-time location asset tags are projected to exceed 322 million units by 2028.

Figure 3: Asset Tracking

Asset tags are used in both general and specialized, industry-specific applications—such as pallet, hospital bed tracking, cold-chain and pharmaceutical tracking. Most rely on batteries that must be replaced upon asset retrieval, complicating logistics due to air travel and temperature constraints. Though rated for 3–10 years, batteries are often discarded prematurely, contributing to over 15 billion discarded units globally each year (Works With 2024).

While traditional asset tracking relies on manual bar-code scanning, IoT technologies have significantly automated and streamlined this process. While some IoT applications need to establish and maintain connections, asset tags operate by beaconing identifiers or listening passively, minimizing energy use. This makes them ideal for protocols such as Bluetooth, Zigbee, proprietary 2.4 GHz 15.4, and sub-GHz. Eliminating the battery removes replacement cycles entirely. Even when energy is depleted, tags can self-reboot once charged.

In principle, the usefullness of an asset track grows with the number of tags—more tags mean fewer lost assets. However, at scale, battery replacement becomes a major cost and logistical barrier, undermining ROI.

Ambient IoT addresses this by eliminating battery reliance and improving asset tracking utility. Batteryless tags never require replacement and can self-reboot once the energy is restored.

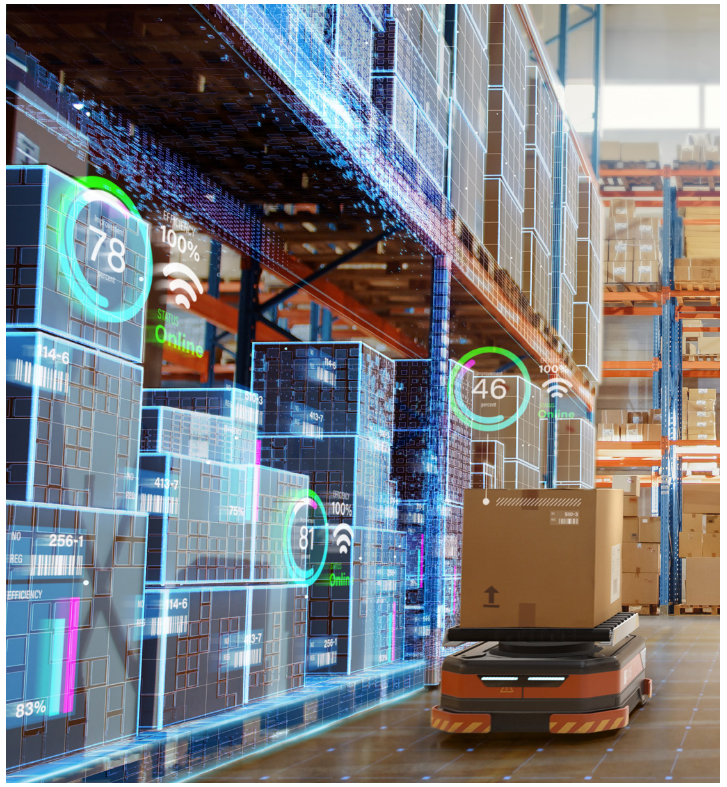


Figure 4: Dracula OPV

Furthermore, without using any complex AI, asset tag firmware can dynamically adjust payload size, transmission PHY, and sleep intervals based on real-time energy availability.

Silicon Labs' EFR platform enables this through simple energy measurements and the RAIL/Connect stack, which abstracts the radio layer to emulate BLE and 15.4 protocols at minimal power.

These energy-aware capabilities make tags adaptive, efficient, and maintenance-free—even in dark storage or long immobile periods. Key energy sources for batteryless tracking include photovoltaic (solar) and RF harvesting. Asset tags can be redesigned to operate on ambient energy—either from light (indoor/outdoor) or RF transmission—regardless of protocol or payload. While hardware must be tailored, the core beaconing function remains unchanged. Batteryless tags are also more practical in regulated environments like hospitals and aircraft.

Photovoltaic (PV) energy is harvested via small, sometimes printed, solar cells. These cells can recharge a storage element in 15–20 minutes and store enough energy to operate for up to 24 hours in darkness. This approach covers most use cases, including indoor and outdoor tags, sensors, and labels. The reference design is discussed in more detail later in this whitepaper.

Alternatively, for use cases with prolonged darkness or transit—such as trucks, trains, freezers, or storage racks—RF-powered tags offer an alternative. These devices remain batteryless and operate within range of an RF transmitter that wirelessly powers them.

As asset tracking models continue to develop and evolve, the future of asset tracking will depend on hybrid networks of battery and batteryless devices, leveraging diverse IoT protocols. This integrated model supports greater economic and ecological scalability, along with increased flexibility and sustainability.

REFERENCE DESIGNS

Energy aware dynamic designs for Solar and RF Ambient IoT Asset Tracking

Silicon Labs continues to lead in wireless asset tracking by offering a comprehensive portfolio of IoT SoCs supporting key protocols such as Bluetooth, Proprietary 2.4 GHz, Wirepas, sub-GHz, Sigfox, and Wi-Fi. Continuing our tradition of pioneering innovation in technology, we now introduce two cutting-edge batteryless designs based on the most in-demand energy harvesting methods—light and RF.

The growing preference for these two energy sources is easy to understand. Solar power can harness both – indoor and outdoor lux spectrums, enabling consistent trickle charging throughout an asset's journey. RF energy, on the other hand, can be wirelessly transmitted to directly power tags within range—ideal when no other ambient source is available.

Each reference design will be detailed in dedicated sections, covering operation specifications, design parameters, and partner contributions. All associated hardware and firmware files are available open-source via the following **GitHub repository**.

GitHub

Key shared features include:

- Beaconing Tag Devices – using Bluetooth LE RAIL packets
- Batteryless operation via capacitor-based energy storage
- Energy-aware, dynamically adjustable behavior
- Compatibility with the Silicon Labs Simplicity Connect mobile app and EFR32 Radio Board Reader Dashboard and GUI

These designs aim to stay true to real-world asset tracking needs while introducing enhanced Ambient IoT capabilities.

REFERENCE DESIGN #1

Solar-powered batteryless asset tag Requirements and Specifications

Solar-powered asset tags offer key benefits: extended lifetime and easier compliance with air travel regulations. This design supports 24 hours of operation without a light source and typically recharges within 15–20 minutes. Even after full energy depletion, the tag can self-recharge and resume operation once light is available.

To achieve this, Silicon Labs collaborated with [Dracula Technologies](#) (a leader in printed organic photovoltaic solar cells and storage elements) and [e-peas](#) (a leader in energy-harvesting PMICs) to develop a custom 3-band, 350 µW PV cell. This was designed and matched to meet the storage selected in the design.

The reference design targets:

- Maximum cold start time: 15 minutes at 1000 LUX.
- Compact board dimensions: 8.6 × 5.4 cm (smaller than a credit card, includes programming/debug components like programming header, pushbutton for reset, force advertising and capacitor discharge).
- Minimum operation time under dark, after a full charge: 24-hours at lowest wake-up frequency

To support varying customer needs, a two-way micro switch allows selection between four pre-set wake-up and beacon configurations. While useful for development, such features are not required in commercial deployments. These settings are also dynamically adjusted based on energy awareness, discussed in later sections.

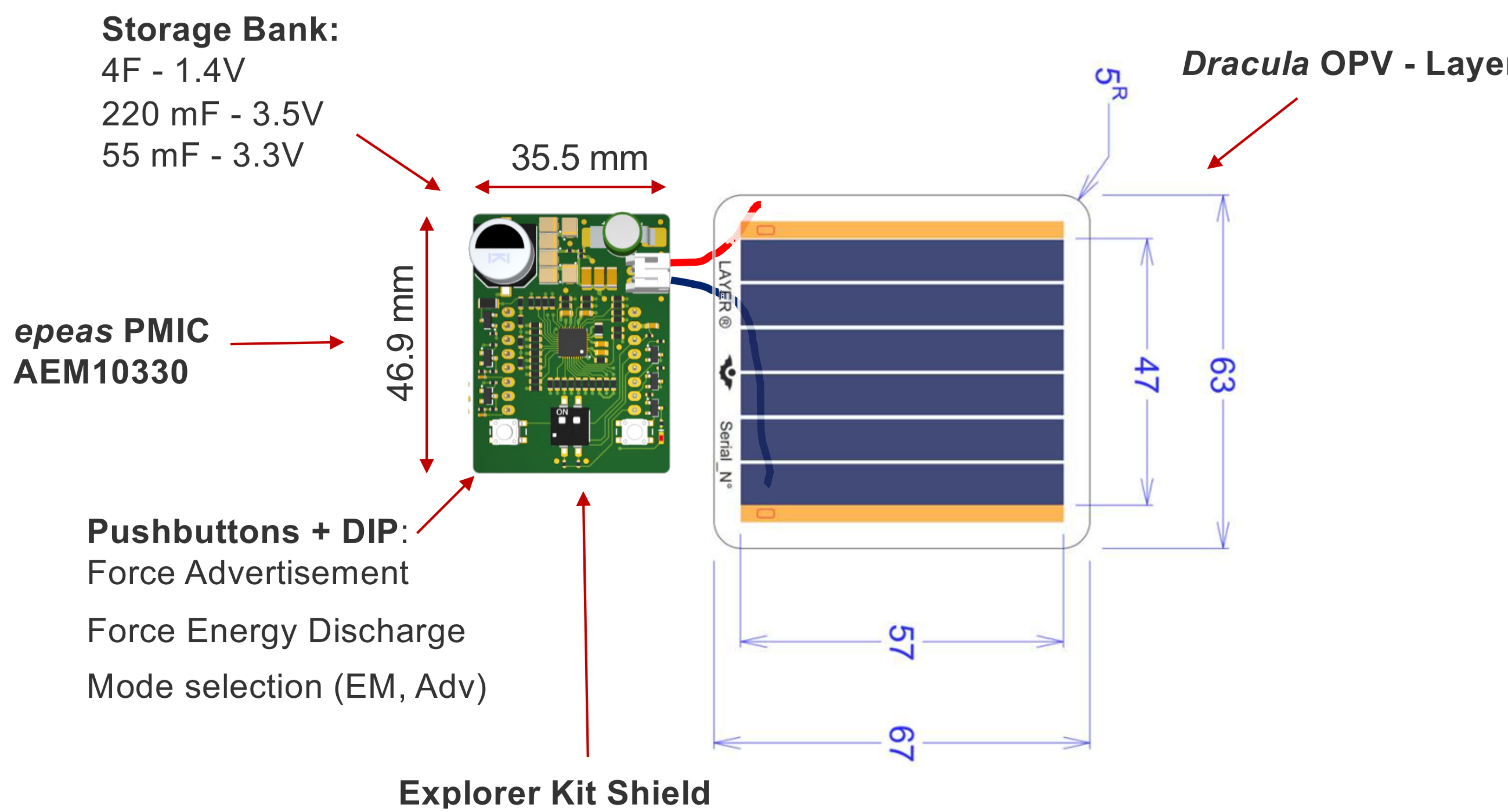


Figure 5: Dracula e-peas PV Asset Tag

REFERENCE DESIGN #1

Hardware Design

The block diagram below shows the main component of the reference design.

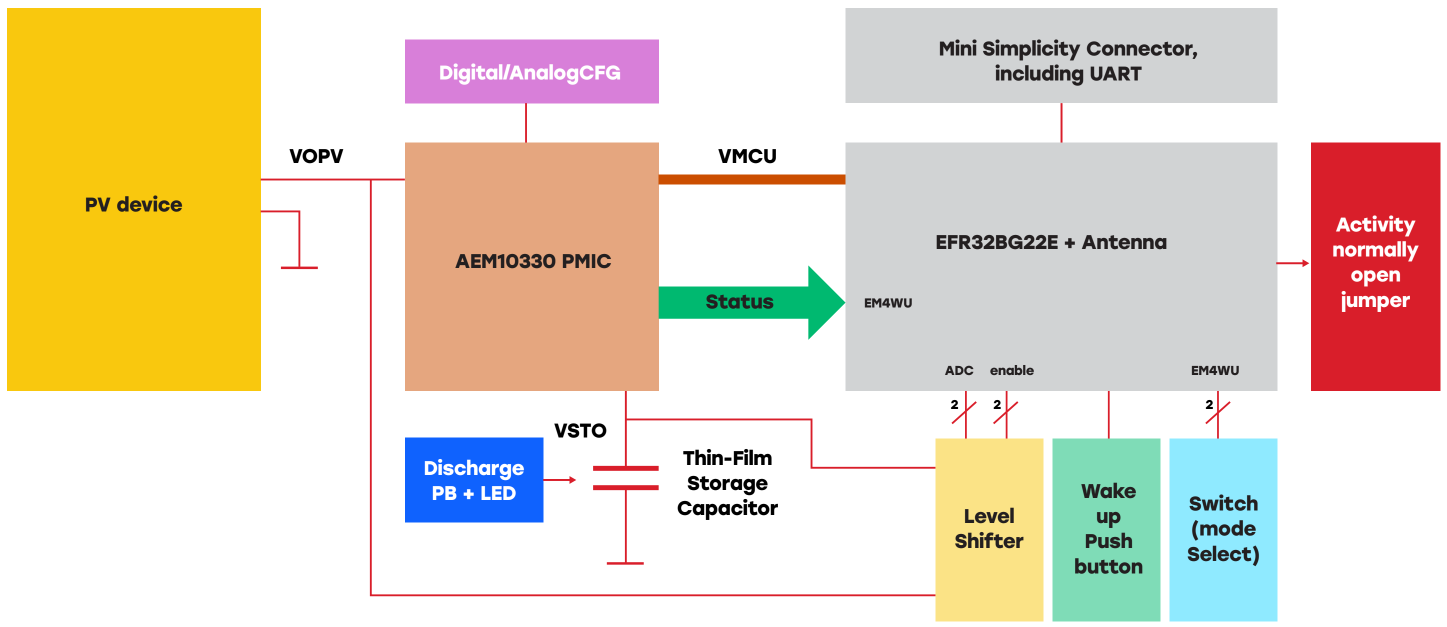


Figure 6: PV Asset Tag Block Diagram

The finished layout is shown below:

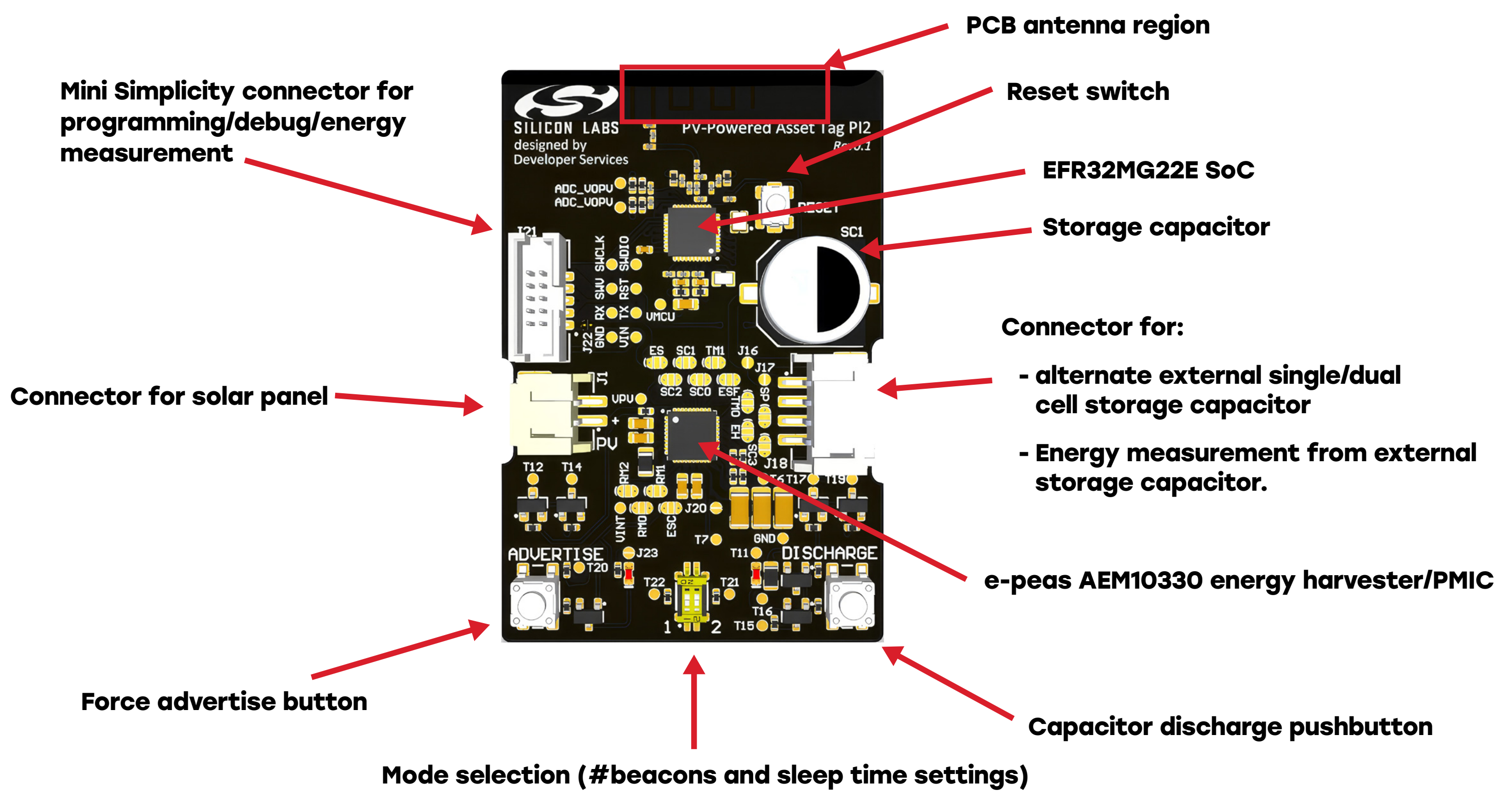


Figure 7: 7- PV Asset Layout Diagram

The solar panel can be fixed to the back side of the board with double-sided tape.

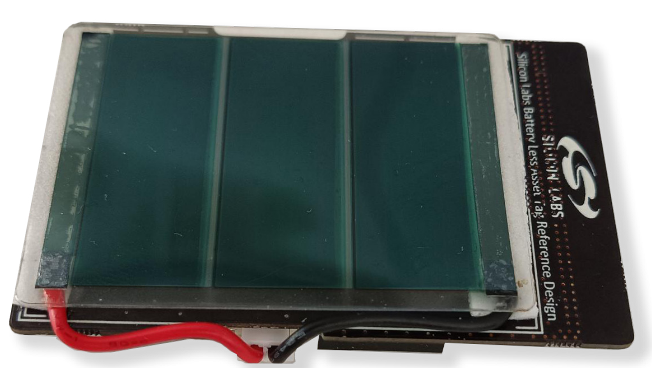


Figure 8: PV Asset Tag

REFERENCE DESIGN #1

Operation – Storage Elements and Measurements

Batteryless devices require a storage element—such as a a supercapacitor—to collect and gradually supply energy during operation. The selection of capacitance and voltage ratings for the storage element depends on several factors:

- **Average Current Consumption:** Driven by wake-up frequency, beacon count, transmit power, payload size, etc.
- **Operation Time in Darkness:** Expected runtime without an energy source after a full charge.
- **Cold Start Time:** Duration needed to harvest sufficient energy from zero to begin operation—determined by the source's power level.
- **Space Constraints:** Larger capacitors increase runtime but reduce compactness.
- **Cost:** Higher storage capacity often comes with higher cost.

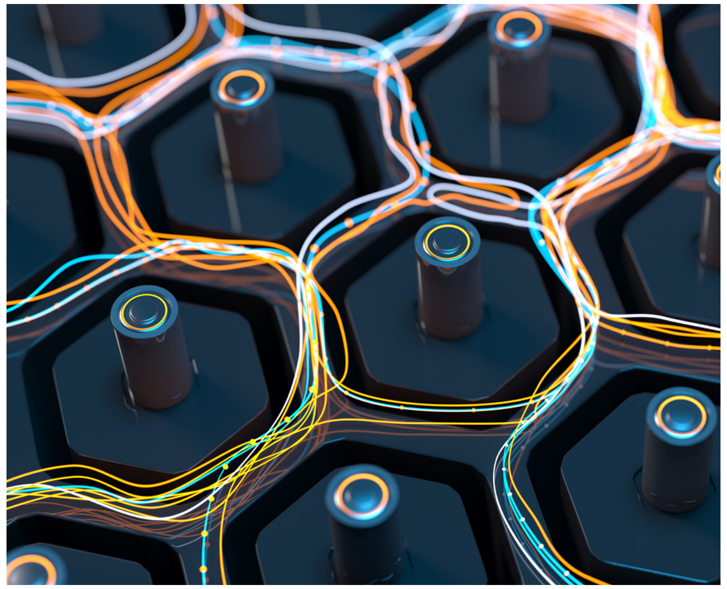
Initial sizing can be estimated using datasheet values, but characterization offers better accuracy. In testing, the following energy metrics were measured:

- Energy spent during transmission at various power levels
- Energy spent to wake-up from EM4 and EM2
- Energy spent by measuring the capacitor voltage
- Energy spent in EM0/1/2/4 in our sample application

A 220 mF capacitor charged to 3V enabled the following:

- **Standard Mode:** 12 beacons at 1-second intervals, every 2.5 minutes, sustained for ~7.5 hours.
- **Extended Mode:** Same beacon pattern every 5 minutes for ~18 additional hours.
- **Low-Power Mode:** One beacon every other 300-second wake-up cycle, lasting ~8 hours until voltage drops below 1V (the over-discharge threshold of the AEM10330).

A corresponding voltage chart illustrates capacitor discharge over time, with dotted lines indicating estimated voltage during non-reporting low-power phases.



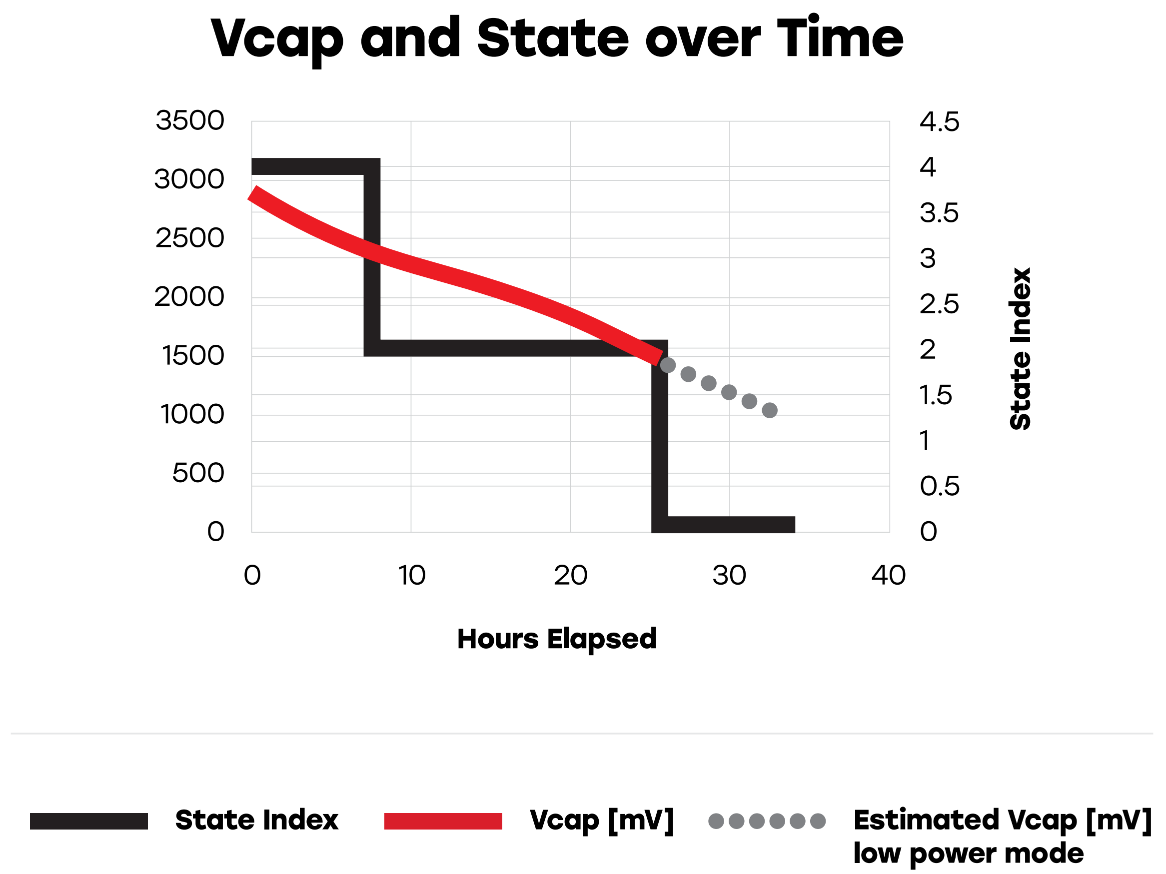


Figure 9: Dynamic Energy States

The Dracula-supplied photovoltaic (PV) device delivers up to 350 µW at 1000 lux. With ~70% system efficiency, the cold-start time remains under 11 minutes—meeting design goals. In full daylight, but without direct sunlight exposure, cold-start time improves by over 10× to 10,000–25,000 lux.

Customers can optimize the system—adjusting capacitor size, AEM10330 settings, and the energy awareness algorithm—to balance cost, physical size, wake-up frequency and beacon count, and cold-start time.

The reference design also supports direct measurement of current at both the EFR32MG22E and the storage capacitor. Detailed guidance is provided in the circuit diagram notes, available via the GitHub repository and application notes.

REFERENCE DESIGN #2

RF-powered batteryless asset tag Requirements and Specifications

RF wireless power is gaining traction, particularly in retail and logistics, where other energy sources may be impractical. It offers convenient installation and delivers substantial power for batteryless operation.

This reference design was developed in collaboration with **Energous** and e-peas, based on Energous' **e-peas** based AEM30940 reference design kit. It integrates Silicon Labs' MG22E SoC, enhanced to utilize Silicon Labs dynamic energy-aware behavior for efficient operation under variable power conditions.

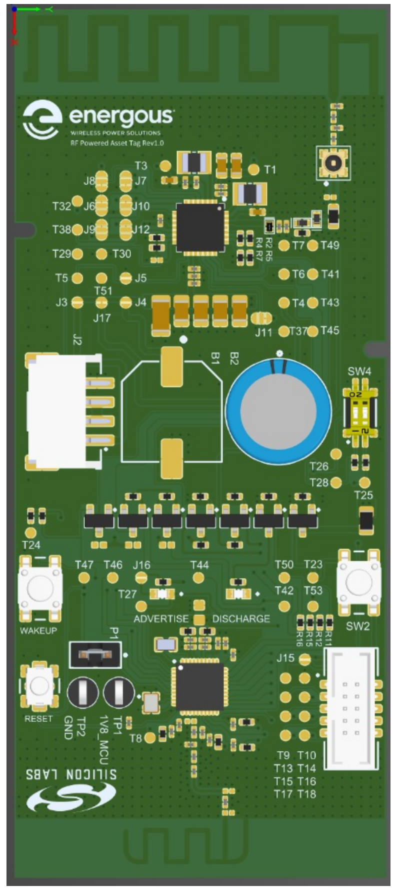


Figure 10: Energous RF Asset Tag (31 x 91mm)

The Energous–Silicon Labs batteryless sensor is a compact, single-board platform optimized for energy harvesting and low-power wireless operation. Designed for maintenance-free deployments, it eliminates the need for traditional power sources.

An Energous-designed RF antenna feeds a high-efficiency RF-to-DC rectifier, supplying power across a wide input range. An energy harvesting enabled PMIC from e-peas manages this unregulated input, directing energy to a storage element while providing regulated supply and system monitoring for Silicon Labs' Bluetooth LE beacon.

The storage element—capacitor, supercapacitor, or battery—supports operation across a 2.5V to 4.4V range.

Ideal for IoT sensors, asset tracking, industrial monitoring, wearables, and smart home devices, this solution advances RF energy harvesting as a sustainable, batteryless alternative—reducing maintenance and environmental impact.

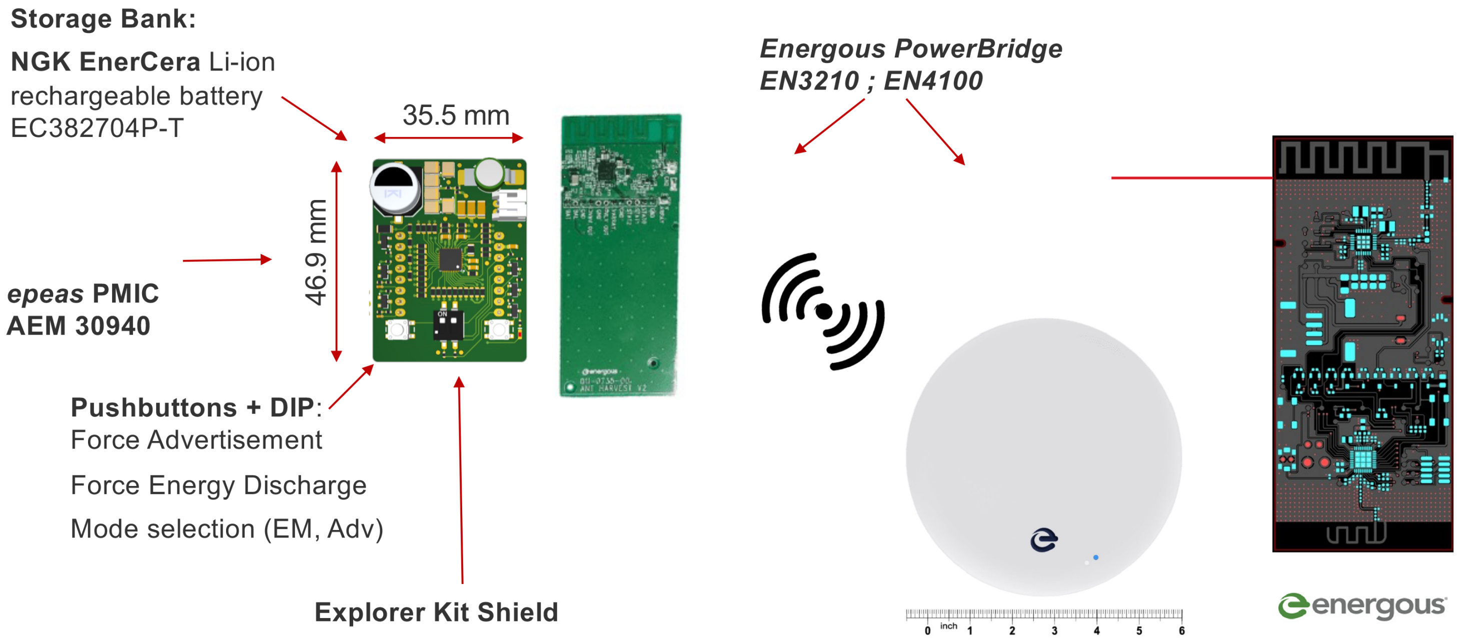


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Figure 11: Energous e-peas RF Asset Tag

REFERENCE DESIGN #2

Hardware Design

The RF-powered asset tag block diagram is very similar to the photovoltaic one. The only difference is the energy harvesting element (an antenna, its matching network and the rectifier), the different PMIC (AEM30940 instead of AEM10330), and the level shifter for optional status signals coming from the PMIC.

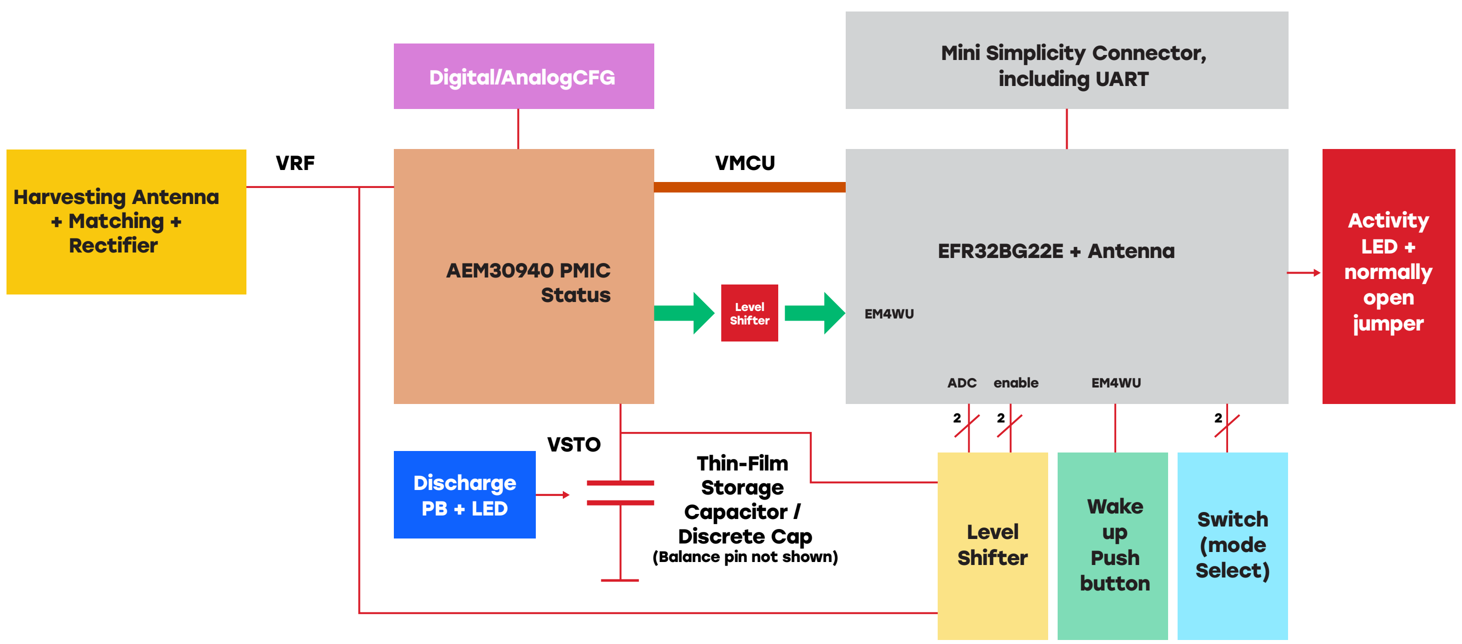
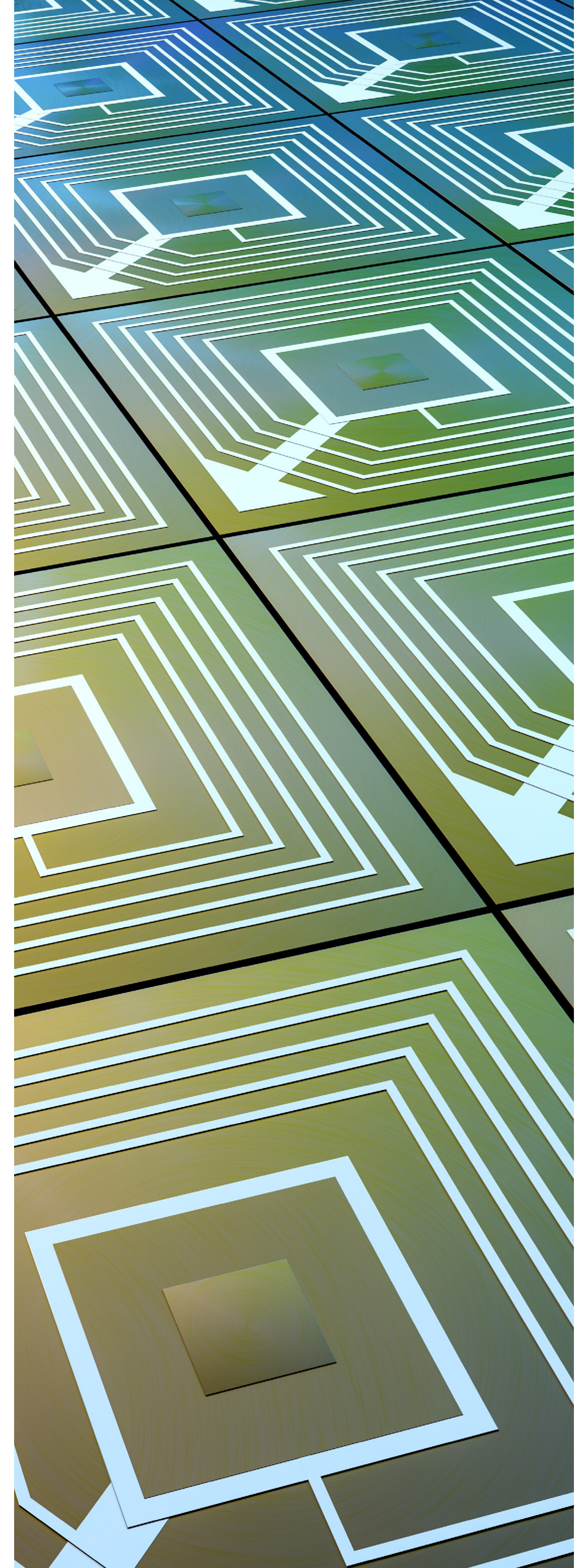


Figure 12: RF Asset Tag Block Diagram

This single-board solution is powered from an external omnidirectional 900MHz ISM band transmitter source (1dBi peak gain). The antenna is a PCB printed PIFA omnidirectional with linearly polarized response ideal for low cost and small size.

The design uses an RF-DC rectifier circuitry finely tuned for -12.5 dBm to +7.0 dBm resulting in approximately 40~75% efficiency in this range using GaAs and CMOS Schottky devices.

The PMIC is designed to accommodate a 4-5V range storage element, in this case, a ceramic capacitor bank or supercapacitor (10mF-47mF).



Operation - Mode

RF input is received via an integrated antenna, rectified to DC, and used to charge the storage capacitor. As the capacitor voltage increases and surpasses 3.28V, the 1.8V LVout turns on to power the BLE and sensors. The 1.8V remains active while the storage capacitor voltage is above 2.2 V. The harvesting PMIC stops charging the storage capacitor near the max voltage of 4.38 V.

The system operates as a function of input power:

- **Continuous Mode:** (Harvested power is greater than the power output by the load)
  - The load is powered, and excess power charges the storage capacitor. Charging stops when the storage capacitor voltage reaches its maximum value.
- **Neutral Mode:** (Harvested power is equal to the power output by the load)
  - The load is powered, but the storage capacitor voltage remains unchanged because there is no excess power for charging.
- **Duty Cycle Mode:** (Harvested power is less than the power used by the load)
  - The load power cycles on and off with a duty cycle that is a ratio of the input power to the circuit's power use.

AMBIENT IoT IN ACTION:

Asset Tracking

This section highlights a truly novel feature that demonstrates the benefit of migrating asset tracking to batteryless energy harvesting using a simple Python GUI. Silicon Labs is the world's expert in IoT and has incorporated these energy-awareness algorithms to become the leader in Ambient IoT.

Asset Tracking Reader and GUI Dashboard

RAIL-based Bluetooth LE beacons are detectable via Silicon Labs' Simplicity Connect mobile app for Android and iOS. However, to demonstrate the payload or the energy level, Silicon Labs has developed an EFR32MG24-based reader kit that captures beacons and displays real-time energy states. A simple Python GUI provides a visual dashboard showing behavior of both PV- and RF-powered batteryless tags. Additional EFR32 radio boards can also serve as readers.

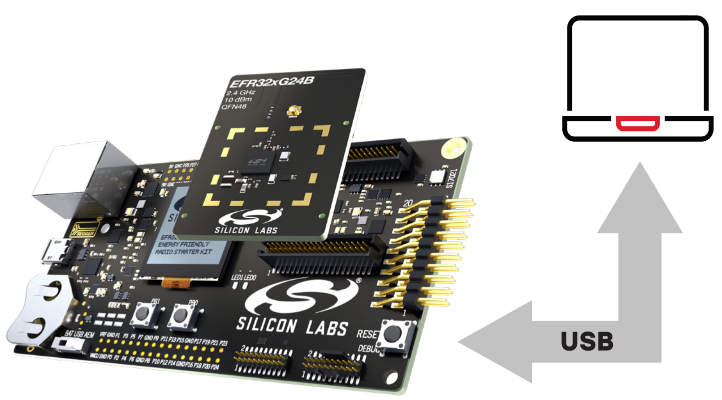


Figure 13: MG24 Reader

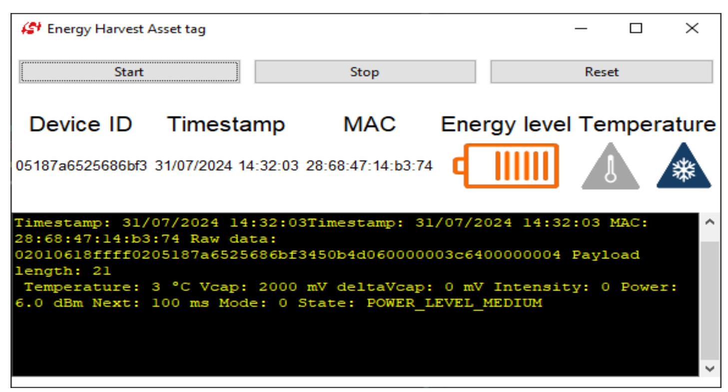


Figure 14: Energy Awareness Asset Tag Python Dashboard

Dynamic Energy Awareness Algorithms

An asset tag's primary role is to beacon its ID and sensor data to a gateway reader, providing health and location updates throughout its journey. This is typically done via repeated beacon transmissions at fixed intervals, with deep sleep in between.

While conventional tags maintain constant intervals, Ambient IoT tags adjust these intervals in real time based on the remaining stored energy — maximizing efficiency and optimizing for energy conservation.

Both reference designs use RAIL to transmit Bluetooth LE beacons and are pre-configured with default intervals. A DIP switch on each board allows users to manually select alternate presets.

CONFIG. MODE	# OF BEACONS ; INTERVAL	SLEEP TIME
MODE 1	3x; 0.1s	0.5 min
MODE 2	6x; 0.2s	1 min
MODE 3	12x ; 0.5s	2 min
MODE 4	12x; 0.5s	3 min

The energy-awareness algorithm takes an energy assessment measure and configures this mode based on its capability. If energy is fleeting, it will half the number of beacons and sleep for longer and vice versa. If energy is in abundance, it will double its beacon count and half its sleep time dynamically at run-time.

Furthermore, based on this energy reading, other critical parameters are adjusted dynamically.

PAYLOAD	TRANSMISSION POWER	TRANSMISSION PHY
FULL: ID, Temperature reading, Energy (VSource, VCap, Delta VCap) Timing to next beacon, dip switch configuration, current power mode	• 6 dBm • 5 dBm • 3 dBm • 0 dBm	• 1M
SHORT: ID only		

The overall operation can be summarized as such:

ENERGY	TX	PHY	PAYLOAD	BEACONS	SLEEP
MAX	6 dBm	1M	FULL	CONFIG. X2	CONFIG. /2
HIGH	5 dBm	1M	FULL	CONFIG. X2	CONFIG. /2
MEDIUM	3 dBm	1M	FULL	CONFIG. X2	CONFIG
MIN	0 dBm	1M	SHORT	CONFIG	CONFIG
POWER SAVING	0 dBm	1M	SHORT	CONFIG	CONFIG, but TX only on second wakeup

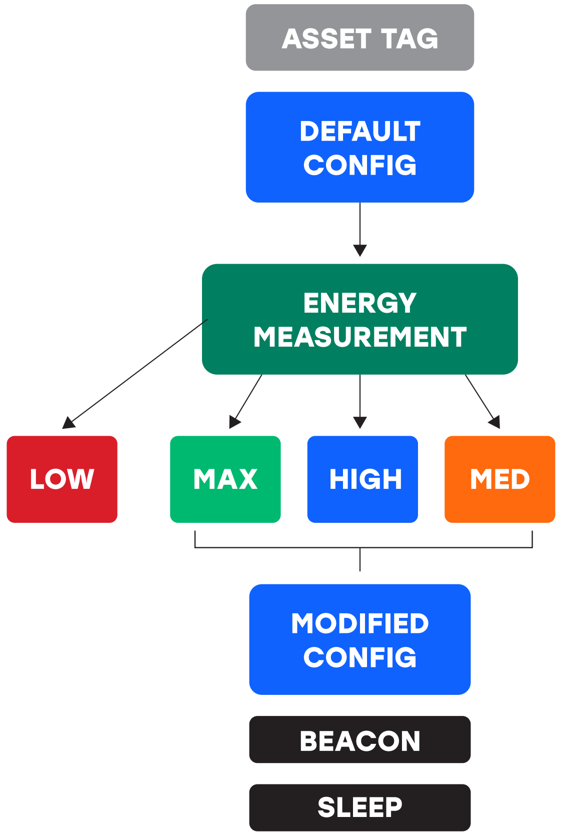
*POWER SAVING mode has the same settings as MIN, but beacons are sent only every second wakeup event.

By default, the tags will operate at their lowest energy mode and increase their behavior when available.

Batteryless tags can operate for extended periods without energy—an advantage in the field, but a challenge for demos. To address this, two pushbuttons are included:

- **Discharge Button:** Drains the storage element to trigger dynamic mode transitions and simulate power depletion.
- **Beacon Button:** Forces a beacon transmission, making tag activity visible in the reader GUI.

These features enable practical demonstration of energy-aware behavior.



GETTING STARTED

Energy Harvesting with Silicon Labs xG22E

Designing an IoT SoC for ultra-low power requires rethinking the platform from the ground up. Based on analysis of Ambient IoT use cases and customer input, key requirements emerged—especially for devices like asset tags and sensors that spend most of their life in deep sleep or shut-off states.

Batteryless devices store harvested energy, but it depletes over time. Intelligent devices can monitor available energy and adjust beacon intervals, sleep duration, transmission PHY, and payload to extend operation. At the core, however, efficient cold-start and wake-up are essential.

EFR32xG22E – key specifications

The xG22E is of course a derivative of the xG22 family of SoCs – offering support for Bluetooth and 802.15.4 protocols, including Zigbee Green Power.

Figure 16: : xG22E IC

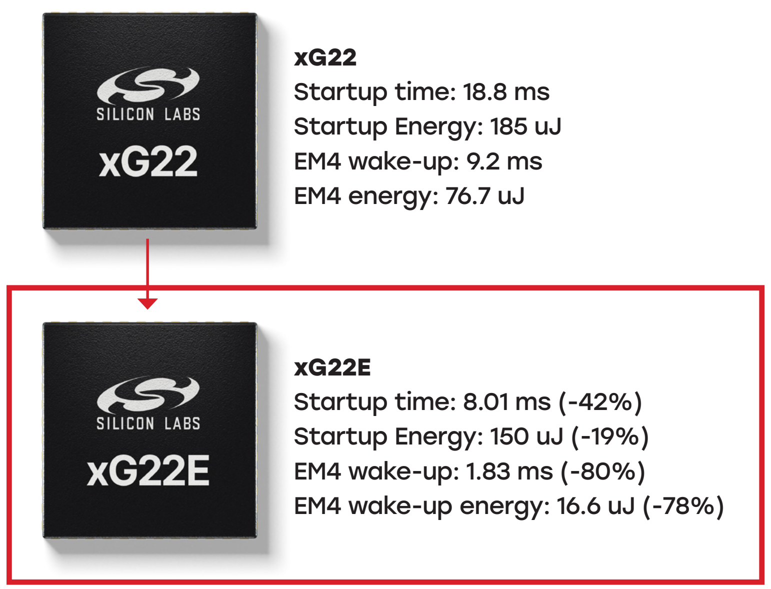
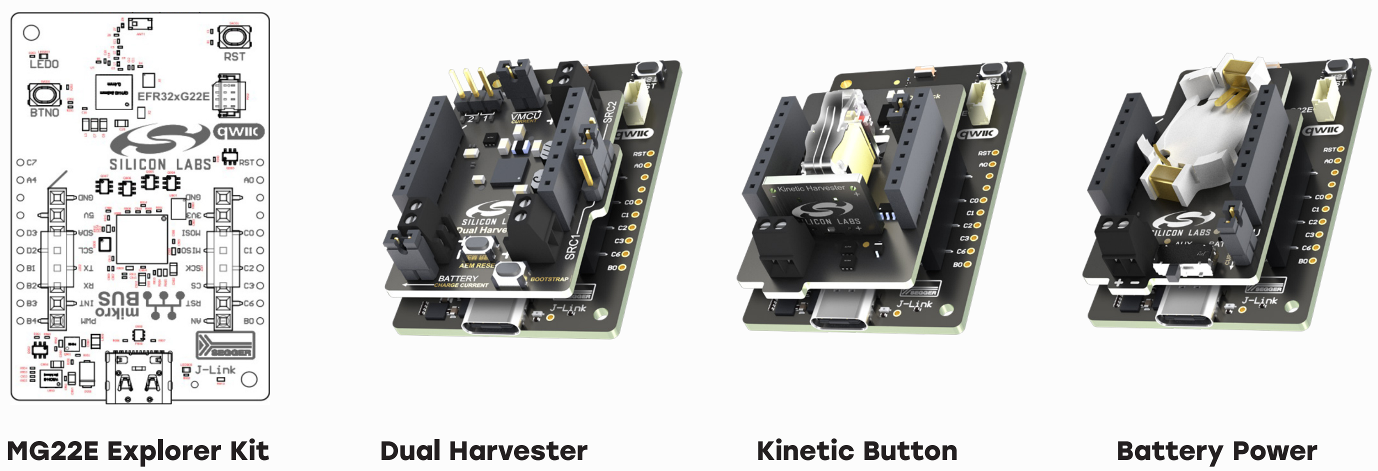


Figure 17: : xG22E specs

Optimized for connection-less applications, the EFRxG22E family of SoC eliminates the time-consuming and energy-intensive Secure Boot verifications process. Furthermore, to support capacitor-based designs, sleep mode transitions have been refined to minimize in-rush currents and voltage spikes.

Energy Harvesting Explorer Evaluation Kit (EH EVK) shields

To support Ambient IoT development, Silicon Labs has partnered with energy harvesting PMIC leader e-peas to create hardware shields and example software applications for the [MG22E Explorer Kits](). These kits accommodate both trickle and transient energy sources—AC and DC—and support a range of IoT protocols.



More about these kits can be found **Learn More**

Figure 18: MG22E Explorer Shields EK8200A

The shield kit provides a flexible platform for experimenting with multiple energy sources. With e-peas PMIC drivers, users can configure applications to suit specific needs. The first shield enables users to connect a coin cell battery to the Explorer kit and perform test-point measurements. The second shield is designed for kinetic button-push energy applications. The third shield is designed for continued development with a variety of energy sources. The kit includes AC/DC regulators, a sample PV cell, a kinetic switch, and capacitor storage for comprehensive prototyping.

Example	Protocol	Device Type
Energy Harvesting Sensor	Bluetooth LE	Sensor
Energy Harvesting Sensor	Bluetooth RAIL	Sensor
Energy Harvesting Sensor	Zigbee Green Power	Sensor
Energy Harvesting Switch	Zigbee Green Power	Switch
Energy Harvesting Switch	Bluetooth RAIL	Switch
Energy Harvesting Observer	Bluetooth LE	Reader

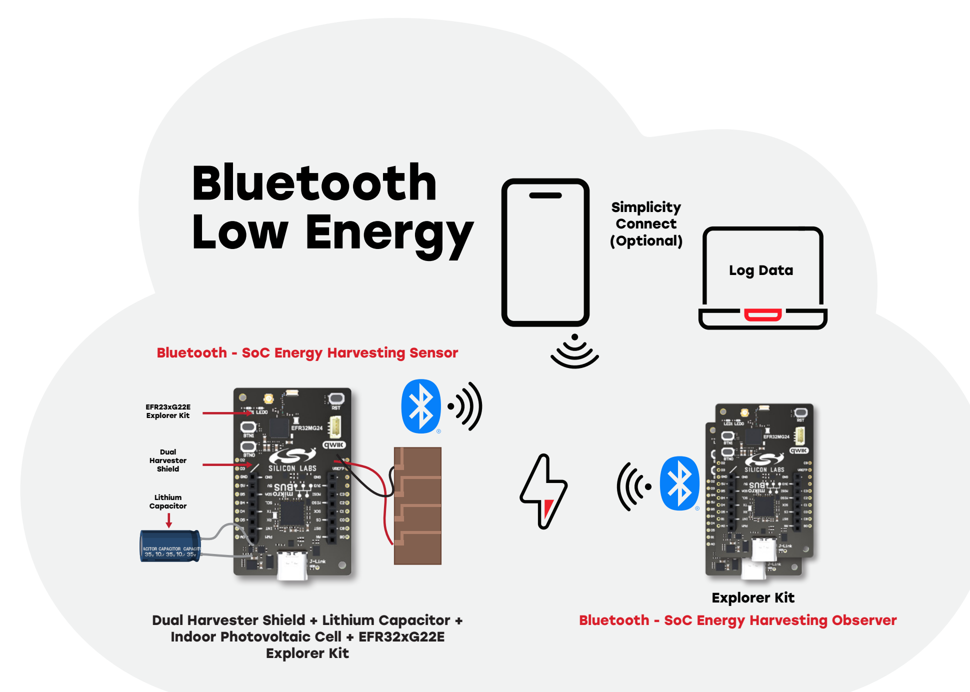


Figure 19: EH EVK User Experience

CONCLUSION

Ambient IoT represents a transformative shift in connected device design, enabling maintenance-free, sustainable operation through energy harvesting. Silicon Labs' batteryless asset tracking reference designs demonstrate how light and RF energy can be effectively harnessed to power scalable IoT networks without reliance on batteries. By combining innovative hardware, intelligent firmware, and strategic partnerships, these solutions pave the way for the next generation of efficient, adaptable, and environmentally conscious IoT deployments.

ADDITIONAL RESOURCES

Silicon Labs Energy Harvesting Webpage

Energy Harvesting Documentation (docs.silabs.com)
AN 1500

EFR32MG22E + Explorer Kit Shields
xG22E Earth Day Launch

UG 591

Sample Application github repository

Works With & Tech Talks:

Works With 2024: Harnessing Ambient IoT: A Leap Towards Sustainable Connectivity
WorksWith 2024

Works With 2023: IoT Trends
Works With 2023

Works With 2022: Optimize IIoT with Wireless Asset Monitoring
Works With 2022

Works With 2022: Optimize IIoT with Wireless Asset Monitoring
Works With 2024

Press:

Blog

BTSIG / NovelBits

Partner web resources:

E-peas

Dracula

Energous

Qoitech

Mouser

Tenxer

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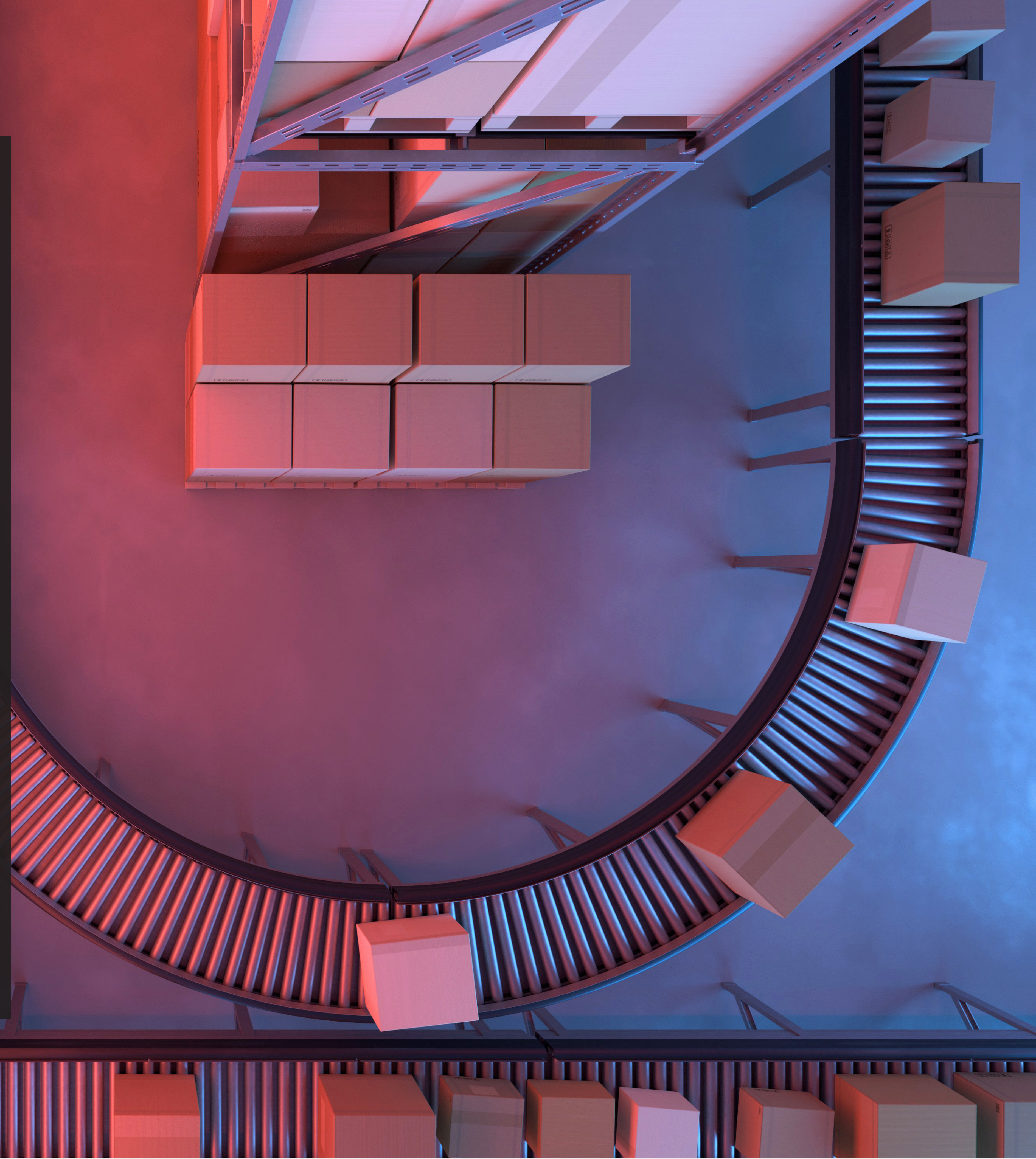

Silicon Labs

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