

By

In collaboration with



RF + PV: Powering Next-Generation Smart Tags with Dual Energy Harvesting



WHITE PAPER 2026

V1-September 2026. This is a first release of this white paper. An evolved version will follow in the coming months.

The global RFID tag market, projected to reach USD 14.95 billion in 2025, is expected to reach USD 39.11 billion¹ by 2035. With the cost of a passive RFID tag running between \$0.03 and \$0.04, this represents an incredible number of tags. However, passive RFID tags are extremely limited in their capabilities. They rely on nearby reader infrastructure for activation and often require human or robotic intervention. The primary application is spot identification with no real geolocation, no sensing abilities, no battery, and activation at short distances only.

Next-generation smart tags promise to extend beyond the capabilities of passive RFID tags by introducing new features such as continuous periodic sensing (i.e., temperature, moisture, movement, active geolocation) and the ability to use remote read-out infrastructures (i.e., wireless communication such as Bluetooth LE).

The major impediment to enabling smart tags has been power. Power ultimately determines a device's capabilities, how often it can perform its own activity, and at what frequency and distance it can share the data it collects.

Recent advances in **energy harvesting technology** have made it possible to bring increased capabilities and intelligence to tags through **Ambient IoT**, where devices power themselves through natural sources without needing traditional batteries and battery replacement.

This whitepaper will discuss how to power smart tags without the use of disposable batteries by harvesting local sources of energy. In addition, it will explore how the use of dual energy harvesting technologies, such as RF and organic photovoltaic (OPV), together can bridge energy gaps caused by environmental conditions. In this way, OEMs can provide the consistent and reliable access to energy next-generation smart tags need including asset tracking, smart factory, smart building, and many others in unpredictable environments.

¹ RFID Tags Market Size, Share & Global Forecast 2026-2035", SnS Insider



Disposable Batteries: Not an Option

Very low-cost, near-field RFID tags are passive. This means they harvest energy from an RFID reader in local proximity to power the tag, typically in the range of tens of meters. In a few milliseconds, the antenna can collect enough energy for the RFID tag to broadcast its unique ID to the reader.

The primary downside of a passive tag is that the tag is powered down except when it is being read. For example, the tag on a cargo container is often read when it is loaded on a ship and when it is removed. However, the tag will be inactive during the entire journey unless someone goes through the ship's hold with a portable reader, which is practically unfeasible considering the container stacking.

An RFID tag can be made active and support smart functions by pairing it with a power storage source like a battery. However, a battery is a limited energy resource, so active tags must conserve power by minimizing transmission frequency and range to avoid quickly draining available battery life. This ultimately constrains how useful a smart tag can be. Batteries also substantially increase the cost, weight, and size of a tag.

Perhaps the most important consideration is that batteries are not logistically feasible at scale. Batteries have a limited lifetime, and once they are depleted, they must be replaced. As such, battery replacement is simply too expensive and unsustainable in terms of battery cost, replacement, and disposal when there are thousands to millions of tags to maintain. In addition, the need to replace batteries limits where tags can be deployed as a person needs to be able to physically reach them.

Ambient IoT: Energy Harvesting

Ambient IoT is an approach to IoT where devices employ energy harvesting technology to power themselves from energy within their environment. Instead of getting all their energy from a limited, disposable battery, devices collect harvested energy in a smaller rechargeable storage cell until it is needed. Since the storage cell is constantly being renewed through energy harvesting, no battery replacement or maintenance is required. The rate at which energy is harvested and the size of the storage cell determines how often a tag can broadcast, how much data can be sent, and how far the tag can be from the reader.

Ambient IoT is proving to be essential for enabling sustainable, cost-effective IoT at scale. Introducing energy harvesting also enables continuous functionality because power is available consistently unlike a passive RFID that can only be active within range of a reader. With access to more power, next-generation smart tags can now support additional functionality such as a sensor plus limited compute.

There are a great many applications for Ambient IoT smart tags. With renewable energy sources such as far-field RF and ambient light, smart tags can be installed nearly anywhere and provide a reliable stream of data. For example, a smart tag with a temperature and humidity sensor could be installed inside a server rack. Without the placement limitations associated with wires and batteries, the smart tag provides an efficient way to accurately and reliably measure the zonal temperature of each server and trigger alerts if environmental thresholds are exceeded.

Dual Energy Harvesting at Scale

While far-field RF provides a significant energy source for harvesting, it has environmental constraints that can limit its use in certain smart factory and smart building applications. As the distance to the RF source varies, so does the energy that can be harvested, which can limit efficacy in some applications where smart tags are mobile.

RF networks are also vulnerable to environmental factors such as metal shielding and RF contention that can lead to interrupted operation. For example, a pallet of metal components moved to a new location can cause interference and obstruct an RF source from reaching a particular smart tag, creating a temporary 'blind spot'. As long as the obstruction remains, the smart tag will have reduced or will have no access to RF harvested energy. Once stored energy has been depleted, the smart tag will be disabled until the obstruction is identified and removed.

Intermittent blind spots and obstructions can directly affect the availability and reliability of smart tags: when smart tags don't have enough energy, they can't do their job. This, in turn, reduces overall visibility of the facility that smart tags are monitoring.

Consider a smart tag that measures the ambient temperature of an asset to make sure it doesn't get too hot and damage the asset. With a far-field RF-only smart tag, the smart tag can only be charged when the RF network is available. Thus, whenever there is interference or obstruction, this represents a potential operational blind spot. For critical assets, such an unpredictable lack of visibility may be unacceptable.

For this and other reasons, RF networks are often estimated to provide 85-90% visibility in simple setups.

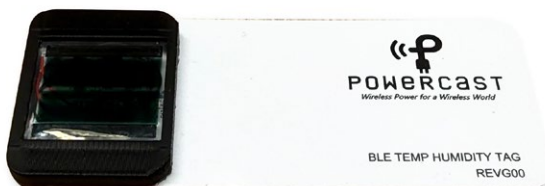
To provide resilience to ever-changing environmental factors, next-generation smart tags can harvest energy from two sources simultaneously: **far-field RF and a second source like photovoltaic (PV)**. A dual energy harvesting approach effectively bridges the energy gap when ambient RF energy is obstructed and not available as the device is still able to harvest energy from a different source that is not obstructed.

Now consider the same smart tag making sure an asset doesn't get too hot. This time the tag is equipped with an RF+PV dual energy harvesting system. This smart tag provides peace of mind by ensuring reliable operation even when RF energy harvesting is unavailable. Because the smart tag has an alternate PV energy source, the smart tag can continue to operate and collect essential sensor data without interruption.

Far-Field RF Energy Harvesting

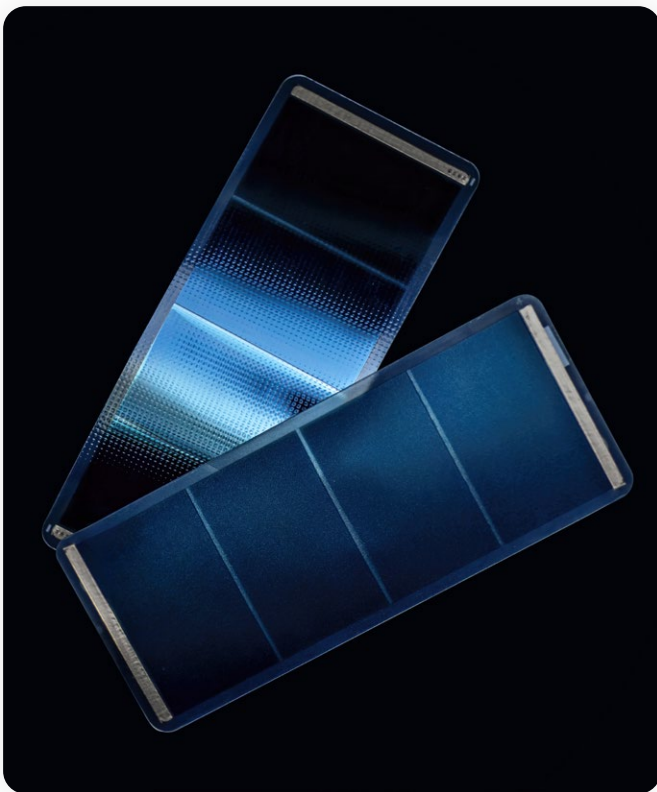
To provide consistent power via far-field RF, smart tags can be powered using an RF power transmitter network. This network comprises RF power transmitters intentionally placed throughout a facility to provide ambient RF energy to power battery-free tags. Data is collected by RFID, gateways, Bluetooth LE, or other wireless communications interfaces.

For example, the Energos PRO and PRO+ Hub are part of an RF power transmissions network that can provide up to hundreds of μ W of power to tags at 10m+ distance in applications like continuous cold chain monitoring, asset tracking, and manufacturing. Similarly, Powercast offers the PowerSpot® and Powercaster® Hubs for various industrial applications such as remote sensors in factories and smart home deployments that provide up to 200mW at close range and μ Ws of power up to a range of over 60 meters.



Organic Photovoltaic Energy Harvesting

Photovoltaic energy harvesting converts available ambient light into a renewable source of energy. Dracula Technologies' Organic Photovoltaic (OPV) technology has been optimized for the low ambient light conditions typical of indoor environments. OPV is highly flexible, providing the specific voltage, determined by the number of parallel OPV cells, and current range, determined by the physical size of the cells, needed for each specific application. For example, a 1.5 cm² OPV module delivers around 65 uW at 3 V in typical indoor LED lighting conditions (1,000 lux). The size of the OPV module can be shrunk or expanded to match the real-world energy needs of a smart tag based on sensing frequency, transmission frequency, transmission range, etc.



With the goal of providing full continuity for embedded sensor networks, dual energy harvesting is designed to bridge gaps between individual sources. As RF energy harvesting is estimated at 85-90% visibility in some applications, adding a complementary energy source like PV energy harvesting can increase visibility for the tag.

Depending on the circumstances of environment and application, PV, naturally, also has its limits. PV harvesting is inherently dependent on the availability, intensity, and consistency of ambient light. Indoor environments can have significant variation in illumination, and tags may experience periods of reduced or no usable light. Consequently, PV

harvesting also introduces its own deployment considerations. Since the amount of energy available to a photovoltaic cell depends on the tag's exposure to ambient light, mounting location, orientation, shading, enclosure design, and changes in lighting conditions can all affect available power.

RF + PV Energy Harvesting

Small-form-factor PV harvesters are particularly well suited to supplying energy gradually over time, but some tag operations can require short bursts of higher power. In these situations, stored energy and a complementary energy source like RF can help bridge the difference between the energy being harvested and the power required by the device. This is why the dual energy source approach is superior. The differences between RF and PV allow them to bridge the potential visibility gaps of the other, creating continuity.

By storing surplus harvested energy, a PV source complements an RF energy source and vice versa to improve smart tag consistent access to energy, offering the following benefits:



Continuous Operation: RF + PV energy harvesting enables continuous and consistent data collection and higher frequency transmission than is possible with a single energy source.



Robustness through Redundancy: Two energy sources provide redundancy when one of the sources becomes temporarily unavailable for some reason.



Improved Reliability: To further improve reliability, a small rechargeable storage element can provide a buffer to ensure smart tags have continuous access to power during longer harvesting interruptions. When energy is plentiful, the storage element is recharged to prepare for the next potential interruption.



Real-Time Monitoring: Because RF + PV energy harvesting can capture energy simultaneously, smart tags can collect data and transmit status more frequently, enabling near real-time monitoring.



Extended Coverage: When the distance between the far-field RF energy source and smart tag increases, the maximum harvested power available drops. This limits how far smart tags can be deployed from the nearest RF source. Therefore, adding a PV energy source as a complementary source to RF is beneficial. Thanks to the PV cell, coverage can be extended by increasing the distance from which a tag can reliably communicate with a reader. Put another way, RF + PV energy harvesting can substantially extend the coverage of each Hub.



Environmental Independence: In many cases, RF + PV smart tags can be deployed relatively independent of the environment, reducing the scope of an RF environmental assessment. This also gives users more freedom and simplicity when placing tags.

Cost

Reducing the cost of tags is important as it determines for which use cases a smart tag is feasible. With higher cost, a single tag/sensor must monitor a large area to be cost-effective. Low-cost tags enable increased sensor density, giving greater data granularity. To succeed, smart tags must be highly integrated to reduce manufacturing cost for applications that require thousands to millions of smart tags. A few factors that positively influence smart tag deployment and usage costs are:



Near-zero maintenance at enterprise scale: Smart tags with dual RF + PV energy harvesting are easy to deploy and require little to no regular maintenance, significantly reducing total cost of ownership.



Reduced RF Network Density: The RF network comprises an infrastructure of RF transmitters. Combining RF and PV energy harvesting effectively extends the coverage of a single transmitter, and so fewer transmitters are needed for complete coverage of a facility.

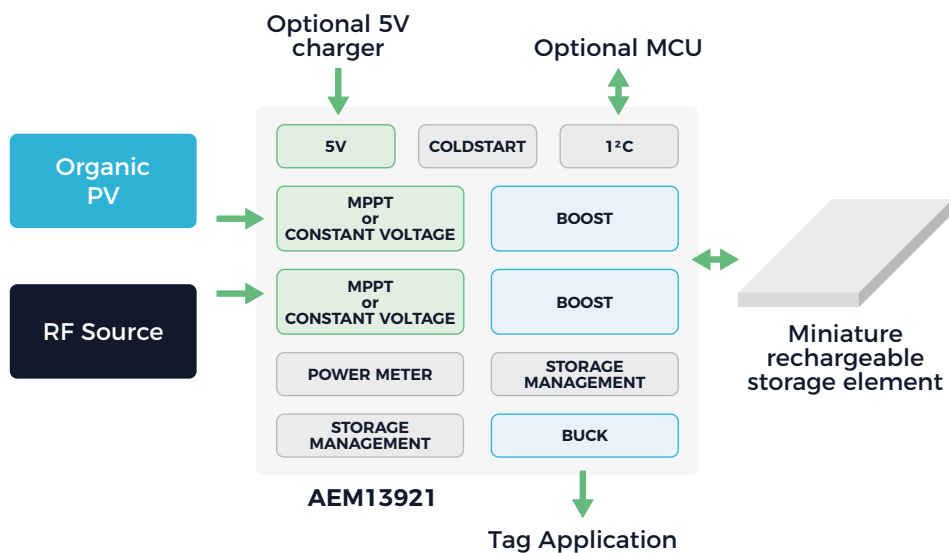


Right-sized: The flexibility of Dracula Technologies' OPV technology enables the OPV module to accurately match the energy requirements of the smart tag. Both the size of the OPV module and overall tag can be tailored to the application to keep cost and size to a minimum. Moreover, energy harvesting allows for a greater variety of use cases to be unlocked that battery-operated devices do not due to their limited capabilities.

Power Management

Harvesting energy from two independent random energy sources requires dedicated power management circuitry to optimize energy capture, storage and usages independent of Ambient conditions .

E-peas' **AEM13921** offers programmable dual input PMIC (Power Management Integrated Circuit) for connecting two independent energy harvesting sources concurrently Because each of the sources have totally different behaviour and electrical characteristics, such PMIC is designed to adapt to the specific configuration of each source. The device can also connect to an optional 5V source for charging from an AC DC wall charger.



Block diagram of a smart RFID tag utilizing dual RF + PV energy harvesting.

As mentioned before, for the RF source Powercast and Energous offer Hubs and antennas, depending upon the application and its requirements. For the PV source, Dracula Technologies offers single-cell and multiple-cell OPV topologies. The size and number of cells change how much energy the cell generates, as does the level of ambient light in the environment.

The benefits of the AEM13921 in such a design include:

- Dual input with two fully independent energy harvesting channels (one for RF energy source, one for OPV)
- Low cold start energy (as low as 1,5uW from any source)
- Can work with either one source or with no-energy from any source when cold started
- Supports a wide range of storage element technologies (Protection included)
- Supports application supply with wide range for load voltage
- Simplifies application design by completely isolating behavior of the RF source, PV source, and storage element from application.

AEM13921 is programmable, such as by setting the maximum power point tracking technics (MPPT) ratio and timing, voltage of the boost converter, to optimize the generation, storage, and utilization of energy of each sources. This results in flexible, intelligent control of energy. The PMIC offers many smart features, including a programmable threshold for metering energy to flag the system if the energy drops below a critical threshold (i.e., suspend non-essential operations while the system charges.) It can also track temperature and trigger alerts to prevent damage to the storage or device.

AEM13921 can be programmed via GPIO or I2C. I2C is useful during development as it provides full visibility into how the overall device functions. With real-time power monitoring, engineers can confirm how much energy is being generated and consumed in real-world operating environments. This enables engineers to verify that the combination of dual energy harvesting sources generates more power than the smart tag consumes over long periods of time, to ensure device services availability and reliable operations. It also enables engineers to evaluate real-time system performance and behavior when energy levels are constant or vary over time (i.e., during periods of reduced ambient light available to harvest). Finally, programming via I2C gives more control overall, such as managing the storage element's temperature, keeping finer control of storage element safety thresholds, wider range of Mppt ratio and MPPT voltages, interrupts on events, etc .

AEM13921 provides excellent conversion efficiency: with a Dracula Technologies 3-cell OPV generating 1.8 V, the AEM13921 operates at 94%+ efficiency.

The Smart Home

The smart home presents different challenges than smart factory or smart building applications. For smart sensors / tags to succeed in the consumer market, they need to get free of the plug. Plugs limit sensor placement and there are cables to deal with. In addition, the charger, connector, and cable add substantial cost to each sensor, pricing them out of the market.

Batteries are not viable either. While a smart home has significantly fewer sensors to maintain, consumers are focused on convenience and consider battery replacement a hassle. On top of that, consumers likely won't remember where they placed all their smart sensors in the first place.

To have consumers comfortably embrace smart tags in their homes, these devices require a foolproof, set-and-forget implementation. Even when the consumer makes a mistake, the tech is often considered at fault. It doesn't take much of an increase in product returns to completely wipe out profit margins.

Thus, ease-of-use is essential, from purchase and setup to deployment and maintenance. Consumers also don't want to have to choose between a multitude of tags. With RF + PV energy harvesting, the same base sensor could be used in hundreds of different ways in the house: light left on, sink leaking, attic too hot, dog out of water, etc. Ultimately, however, for consumers to be willing to buy hundreds of sensors, the cost of each tag needs to be low enough to justify the total. Once more, dual energy harvesting is key to making Ambient IoT possible.

Another home application is low-power consumer electronics devices such as battery-free remote controls, computer mice, and headphones, to name a few. The PV source serves as a voltage source, combined with an RF source that provides the necessary current to power the device. Together, these sources enable functionality that neither energy harvesting technology could easily achieve alone.

Dual energy harvesting is the foundation of enabling smart tags in the smart factory, smart building, and smart home. The dual approach increases the range, frequency, reliability, and visibility of traditional tags and extends what is possible at the edge, enabling a new level of smart functionality with two ways of providing continuous power. Together, RF and PV energy harvesting complement each other to provide the reliable, consistent access to energy necessary to bring affordable real-time monitoring and intelligence to the edge at scale.

To learn more about how RF + PV dual
energy harvesting can bring next-generation
capabilities to your applications, visit:



dracula-technologies.com



energous.com



powercastco.com



e-peas.com