Revision History

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February 14, 2020	0.50	Initial version created.
April 16, 2021	0.51	Updated format, no content change.
June 23, 2021	0.52	Updated Introduction and Photovoltaic (PV) Harvesting sections.

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Introduction

The Atmosic ATM3 series is the first integrated Bluetooth LE SoC with advanced energy harvesting and power management that enables Bluetooth LE solutions to be either battery free or have batteries that last forever. Combining ultra low-power design, integrated RF energy harvesting, and advanced energy management, the ATM3 is capable of capturing energy from a variety of harvesting devices while managing energy usage and storage to either eliminate batteries or optimize battery performance in connected Bluetooth LE products.

The ATM3 can harvest RF energy directly from an RF antenna. In addition, it has a separate input to capture power from other sources, such as photovoltaic (PV), thermal, or mechanical energy harvesters.

This white paper will describe the energy harvesting capabilities of the ATM3 series with information about the four specific types of energy harvesting currently supported. In thinking about the design of a product looking to utilize energy harvesting, one must consider the expected energy consumption and how it matches up to the source availability. For a given source, how much energy will be available and will it be continuous or intermittent? Will the product require continuous operation or only momentary action based storing up a sufficient quantity of harvested energy? These considerations will be explored in this white paper as we cover the energy harvesting capabilities of ATM3.

ATM3 Power Management Unit

The ATM3's integrated Power Management Unit (PMU) is responsible for the dynamic management of energy between the sources (harvesters and storage elements) and sinks (Bluetooth LE system and peripherals). A high level depiction of the PMU in the ATM3 is shown in the Figure 1 below.

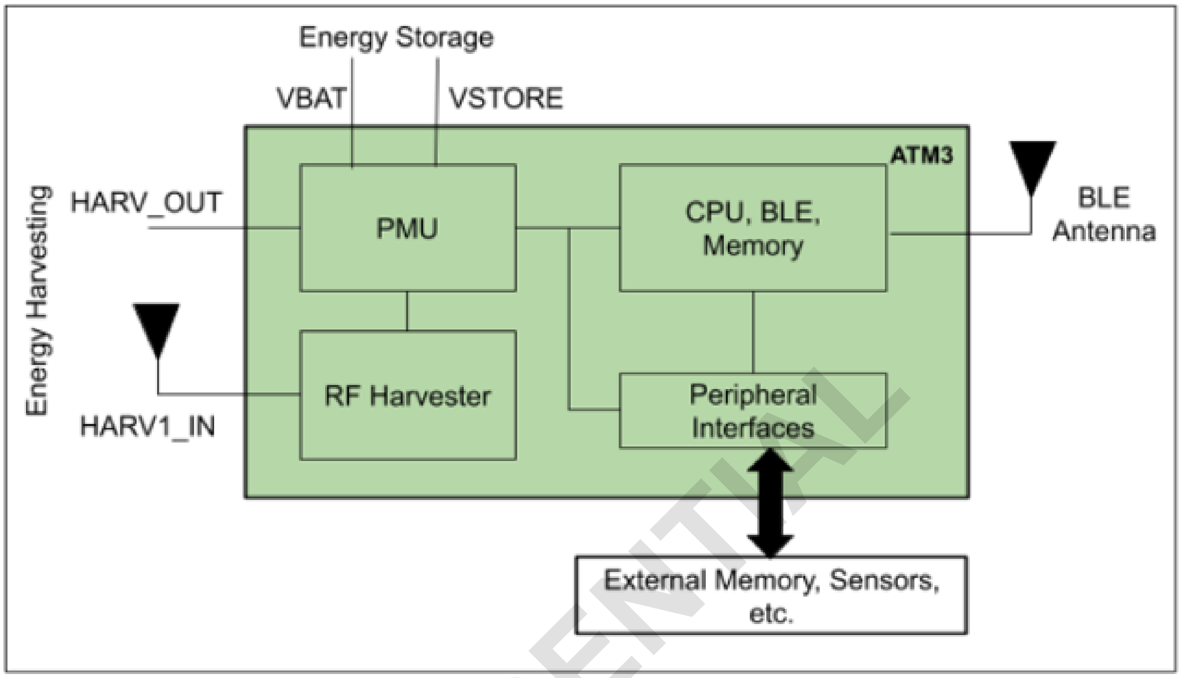

Figure 1 - PMU Energy Harvesting Block Diagram

The PMU manages two harvesting inputs, one from an RF antenna connected to the HARV1_IN pin and another external harvesting source connected to the HARV_OUT pin. Two separate storage connections, VBAT for a battery and VSTORE for a capacitive storage element are potential energy sources for the PMU to draw from. While the VBAT connection is only available as a source to the PMU, the VSTORE connection is also used by the PMU to store excess energy from the harvesting inputs.

In the event that sufficient energy to operate the ATM3 is no longer available, the PMU is capable of suspending operation until sufficient energy becomes available to resume operation.

The PMU settings are configured by the application based on the energy harvesting and storage hardware available. First, we will discuss the supported energy storage options before describing the operation of the PMU for each storage option.

Energy Storage Options

There are three possible energy storage configurations for the PMU: battery free, rechargeable battery, and standard battery with extended life. Factors such as the amount of energy available from harvesting, storage requirements, and the power profile of the application determine the feasibility of one or more of these configurations.

Battery Free

Being able to completely eliminate the battery from a product is only possible when sufficient energy is available through harvesting to meet both the startup and steady state power requirements of the application. In this configuration there is no battery connected to VBAT, so the PMU will rely only on energy harvesting to run the ATM3 and charge a storage capacitor connected to VSTORE when excess energy is available. During periods of insufficient energy harvesting the PMU will operate the ATM3 from the energy available on VSTORE until such time as the VSTORE level drops below a threshold sufficient for Bluetooth LE transmissions. Once this happens the PMU will shut the CPU down until sufficient energy has been harvested to continue operation.

In a battery free configuration sizing of the storage capacitor is an important design consideration. Since the smaller amount charge stored on capacitors and supercapacitors will leak away faster than batteries, it is not possible to guarantee there will be available charge on the capacitor after a significant period without energy harvesting. In this case the PMU will need to charge up the capacitor to the operational threshold level for the ATM3 to start the application. A larger storage capacitor will require a longer time to reach the ATM3's operational threshold, which can be a significant amount of time for a large capacitor when small amounts of energy are being harvested. This will be discussed in more detail when the Cold Start behavior of the PMU is described in a subsequent section.

Rechargeable Battery

Using a rechargeable battery in conjunction with energy harvesting offers the possibility of removing the need to ever change the battery or plug in the device periodically for recharging. Use of rechargeable battery as a storage element is prefered in cases when the harvested energy source may be too intermittent to ensure a capacitor will always have sufficient charge to startup and run the application, or where the startup time requirements do not allow enough time for energy harvesting to charge a capacitor in a battery free configuration. The rechargeable battery is connected to VSTORE through a series resistor for charging when excess harvested energy is available, and to VBAT directly as the power source when harvested energy is not immediately available.

The PMU has the intelligence to manage the re-charging of the battery while also providing power to the rest of the ATM3 as needed by the application. When the PMU is set for rechargeable battery operation there are configurable settings for operational and charging levels that ensure proper operation and protection of the battery.

The PMU is only able to support single and double cell rechargeable batteries up to 3.3 V. Batteries that require a higher voltage for charging (i.e. 4.2 V Lithium Ion) cannot be supported directly by the ATM3. Support for charging at higher voltages requires additional charging hardware external to the ATM3.

Standard Battery

The PMU also supports operation from single or dual cell battery voltages between 1.1 V and 3.3 V in conjunction with energy harvesting.   In this configuration the PMU will use harvested energy to operate the ATM3 and store excess energy to a capacitor connected to VSTORE just as in a battery free configuration. The battery is only used when there is insufficient energy available from VSTORE and energy harvesting. The battery will also cold start the ATM3 immediately instead of waiting for sufficient VSTORE energy as required in battery free designs.

The primary application for using a standard battery with energy harvesting is for battery life extension.

PMU Operation

Booting and operation of the ATM3 requires a specific level of available energy at either VBAT, VSTORE, or HARV_OUT. This section will discuss the conditions and expected operation of the PMU during both the startup phase and under regular operation for each of the energy storage configurations just outlined.

Cold Start

In a battery free configuration the PMU can cold start if the voltage level at HARV_OUT is above 1.65 V and the available input power is at least 30 µW. The PMU will begin to harvest and direct energy to VSTORE until it reaches its operational threshold.

The time it takes for VSTORE to reach this threshold will depend on the size of the capacitor connected to VSTORE and the amount of energy harvested. Figure 2 is a calculation of the time for VSTORE to reach this threshold based on the capacitor size (100, 220, and 400 µF), the rate at which energy is harvested (in µW) and the PMU’s storage efficiency.

As different applications will have different start up time requirements, it is important to understand how the sizing of the storage capacitor and the expected level of harvested energy will impact the behavior of the end product.

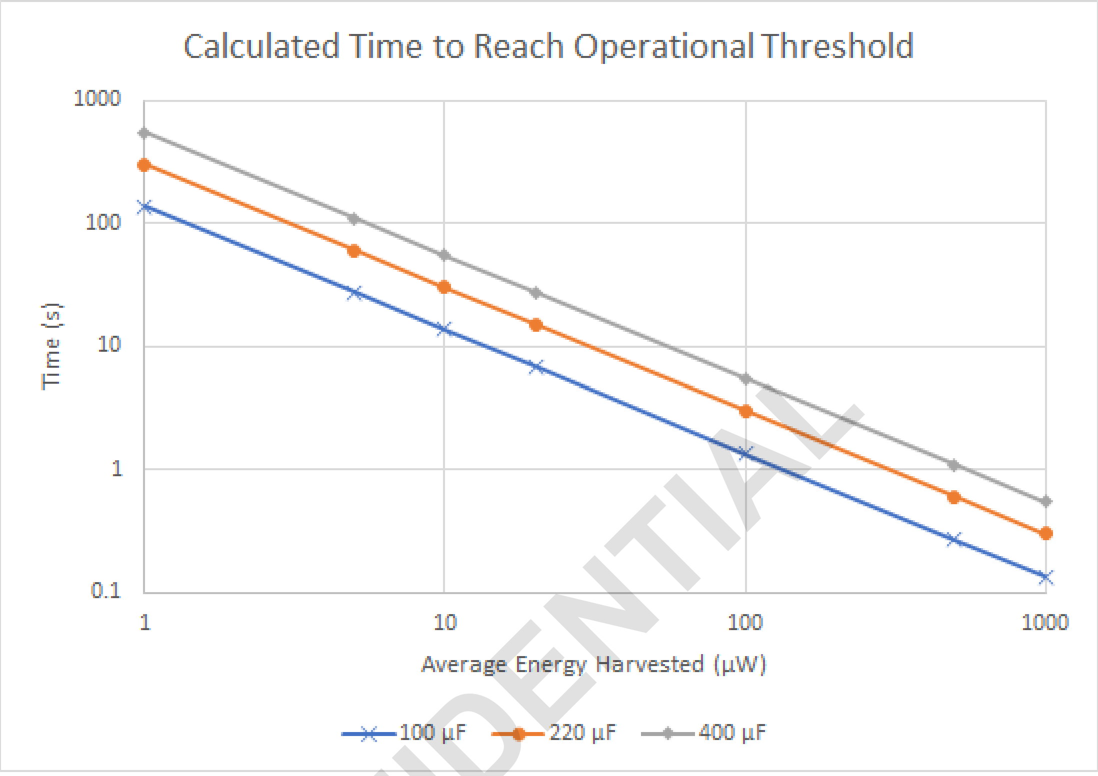

Figure 2 - Time to Reach Operational Threshold

For configurations that include a battery, the PMU will start without any latency or input power requirement provided a source above 1.1 V is available on VBAT. When VBAT is insufficient, the PMU will need some harvested energy to begin operating.

For a non-rechargeable battery, undervoltage on VBAT means the battery is effectively "dead" and the PMU will operate in a battery free mode relying on energy harvesting and any capacitive storage on VSTORE to operate until the battery is replaced. Depending on the application's energy requirements and available energy from harvesting, this may severely limit or even prevent operation of the device.

In a rechargeable battery scenario, the PMU draws from VBAT to cold start the PMU as the VSTORE connection is only used for trickle charging the battery. If VBAT is below the battery's under voltage protection limit, cold start requirement should be met to start PMU operation, like in battery free scenario. If VBAT is below the battery's under voltage protection limit the battery must be recharged by via HARV_OUT or the RF harvester. Note that in this state the rechargeable battery may require a significant amount of time for the battery to recharge to an operational level.

Regular Operation

Once operation has started the PMU will endeavor to meet the power needs of the application while continuing to monitor the levels of VBAT, VSTORE and HARV_OUT.

In battery free configurations energy on HARV_OUT will be used as the primary source to directly supply the load, with any excess energy dynamically stored on VSTORE. When insufficient energy is available on HARV_OUT, VSTORE will be used as a source provided it has available energy.

When a non-rechargeable battery is included in the design it becomes the power source of last resort, so VBAT will be used only when the energy available at HARV_OUT is insufficient and VSTORE has dropped below the minimum level required by the PMU.

When a rechargeable battery is used, the PMU is using VSTORE for charging the battery with excess harvested energy. In this configuration there is no capacity for the PMU to draw energy from VSTORE, only from HARV_OUT and VBAT. Energy on HARV_OUT is used as a primary source with the VBAT connection to the rechargeable battery used when HARV_OUT is insufficient.

Shutdown

The PMU will shutdown execution of the application when insufficient energy is available across VBAT and VSTORE, and HARV_OUT. During this period the PMU will continue to operate and harvest energy until sufficient energy has been restored. If there is not enough harvested energy available at this time, the system may lose power and a cold start would be required again.

Harvesting Source Options

There are four harvesting source options supported for the ATM3: RF, photovoltaic, thermal and mechanical harvestings. The sections that follow will detail the important specifications and considerations when using these methods.

RF Harvesting

The ATM3 harvests RF energy from an external RF antenna. The amount of RF energy that can be harvested depends on a number of factors outlined in this section.

With RF harvesting, it is possible to realize battery free Bluetooth LE products like asset tags and security badges or HID devices like mice and keyboards. RF harvesting can also be used to recharge or extend the life of a battery powered device, like a remote control or electronic shelf label.

RF Energy Transmission

The amount of RF energy available for harvesting at the ATM3 RF harvester's antenna input will depend on the source's transmitter strength, RF frequency, duty cycle, and range to the receiver.

- Source Frequency - The ATM3 supports RF sources between 400 MHz and 2.5 GHz. Preferred frequency bands are the ISM bands at 915 MHz and 2.4 GHz, but other bands can be supported based on local regulatory requirements. Lower frequencies will have less attenuation over the same distance as higher frequencies.
- Source Strength - Regulatory standards dictate the maximum amount of energy that can be transmitted in various frequency bands.
- Duty Cycle - Keeping the RF source on 100% of the time will maximize the energy available, while lower duty cycle transmitters may be required to meet the regulatory requirements or reduce undesired RF interference.
- Range - RF energy decreases with the square of the distance from the source, so the closer the device is to the source the more energy is available.

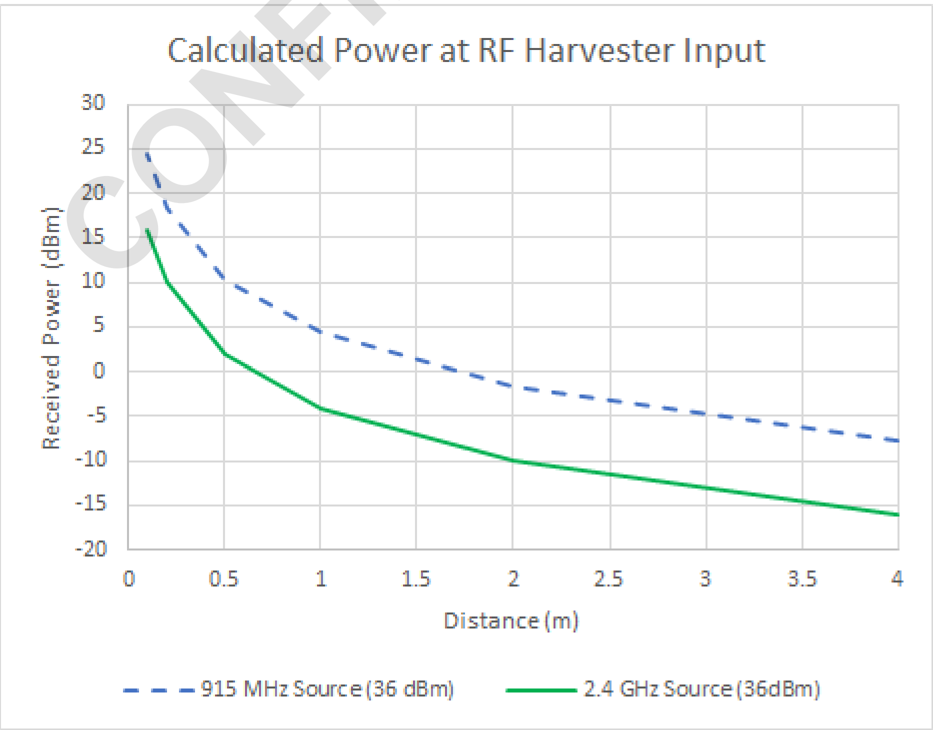

Figure 3 - Power at RF Harvester Input

From a 36 dBm (4 Watt) source, Figure 3 shows the calculated received power vs. distance for both 915 MHz and 2.4 GHz frequencies using the formulas provided in the next section.

ATM3 Energy Harvester

The on-chip RF harvester is capable of harvesting RF inputs between -10 dBm and +9 dBm. The harvester has automatic maximum power point tracking (MPPT) that regulates the activity of the DC/DC converter to optimize the power transfer. For battery free implementations the RF harvester has a minimum cold start input level of -7.5 dBm.

The efficiency of the harvester will be between 30% and 45% over the entire range of 915 MHz input levels subject to the matching network between the antenna and RF harvester input.

Putting all this together, the following formulas may be used to calculate the amount of energy harvested:

$$E_r = E_s - 20\,log\,(\frac{4\,\pi\,d\,f}{c})$$

Where:

E_r = Energy received (dBm)
E_s = Source energy (dBm)
d = distance from source (m)
f = frequency of source (Hz)
c = speed of light (m/s)

This first formula calculates the RF signal strength received at the RF harvester based on the strength of the source, distance, and frequency.

Then, to compute the amount of harvested energy available based on this received RF signal strength the formula used is:

$$E_h = e_h \times D \times 1000 \times 10^{\frac{E_r}{10}}$$

Where:

E_h = Energy harvested (μW)
e_h = RF harvester efficiency (0.30 - 0.45)
D = Duty cycle of RF source

This is a calculation of the energy at the output of the RF harvester. Note that the actual amount of energy available to be used for application execution will depend if the energy is used directly by the PMU or is stored by the PMU in VSTORE. Energy sent directly from the harvester to the PMU will be decreased by the efficiency of the ATM3 DC/DC converter, while energy stored in a capacitor at VSTORE will have an efficiency of 70% vs. energy used immediately.

Photovoltaic (PV) Harvesting

The use of PV cells to power wireless devices has typically required large cell arrays to provide enough operating power at indoor light levels. With the low power consumption of ATM3, it is now possible to reduce the required size of these PV arrays to operate in both indoors and outdoor environments. As will be shown in the example below, an amorphous silicon array of only 1.5 in^2 (~10 cm^2) is sufficient to power the ATM3 at indoor light levels. In an outdoor environment, the required cell size can be much smaller.

Applications like asset tags, remote sensors, locating beacons, and environmental monitors can now operate battery free by leveraging ambient light. Devices with rechargeable batteries like electronic shelf labels or remote controls can now capture enough light energy to effectively have batteries last forever and never require replacement.

PV Cell Specification

When selecting a PV cell it is critical to ensure the parameters of the cell will meet the ATM3's harvester input limits at the light levels expected during operation. Light levels are measured in lux and the table below shows the range of lux levels for typical lighting conditions. See Table 1.

Table 1 - Lux Levels for Typical Lighting Conditions

Lux	Conditions
50-200	Indoors, low-light
300-500	Indoors, typical
500-1000	Indoors, retail lighting
5K - 20K	Outdoors, cloudy
50K - 100K	Outdoors, sunny

PV cells will specify an open circuit voltage and expected voltage and power output at various light levels. Some cells may be specified as indoors or outdoors only and will only be able to operate over a limited range of lux levels.

For designs that are battery free or in cases where a depleted rechargeable battery must be charged prior to operation, the PV cell must have an open circuit voltage of 1.65 V or higher with at least 30 µW of energy to meet the cold start requirement.

Once operating, the PMU regulates the PV input levels between 1.1 V and 1.9 V. There is internal protection up to 3.3 V, but inputs above 3.3 V with 10 mW of power will exceed the limits of the HARV_OUT input.

Actual measured data for a 10 cm^2 PV cell operating at 320 lux is shown in Figure 4 below. At an operating voltage of only 1.5 V the cell produces over 100 µW, more than enough to support a typical beaconing application described later in this document.

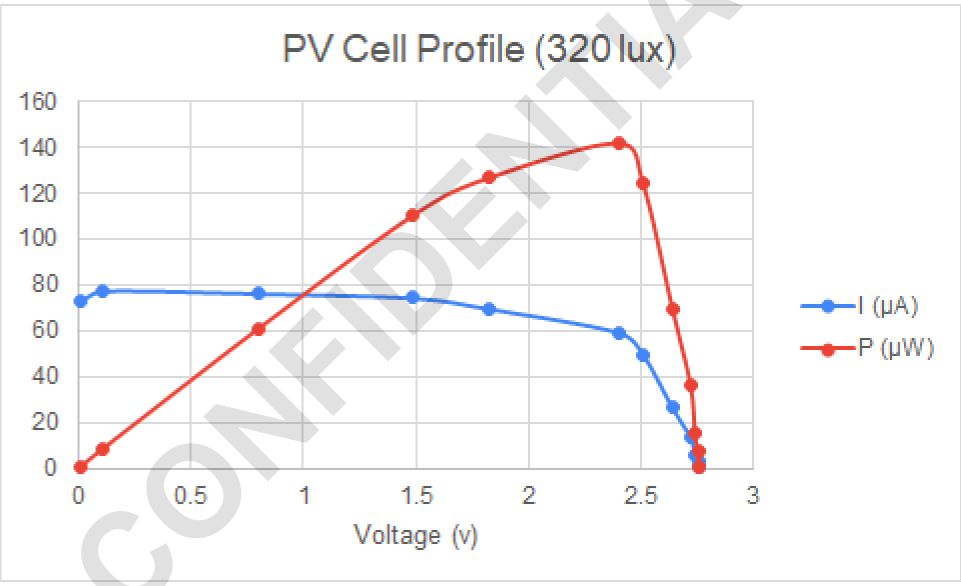

Figure 4 - PV Cell Profile

The PMU does not perform maximum power point tracking on the HARV_OUT input pin, so the voltage regulation level on the input is programmed manually by the software based on the energy profile curve of the cell used.

Thermal Harvesting

The generation of energy based on a thermal gradient between two dissimilar conductors is a well understood phenomena that was first discovered almost 200 years ago. This thermoelectric generator (TEG) technology is capable of generating enough energy from even small temperature differences to power devices like the ATM3.

Thermal harvesting can be considered anytime there is an available heat source or air flow generating a temperature gradient. Heat sources like the human body for consumer and healthcare applications; motors and machines for industrial environments; water and gas pipes; or forced air through a heating and ventilation system in commercial or residential buildings can be harvested to extend or eliminate batteries in sensing, monitoring, and control applications.

Atmosic has partnered with MATRIX Industries to combine the ATM3 with MATRIX's Mercury boost converter to provide a complete thermal energy harvesting solution with TEG. Figure 5 shows a high level depiction of the system.

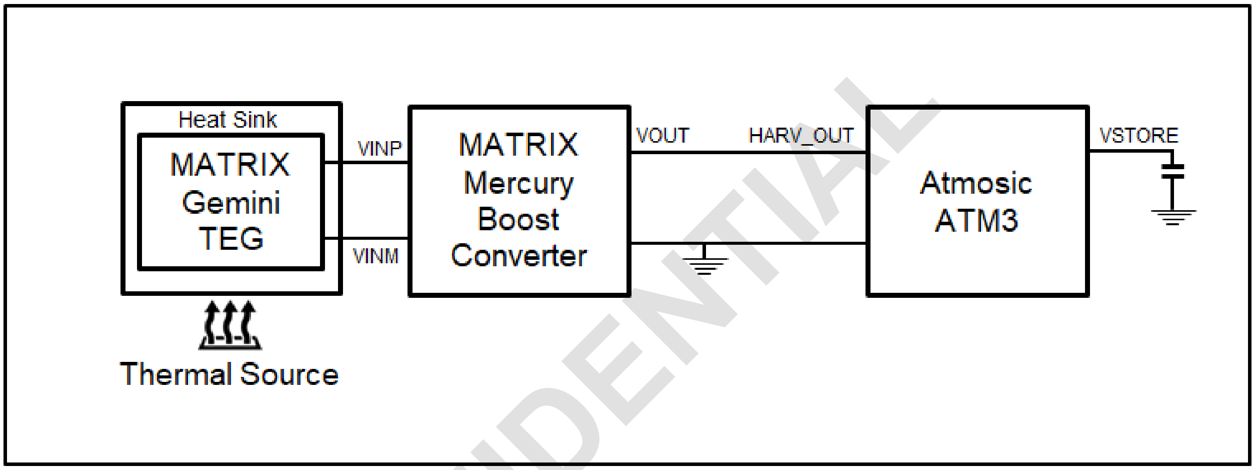

Figure 5 - Thermal Harvesting System Block Diagram

The voltage available directly from the TEG is too low for the ATM3's harvesting input, so the the Mercury boost converter raises the voltage to a level suitable for the HARV_OUT input. All three energy storage options are possible depending on the needs of the application.

The amount of energy produced by the TEG is dependent on the physical size of the harvesting element and heat sink; the temperature delta, and the amount of air flow. The data in Figure 6 is from the MATRIX Gemini module specification, an 18mm x 18mm TEG attached to a heat sink operating at 25 ^{o}C.

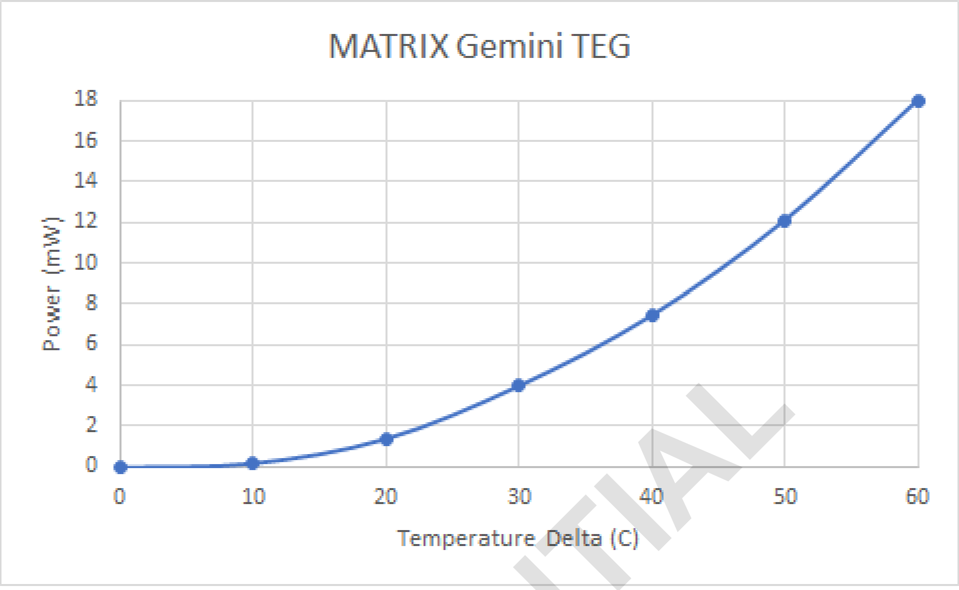

Figure 6 - Thermal Harvesting Temperature v.s. Power

A thermal delta of 20 ºC is sufficient to generate more than 1 mW of energy given a sufficient heat sink or air flow. For smaller temperature differences it may be necessary to use a larger heat sink or take steps to circulate the air across the TEG to increase the harvested power.

Due to the inertia of thermal energy, cold start times for thermally harvested battery free devices can be significant depending on the amount of thermal energy available and the size of the heat sink. Understanding the application's energy requirements and the thermal environment in which the device will be operating is critical to sizing the TEG and heat sink. Working with a company like MATRIX that has extensive thermal and mechanical design expertise will enable fast time-to-market design of a thermal harvesting project.

More information about MATRIX Industries products can be found at www.matrixindustries.com.

Mechanical Harvesting

Mechanical energy harvesting produces energy either based on a single mechanical motion or more continuous motion like the vibration of a motor. This white paper will only cover single mechanical motion harvesting used in battery free switch products for lighting control and home automation applications.

Mechanical energy generators from companies like ZF (AFIG-007 or AFIG-006 - see https://switches-sensors.zf.com/us/product/energy-harvesting-generators/) harvest the energy from the press and release of a switch button to generate 0.3 mJ of energy. The press actuation creates a positive electrical pulse while the release actuation creates a negative pulse. Both pulses are captured directly from the generator into a storage capacitor attached to

VSTORE through a full wave rectifier and zener diode. For this type of energy harvesting it is not necessary to use the HARV_OUT input since the pulse of energy is directly captured by the storage capacitor.

The stored energy is used to signal the state of the switch via Bluetooth LE advertisements. Detection of the actual switch state or the press and release event requires also connecting the switch signal to a GPIO on the ATM3.

Application software defines the number of beacons to be sent per button press so that it can be reliably received. In this battery-free implementation, a button press triggers the transmission of Bluetooth LE beacons.

Other mechanical energy sources such as vibration can also be considered.

ATM3 Energy Requirements

Finally, we address the question: “How much power is required to run an application on the ATM3”. The answer depends on a number of factors, including the type of application running (beacon advertisements only, connected, etc.), if the application is running on-chip or from external flash, as well as other sensors or devices used.

The benchmark power consumption number is for a once per second scannable and connectable beacon running from ROM with no peripherals or external memory. In this configuration the ATM3 consumes on average 7.5 µA at 3 V (22.5 µW).

To get a better idea of the lower bounds of power consumption, please refer to Atmosic white paper that covers the lower power modes in much more detail.

More advanced applications beyond a Bluetooth LE beacon may require running from external flash. This will increase the power consumption depending on the application as well as how it is accessing other devices and sensors off-chip. To get the best possible information about the energy consumption Atmosic recommends prototyping using the ATM3 Evaluation Kit. Contact your Atmosic sales representative for additional information.

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