Perovskite Solar Module Enabled IoT Asset Tracking for Wildlife Conservation

Vivek Babu 1, Rosinda Fuentes Pineda 1, Maciej Bizan 1, Adrian Wojak 1, Szymon Wierzowiecki 1, João Henrique D. B. Gervásio 1, Jakub Szklarz 1, Luigi Angelo Castriotta 2, and Aldo Di Carlo 1

1Affiliation not available
2University of Rome Tor Vergata

December 7, 2023

Abstract

Perovskite technology has shown impressive improvement in the last decade. Here, the first GPS-perovskite-powered application is showcased by integrating flexible perovskite modules (fPSMs) onto an animal tracking collar for powering the IoT device that monitors wildlife bison to preserve the species and its habitat. A prototype of a solar-powered collar was designed to be more optimal for monitoring ample wildlife than commercially available asset-tracking devices, so it can provide necessary data to successfully introduce bison to new habitats. The fPSM were fabricated on a plastic substrate and connected in series configuration to generate power of 400 mW. A robust packaging with polycarbonate sheets and mechanical rivets was realized to withstand harsh environmental conditions, validated by conducting scratch and bending tests. The electronics and software system were optimized for ultra-low power mode operation, consuming only 1.9 mWh, which is 200 times less than the energy generated by our modules. The packaged modules in the outdoor testing setup retained over 30 % of their initial PCE and power after 350 days (8400 hours), giving still 60 times more power than necessary over ~1 year of operational condition.
Perovskite Solar Module Enabled IoT Asset Tracking for Wildlife Conservation

Vivek Babu1,2, Rosinda Fuentes Pineda1, Maciej Bizan1, Adrian Wójcik1, Szymon Wierzowiecki1, João Gervásio1, Jakub Szklarz1, Luigi Angelo Castriotta2,*, Aldo Di Carlo2,3

Perovskite technology has shown impressive improvement in the last decade. Here, the first GPS-perovskite-powered application is showcased by integrating flexible perovskite modules (fPSMs) onto an animal tracking collar for powering the IoT device that monitors wildlife bison to preserve the species and its habitat. A prototype of a solar-powered collar was designed to be more optimal for monitoring ample wildlife than commercially available asset-tracking devices, so it can provide necessary data to successfully introduce bison to new habitats. The fPSM were fabricated on a plastic substrate and connected in series configuration to generate power of 400 mW. A robust packaging with polycarbonate sheets and mechanical rivets was realized to withstand harsh environmental conditions, validated by conducting scratch and bending tests. The electronics and software system were optimized for ultra-low power mode operation, consuming only 1.9 mWh, which is 200 times less than the energy generated by our modules. The packaged modules in the outdoor testing setup retained over 30% of their initial PCE and power after 350 days (8400 hours), giving still 60 times more power than necessary over ~1 year of operational condition.

Index Terms—Perovskite Solar Module, IoT Tracking, Electronic Devices

I. INTRODUCTION

European bison (Bison bonasus Linnaeus, 1758) is the largest herbivore in Europe1. The species undoubtedly had an essential role in the formation of the prehistoric European broad-leaf forest and forested steppe ecosystems. A recent review from WWF indicates that the density of European bison in Ukraine needs to be improved, and an action plan was executed to reallocate the bison from Poland to the Chernobyl Exclusion Zone, Ukraine through the coming ten years (WWF Ukraine, 2020).1. Reintroduction and captive breeding are very important in preserving the species, and it serves to maintain its genetic purity2. Animal tracking is essential to studying the behavior of wild animals concerning their natural environment. The gathered information can be utilized to analyze and design effective strategies to protect the endangered species and ecosystem, such as planning the construction works in the forestry or learning about their habitat during each season3. Developing the technology requires tight collaborative work between engineers and wildlife conservationists. For instance, choosing the size and weight of electronic components, the design of the tracking system, and the mounting method have a strong implication on the type of animal and its natural behavior. It is also essential to consider the habitat the animals are living in. The harsh environmental conditions require an environmentally friendly, water-resistant, low-power, and wireless system.

With the development of IoT technology, several companies are working on such solutions. Table 1 shows the product specifications of some commercially available systems. Among all the technologies mentioned, the tracking collar uses silicon-based solar cells for energy harvesting. Although they are dominant in the PV industry, they have a few drawbacks, such as poor performance in shadow regions and non-compatible with highly flexible plastic foils. One of the primary requirements for wildlife animal tracking collars is

<table>
<thead>
<tr>
<th>Device</th>
<th>Company</th>
<th>Solar Cell</th>
<th>Battery</th>
<th>Weight</th>
<th>Size in mm (W x L x H)</th>
<th>Lifespan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Argos/ GPS 17g Telemetry</td>
<td>Microwa ve (Silicon-Based)</td>
<td>Yes</td>
<td>17 g</td>
<td>63 x 17 x 17</td>
<td>3 years</td>
<td></td>
</tr>
<tr>
<td>Pinpoint VHF Solar</td>
<td>Lotek</td>
<td>Silicon-Based</td>
<td>Yes</td>
<td>6 – 16 g</td>
<td>40 x 18 x 11</td>
<td>6 months</td>
</tr>
<tr>
<td>Geotrack</td>
<td>Silicon-Based</td>
<td>Yes</td>
<td>22 g</td>
<td>62 x 21 x 16</td>
<td>3 years</td>
<td></td>
</tr>
<tr>
<td>Telsonics</td>
<td>No</td>
<td>140 g</td>
<td>82 x 35 x 34</td>
<td>1.5 years</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The authors acknowledge the Worldwide Fund for Nature (WWF) Ukraine (local partner), the WWF Poland, and the West Pomeranian Nature Society on the implementation of the initiative "Perovskite Solar Module Enabled IoT Asset Tracking for Wildlife Conservation" under the Challenge Fund: Polish Solutions for SDGs.

1Saule Technologies, Wrocław Technology Park, 11 Dunska, Wrocław, 54-427, Poland
2CHOSE (Centre for Hybrid and Organic Solar Energy), Department of Electronic Engineering, University of Rome “Tor Vergata”, 00133, Rome, Italy
3ISM-CNR, Istituto di Struttura della Materia, Consiglio Nazionale delle Ricerche, Rome, 00133, Italy

*Corresponding author luigi.angelo.castriotta@uniroma2.it
excellent performance under low light conditions, as most animals like to spend their time in the shaded region.

Perovskite is well known for its high efficiency under one sun illumination. Interestingly, due to its fundamental properties, it also functions well in low light environments such as cloudy weather and early morning or late evening⁴. For operation under those conditions, it is vital to control the surface defects that suppress the non-radiative recombination centers. Recently, Xiilai He et al. performed a holistic passivation strategy to reduce the trap states on the surface, and the bulk of the perovskite layer leads to a record efficiency of 40.1% under 301 μW/cm²². This was possible by introducing a tiny amount of Guanidinium (GA) into the perovskite film for a 2D FAgAPbI₄ perovskite that passivates the grain boundaries and is later treated by CH3O-PeABr, which mitigates the charge recombination at the interface.

However, perovskite can readily degrade in exposure to harsh weather conditions, and limited research has addressed the stability concerns on a module level. Nevertheless, a consensus on testing the PSC reliability between multiple research groups working on perovskite technology was established in 2020⁶. In the community, a tendency is to replace the most used MAPI based perovskite with more stable FA-based, Cs-based, or multi-cation-based perovskites to achieve better stability⁷,⁸. Alternatively, the perovskite crystals with 2D,1D, or 0D structures are considered promising candidates to improve stability⁹. These well-established strategies could work to a certain extent. Ultimately, we need to find a robust encapsulation strategy to integrate the perovskite modules into a tracking collar for wildlife applications.

Here, we discuss the strategies implemented to develop the perovskite-powered animal tracking collar. The modules were fabricated with the n-i-p architecture developed during the stability study and were measured under different sun intensities. Robust packaging was developed and tested under operational and mechanical stress conditions. We designed the PCBs equipped with environmental sensors and a GPS tracking module. The LoRaWAN (long-range wide-area network) communication protocol was utilized to transfer data between the collars and gateways. For the project implementation, Saule Technologies cooperated with WWF Ukraine (local partner), WWF Poland, and West Pomeranian Nature Society on the initiative "Perovskite Solar Module Enabled IoT Asset Tracking for Wildlife Conservation" under the Challenge Fund: Polish Solutions for SDGs. As part of the final project implementation, we captured one male bison named "Adam" on 26/02/2021 and one female bison named "Ewa" on 27/02/2021 and collared our solar-powered tracking system.

**Perovskite Solar Panel**

We fabricated perovskite solar modules to power up the animal tracking system using a specific module design, a carbon printed electrode and a systematic encapsulation procedure starting from our previous works⁸,¹⁰. The modules were fabricated on plastic foil following the n-i-p device architecture; PET/ITO/SnO2/Perovskite/PTAA/Carbon, as shown in Figure a. By using this device stack, we can fabricate modules entirely through solution processing, making it ideal for low-cost and high-throughput manufacturing. For the ETL, we blade coated SnO2 solution forming a thickness around 30 nm. Next, the perovskite was deposited with a composition of Cs0.17FA0.83PbI2.7Br0.3 to form a uniform layer. For HTL, we blade coated PTAA on top of the perovskite layer to efficiently extract holes. For the interlayer connections, we performed P1 (removal of ITO) and P2 (removal of SnO2/Perovskite/PTAA stack) by laser processing. Finally, the carbon electrode was screen printed with P3 on top of the device stack. The modules were designed by having 5 cells connected in series to provide a 5V to power the IoT system (picture shown in Figure a). The external contacts were realized by applying conductive busbars to both terminals.

![Figure 1](image)

**Fig. 1.** (a) Picture of perovskite module with 5 cells connected in series; (b) the n-i-p device stack used for module fabrication; (c) JV characteristics of the module measured at different light intensities.

**TABLE II**

<table>
<thead>
<tr>
<th>Sample code [W m⁻²]</th>
<th>PCE [%]</th>
<th>FF [%]</th>
<th>Voc [V]</th>
<th>Pmax [mW]</th>
<th>Jsc [mA cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>6.170</td>
<td>51.1</td>
<td>4.61</td>
<td>89.2</td>
<td>10.9</td>
</tr>
<tr>
<td>404</td>
<td>6.43</td>
<td>50.8</td>
<td>4.44</td>
<td>45.0</td>
<td>5.75</td>
</tr>
<tr>
<td>285</td>
<td>5.96</td>
<td>48.7</td>
<td>4.40</td>
<td>29.4</td>
<td>3.96</td>
</tr>
<tr>
<td>137</td>
<td>6.24</td>
<td>50.6</td>
<td>4.32</td>
<td>14.8</td>
<td>1.96</td>
</tr>
<tr>
<td>69</td>
<td>5.83</td>
<td>49.8</td>
<td>4.24</td>
<td>10.2</td>
<td>1.40</td>
</tr>
<tr>
<td>45</td>
<td>6.19</td>
<td>45.5</td>
<td>4.08</td>
<td>4.83</td>
<td>0.75</td>
</tr>
<tr>
<td>23.4</td>
<td>11.7</td>
<td>51.4</td>
<td>4.08</td>
<td>4.75</td>
<td>0.65</td>
</tr>
<tr>
<td>15</td>
<td>4.24</td>
<td>37.6</td>
<td>3.62</td>
<td>1.10</td>
<td>0.23</td>
</tr>
<tr>
<td>11.7</td>
<td>9.66</td>
<td>47.7</td>
<td>3.83</td>
<td>1.96</td>
<td>0.31</td>
</tr>
<tr>
<td>8.35</td>
<td>6.64</td>
<td>40.8</td>
<td>3.54</td>
<td>0.66</td>
<td>0.19</td>
</tr>
<tr>
<td>3.34</td>
<td>4.36</td>
<td>34.7</td>
<td>2.60</td>
<td>0.28</td>
<td>0.08</td>
</tr>
<tr>
<td>1.67</td>
<td>2.24</td>
<td>30.3</td>
<td>1.78</td>
<td>0.07</td>
<td>0.04</td>
</tr>
</tbody>
</table>

One of the main requirements for a solar-powered animal tracking collar is its low-light efficiency since the bison spend...
their time in shaded regions. Therefore, we measured the performance of a carbon module at different light intensities of 1.67 W/m², 3.34 W/m², 8.35 W/m², 11.7 W/m², 15 W/m², 23.4 W/m², 45 W/m², 69 W/m², 137 W/m², 285 W/m², 404 W/m² and 1000 W/cm². The JV scan of the carbon module at different light intensities is shown in Figure c, with its PV parameters shown in Table. We obtained a maximum PCE of 11.74% at 23.4 W/m² illuminations. The main requirement for the operation of the energy harvesting unit is a minimum VOC of 150 mV, and our module provided a VOC of 1.783 V at the lowest intensity of 1.67 W/m². This is ten times more than the required voltage and ensures the continuous charging of the battery even in shaded regions. For the collar integration, we prepared two module strips containing 4 modules in total that were connected in series calculated with an estimated power of around 400 mW at one sun illumination.

Packaging and enclosure

To date, various encapsulation techniques have been developed, out of which glass-glass lamination is the most used one, particularly in laboratories. However, this approach is very suitable for modules on rigid substrates and is incompatible with flexible applications. Since we need to integrate our flexible perovskite modules onto the curved collar surface, we used materials that are bendable, flexible, and robust for the packaging. During our collaborative meetings with WWF experts, we gained substantial knowledge on bison’s habitat and how aggressive they behave in nature. Therefore, it was necessary to have robust protective packaging for the flexible module stripes. The packaging was realized with a primary lamination followed by a secondary lamination and mechanical rivets that provide additional strength.

Mechanical and aging tests

Ensuring the efficiency and long-term performance of solar modules is crucial, especially when they are deployed in challenging environments. To achieve this, it is essential to assess the durability and resilience of these modules under different wear and tear scenarios. The unique conditions of some natural habitats make this evaluation even more critical. For instance, bison habitats with their rugged terrains and specific environmental factors offer an interesting case study to investigate these modules' performance. Following the module fabrication and packaging, we performed different aging experiments, such as the scratch, bending, and operational tests, considering the harsh living habitat of bison. For the scratch test, we used sandpapers of different types, such as P320, P202, and P40, representing the grit sizes, 46 µm, 70 µm, and 425 µm, respectively. Figure 3a shows the images of solar modules before and after scratching with different sandpapers. Consecutively, we measured the JV curves of the module stripes (4 modules in series) Figure 3b. We observed no drop in performance for the modules after scratching, which shows no optical losses with the scratches on the transparent polycarbonate sheets. However, when we put dirt on top of the module, it dropped the PCE (red arrow) due to the drop in JSC, which can be explained by partial shading of the active area. Further, it regained the PCE after removing the dirt (green arrow).

The primary lamination process was similar to the UV curable roll-to-roll lamination technique that we utilized while developing four-terminal all-perovskite tandem solar modules on flexible substrates (Figure 2). The module was sandwiched between two high ultra-barriers: Figure 2a shows the picture of the perovskite carbon module after the lamination process. For the secondary packaging, we attached the carbon side of the laminated module to the collar belt via applying silicone adhesive (Figure 2b) and the PET side of the module to the polycarbonate sheet by double-sided tape. We selected 1 mm thick polycarbonate as the cover material to provide mechanical protection without compromising flexibility. Besides the mechanical protection, polycarbonate is transparent, allowing sunlight to reach the perovskite module for harvesting energy. Finally, we used mechanical rivets to pack the whole stack together, which provides excellent (Figure 2c). Figure 2d shows the picture of a packaged module attached to the collar belt and the laminate stack.

![Fig. 2. (a) Picture of the perovskite carbon module after the UV curable lamination process; (b) Picture of applying silicone adhesive to the barrier foil to attach to the collar belt; (c) Picture of the module after complete lamination and (d) schematics of the laminated stack.](image-url)
The flexibility of the modules needs to be tested to ensure the long-lasting performance of the collar. To evaluate, we did mechanical bending tests on the modules with primary packaging. The modules were bent to a radius of 2.5 cm diameter from a flat position and repeated over several cycles. Figure 1c shows the data points of PCE, FF, VOC, and JSC plotted by measuring the JV curve every 200 cycles under the solar simulator. We observed an initial 10 % drop in PCE during the first 500 cycles and was stable over 3000 cycles. Finally, we monitored the PCE evolution of module stripe under operational conditions. We utilized the outdoor station with MPPT developed at Saule technologies. The initial PCE of the module was 7.12 % and retained almost 70 % after monitoring for 350 days, as shown in Figure d. These mechanical and aging tests demonstrate the survival possibilities of our packaging during harsh operational conditions.

**Printed circuit board design**

Wildlife tracking requires devices that are precise and efficient, especially in challenging terrains. With the advancement in technology, the approach to designing and integrating these devices has evolved for optimal performance. One of the crucial components is the Printed Circuit Board (PCB) design, which serves as the backbone of the tracking system. The PCB needs to be compact yet powerful enough to accommodate all the essential functionalities required for comprehensive tracking. The basic requirements we considered were the sensors that can measure the humidity and temperature, an accelerometer to measure the movements, and a GPS receiver to acquire the exact position of the animal. The PCB was designed with several electronic components such as an RF module for receiving and transmitting data, an ultra-low-power microcontroller to govern a specific operation in an embedded system, a Global Navigation Satellite System (GNSS) standalone module to precisely track the position of the animal tracker, a memory chip to store data's collected, an energy management module to efficiently transfer and store the converted solar energy in rechargeable battery. The PCB design was optimized to a dimension of length x width of 49 mm x 28 mm (Figure 4a) to fit the electronic components compactly inside the enclosure, as shown in Figure 4c.

Out of several communication protocols available, we choose LoRaWAN, a low power wide area networking protocol designed to wirelessly connect “things” to the internet in a regional or global network. This was best suited for our project, as it was hard to find a cellular network coverage for LTE or GSM connection in Ukraine forestry or require high power in case of satellite communication systems. We chose the Murata Type ABZ LoRa Module compact with low-power wide-area network (LPWAN) wireless modules that support the LoRAWAN long-range wireless protocol. The LoRA module includes a Semtech SX1276 ultra-long range spread spectrum wireless transceiver and ST Micro STM 32L0 series ARM Cortex M0+32-bit microcontroller (MCU). It is featured with pre-certified radio regulatory approvals for operating in the 868 MHz and 915 MHz industrial, scientific and medical (ISM) spectrum, which was suitable for our implementation in Ukraine. The module has a transmission power +14dBm or +20dBm with a PA boost function for long-range applications.

Further, as the location tracker module, we choose the Teseo-LIV3F module, an easy-to-use GNSS standalone module, working simultaneously on multiple constellations (GPS/Galileo/Glonass/BeiDou/QZSS). Teseo-LIV3F offers superior accuracy due to its onboard 26 MHz temperature...
compensated crystal oscillator (TCXO) and a reduced time to first fix (TTFF) relying upon its dedicated 32 kHz real-time clock (RTC) oscillator. With the embedded 16 Mbit flash, the module offers extra features such as data logging, 7 days of autonomous assisted GNSS, FW reconfigurability, and FW upgrades. Teseo-LIV3F also provides an autonomous assisted GNSS able to predict satellite data based on previous satellite observations. The module has a tracking sensitivity of -163 dBm, which was crucial in the case of implementation in dense forestry. For the GPS fixing (receiving location coordinates), we choose a ceramic antenna from toaglass. The frequency for GPS is in the range of 1575.42 ± 1.023 MHz. The average antenna gain in free space is -1.97 dBi (XZ plane) and -2.07 (YZ plane). The data from the sensors and GPS will be stored in a memory unit before sending it to the cloud. The M95M04 device from STM was used for the memory allocation: electrically erasable programming memories (EEPROMs) organized as 524288 x 8 bits accessed through the SPI bus.

The power generated by the perovskite module needs to be efficiently stored in a rechargeable battery, and we utilized the energy harvesting module from STMicroelectronics (SPV 1050) for this purpose. MPPT technology was used to extract the maximum available power from a PV module under operational conditions. The maximum power of a solar cell could vary with the solar irradiation or the degradation of the device (internal or external). We observed our module's changes to different illumination shown in Error! Reference source not found. and module degradation in Error! Reference source not found.d. Therefore, it is essential to manage the energy instead of connecting directly to the battery.

![Image of buck-boost configuration](image-source: SPV1050 datasheet)

**Fig. 5.** The buck-boost configuration of SPV1050 energy harvesting module is connected to the solar cell and MPP tracking configuration, and the red rectangle as the ladder resistors used.

Error! Reference source not found.). Thus, setting the voltage at IN_HV to \( V_{\text{mpp}} \) helps to extract the maximum energy from the solar cell. However, as we mentioned earlier, the maximum power of a solar cell could vary with the solar irradiation or stability of the device (internal or external). Therefore, it is essential to check if the cell is working at the \( V_{\text{mpp}} \). We activate the circuit connected to the MPP_REF terminal and measure the \( V_{\text{OC}} \) at frequent intervals to perform this action. The time for each measurement is typically 0.3–0.5 sec and is measured at a time interval of 12 – 20 sec. Later, a new MPP voltage is set through the MPP_SET terminal and helps to provide maximum power.

System communication and power budget calculation
After finalizing the hardware components, we shifted our focus towards optimizing the tracker's software capabilities. Using the STM32CubeIDE software development tool, we developed firmware that prioritizes power conservation while maintaining seamless communication (Figure 6). As previously mentioned, we utilized the LoRaWAN communication protocol with the EU863-870 frequency plan that uses a channel range from 868 – 868.6 MHz in Ukraine. Figure 6a displays the block diagram of each event involving GPS fixing and LoRa communication. Upon cold start, the RTC timer wakes up the microcontroller from sleep mode and attempts to fix the GPS position. If successful, the location coordinates are saved in the EEPROM memory chip. Meanwhile, the temperature and humidity sensors monitor the

---

**Babu et al.** Perovskite Solar Module Enabled IoT Asset Tracking for Wildlife Conservation
environment and store the data in EEPROM. The microcontroller retrieves the latest data from EEPROM and sends it to the gateway once connected. The cycle then repeats, sending the remaining stored data in memory. After sending all the data points, it enters sleep mode by updating the RTC event.

The data received by the gateway was later transmitted to the cloud by using a cellular internet connection. The gateway system was purchased from RAKwireless Technologies Co., Ltd., which is Class A and C compliant, designed for harsh outdoor conditions. The system comes with a LoRa antenna transmitting power of 27dBm (max) and receiver sensitivity of -142dBm (min). It also included one LTE antenna for a cellular internet connection to the cloud server. To avoid damage to the gateway, especially in the windy season, we designed and machined mounting brackets to hold it firmly. The system was powered by connecting the Ethernet cable to the PoE port in the PoE injector and the other end to the 220V AC supply.

The gateways use Semtech UDP packet forwarder to forward the data points to services operating on the cloud server. The cloud server hosts Chirpstack open-source LoRaWan network server stack, which handles the tasks connected with the management of the devices, i.e., de-duplication of received frames, authentication, handling join-request of the devices, encryption of application payloads. We integrated the Postgresql database with the application server, allowing easy storage, sharing, and data access while maintaining high-security levels. The exemplary architecture of the Chirpstack network stack is shown in Figure 6b. The database provides Grafana’s open-source service, enabling flexible visualizations of forms from multiple data sources. Worldmap Panel by Grafana Labs plugin was used to plot the data points on the map.

Further, we calculated the energy budget for the tracking system based on the requirement from WWF, which is collecting data points every hour. As detailed in Table 3, the energy required for tasks such as operating the microcontroller, fixing the GPS, and the Lora transmission is approximately 1910 µWh. We used a rechargeable Li-ion battery with a capacity of 8.25 Wh for storage. With this configuration, the collar can collect 4319 data points on battery power alone, resulting in a collar lifespan of around 0.5 years. Our perovskite solar module stripe can produce 400 mWh under optimal sun illumination, which is 200 times more than the energy required for one operational cycle. The lifetime with solar panels varies on different factors such as the exposure to sunlight, the habitat of bison in which area it is spending more time, and any damage it can be caused. With rough estimation, we expect the tracking collar lifetime to be over ten years, which is enormous considering the lifetime of products available in the current market. Even with an 50% drop in the solar panel’s power generation performance, the tracker remains functional. However, the limiting factor in this tracker is the lifetime of the Li-ion battery, which generally spans 2-3 years under typical usage patterns. Looking towards the horizon, a promising solution to extend the tracker’s lifespan lies in transitioning from Li-ion batteries to supercapacitors. These components not only offer longer lifespans but also present opportunities to enhance the overall energy efficiency of the tracking system.

### Table III

<table>
<thead>
<tr>
<th>Description</th>
<th>Energy Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-low power mode for 1 hour</td>
<td>140 µW × 1h = 140 µWh</td>
</tr>
<tr>
<td>GPS fixing (-30 sec)</td>
<td>210 mW × (30 sec)/(3600 sec) = 1750 µWh</td>
</tr>
<tr>
<td>Lora data transmission (SF10)</td>
<td>72 mW (1 sec)/(3600 sec) = 20 µWh</td>
</tr>
<tr>
<td>Total energy required per cycle</td>
<td>140 µWh + 1750 µWh + 20 µWh = 1910 µWh</td>
</tr>
<tr>
<td>Battery capacity</td>
<td>One battery of 8.25 Wh = 8250000 µWh</td>
</tr>
<tr>
<td>Total data points</td>
<td>(8250000 µWh)/(1910 µWh) = 4319 points</td>
</tr>
<tr>
<td>The lifetime of the collar without solar panels</td>
<td>4319/24 = 180 days = 0.5 years</td>
</tr>
</tbody>
</table>

**Tracking collar implementation and data collection**

The final challenge was to find the right bison population to track and understand their habitat. We visited three different forestry in Ukraine and decided to implement the project in the forestry under Styr Hunting Enterprise. The bison population in forestry consists of around 80 bison moving around 18000 hectares with a total area of 48642 hectares. Approximately 50 animals stay as one herd during the winter, and in the summer, certain males join the breeding stock. In 2012, the 'fresh blood' influx had a positive effect on the group’s well-being, demonstrating a higher growth rate among the domestic subpopulations.
Tracking collar for monitoring the European bison in Ukraine. In summary, we have developed a perovskite fabricated of the collar, respectively. of members involved in the project and the final design and rivets was realized to withstand the harsh environmental conditions, validated by performing scratch and bending tests. The packaged modules in the outdoor testing setup retained over 30% of their initial PCE after 350 days. The electronics and software system were optimized for an ultralow-power mode operation (1.9 mWh), which was 200 times less than the energy generated by our modules. With rough estimation, we expect the tracking collar to operate for over ten years, which is enormous considering the lifetime of products available in the current market. Furthermore, the tracking collars were successfully integrated into the European bison in Ukraine during the unprecedented pandemic times.

During the visit to Ukraine, we analyzed the forestry for a perfect spot to install the gateways. Figure 4a shows the picture of a project member mounting the gateway in the forestry building, supplied with LTE internet and electrical connection for the gateways. We planned to install three gateways at three different locations forming a triangular shape with maximum coverage over the area, as shown in Figure 4b. The red dot marked on the map shows the exact locations with coordinates such as Gateway in Administrative building - 50.138018, 24.956821, Gateway in Velyn - 50.071286, 24.979260 and Gateway in Forestry building - 50.105376, 25.053107. The LoRa communication system claims to have a transmission range between 10 – 15 km in open space. Nevertheless, considering being in the dense forest, we anticipate a range between a 3 – 5 km radius. Winter is an excellent time to capture bison as they will be in search of food. We planned our strategy to attract Bisons close to the desired location by feeding them artificially. The bison were fed by cut corn plants and seeds for one month before the date of immobilization. We successfully captured one male bison named ”Adam” on 26/02/2021 and one female bison named ”Ewa” on 27/02/2021 and collared our solar-powered tracking system (Figure 7f). The location coordinates from the Bisons were displayed in the graphing user interface, shown as green dots in Figure 7c. We believe our solution will support the studies made by WWF on wildlife conservation. Tracking the bison will help to understand the habitat it lives in and the food they prefer during each season. Additionally, it helps manage general forestry infrastructure and track and prevent poaching activities in the field. Figure 7d and 7e show pictures of members involved in the project and the final design and fabrication of the collar, respectively.

Conclusion
In summary, we have developed a perovskite-powered animal tracking collar for monitoring the European bison in Ukraine.

References