Energy Harvesting and Storage Solutions for Low-Power IoT Devices in Livestock Industry

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***Abstract*—The Internet of Things (IoT) holds immense potential for enhancing livestock productivity, driven by the increasing affordability, miniaturization, and computational capabilities of electronic devices. Achieving energy autonomy is critical for developing IoT applications in the livestock industry. This paper explores a range of energy harvesting and storage technologies tailored for low-power IoT devices in livestock applications, addressing current challenges and limitations. Examining technologies such as smart cattle waterers (waterers with the ability to self-sense their water level), virtual fences (animal-born devices capable of applying stimuli to delimit a confinement area), and animal behavior monitoring devices, we provide insights into the selection criteria for energy harvesting and storage. Additionally, the paper discusses specific study cases within the livestock industry, illustrating the practical application of the reviewed technologies and offering valuable considerations for the device development process.**

***Index Terms*—Energy harvesting, Batteries, Super-capacitors, Embedded systems, Internet of Things**

I. Introduction

Currently, there are approximately 31 billion Internet of Things (IoT) devices in the world, and it is estimated that by the year 2050, this figure will grow to 170 billion [1]. IoT devices will have a significant role in the future, so any effort to maximize their efficiency and reduce their environmental impact will be of great help for future generations.

One of the sectors exhibiting substantial potential for advancement through the implementation of this technology is the agriculture industry [2] [3]. Although there is a great diversity of heterogeneous activities in this industry, such as livestock farming, apiculture, vegetable farming, and other agricultural pursuits, most of them are generally carried out in remote places, with little accessibility and few human resources. For this reason, IoT devices represent a great opportunity to improve productivity, being able to remotely monitor different variables that are crucial for the management of establishments, such as, for example, crop conditions (nutrients and soil humidity, temperature, size, presence of pests, etc.) or animal activities and supplies (geographical location, movement, temperature, weight, water level in drinkers, voltage level in electrical wiring, quality and height of pastures, among others). By monitoring production it will be possible to improve food quality and animal well-being, taking actions on time, such as applying fertilizers or other treatments to crops, or providing assistance to animals in need of water or a better quality of food.

One of the main challenges presented by the development of this type of remote sensors, along with communication and the cost of the equipment, is the need to have high energy autonomy and a longer useful life that justifies the long-term investment [4]–[6]. In many cases, primary batteries with sufficient capacity could offer a reliable power source for the device's entire lifespan, necessitating careful consideration of size and specifications. When energy from a primary battery is insufficient, energy harvesting systems can provide a sustainable, potentially limitless power supply. However, the latter demands intricate engineering for efficiency. The choice depends on specific application needs, environmental factors, and design goals.

Regarding the equipment autonomy, there are three key factors at play: operational power consumption (generally sensing, processing, communication, and sleep mode), energy harvesting capacity, and energy storage capability. One of the primary determinants of the equipment's lifespan is the battery, as noted in prior research [7]. Even in the case of rechargeable batteries, their capacity gradually diminishes over time as charge-discharge cycles increase. Furthermore, in certain applications such as portable livestock devices, size and weight are crucial factors for the project's viability.

This work aims to address the study of different energy storage and energy harvesting technologies, which enable the operation of these devices in agriculture applications. As we will explain in the next section, we will focus our attention on specific case studies within the livestock industry.

II. Application cases in livestock industry

The livestock industry is a crucial economic activity in the region, with more than 300 million head of cattle in South America, which represents 30 percent worldwide [8]. Extensive livestock farming, where animals walk freely over large territories typically feeding on a wide variety of herbs and pastures that grow without human intervention, presents great benefits both for animal well-being and for the production of higher quality meat [9], [10]. In Latin America, 80 percent of livestock farmers adopt this system, concentrating 75 percent of production in six countries, Brazil, Uruguay, Mexico and Argentina [8]. In this context, there's a tremendous opportunity to develop technologies that can significantly boost productivity in the sector. The management of livestock faces significant logistical challenges, exacerbated by limited information on the condition of the livestock. This lack of data hinders timely decision-making, and the sector also struggles with the scarcity of labor. In this work we will focus on three case studies in which the implementation of such technologies holds the potential for significant improvements.

Firstly, ***animal behavior monitoring devices***, where wearable devices placed on animals predict events such as childbirth, heat, illness or livestock theft [11]–[13]. For example, in sheep farming, high mortality rates in the birth of unassisted lambs increasingly motivate the study of calving prediction systems [12]. Furthermore, combating livestock theft and predator attacks may be achievable by deploying these technologies, if reliable remote detection and action mechanisms are found. The primary challenges lie, on the one hand, in the development of the equipment, with critical considerations regarding weight, size, attachment, and battery life for its feasibility. On the other hand, substantial research is required for processing vast datasets to discern behavioral patterns and specific events.

Secondly, the remote ***monitoring of animal supplies and assets*** such as water levels in drinkers, pasture height, electric fence voltage, or climatological variables like humidity and ambient temperature can help producers avoid large losses of time and money. The equipment used to sense these variables is distinguished from the rest of the cases presented by being fixed in a specific location, facilitating some aspects of implementation.

Finally, ***precision grazing***, applicable in semi-extensive farming systems, is a technique for cattle feeding (typically bovine), in which the accessible grazing area is delimited, generally with electric fences or some other easily moved delimiter. These boundaries are gradually shifted to open up new pastures. This method enables more efficient utilization of available pastures, resulting in a significant increase in productivity. To automate these processes, efforts have been made for several years to develop portable devices capable of generating stimuli that can remotely confine the animal to a specific area, with the ability to modify these boundaries over time. To do this, a brief training period is required, in which the animal learns to interpret these stimuli (typically sound, vibration and small electric shocks) appropriately. We shall refer to this technology as Virtual Fences (VF) [14], [15].

These applications share common constructional elements, all featuring an embedded electronic system based on a microcontroller, low-power communication, an energy supply system, and one or more sensors and actuators. Notably, the design challenges vary among these applications, with some presenting more complex requirements, like weight, size, and energy needs, while others entail relatively straightforward design considerations. Successfully adopting these technologies also requires a low initial investment, easy installation, low operating costs, and considerations for animal welfare, ensuring trusted communications. In the next two sections, we will address the study of different energy storage and harvesting technologies, providing insights and selection criteria essential for the device development process.

III. Energy Storage

In this section, we introduce the main energy storage technologies, including primary and secondary batteries and supercapacitors, that can be used in the targeted applications.

A. Electric batteries

An electric battery is a device made up of electrochemical cells capable of converting stored chemical energy into electrical current by means of a chemical reaction [16]. There are two main types of batteries. On the one hand, primary batteries, characterized by once the reaction has occurred, cannot return to their original state, depleting their ability to store electrical current. They are also known as non-rechargeable batteries. On the other, secondary batteries that can receive an application of electrical energy to restore their original chemical composition, and can be used numerous times before being completely exhausted. They are also known as rechargeable batteries.

Batteries are characterized by their primary constituent chemical elements, its nominal voltage (Vdd), energy density (Wh/Kg and Wh/L), specific power (W/L), the number of charge and discharge cycles they support, operating temperature range, self-discharge rate, security vulnerabilities, environmental impact, cost, among others. Tables I and II provide a comparison featuring some of the primary and secondary batteries currently accessible in the market in terms of the previously mentioned characteristics.

TABLE I
PRIMARY BATTERIES. DATA OBTAINED FROM DATA SHEETS AND MANUFACTURERS' WEBSITES

Chemistry	Nominal Vdd (V)	Wh/kg	Wh/L	Operational life (years)
Zinc–carbon	1.5	40-60	92	3-5
Alkaline	1.5	85-190	250-600	5-10
LiMnO2	3.0	150-330	300-710	5-10
LiFeS2	1.5	297	580-650	15
LiSoCl2 (LS)	3.0	400-700	1200-1400	20+
LiSoCl2 (LSH)	3.0	710	1420	20-40
Zinc–air	1.45	442	1673	3+

TABLE II
SECONDARY BATTERIES. DATA OBTAINED FROM [17], [18], [19], [20]

Chemistry	Nominal Vdd (V)	Wh/kg	Wh/L	Cycles (years)
Lead Acid (Pb-acid)	2.1	30-50	60-90	200-2000
Nickel Cadmium (NiCd)	1.2	30-80	50-150	1000-2000
Nickel-Metal Hydride	1.2	60-120	140-300	180-2000
Lithium NMC	3.6	150-220	500-700	1000-2000
Lithium NCA	3.6	200-260	550	500-1000
Lithium LCO (LiCoO2)	3.6	150-200	400	500-1000
Lithium LFP (LiFePO4)	3.2	90-160	300-350	1000-4000
Lithium LMO (LiMn2O4)	3.7	100-220	350-420	300-700
Lithium LTO (Li2TiO3)	2.4	50-110	177	3000-7000

B. Supercapacitors

Supercapacitors, also known as electrochemical capacitors or ultracapacitors, are energy storage devices that differ from traditional capacitors in several key ways. In contrast to regular capacitors (electrostatic capacitors), supercapacitors exhibit significantly higher specific power and a faster charge-discharge rates. Additionally, they feature a longer cycle life, capable of enduring numerous charge-discharge cycles without significant degradation [21]. Unlike batteries, they have a maintenance-free design and can also operate in a wide range of temperatures, making them suitable for extreme environments.

A supercapacitor can be used as an energy storage device similar to secondary batteries but differs in that supercapacitors are well-suited for applications requiring rapid, high-power bursts, while secondary batteries provide higher specific energy and stable, long-term power output. Additionally, supercapacitors generally have lower energy capacity compared to secondary batteries. Table III compares Specific Energy (Wh/L) and Specific Power (W/L) for the main energy storage elements.

TABLE III
ENERGY STORAGE COMPARISON. DATA OBTAINED FROM [22]

	Specific Energy (Wh/L)	Specific Power W/L
Capacitors	0.01-0.1	10.000-1.000.000
Supercapacitors	0.1-10	1-100.000
Batteries	10-800	1-100

IV. ENERGY HARVESTING

In this section, we will explore various sources of energy harvesting, including electromagnetic energy, piezoelectric devices, thermoelectric modules, and solar panels, with the aim of analyzing their advantages, limitations, and applications in the livestock industry.

Electromagnetic energy harvester devices are a promising technology in the field of energy harvesting. They operate by converting ambient electromagnetic radiation, such as RF signals or other electromagnetic waves, into electrical energy, making them suitable for several IoT applications. These devices are often compact and lightweight, allowing for easy integration into small-scale sensors and wireless nodes, enabling long-term, maintenance-free operation. Despite their potential, electromagnetic energy harvesters for precision agriculture in rural areas face limitations in power output, influenced by the sparse distribution of RF sources, which poses challenges to their effectiveness in generating sufficient power for devices.

Thermoelectric modules harness the Seebeck effect to convert temperature differentials into electrical energy. Their distinct advantage lies in their ability to generate electricity from temperature differences commonly encountered in agricultural and industrial environments, providing a reliable and sustainable power source. Their solid-state and compact nature offers durability and low maintenance, contributing to long-term deployments. However, thermoelectric modules typically exhibit lower energy conversion efficiency than other energy harvesting methods. More significantly, the nature of thermoelectric energy poses a challenge in scenarios like livestock production, where establishing a stable temperature difference can be difficult, whether in the implementation of wearable or implantable devices or in the monitoring of animal supplies and assets.

Piezoelectric modules leverage the piezoelectric effect to convert mechanical vibrations and deformations into electrical energy. Vibrations, motions, or mechanical stress induced by agricultural machinery or even livestock movements can serve as readily available energy sources for IoT devices. These modules are typically robust, compact, and have a long operational life, making them well-suited for deployment in challenging outdoor environments. However, they do have some limitations, particularly related to the relatively low power output and the need for a specific mechanical stimulus to generate electricity. To fully exploit the potential of piezoelectric modules, it is crucial to tailor their design to the targeted agro-industrial application and consider the nature and frequency of mechanical events in the field. Despite these challenges, piezoelectric modules offer an innovative approach to sustainable energy generation in the agro-industry, reducing the reliance on conventional power sources and enhancing the autonomy of IoT devices.

Solar panels are the prevailing choice for energy harvesting, taking advantage of the photovoltaic effect to convert sunlight into electrical energy. They offer a reliable and sustainable power source for IoT devices, especially in remote or off-grid locations, making them suitable for agricultural and livestock environments. Solar panels are recognized for their durability and straightforward installation, establishing them as a preferred option for generating energy in outdoor environments. However, they are subject to limitations, such as reduced efficiency during cloudy or overcast conditions, and the need for proper maintenance to ensure optimal performance. To fully maximize the potential of solar panels, it is essential to consider factors like location, orientation, and weather patterns when deploying them in agro-industrial applications. Nevertheless, solar panels stand as a prominent approach to sustainable energy generation in the agro-industry, contributing to reduced dependence on conventional power sources and enhancing the autonomy of IoT devices. Table IV compares Power (μW/cm^2) and Efficiency (%) for the main energy harvesters elements.

TABLE IV
ENERGY HARVESTERS COMPARISON. DATA OBTAINED FROM [23]

Source	Power (μW/cm^2)	Efficiency (%)
RF signals	0,0002 to 1	19,2-31,2
Thermoelectric	60	5-10
Piezoelectric	10-100	0,5-20
Photovoltaic (indoor)	100-1.000	15-30
Photovoltaic (outdoor)	100.000	15-30

V. DISCUSSION

In this section, we present some design criteria for selecting and sizing energy storage and harvesting components using the mentioned study cases in the livestock industry as examples.

Firstly, it is imperative to understand the requirements of the application and the environment in which the IoT device will be operating. The factors that we consider most relevant are the following. *Location, size and weight limitations*: we need to define if our device is wearable or fixed, and if it has access to sunlight. *Power consumption profile*: average and peaks power. *Data*: amount, transmission frequency and data importance (acceptable data loss over time). *Maintenance service or desired autonomy*: general cleaning, battery recharge or replacement periods.

Regarding energy sources for livestock industry applications, priorities will be placed on ease of implementation and suitability. Therefore, considering the drawbacks mentioned in the previous section, we will narrow down the analysis to solar panels. We are now in a position to select the IoT device power supply, among which we will focus on systems with a primary battery only, a secondary battery only, a secondary battery along with a solar panel, and finally, hybrid adding a supercapacitor.

A. Primary battery vs Secondary Battery only

If we do not have access to sunlight and regular maintenance servicing for recharging batteries is not feasible, primary batteries may serve as a viable solution. Certain primary batteries, such as LS, LSH, and Zinc-air types, exhibit significantly higher energy densities when compared to rechargeable counterparts, nearly doubling it. This implies they could occupy roughly half the volume for an equivalent capacity. Furthermore, these primary batteries may boast a lifespan exceeding 20 years.

Depending on our daily energy consumption, the choice may be more or less evident. For instance, in the case of an ultra-low-power application, such as a device transmitting data once per hour with no other significant power draw, it could operate for nearly 20 years using NB-IoT or up to 30 years with LoRaWAN (SF7), utilizing only a 3000 mAh battery readily available in the market [24]. With these extended autonomy periods, one could consider volume reduction by employing a typical lithium button cell battery like the CR2032, which offers an approximate capacity of 300 mAh, resulting in a 2-year autonomy with NB-IoT and up to 3 years with LoRaWAN (SF7).

In these scenarios, calculating the total battery capacity is straightforward. It is obtained by multiplying the estimated daily power consumption of the application by the desired number of years of autonomy, while it is advisable to leave a margin of between 10 and 20 percent based on the specific application and the chosen battery type (accounting for the battery's self-discharge and efficiency loss due to operation at reduced temperatures).

The higher the application's power consumption and the lower the desired autonomy (or the greater the possibility of maintenance), the more feasible it becomes to opt for a secondary battery and recharge it during maintenance periods. While secondary batteries may occupy more volume than primary ones, they can be considered more environmentally friendly since they generate less waste over time. It is estimated that an alkaline battery can potentially contaminate up to 167000 liters of water, equivalent to a quarter of an Olympic-sized swimming pool [25].

These power supply systems can be a good choice for livestock supplies and assets monitoring applications, since the measurement does not involve large energy consumption, the data volumes are small and they do not need to transmit so frequently. On the other hand, as we will see below, since these devices are fixed in the field and have access to sunlight, one could also opt for a system with rechargeable batteries and a solar panel, being able to use batteries of lower capacity, size, and weight.

B. Secondary battery and Solar Panel

When we have regular access to sunlight, and our desired autonomy ranges from 5 to 10 years, these systems become highly convenient, especially when aiming to design compact and lightweight devices. For sizing both the solar panel and determining the capacity, it is essential to have knowledge of the climatic characteristics of the region, particularly the peak sun hours (PSH) and the monthly average of cloudy or rainy days. In Uruguay, for example, we can consider an annual average of 4 PSH and approximately 7 days of high cloud cover or rain per month [26].

A valid design criterion for determining the total battery capacity is to consider the possibility of a negative streak equivalent to the monthly average of rainy days in the region. The battery capacity should be sized to cover the entirety of this period starting from a full charge. In this manner, we multiply our daily power consumption by the number of days to obtain our desired capacity, being able to add between 10-20 percent to be more conservative. The choice of battery type will depend on the specific characteristics of our application. As seen in Table II, there is a wide variety of options with standout features such as capacity, power, safety and longevity, often at the expense of other properties.

As a general design guideline for sizing the solar panel, we can set a target to generate enough energy during the day to triple the daily energy consumption of the device. For example, if we have 4 PSH, we should select a panel with a power rating such that the energy generated over 4 hours at peak irradiance is equivalent to the consumption of three days of the device's operation. Therefore, starting with a fully discharged battery, if we follow the first design criterion for battery sizing, we can potentially recover 100 percent of the capacity in less than 3 days.

C. Hybrid Systems: Solar Panel, Supercapacitor and Primary Battery

Depending on the capacity of the selected battery, it may be necessary to add a capacitor or supercapacitor in parallel with the battery to assist with peak power demands, such as during transmissions or when sensing or actuating specific peripherals.

VI. Conclusions

The Internet of Things (IoT) holds immense potential for enhancing livestock productivity, where energy autonomy is critical. This paper delved into various energy harvesting and storage technologies designed for low-power IoT devices in livestock settings, tackling existing challenges and limitations. Furthermore, we have examined specific applications within the livestock industry to showcase how these technologies can be practically applied, providing insights into the device development journey.

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