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Feasibility Analysis of an Energy Storage System Without Batteries for Isolated Street Lighting

Atef Silini

Université de Monastir
Ecole Nationale d'Ingénieurs de
Monastir, Laboratoire EMIR,
LR20ES08
Monastir, Tunisia
atefsilini@gmail.com

Zouhour Araoud

Université de Monastir
Ecole Nationale d'Ingénieurs de
Monastir, Laboratoire EMIR,
LR20ES08
Monastir, Tunisia
zouhour.ara@enim.rnu.tn

Pascal Dupuis

IEEE Senior member
LAPLACE UMR 5213,
CNRS-INPT-UT3,
Université Toulouse 3,
Toulouse, France
pascal.dupuis@laplace.univ-tlse.fr

Laurent Canale

IEEE Senior member
LAPLACE UMR 5213,
CNRS-INPT-UT3,
Université Toulouse 3,
Toulouse, France
laurent.canale@laplace.univ-tlse.fr

Abstract— This paper investigates the feasibility of non-battery energy storage systems for isolated street lighting, focusing on mechanical storage technologies such as gravity storage, compressed air energy storage, and flywheels. As the global shift toward renewable energy accelerates, the challenge of intermittency in sources like solar and wind becomes increasingly significant. Traditional batteries, while widely used, present limitations in cost, lifespan, and environmental impact. Mechanical storage systems offer promising alternatives, with potential for greater sustainability and efficiency. Through a detailed analysis and comparison of investment costs, this study evaluates the practicality and effectiveness of these non-battery solutions in providing reliable energy storage for a sustainable future.

Keywords— Renewable energy, energy storage, mechanical storage systems, gravity storage, compressed air energy storage, flywheels, investment cost analysis, sustainable energy solutions.

I. INTRODUCTION

In remote areas, street lighting is commonly powered by solar panels paired with energy storage systems, most often using NiMH batteries [1]. However, achieving more environmentally sustainable solutions in this field calls for exploring alternative energy storage options. Although batteries are widely used, they present notable challenges, including high costs, limited lifespans, and environmental concerns. As a result, there is increasing interest in non-battery energy storage technologies. This study focuses on mechanical storage systems, specifically gravity-based storage, compressed air energy storage, and flywheels. By examining the investment costs and performance of these technologies, the research aims to evaluate their feasibility and potential contribution to a more sustainable energy landscape [2].

II. DIFFERENT ENERGY STORAGE SYSTEMS

Energy storage systems are essential for maintaining the reliability and stability of modern energy grids, especially as the adoption of renewable energy sources continues to grow. These systems are generally classified into two main categories: battery-based storage solutions and alternative

energy storage technologies. Each category has unique strengths, depending on the application and requirements.

A. Battery storage technologies

Battery storage is one of the most versatile and widely adopted forms of energy storage, thanks to its scalability and ability to deliver energy quickly. Below are some key battery technologies:

1. **Lead-Acid Batteries:** Among the oldest battery technologies, lead-acid batteries are prized for their low cost and reliability. They are commonly used in automotive systems, uninterruptible power supplies, and backup power applications. While they offer high surge currents, their low energy density and shorter lifespan limit their suitability for modern, high-demand applications.
2. **Lithium-Ion Batteries:** Lithium-ion batteries dominate the energy storage market, especially in consumer electronics, electric vehicles, and grid storage. These batteries boast high energy density, long cycle life, and fast charging. However, they are costly and come with safety concerns, such as the risk of thermal runaway.
3. **Sodium-Sulfur Batteries:** These high-temperature batteries are designed for large-scale energy storage, relying on chemical reactions between molten sodium and sulfur. They deliver high energy density but require elevated operating temperatures, which can pose safety risks.
4. **Metal-Air Batteries:** Technologies like zinc-air and aluminum-air batteries offer high theoretical energy densities, making them appealing for lightweight applications. However, their limited rechargeability, efficiency, and durability hinder widespread adoption [3].
5. **Nickel-Based Batteries (NiCd, NiMH, NiZn):** Nickel-based batteries, including NiCd, NiMH, and NiZn, are valued for their robustness and ability to function in extreme temperatures. While NiCd batteries face environmental concerns due to cadmium toxicity, NiMH and NiZn provide safer alternatives with enhanced energy density and performance.

6. **Flow Batteries:** Flow batteries, such as vanadium redox flow systems, store energy in liquid electrolytes housed in external tanks. They are well-suited for large-scale and long-duration applications due to their scalability. However, their bulkiness and lower energy densities compared to solid-state batteries are notable trade-offs [4].

B. Other Storage Technologies

Beyond batteries, alternative storage solutions offer unique advantages, particularly for large-scale or long-duration energy needs:

1. **Flywheel Energy Storage:** Flywheels store energy as rotational kinetic energy, allowing for rapid charging and discharging. They are ideal for grid stabilization and other short-duration, high-power applications but have limited energy capacity [5].
2. **Compressed Air Energy Storage (CAES):** CAES systems compress and store air in large underground spaces or tanks, which is later released to power turbines. These systems excel in storing vast amounts of energy for extended periods but require substantial infrastructure and have lower efficiency than other technologies [6].
3. **Gravity Energy Storage:** These systems store energy by lifting a heavy mass to a height, converting electrical energy into gravitational potential energy. When energy is needed, the mass is lowered to drive electricity generation. While highly efficient, gravity storage depends heavily on suitable geographical and infrastructural conditions [7].
4. **Hydrogen Fuel Cells:** Hydrogen fuel cells generate electricity through a chemical reaction between hydrogen and oxygen, emitting only water as a byproduct. These systems are efficient for long-duration storage and transportation but require significant investment in hydrogen production and distribution infrastructure.
5. **Superconducting Magnetic Energy Storage (SMES):** SMES systems use superconducting coils to store energy in a magnetic field, providing rapid response times and high efficiency. However, their dependence on extremely low temperatures and advanced cooling systems limits their broader adoption. [3]
6. **Thermal Energy Storage (TES):** TES systems capture and store heat or cold, which can later be converted into electricity or used directly for heating and cooling applications. These systems are particularly effective in concentrated solar power plants and industrial processes, with efficiency varying based on the storage medium and operating temperatures.

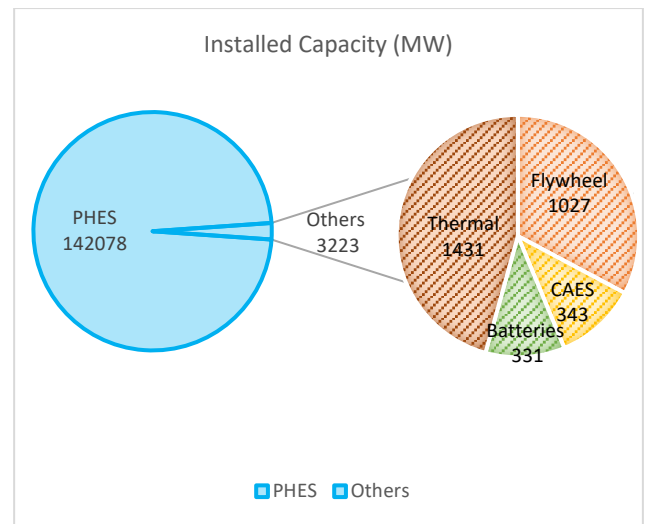


Fig. 1. Global Installed Energy Storage Capacity [8]

Fig. 1 illustrates the global installed capacity for energy storage, measured in megawatts. The chart clearly shows that Pumped Hydro Energy Storage dominates with a substantial capacity of 142,08 MW. In contrast, all other forms of energy storage combined, account for only 3,22 MW. Among these, thermal storage is the largest with 1,43 MW, followed by flywheel systems at 1,03 MW, Compressed Air Energy Storage at 343 MW, and batteries contributing 331 MW. This stark contrast highlights the overwhelming reliance on PHEs compared to other storage technologies on a global scale.

III. CASE STUDY

This case study focuses on the use of solar photovoltaic streetlights for public lighting in areas of Tunisia where the national power grid does not reach all roads. Solar photovoltaic streetlights provide a viable solution to this challenge, especially in rural regions, but their effectiveness is closely tied to the energy storage systems that power them during nighttime hours (Fig. 2).



Fig. 2. Typical photovoltaic solar public lighting (Elinkine, Casamance, Senegal), CC license, public domain, (source: Wikipedia) [9]

Traditionally, batteries have been employed to store energy, yet the harsh climate conditions in Tunisia significantly reduce their lifespan and efficiency. This study explores a comparative analysis between gel batteries and flywheel energy storage systems, aiming to identify the most cost effective and sustainable solution. By enhancing energy efficiency and reducing environmental impact, this analysis seeks to introduce innovative storage technologies into the infrastructure of solar lighting systems.

A. Choice of storage technologies to compare

In this section, we will compare storage solutions using Green Cell gel batteries with a capacity of 110 Ah (12 V, 27.5 A) and the VOSS flywheel from ENERGIESTRO, which has a power of 2 kW and a capacity of 10 kWh. The photovoltaic streetlights have a power consumption of 30 W per LED, and there are 50 streetlights. For the batteries, with a depth of discharge (DOD) of 50% and many cycles, the system provides a backup of approximately one and a half nights, given that the lights are on for 15 hours each night. Similarly, for the flywheels, which need to provide power for 15 hours and have a storage duration of 5 hours per unit, three VOSS flywheels will be installed to meet the storage requirements.

TABLE I. ENERGIESTRO SOLAR STORAGE FLYWHEEL PRODUCTS

Capacity	Discharge time	Diameter (m)	Height (m)	Weight (t)	Power (kW)
10 kWh	5 h	1.3	2.5	6	2
	1 h				10
	15 min				40
20 kWh	5 h	1.6	3.1	12	40
	1 h				20
	15 min				80
50 kWh	5 h	2.2	4,3	30	10
	1 h				50
	15 min				200

The power of the streetlights is 1.5 kW. Therefore, the VOSS model most suited to our needs has a capacity of 10 kWh. To cover the total capacity required for lighting throughout the night, we will need to use a total of 3 units of this model (Table I).

Fig. 3 illustrates the relationship between battery lifespan and temperature, showing that the lifespan of gel, Li-ion, and NiMH batteries significantly decreases as temperatures rise. In Tunisia's climate, where temperatures can exceed 35°C, the lifespan of these batteries is notably shortened. For a project with a duration of 25 years, this reduced lifespan necessitates the replacement of the battery system at least four times, leading to increased investment costs. In contrast, a flywheel energy storage system, which can last up to 30 years, does not require such frequent replacements, offering a more cost-effective and reliable solution over the project's lifetime.

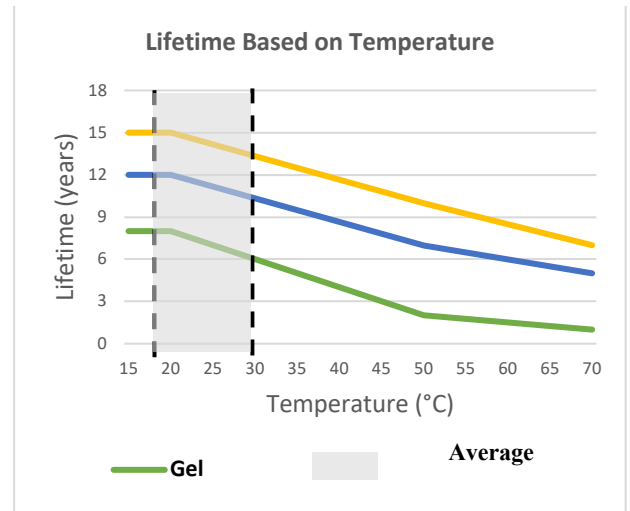


Fig. 3. Average Battery Lifetime Based on Temperature [9]

B. Economic study

In this section, we will estimate the installation costs by comparing the use of batteries with the flywheel energy storage system. In Table II, the battery costs are estimated at 40 k€. However, the actual investment cost in batteries for this project exceeds 100 k€. Indeed, the budget is set in 2024, and the investment is made every 5 years. During this period, the value of money decreases. Therefore, it is necessary to account for this depreciation to make a fair comparison with the flywheel, whose total investment is made on the first day of the project.

TABLE II. INSTALLATION COST OF BATTERIES

	Year	2024	2029	2034	2039	2044	Total
TCAC Growth Rate	4.2%	-	-	-	-	-	-
Battery Price (€)	145	7248	8903	10936	13434	-	40520
Residual Value (€)	10%	0	- 725	- 890	-	-	- 4052
Overall Total							36468
Present Value of Battery Price (€)	10%	7248	14338	28366	56117	-	106068
Discounted Residual Value (€)	-	-	- 450	- 343	- 262	-	- 1255
Storage Cost per Cycle (€/cycle)		0.10	0.12	0.15	0.18	-	-
Total Budget in 2024 (€)							104813

According to Table III, the storage capacity exceeds our needs by 6.6%, which allows for powering 3 streetlights or illuminating 120 meters of road. Indeed, it is not possible to install a capacity lower than our needs (16 kWh instead of 22.5 kWh), so it is necessary to increase the capacity. Table 11 also indicates that the storage cost is very low due to the high number of cycles and the long lifespan of the storage systems, estimated at 30 years.

TABLE III. TABLE OF DIMENSIONS, STORAGE REQUIREMENTS, AND PURCHASE COST OF FLYWHEEL ENERGY STORAGE SYSTEMS

Streetlight Power	1.5 kW
Storage Duration	15 h
Energy Consumed	22.5 kWh
VOSS Power	2 kW
Discharge Duration	5 h
Number of VOSS	3
Units Capacity of One VOSS	10 kWh
Efficiency	80 %
Total Capacity	24 kWh
Cost of VOSS	30 000 €
Maintenance costs (5% per year)	37 500 €
Civil engineering (10%)	3 000 €
Residual value (10%)	3 000 €
Investment cost	67 500 €
Number of Cycles Storage	1E+06
Cost per Cycle	0.06 €/cycle

IV. CONCLUSION

In this feasibility study, we analyzed various electrical energy storage technologies in detail, including battery systems and mechanical systems such as compressed air, gravity storage, and flywheels. Significant limitations of battery systems were identified, including low energy density, inability to meet large-scale energy needs, and high costs. In contrast, mechanical storage emerged as a promising alternative, offering more cost-effective and efficient solutions for a variety of applications. Among the technologies evaluated, three non-battery systems were prioritized: compressed air, gravity storage, and flywheels. Ultimately, our case study selected flywheels for energy storage in public lighting systems.

The study results show that the total project cost of flywheel storage is two-thirds lower than that of battery systems, with the cost per cycle of batteries being ten times higher.

Moreover, flywheels offer significant advantages in terms of technological sustainability and environmental impact, making them particularly suitable for the climatic and economic conditions of hot countries such as Tunisia. By reducing the costs of construction and energy storage, we also lower the costs of photovoltaic solar streetlights. This enables increased investment in research and development to enhance LED quality, improve their energy efficiency, and reduce their environmental impact. Additionally, this paves the way for solutions to address issues such as light pollution and the harmful effects of blue light, contributing to more sustainable and human-friendly lighting systems.

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