Experimental and Theoretical Investigation of Flywheel-based Energy Storage in Off-Grid Power Plants Using Renewables

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Abstract: The objective of this work is to investigate, from both experimental and simulation points of view, the feasibility of a flywheel energy storage system (FESS) for buffering energy when implemented in off-grid (autonomous) electricity production. Toward this aim, a prototype FESS was built and measured to identify its optimal design and operational characteristics as they have been obtained theoretically. After simulating two different materials and shapes for the rotating mass, the hollow aluminum cylindrical design found to provide excellent energy storage results. By identifying the storage capacity of a prototype laboratory-scale FESS, it is also found that such a device can be promoted as a UPS system to cover peak loads during limited time periods. Finally, the scale of the project found to be a crucial parameter for its feasibility. **DOI: 10.1061/(ASCE)EY.1943-7897.0000256.** *© 2014 American Society of Civil Engineers.*

Author keywords: Flywheel; Off-grid hybrid systems; Energy storage; Renewables; Zero emissions.

Introduction

Over the last 20 years that have seen a rapidly increasing world population, electricity demands also have increased due to the industrialization, urbanization, and motorization that are strongly associated with increased energy consumption, which strongly affects fossil fuel access (REN21 2011). The use of renewable energy sources (RESs) seems to be an alternative option, while relative energy technologies have begun to play an important role in the global energy market.

An attractive option toward optimization of global electrification in terms of environmentally friendly solutions is the development of off-grid hybrid electricity production systems (Akella et al. 2007; Sreeraj et al. 2010). Such a hybrid system can be supported by several combinations of different RES-based technologies to produce "green" energy without grid connection to keep its eco-friendly character. Depended on the level of RES involvement on their design, these systems are characterized by zero pollutant emissions and lack of excessive operational and maintenance costs. Such systems are currently established in isolated remote areas for rural electrification where connection to the grid is difficult and expensive (Bekele and Tadesse 2012).

The main drawback characterizing all RES-based autonomous systems is that the environmental energy potential is quite unpredictable since it fluctuates with time and is strongly dependent on local meteorological conditions. Therefore, temporary energy storage (buffering) is crucial for stand-alone RES-based systems to ensure an uninterruptable energy supply (Prodromidis and Coutelieris 2011). The choice of a suitable energy storage unit can be tricky because an optimum system design must maintain its zero emission character, low life-cycle costs, and the longevity of the entire autonomous system.

Besides the well-known electrochemical batteries, which are an adequate solution for autonomous systems (Celik 2002; Peter and Euan 2008), numerous buffering technologies are used in mobile or medium-scale stationary applications, such as hydrogen storage (Clarke et al. 2010), flywheels, super capacitors, and compressed air pumps (Wang et al. 2013). Although electrochemical batteries is the most widespread solution for energy buffering, they also have several drawbacks: limited lifetime compared to that of the entire project, unpredictable fluctuations of their efficiency due to the environmental conditions, and the fact that extra energy is necessary in order to be recycled at the end of their life, which makes the technology less eco-friendly (Shabani and Andrews 2011; Ulleberg et al. 2010).

An attractive alternative for energy storage is the flywheel energy storage system (FESS). Its long lifespan is one of its main advantages, as such a system can be charged and discharged at high rates for many cycles without sacrificing efficiency (Bleijs et al. 2000; Ledjeff 1990; Liu and Jiang 2007). Moreover, a FESS can be connected either to an alternating current (ac) bus, which offers a wide variety of frequencies, or to a direct current (DC) bus, depending on the demands of the established hybrid system to cover the desirable load (Bolund et al. 2007). Flywheels could offer an integrated green technology because their operation does not require chemicals and their raw materials are totally recyclable (Liu and Jiang 2007). However, the drawbacks of this solution include limited storage time since a significant percentage of flywheel stored capacity is wasted due to self-discharge. In optimum operation conditions (magnetic bearings, vacuum-enclosed devices, etc.), these rates are found to be in the range of 0.18–2.0 times the stored capacity per hour (Farret and Simoes 2006). These values are valid for very low friction losses and are significantly higher in real-life scenarios. This phenomenon can be reduced by using state-of-the-art construction materials, such as carbon fibers, or by the combined use of more conventional technologies. However, this does increase the cost of such an installation dramatically; therefore, the combination of different

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technologies prevents a more suitable solution for real-life RES-based systems.

A wide variety of FESSs are encountered in both stationary and mobile applications. Initially, FESSs were used in space applications acting as UPS (Olszewski 1988; Liu and Jiang 2007). Then, such systems were embodied in mobile applications to promote eco-friendly transportation (Tripathy 1992, 1994). Also, the kinetic energy recovery system (KERS) in the F1 world has been developed based on flywheel technology (Boretti 2010). Regarding off-grid, RES-based building-scale applications for energy storage, flywheel systems are in the early stages of development (Arghandeh et al. 2012; Brown and Chvala 2005; Suzuki et al. 2005).

Although their technology is well developed, flywheels have only recently been used as an alternative to electromechanical batteries (EMBs) for intermediate energy storage in off-grid applications (Niiyama et al. 2008). Obviously, the elimination of friction losses is the key criterion to evaluate the efficiency of a flywheel, so the theoretical design of such a FESS (especially the rotating mass) is crucial because the amount of stored energy depends on the spinning rotor, which has an upper speed limit determined by the tensile strength of the material (Bleijs et al. 2000; Liu and Jiang 2007). Finally, for an integrated theoretical design, both the operational parameters and the investment and maintenance costs have to be taken into account. To compare conventional storage technologies (batteries) with novel ones (i.e., flywheels and hydrogen) when used for energy buffering in RES-based stand-alone energy production systems, several simulations in worldwide locations can be found in the literature, while related actual projects have not yet been established for operation under real-life conditions. Thus far, they have been employed only in experimental situations. Prodromidis and Coutelieris (2011) extensively studied the environmental potential of different buffering technologies by selecting four remote areas (islands) and simulating three different off-grid systems (a single photovoltaic, a single wind turbine, and a hybrid photovoltaic-wind system) that are supposed to be installed on each of them, with electrochemical batteries as the main backup energy system. Then the incorporation of a flywheel in such a system throughout the design of an innovative hybrid storage bank was presented by Prodromidis and Coutelieris (2012). The numerous advantages of using flywheel systems as a backup energy storage unit are outlined by the technoeconomic analysis in Kaldellis et al. (2009), which they conducted on the Aegean Islands for different storage systems embodied in RES-based autonomous electrical networks. Based on a real-life scenario, another study (Ichihara et al. 2005) revealed that a flywheel energy storage system, being able to supply up to 10 kW in a wide range of spinning velocities for a relatively long time period, is characterized by reducing friction losses and stable operation. Therefore, it can be integrated into a small-scale, hybrid project as a backup energy system. The specific flywheel with superconducting magnetic bearings was accelerated up to 7,500 revolutions per minute (rpm), with rotation losses of approximately 40 W at these spinning velocities, and the total running time was approximately 6.5 h. The energy supplied was equivalent to 2.24 kWh (Ichihara et al. 2005).

This paper focuses on the design and construction of a laboratory-scale FESS for energy storage, which is integrated into an off-grid, small-scale, RES-based system in order to satisfy specific desirable loads. This storage device is based on a rotating flywheel driven by an electric motor supplied by the excess energy produced from RES systems (e.g., PVs, wind turbines). The present work initially discusses the optimal design (geometry) for the rotational mass to store the maximum available energy. Furthermore, it investigates whether such a system could be comparable with other mature, commercially available technologies used in relatively small-scale applications. To obtain the characteristics of flywheels during their operation and determine how their evolution could contribute to energy storage, the theoretical results are validated against an established experimental laboratory-scale system. Finally, the size of the system is theoretically examined as a factor toward its feasibility.

Theory: Physics and Economics

When selecting the design characteristics of such an experimental project, both the operational parameters and the investment and maintenance costs must be taken into account. For a given rotation speed, the amount of kinetic energy is determined by the shape of the rotating mass.

The energy stored in a rotating mass can be calculated as

$$E = \frac{1}{2} I \omega^2 \tag{1}$$

where ω is the rotational velocity and I is the inertia of the rotor, given as

$$I = \int \rho(x) r^2 dx \tag{2}$$

where $\rho(x)$ is the density of the rotational mass and r is the radius.

Given the typical power of an electrical motor, as well as a specific cylindrical mass acting as a typical load for the motor, its torque can be calculated through the following expression:

$$F_{\text{motor}} = \frac{\tau}{\int_0^{R_c} dr} \tag{3}$$

where τ is the torque of the motor and R_c is the radius of cylindrical mass. F_{motor} is the force that motor develops on the load, which has to overcome gravitational force in order to rotate the obstacle under full rotational speed. The differential mass of the cylinder is given as

$$dm = \rho r dr d\theta dz \tag{4}$$

where ρ is the density of the material used for cylinder construction. Finally, the force of gravity can be calculated as

$$B = \int_0^r g \rho 2 \pi r l dr \tag{5}$$

where g is the gravitational acceleration. In cases where the gravitational force is higher than the force provided by the electrical motor, the velocity is reduced and its magnitude can be calculated as

$$\omega_{\text{new}} = \frac{P_{\text{motor}}}{\tau_{\text{mass}}} \tag{6}$$

where P_{motor} is the power offered by the electrical motor (which is considered constant), and τ_{mass} is the torque that has to be overcome during the rotation.

Financial analysis is also necessary to determine the feasibility of FESS, as well as the minimum requirements to be included in RES-based systems. This is mainly based on the net present cost (NPC) of such a system, given by

$$\text{NPC} = \frac{C_{\text{ann.tot}}}{\text{CRF}(i, R_{\text{proj.}})} \tag{7}$$

where $C_{\text{ann.tot}}$ is the total cost on an annual basis (including capital, operational, and maintenance costs). The capital recovery factor $\text{CRF}(i, R_{\text{proj.}})$ is given as

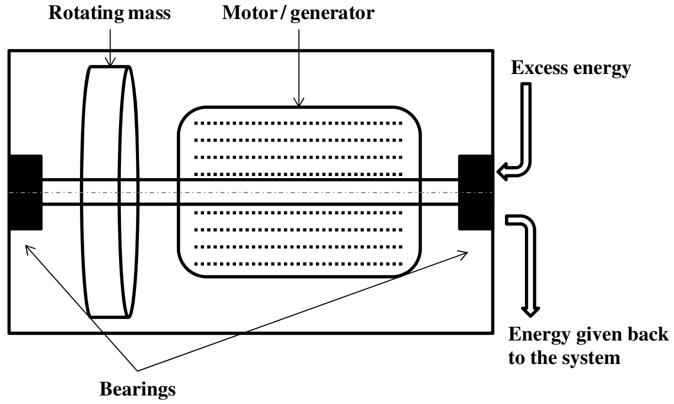


Fig. 1. Presentation and design of a typical FESS

$$\mathrm{CRF}(i, R_{\text{proj.}}) = \frac{i(i+1)^{R_{\text{proj.}}}}{(1+i)^{R_{\text{proj.}}} - 1} \tag{8}$$

where i is the real interest rate and $R_{\text{proj.}}$ is the project lifetime.

Materials and Methods

Based on this theoretical analysis, a laboratory-scale FESS was designed and constructed as depicted schematically in Fig. 1. An electric motor of 1 horsepower (hp) peak power at 1,800 rpm has been selected to be fed by the excess energy of RES technologies when the environmental potential fluctuates at high levels. This electrical energy is transformed into kinetic energy and stored in a rotational mass. When necessary, the motor could operate as a generator (alternator), giving the stored energy back to the system. Although friction losses are crucial, as discussed previously, conventional lubricated roller bearings were used in the present experimental layout because other state-of-the-art techniques require extremely high costs and an electromagnetic clutch that is activated by the presence of the excess eco-friendly electric energy. When the renewable potential is high, the voltage-driven clutch engages the motor with the rotating mass, thus charging the flywheel. As soon as the voltage from RES drops below a predefined limit (10.5 V in this case), the clutch disengages the motor, allowing the rotating mass to return the stored kinetic energy to the system. The power of the specific motor is determined by the power of the battery initially used for backup energy in the system (approximately 660 W) and by the rotational speed of the specific motor (which peaks at approximately 1,800 rpm ≈ 188.5 rad/s).

Fig. 2 presents the operational curve of the electric motor without load. The measured angular velocity is slightly higher than that given by the manufacturer because the standard value of 1,800 rpm corresponds to the standard supply voltage under the manufacturer's standard conditions, which is not attained in laboratory experiments. Hereafter, the maximum velocity is that of the experiments (approximately 2,150 rpm), measured under 12 V of continuous DC supply without imposing load on the motor.

Several problems had to be overcome during the construction of the experimental FESS, mostly concerning the solidity of the rotational parts and the stability of the whole project. Numerous small parts were designed from scratch. These parts are presented in Fig. 3 and described in Table 1, and their final combination was an innovative venture. The majority of the system's parts were built of aluminum to reduce weight without affecting the design's compactness, as discussed in detail later in this paper. The crucial dimensional parameters were the thickness of the flywheel L and the maximum and minimum radii of the hollow cylindrical mass.

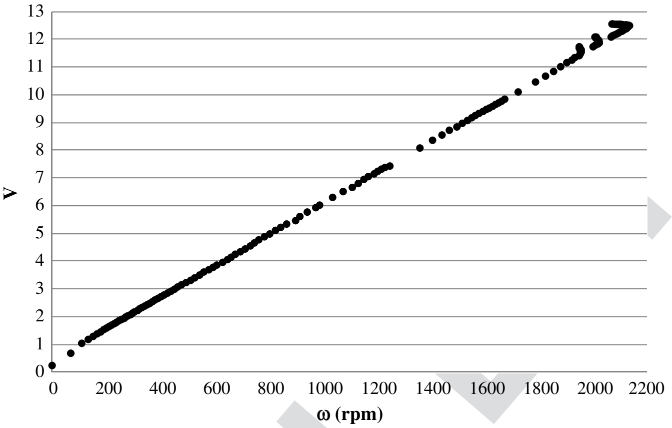


Fig. 2. The operational curve of the electric motor without load

The ideal hollow aluminum rotational mass has been calculated as shown in the "Laboratory Scale" column of Table 2. Although the theoretically calculated thickness of $L = 0.0017$ m is the ideal thickness in terms of the weight and compactness of the rotational mass, it is considered dangerous because of the vibrations that could destroy the rotational mass. As a result, significant safety issues arise. Therefore, dimensional characteristics of the cylindrical mass were modified as presented in Fig. 4 and Table 3, while the final mass of the main rotational body was kept constant so it can be rotated with full angular velocity. This design eliminates the distortion of the rotational mass during rotation due to its increased thickness. The mass of the final construction was 0.700 kg heavier than the ideal because the adapter is also included in the axle.

Theoretical and Experimental Results and Discussion

The theoretical energy analysis, as presented here, was finalized for two different shapes of the cylindrical mass, as shown in Figs. 5(a and b) for a laboratory-scale project. Given the peak values of 1 hp/1,800 rpm at 12 V for the electric motor, it is rather easy to use Eq. (3) to calculate the torque provided at a maximum power of approximately 3.956 Nm. For each layout, two different materials were simulated to determine which could store the highest amount of kinetic energy, as calculated using Eqs. (1) and (2). As Table 2 presents the materials used for the simulations of the construction of rotational mass of a laboratory-scale FESS are steel and aluminum, with densities $\rho_{\text{steel}} = 7{,}874\ \text{kg/m}^3$ and $\rho_{\text{aluminum}} = 2{,}700\ \text{kg/m}^3$, respectively. The simulation process for several cylindrical masses on a small-scale project reveals that the layout of Fig. 5(b) is the most suitable because it is lighter and has a larger radius—i.e., it can store more energy. The efficiency is calculated at 0.0634%, a value that greatly varies from those presented by other researchers (for example, Ledjef 1990; Kaldellis et al. 2007). In the present study, this percentage is calculated by dividing the mean energy stored in a specific time interval by the energy consumed by the electric motor in the same period. Obviously, this magnitude depends on the time scale of the whole process. Thus, the value of 0.0634% corresponds to an hourly time scale, while the flywheel can be rotated only for a few seconds, as discussed later in this paper. Therefore, it is preferable to limit the time interval to a


(a)

(b) (c)

(d) (e)

(f) (g)

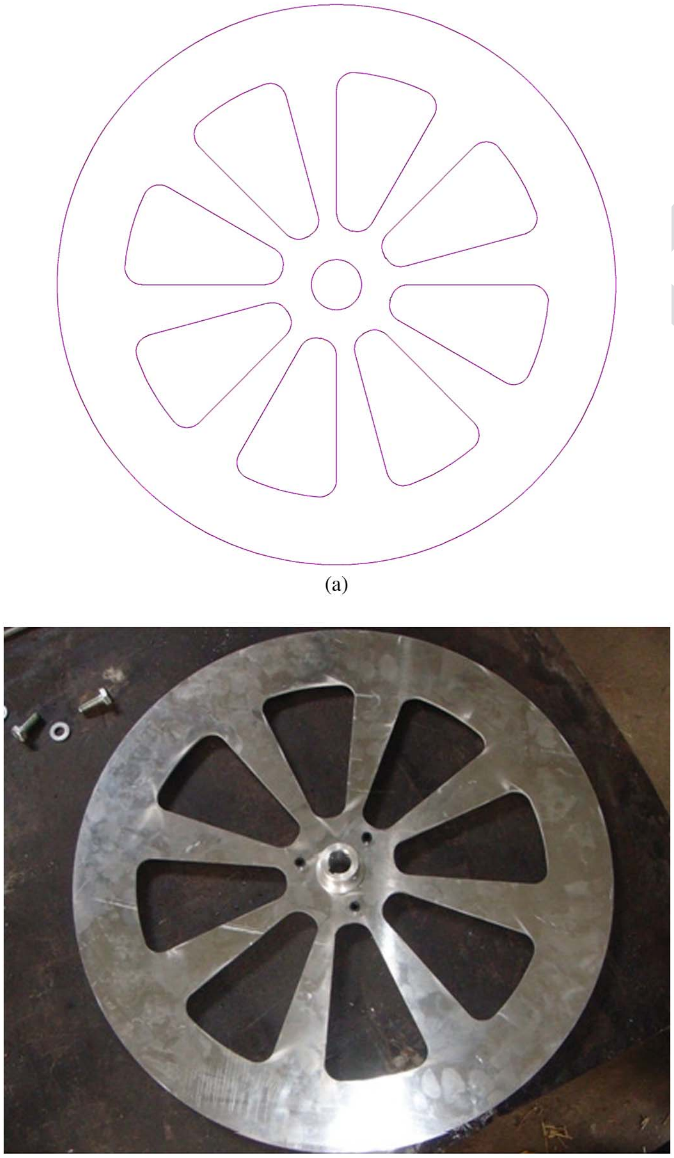
(h) (i)

Fig. 3. The experimental apparatus: (a) and its specific parts; (b) electric motor; (c) axle; (d) electromagnetic clutch; (e) roller bearings with housing; (f) adapter for the axle; (g) adapter for the rotational mass; (h) steel base; (i) frame

Table 1. Description of the Parts of the Established FES System

Part	Description	Quantity
Axle	Aluminum (15 cm long); supports the rotational mass	1
Bearing housing	Steel case, lubricated with oil for the roller bearing at the end of the axle, which is supported on the frame	1
Adapters	Made of aluminum; one adapts the clutch to the motor's axle and one permanently connects the rotational mass to the axle	2
Electromagnetic clutch	Mayr ROBATIC, 24 V, 20 W, 20 Nm; engages the rotational mass when appropriate	1
Roller bearing	Diameter of 0.02 m; responsible for reducing friction losses during rotation	2
Rotational mass	Stores the kinetic energy from the electric motor; inner radius: 0.19 m; outer radius: 0.25 m; mass: 1.8 kg; thickness: 0.005 m, with 8 connecting radii included (Fig. 4)	1
Steel base	Mounted onto the electric motor to keep the outer housing of the clutch stable	1
Voltage source	Fed by the grid; offers 24 V to the clutch during its engagement with the system: Phoenix Contact, 100–240 V ac input, 22.5–29.5 V DC output	1

few seconds in order to obtain higher efficiency values. However, before changing the time scale, it is essential to examine whether the efficiency can be improved by changing the project scale, therefore approaching a real-life scenario.


(a)

(b)

Fig. 4. (a) Design of the rotational mass; (b) construction of the rotational mass

The cylindrical mass was simulated for two additional different scale scenarios and the "Industrial Scale" column of Table 2 shows that the highest efficiency obtained is 0.721%. It should be noted that the best result of the final choice of the rotational mass has to be characterized by a balancing correlation between the radius and length of the cylinder, which determines the rotational speed for the maximization of kinetic energy. Although the energy analysis study shows that an FESS cannot be promoted commercially due to its low efficiency in terms of energy, the final decision should be made following a thorough financial analysis.

For the present economic analysis, the project lifetime is assumed to be 25 years, following the average lifetime of RES-based technologies as stated by various manufacturers (e.g., http://www.sovello.com). The interest rate was chosen as 4.5%, which is the averaged value suggested by the European Central Bank (http://www.tradingeconomics.com/euro-area/interest-rate). Tables 4 and 5 present the initial costs for each component as they emerged from a local market search, their summation, and the NPC of each project. For small-scale projects, the capital costs and NPC are higher for the establishment of an FESS (Table 5), so this is not a feasible investment. For large-scale projects characterized by hundreds or thousands of produced kilowatts, the prospects are more encouraging, and these systems appear to be more economically feasible than the use of common electrochemical batteries (Table 4). This difference can be attributed to the limited lifetime of batteries (4–5 years) compared to the almost unlimited life cycle of flywheels.

A comparison of Tables 4 and 5 clearly shows that in an industrial-scale project, the NPC of an FESS is 73.98% lower than an electrochemical storage bank of the same energy storage capacity. This value can be even higher in large-scale applications because the installation of such an enormous electrochemical layout requires a spare room with complicated air-conditioning systems needed to stabilize temperatures and operate the whole system with the same efficiency factor during its lifetime. However, it should be noted that, at the end of its lifetime, a battery is a major environmental pollutant that requires special recycling treatment. On the other hand, an FESS constitutes a more environmentally friendly solution for energy storage, especially when it is produced in RES-based, stand-alone systems.

Although battery technology is well established and stable in global markets, it could face competition by FESSs in terms of energy buffering. As stated previously, the duration of the rotational motion of the cylindrical mass is a crucial parameter for the estimation of the efficiency of a typical FESS. Table 2 shows that the industrial-scale FESS consumes 100 kWh in 1 h and stores an average of 0.721 kWh. Under these circumstances, its efficiency is 0.721%. This very low percentage can be increased by changing the rotational time taken into account to calculate the efficiency

Table 2. Simulated Scenarios

Motor info	Laboratory scale				Building scale	Industrial scale
P_{motor} (W)	745.69				8,000	100,000
ω (rad/s)	188.5				733.04	628.32
Rotational mass dimensions	Solid steel	Solid aluminum	Hollow steel	Hollow aluminum	Hollow aluminum	Hollow aluminum
R_{max} (m)	0.215	0.310	0.270	0.380	0.55	1.40
R_{min} (m)	N/A	N/A	0.235	0.325	0.49	1.31
m (kg)	1.940	1.390	1.600	1.070	2.054	11.766
ω_{rot} (rad/s)	181.88	176.95	181.99	187.50	721.91	618.85
L (m)	0.0017				0.0017	
Operational results						
$E_{kinetic}$ (Wh) [by Eq. (1)]	0.207	0.290	0.317	0.473	27.720	720.902
I (kg m^2)	0.045	0.067	0.069	0.097	0.383	13.542
n (%)	0.0278	0.0389	0.0425	0.0634	0.347	0.721

Table 3. Rotational Mass: Ideal versus Constructed

Dimensional characteristics	Ideal rotational mass	Constructed rotational mass
R_{max} (m)	0.380	0.250 ($\pm$0.0005)
R_{min} (m)	0.325	0.190 ($\pm$0.0005)
m (kg)	1.070	1.800 ($\pm$1%)
ω_{rot} (rad/s)	187.50	199.77 ($\pm$0.105)
L (m)	0.0017	0.005 ($\pm$0.0005)
I (kg/m^2)	0.097	0.064

Table 5. Financial Analysis of FESS

FESS	Small (laboratory) scale	Medium (building) scale	Large (industrial) scale
Electric motor	450 $	1,000 $	5,500 $
Rotational mass	300 $	400 $	1,000 $
Magnetic clutch	300 $	600 $	3,000 $
Bearings	100 $	200 $	400 $
Electronic parts	200 $	300 $	1,000 $
Sum	1,350 $	2,500 $	10,900 $
NPC	1,327.77 $	2,451.48 $	10,661.22 $

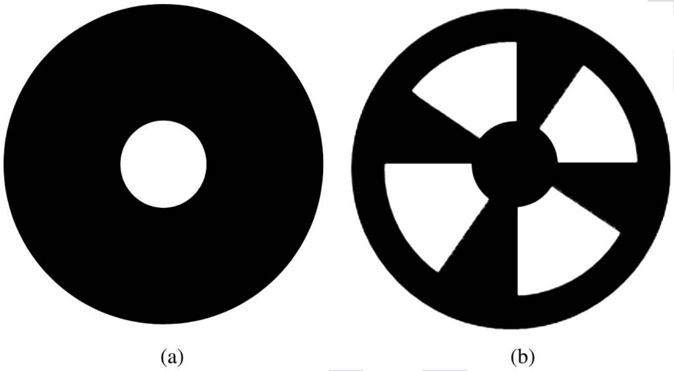


Fig. 5. Theoretical rotational mass: (a) shape of solid cylinder; (b) shape of hollow cylindrical layout

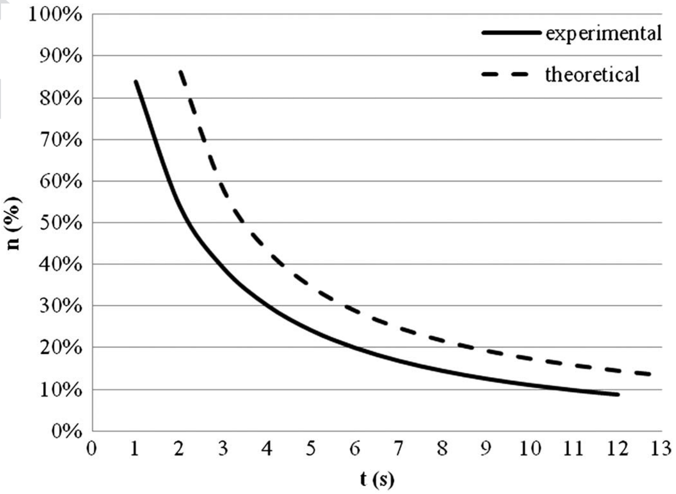


Fig. 6. Theoretical versus experimental curve of FESS efficiency as a function of time

Table 4. Financial Analysis of the Battery Technologies

Batteries	Small (laboratory) scale	Medium (building) scale	Large (industrial) scale
12 V/55 Ah	1 × 180$	–	–
12 V/100 Ah	N/A	5 × 250$	63 × 250$
Charger/controller	200 $	1,000 $	12,600 $
Sum	380 $	2,250 $	28,350 $
NPC	524.39 $	3,252.63 $	40,982.95 $

of a FESS. This approach is allowed since the energy stored in the FESS attains after just a few seconds, being at the same level for each higher time step. By decreasing the time spent on charging, the energy stored in the FESS remains constant while the energy consumed by the electric motor can be directly comparable to that given back to the system through the reverse path by the rotation of the mass. Under these operational conditions, and bearing in mind the financial results presented in Table 3, a FESS can rival competitive storage technologies widely available on the market, but only for applications such as UPS systems, which use a storage energy bank to support a system for a short time during its operation or to cover a peak load for a limited time during a single day.

The experimental process also demonstrates that an FESS is capable of being rotated for about 40 s and then stopping due to friction losses because the apparatus is not vacuum-enclosed. In addition, the whole rotation of the axle is based on typical roller bearings, which have high friction losses compared to electromagnetic bearings. The efficiencies ranged between 83.78% and 8.75%, and the operational time varies from 2 to 13 s (Table 6),

Table 6. Experimental Measurements

t (± 0.01) (s)	ω (± 0.105) (rad/s)	E_{FES} (kWh) [Eq. (1)]	Mean E_{FES} (kWh)	E_{consumed} (kWh) $=[(745.69)/(3{,}600)t]$	n (%) [Mean $E_{\mathrm{FES}}/E_{\mathrm{consumed}}$]
1	199.77	0.000357	N/A	0.000207	N/A
2	194.05	0.000337	0.000347	0.000414	83.78
3	186.97	0.000313	0.000336	0.000622	54.02
4	179.49	0.000288	0.000324	0.000829	39.09
5	172.11	0.000265	0.000312	0.001036	30.13
6	164.94	0.000244	0.000301	0.001243	24.19
7	158.26	0.000224	0.000290	0.001450	19.98
8	151.86	0.000207	0.000279	0.001658	16.86
9	145.75	0.000190	0.000270	0.001865	14.45
10	140.58	0.000177	0.000260	0.002072	12.56
11	136.01	0.000166	0.000252	0.002279	11.04
12	131.20	0.000154	0.000244	0.002487	9.79
13	126.52	0.000143	0.000236	0.002694	8.75

Table 7. Theoretical Results

t (s)	ω (rad/s)	E_{FES} (kWh) [Eq. (1)]	Mean E_{FES} (kWh)	E_{consumed} (kWh) $=[(745.69)/(3{,}600)t]$	n (%) [Mean$\mathrm{E}_{\mathrm{FES}}/E_{\mathrm{consumed}}$]
1	199.77	0.000357	N/A	0.000207	N/A
2	199.77	0.000357	0.000357	0.000414	86.22
3	199.77	0.000357	0.000357	0.000622	57.48
4	199.77	0.000357	0.000357	0.000829	43.11
5	199.77	0.000357	0.000357	0.001036	34.49
6	199.77	0.000357	0.000357	0.001243	28.74
7	199.77	0.000357	0.000357	0.001450	24.63
8	199.77	0.000357	0.000357	0.001658	21.56
9	199.77	0.000357	0.000357	0.001865	19.16
10	199.77	0.000357	0.000357	0.002072	17.24
11	199.77	0.000357	0.000357	0.002279	15.68
12	199.77	0.000357	0.000357	0.002487	14.37
13	199.77	0.000357	0.000357	0.002694	13.26

although the flywheel can be rotated for 40 s due to the moment of inertia. The analysis is meaningless for such long time periods because the angular velocity of the flywheel decreases under 126.5 rad/s for $t > 13$ s, and so the motor returns voltages lower than 12 V (Fig. 2). By assuming that the theoretical results in Table 7 vary at the same level without significant discrepancy from the experimental ones, the angular velocity remains a constant parameter throughout time. The time-dependent efficiency, as presented in Fig. 6, could be improved by the use of an electric motor of higher angular velocity that consumes the same amount of energy. The augmentation of the angular velocity will lead to the increase of stored kinetic energy on the rotational mass. Obviously, efficiency decreases with time due to friction losses, while the theoretical estimations are always higher than experimental observations because rotational speed has been considered constant for the theoretical approach.

Conclusions

In this study, an FESS was simulated under different scenarios, one of which (laboratory scale) was built and measured to validate the theoretical analysis. This process revealed the outstanding characteristics of flywheels during their operation. More precisely, two different materials and shapes were simulated for the rotational mass. It has been proved that a hollow aluminum cylindrical mass is the preferable option since it can give better energy storage results. This mass shape was included in projects of three different scales (laboratory, building, and industrial) to investigate the feasibility of an FESS compared with electrochemical batteries. It was found that the scale of the project is a favorable parameter for its implementation feasibility. Finally, an experimental apparatus was designed and built to validate the theoretical results. It was proved that FESSs can be used as UPS systems to cover the peak load of a system during limited time periods.

To conclude, the development a low-cost, state-of-the-art, and eco-friendly device, which can be charged and discharged several times with high efficiency and with reliable performance during a project's lifetime, is crucial for the total commercialization of FESS. That is exactly the basic scope of the present study: to investigate theoretically and experimentally whether flywheels can provide a feasible energy storage solution because they have numerous advantages compared to other, more mature technologies. Finally, the evolution of material science and advanced control units are expected to improve flywheel systems and promote their role in fully supporting an off-grid, totally eco-friendly power plant.

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3. Spell out UPS (uninterruptible power supply)?

4. Please check the hierarchy of the section headings.

5. how does self-discharge waste the flywheel stored capacity?

6. uninterruptible power supply?

7. spell out PV on first reference in this paper.

8. it's not clear what the label for (a) is saying; is this the apparatus and its specific parts? If they are specific parts, should we specify them?

9. Table 2 is confusing to read; it's not clear what the scenarios are, or what the stats are pertaining to. Rearrange it, or perhaps give the information in multiple tables?

10. on the reference list, the year for Kaldellis et al. is given as 2009; is this another source, or should we change this year?

11. In Table 4, do the dollar signs mean that these figures are in US dollars? if so, we should just put that in a note (would be less confusing/repetitive).

12. same question for Table 5 as Table 4.

13. with the term FESS, is it pronounced as a word (fess), or spelled out (F-E-S-S)? If the former, then "a FESS" is correct; but you also have "an FESS" later in this paper. Please make this consistent, whichever is the correct way.

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15. for the Arghandeh et al. (2012) entry, can this be updated? it's from 2012, so it can't still be in press, right?

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