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Supercapacitors: Alternative Energy Storage Systems

Abstract-*The use of supercapacitors as energy storage systems is evaluated in this work. Supercapacitors are compared with other technologies such as compressed air, pumped hydro, superconductors and flywheels. This paper is focused on medium scale energy storage systems (applied to 100 kW photovoltaic generation plants). The supercapacitor is studied in detail, presenting these device structures, how they can be modeled, the balancing, their useful life and their principal applications. The overview is carried out after a detailed reference selection.*

Streszczenie.

Keywords: Overview, supercapacitor, Energy Storage Systems
Słowakluczowe:

Introduction

Humanity is demanding a bigger quantity of energy as its level of development is growing. Conventional energy resources are limited, so authorities and governments are promoting energy savings and energetic efficiency. Also, renewable energies have been sustained and promoted by these authorities and governments as an alternative to limited conventional energy resources.

Nowadays, the most relevant renewable energies used in generation plants are solar (photovoltaic or thermal) and wind energy. The main disadvantage of these kinds of renewable energy is its generation discontinuity, as well as the fact that its energy generation is not controlled by the system operator thus making it more difficult to integrate these plants in the generation pool than in the case of conventional plants.

Energy storage becomes a critical factor that can solve the problems described above. A renewable energy generation plant with its corresponding energy storage system can behave as a constant power generation plant (following the reference power generation given by the regulator), at least for time intervals in the order of half an hour to a day, depending on the energy storage capacity.

In the first section of this paper, an overview of different energy storage systems is carried out, taking into account storage capacity, voltage and current ratios, and energy availability. The second section is focused on the supercapacitor technology.

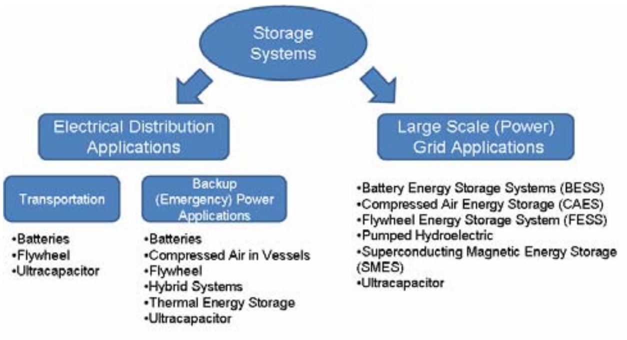

Fig. 1. Classification of the principal energy storage systems.

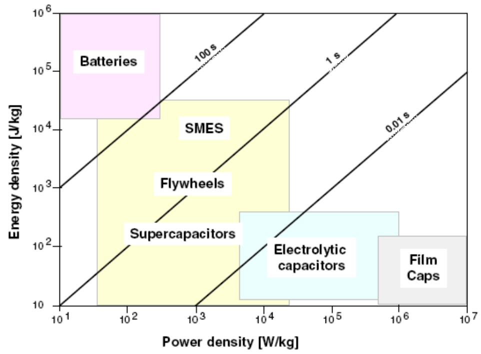

Fig. 2. Power versus energy.

Energy Storage Systems

The principal energy storage systems (ESS) are summarized in Fig. 1 [1], where these systems are classified according to their application. We will focus this paper on the systems classified into the Large Scale (>50 kW) in this figure.

Most relevant ESS technology characteristics are summarized in Table I [2]. The ESS considered for medium scale applications are classified in Fig. 2 by their power and energy densities [2].

A. CAES (Compressed Air Energy Storage)

CAES uses the peaks of energy generated by renewable energy plants to run a compressor that compresses the air into a hermetic underground reservoir or surface vessel/piping. The compressed air is used, combined with a variety of fuels in a combustion turbine to generate electric energy when demand is high. The energy storage capacity depends on deposit volume and maximum storage pressure of the compressed air. Start up time is usually high. [1]-[12]. CAES is used for large and medium (micro CAES) scale systems.

B. Pumped Hydroelectric

Pumped hydroelectric storage has been commonly used for 70 years. These plants are the most used for large scale applications at present [7],[13].

C. Superconducting Magnets

A Superconducting Magnetic Energy Storage (SMES, Fig. 3) system stores the energy as magnetic energy in a superconducting magnet cryogenically cooled, achieving a system with negligible losses. The AC energy is stored as DC energy and brought back from DC to AC energy from the superconducting magnet by a reversible AC/DC Power Converter Module (PCM).

The superconducting magnet can present two different shapes: toroid or solenoid. The first has a lower external field but higher superconductor and components cost than the second.

Table 1: Energy storage technologies

Technology	Power	Energy density	Back-up time	Response time	Efficiency	Lifetime (years)
Pumped hydro	100 MW – 2 GW	400 MWh – 20 GWh	hours	12 minutes	70 - 80 %	50
CAES	110 MW – 290 MW	1.16 GWh - 3 GWh	hours	12 minutes	99 %	< 50
BESS	100 W – 100 MW	1 kWh - 200 MWh	hours	seconds	60 - 80 %	< 10
Flywheels	5 kW – 90 MW	5 kWh – 200 kWh	minutes	12 minutes	80 - 95 %	20
SMES	170 kW – 100 MW	110 Wh – 27 kWh	seconds	milliseconds	95%	30
Supercapacitors	< 1 MW	1 Wh- 1kWh	seconds	milliseconds	> 95%	> 10

The energy stored by an SMES is

$$E = \frac{1}{2} L I^2 \qquad (1)$$

where L is the equivalent self-inductance of the superconductor system, and I is the DC current that flows trough the winding. This current is the principal magnitude that the PCM uses for controlling the energy stored or generated by the system [14], [15].

SMES efficiency is between 95 % and 98 %. It has a high availability, being able to supply high energy quantity in time intervals of milliseconds [4], [7], [16], [17].

First SMES systems (in the 1970s) were focused for large scale applications, with energy storage capacities between 1,000 and 10,000 MWh [18], powers about 1,000 MW (for 5,000 MWh applications [16],[18]) and were underground systems [17]. Application of superconducting in SMES took place for the first time in 1974 in Los Alamos National Laboratory (LANL) [19] using a three-phase converter. Bonneville Power Authority (BPA) and LANL team designed in 1976 a SMES of 8.33 kWh (30 MJ) and 10 MW [17],[19]. At present, typical SMES Systems are designed with an energy storage capacity of from 0.15 kWh (600 kJ) to 28 kWh (100 MJ) [20]-[22].

The main disadvantage of the SMES system is that the energy density is low and there is a need for a criogenization system that could be very complex for large scale application. A possible solution is to combine them in hybrid ESS increasing their energy and power [23].

D. Flywheels

Due to their simplicity, flywheel energy storage systems (FESS, Fig. 4) have been widely used in commercial small units (about 3 kWh) in the range of from 1 kW – 3 hours to 100 kW – 3 seconds [7].

Energy is stored as kinetic energy using a rotor that rotates with high angular speed

$$E = \frac{1}{2} J \omega^2 \qquad (2)$$

where J is the momentum of inertia and ω is the angular velocity.

The rotor is a hollow cylinder and has magnetic bearings to minimize the friction. The rotor is located in a vacuum pipe to decrease the friction even more. The rotor is integrated into a motor/generator machine that allows the energy flow in both directions.

The energy storage capacity depends on the mass and shape of the rotor and on the maximum available angular velocity.

There exist two topologies, *slow* flywheels (with angular velocity below 6,000 rpm) based on steel rotors, and *fast* flywheels (below 60,000 rpm) that use advanced material rotors (carbon fiber or glass fiber) that present a higher energy and power density than steel rotors [24].

The flywheel designs are modular and systems of 10 MW are possible [7][25]. FESS presents an efficiency of 80-85 %, with a useful life of 20 years.

Fig. 3. SMES (200 kW, 2 MJ. Thanks to ACCEL).

Fig. 4. Flywheel Energy Storage System (ENERCON, 200 kW, 5 kWh. Thanks to PEGE).

The advances on the rotor technology and on the PCM for FESS have permitted a high dynamic and a high durability of tenths of thousands of cycles [25]. These characteristics make these systems suitable for power quality applications: frequency deviations, temporary interruptions), voltage sags and voltage swells.

Smart Energy Matrix is a commercial system by Beacon Power, composed of a Flywheel ESS and PCM [25]. At present, two pilot projects using Smart Energy Matrix for large scale applications are being carried out by the Department of Energy (DOE), California Energy Commission (CEC) and the New York State Energy Reseach and Development Authority (NYSERDA). The first Project is located in an industrial zone of New York; the second one is connected to a transmission line in a substation of California. Both projects prove the FESS capacity for improving power quality [28].

FESS applied to the renewable energies trend is to combine them with other technologies, like micro CAES or thermal energy storage systems [27].

E. Batteries

These systems could be located in any place and be rapidly installed. Large systems (known as Battery Energy Storage System, BESS, Fig. 5) don't have the medioambiental impact of other ESS technologies and can be located in a building (or similar) near the point of demand [26].

BESS uses a PCM to convert the battery DC energy into AC grid-compatible energy. These units present fast dynamics with response times near 20 miliseconds and an efficiency from 60 % to 80 % [7].
The energy is stored as electro-chemical energy. The battery temperature change during charge and discharge cycles must be controlled because it affects its life expectancy.

Depending on how the battery and cycle are, the BESS can require multiple charges and discharges per day. The battery cycles will be normal while the discharge depth is small, but if the discharge depth is high the battery cycle duration could be degraded. The expectated useful life of a Ni-Cd battery is 20,000 cycles if the discharge depth is limited to 15% [1].

Large scale BESSs that exist at present are the 10 MW (40 MWh) system installed in Chino, California and the 20 MW (5 MWh) installed in Puerto Rico [7], [28].

New battery technologies are being developed for a higher energy store capacity and at a lower cost than the Lead Acid battery. Some of these new technologies are Lithium Ion, Hydrogen Vanadium Redox, Regenesys® Redox, Sodium Sulfur, Nickel Metal Hydride, Nickel Cadmium, and Zinc Bromide [29]-[31].

F. Supercapacitors (ultracapacitors)

Supercapacitors will be presented in more detail in the next section.

Supercapacitors

Supercapacitors, ultracapacitors (commercial denominations given originally by its manufactures Nippon Electric Company, NEC, in Japan, and by Pinnacle Research Institute, PRI, in USA) or electrochemical double-layer capacitor (EDLC, technical name) are devices that can be used as energy storage systems, that have high energy and power densities, a high efficiency, nearly 95% and a large life expectancy [32]-[34].

Supercapacitors store charge in a similar way to conventional capacitors, but the charge does not accumulate in two conductors, but in the interface between the surface of a conductor and an electrolytic solution.
Supercapacitor devices consist of two electrodes which allow a potential to be applied across the cell, therefore they present two double-layers, one at each electrode/electrolyte interface. An ion-permeable separator is placed between the electrodes in order to prevent electrical contact, but still allows ions from the electrolyte to pass through. The electrodes are made with high effective surface materials, such as porous carbon or carbon aerogel. Two principal technologies are used: aqueous (maximum voltage of 1.2 V and work voltage of 0.9 V) and organic (voltage near 3 V but with a much higher series resistance).

The principal supercapacitor characteristic that makes it suitable for using in ESS, is the possibility of fast charge and discharge without lost of efficiency, for thousands of cycles.

This is because they store electrical energy directly [35]-[37]. Supercapacitors can recharge in a very short time having a great facility to supply high and frequent power demand peaks.

Supercapacitor can be manufactured in any size because they do not need a dielectric, form high capacitance supercondensators for hybrid vehicles [2], [38]-[41], to small capacitance ones to be used in low power applications such as wireless systems [42]-[43].

Fig. 5. Battery Energy Storage System (ZESS 50, 50kWh, 25kWh).

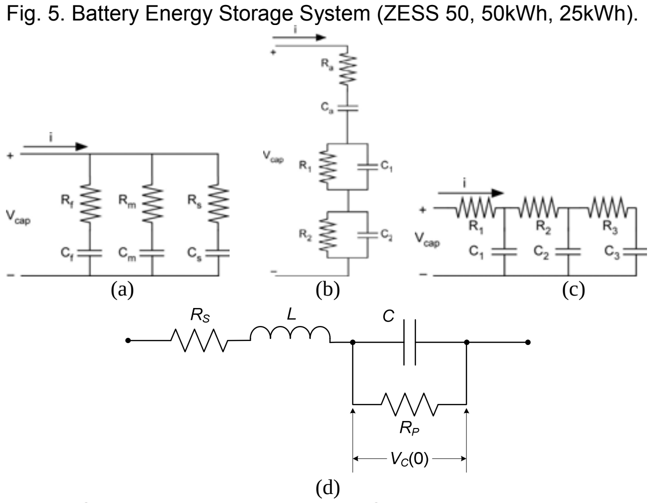

Fig. 6. Supercapacitor models: (a) RC parallel branch model, (b) RC branches series-parallel model, (c) RC transmission line model, and (d) first-order circuit supercapacitor model.

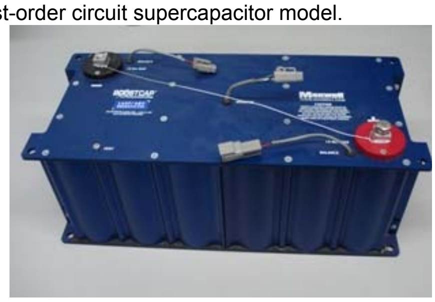

Fig. 7. The 48V series BMOD0165P048B supercapacitor (courtesy of MAXWELL).

A. Supercapacitors principles and models

Supercapacitors are based on the same physical principles as conventional capacitors, but the first ones present a higher area and thinner electrodes (with lower electrodes distances) than the second ones. This increases the capacitance values and the energy that can store.

An estimation of the capacitance value can be obtained from the double-layer model proposed by Helmholtz in 1853, considering the double-layer charge as two charge monolayers. The specific capacitance of such a double-layer is given by

$$C = \varepsilon_0 \varepsilon_r \frac{A}{D} \tag{3}$$

where C is the capacitance, ε_0 the dielectric constant of free space, ε_r the dielectric constant of the medium between the two layers, A the surface area, and D is the distance between the two layers (the distance from the electrode surface to the centre of the ion layer). This approximation is roughly correct for concentrated electrolytic solutions [34].

The energy stored in a supercapacitor, as in a conventional capacitor, is

(4) $$E = \frac{1}{2}CV^2$$

where V is the supercapacitor voltage.

The simplest equivalent circuit to model a supercapacitor is a capacitor, C, with an equivalent series resistance (ESR), R, which represents the Joule losses[44].

More detailed supercapacitor *RC* models are various parallel *RC* branches (Fig. 6(a)) [44], [46]; *RC* series-parallel branches (Fig. 6(b)) [44], [46]; and transmission line model (Fig. 6(c)) [44]-[47]. These models are linear presenting fixed capacitance and resistance values. Sometimes non linear models must be used considering capacitance or resistance values that depend on the temperature and supercapacitor voltage [44], [48], [49].

In Fig. 6(d) other equivalent circuit is shown that includes a series inductor, L, and a parallel resistance, R_P [50]-[52]. R_S (ESR) models the energy losses in charges and discharges and R_P models the escape current and the energy losses due to the capacitor self-discharge. In practical capacitors R_P is much higher than R_S.

One of the most useful/desirable characteristics of an SAE is that the discharge is minimum. The discharge process of a supercondenser is controlled by the equation:

(5) $$V(t) = V_C(0)e^{-\frac{t}{R_P C}}$$

where $V_c(0)$ is the initial voltage of the supercapacitor.The stored energy in the supercapacitor being:

(6) $$E(t) = \frac{1}{2}CV_C^2(0)e^{-\frac{2t}{R_P C}}$$

The evolution of the supercapacitor tension in the discharge is shown in Fig. 8 [53][54].

Associating Supercapacitors in series/parallel structures needs circuits to balance the voltage and current of each individual supercapacitor. Two principal kinds of methods exist to implement this balance:

- Active Method: this method uses semiconductors to limit and balance the tension between cells; it is the best method for cycles of ardous work/long cycles of work, or when effeciency (or losses in the escape current) are an important factor [55].
- Resistive Method: here a parallel resistance is installed; the force of this resistance is calculated as 10 times less than the parallel resistance for slow dynamic requisites, and 100 times less than for rapid dynamic requisites. In this method the efficiency of the system is considerably reduced [55].

In Fig. 9 we can see two circuits of actively balanced cells developed by Maxwell. Both versions are based on a design of a precision operated amplifier. The tension-balancing circuit between cells is designed to limit an overload in the supercapacitors and is capable of supplying a current of up to 300 mA to reduce overload in the cells. Once the cells are balanced the circuit reduces this current to a force of less than 50 μA (approximately 1% of the normal escape current in a cell of 3000 F) guaranteeing that the balancing circuit does not notably affect the efficiency or the discharge periods of the system.

The modular systems of Maxwell, e.g. BMOD0165, are now equipped with an active tension-balancing circuit, which protects and monitors every cell within the module. Balancing between different modules is therefore not necessary as each module is balanced internally.

The criteria which determine the life of the supercapacitors are capacity and ERS. Maxwell defines this criteria as a reduction of 20% in capacity and a 100%

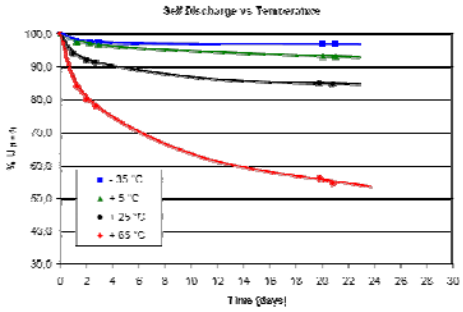

Fig. 8. Courtesy of Maxwell Technologies. Discharge of the supercapacitor due to escape resistances.

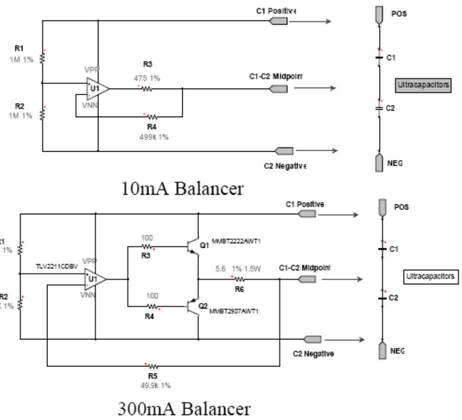

Fig. 9. Courtesy of Maxwell Technologies. Balancing circuits of Maxwell technologies

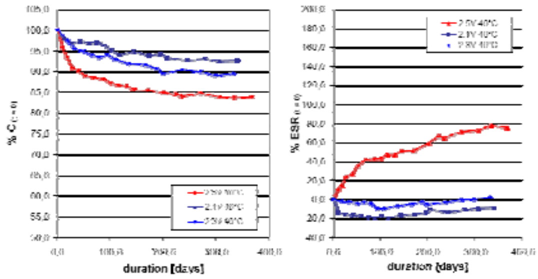

Fig. 10. Courtesy of Maxwell Technologies. Changes in the value of internal parameters of the supercapacitor during its useful life

Table 2: Capacitance of Selected Electrode Material

ELECTRODE MATERIAL	DENSITY (G/CM^3)	ELECTROLYTE	F/G	F/CM3
CARBON CLOTH	0.35	KOH	200	70
		ORGANIC	100	35
CARBON BLACK	1.0	KOH	95	95
AEROGEL CARBON	0.6	KOH	140	84
PARTICULATE FROM SIC	0.7	KOH	175	126
		ORGANIC	100	72
PARTICULATE FROM TIC	0.5	KOH	220	110
		ORGANIC	120	60
ANHYDROUS RuO_2	2.7	H_2SO_4	150	405
HYDROUS RuO_2	2.0	H_2SO_4	650	1300
DOPED CONDUCTING POLYMERS	0.7	ORGANIC	450	315

increase in ERS.The capacity descends/drops in the first hours/cycles in an exponential form, and then in a lineal form during the rest of its useful life (Fig. 10). Although a recovery phenomenon exists if the tension in the supercapacitor is interrupted after a long period of continuous use, both capacity and ERS show this recovery as a rest period function.

TABLE 3
MANUFACTURERS OF SUPERCAPACITORS

Type of composites	*Company or lab*	*Country*	*Device name*	*Capacitance range (F)*	*Voltage range (V)*	*Energy density (Wh/kg)*	*Power density (kW/kg)*	*Mass (Kg)*	*Web address*
Carbon fiber composites	Maxwell	United States	Boostcap	4 - 3000	2.5 - 2.7	0.868 - 5.52	1.35 – 26	0,004 - 0,55	www.maxwell.com
			Boostcap Modulen	52 - 500	15 - 125	1.9 - 3.98	4.4 - 14	0.566 - 58	
carbon particulate composites	APowerCap Technologies	Sweden/Ukraine		4 - 550	2.7	5.5 - 5.8	4.4 – 5.7	-	www.apowercap.com
	NIPPON CHEMI-CON	Japan	Electric Double Layer Capacitor Module	58 - 500	13.8 - 210	1.5 - 4.5	1	1 - 445	www.chemi-con.co.jp
			Electric Double Layer Capacitor	350 - 3200	2.3 - 2.5	1.5 – 4.5	1	0.09 - 520	
	Nesscap	korea	EDLC Pseudocapacitor Module	1.5 - 5000	2.3 - 340	1.67 - 8.75	5.2	0.001 - 384	www.nesscap.com
	Cap XX	Australia	Supercapacitor	0.075 - 1.8	2.3 - 5.5	0.05 - 10	0.01 – 10.3	-	www.cap-xx.com
	ELIT	Russia	UPS type xxxПП-x/0,xx	2,86 - 0,23	0,8 - 200	0,556 - 2,778	0.9-1	-	www.elit-cap.com
	NEC	Japan	Super Capacitors	0.022 - 100	2.7 - 7.0	0.5	0.005-0.01	4.5 - 24	www.nec-tokin.com
	Panasonic	Japan	Gdd capacitor	800 - 2000	3	3.1 - 4.4	0.127 – 0.392	0.32 - 0.57	-
Aerogel carbon	Cooper Electronic Technologies (COOPER Bussmann)	United States	PowerStor	0.22 - 100	2.5 - 5.5	0,4	-	0.0005 - 0,022	www.cooperet.com
	WIMA	Germany	SuperCap	100 - 3000	2.5 - 14	1.5 - 4.7	0.25	40 - 1700	www.wima.de
Hybrid	Evans	United States	Hybrid (DSCC) Capacitor Banks Capattery	0.001 - 1.5	5.5 - 125	0,1	30	-	www.evanscap.com
	ESMA	Russia	Capacitor Modules	100 - 500	16 - 52	2,58 - 7,3	38 - 42	-	www.esma-cap.com

B. Supercapacitor estructure and manufacturers

Supercapacitor structure consists of two electrodes of active carbon (built with porous or aerogel carbon to maximize the electrode surface) that are isolated by a permeable membrane (electrolitic impregnated and isolating) that allows the ionic conduction between them.

These electrodes are wound in layers and introduced into rectangular containers [50].

The supercapacitor capacitance depends principally on the electrode material: distribution and size of the porous. In Table II different materials with their respective density and capacitances are shown [32].

At present, research is focused on developing new supercapacitor applications, most of them in electric and hybrid vehicles and in domestic electronic devices.

C. Applications

As aforementioned, the principal research lines are focused on the use of supercapacitors in hybrid storage systems combined with cell fuel or SMES [54]-[63], because these systems are complementary.

A typical supercapacitor application is its use as a storage system in electric or hybrid vehicles, improving their performance, efficiency and economic viability [66]-[94].

Due to advances in technology and the increase in the energy storage capacity, these Systems are beginning to be considered for energy storage systems in renewable energy generation plants [95]-[98].

Other scenarios where the use of supercapacitor based systems are beginning to be researched are: active power filters [99]-[101]; power quality improvement of distribution and transport systems [57], [102]-[105]; locomotives [2]; for battery substitution in electronic devices (due to their large useful life) [106]-[107]; intermediate energy storage systems [108]; and in whatever medium level power application that requires an energy storage of high reponse times, low instalation and maintenance costs, and small energy storage capacity.

Conclusion

In this paper, the six ESS technologies which have been described, namely battery energy storage system (BESS), compressed air energy storage system (CAES), flywheel energy storage system (FESS), pumped hydroelectric, supercapacitor energy storage system (SESS), and superconducting magnetic energy storage (SMES), are applied for power fluctuation suppression in the renewable energy. The study focuses on supercapacitors, due to their easy installation and use, their storage of electrical energy and the great technological development experienced in the last years.

Supercapacitors are actually available with energy densities around 5 Wh/kg, still relatively low densities with a high cost. It is expected that in the future their energy density will reach 30 Wh/kg. This leads us to consider supercapacitors as an interesting option in a near future when problems of high cost and low energy density are solved.

Nowadays, supercapacitors would be a solution to a system that injects power for one hour, but they wouldn't be a solution to a system that injects power for one day. The fact that they don't store high quantities of energy and that they need a high number of modules increases the costs a lot.

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