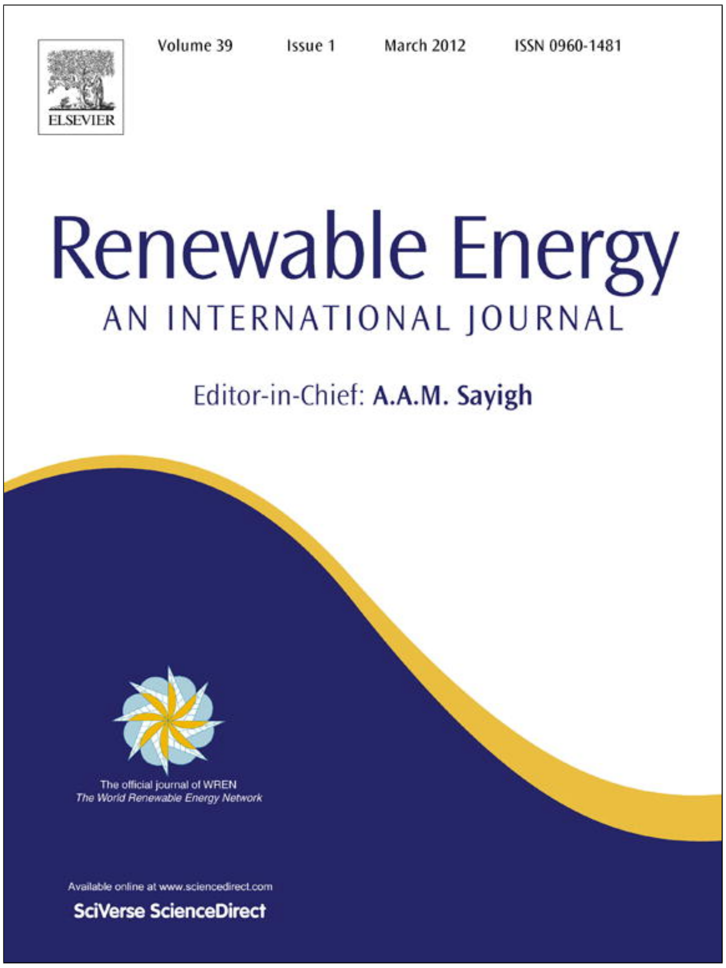

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Simulations of economical and technical feasibility of battery and flywheel hybrid energy storage systems in autonomous projects

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ABSTRACT

This paper deals with the feasibility of a Renewable Energy Sources (RES)-based stand-alone system for electricity supply based on a Flywheel Energy Storage System (FESS) located on the Greek Island of Naxos. The innovative use of flywheels in parallel connection with electrochemical batteries, as an integrated storage device in the same power plant, was selected to be simulated as it is a necessary buffer covering the load of a typical house. The optimal configuration for the electromechanical connection between the electrochemical batteries and flywheels is also considered in this study. Operational characteristics of the new storage systems were estimated and used in the simulations, while the financial aspects of the projects finalized using hand-made calculations and the HOMER software was used only for the energy calculations. It was found that an off-grid project using advanced and totally "green" technologies is possible and comparable to more conventional RES-based systems, in terms of energy and economical feasibility. Finally, it can be concluded that systems with low price flywheels are equivalent to those with electrochemical batteries.

1. Introduction

Renewable Energy Sources are characterized by their unpredictable behavior, since their availability depends on local meteorological conditions. Therefore, the use of intermediate energy storage (buffering) is essential for an uninterrupted energy supply, especially for off-grid stand-alone systems. These storage devices offer hybrid systems the balance of load frequency [1,2] and are currently limited to batteries, including lead-acid, lithium, nickel-based and flow batteries [3]. Advanced technologies of energy storage systems not dealing with the conversion of chemical energy to electricity include Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), Hydrogen-based Energy Storage [4] and Flywheels [5], however, they are at early stages of commercial application because of efficiency, safety and installation issues, although some of them are very well developed during the last century.

In the present study, the advanced technology of a Flywheel Energy Storage System (FESS) is simulated in combination with the staple technology of electrochemical batteries for long-time storage of excess energy from RES. One of the main advantages of flywheels is their lifetime. They can be charged and discharged at high rates for many cycles without losing on their efficiency which approaches 92–96% [6,7]. Moreover, a FESS is capable of offering a huge variety of power levels to protect a power plant from sudden fluctuations of the desirable load, which must be covered at any time step [1,2]. It can also be connected to a DC bus depending on the demands of the established hybrid system to cover the desirable load. Flywheels constitute an integral green technology because their operation is not supported by chemicals. In addition their raw materials are completely recyclable. However their drawbacks include their limited storage time of, 5–30 s for the majority of those commercially available [1]. They also demonstrate high standing losses since a significant percentage of their stored capacity is wasted through self-discharge. These rates are found to be in the range of 0.18–2.0 times the stored capacity per hour [7,8].

Flywheels are not presently commonly used for energy storage because they are costly. The cost of a flywheel system is directly connected to its storage time (200–500 $ per kW for several minutes and 1000–3000 $ per kW for 1 h, however flywheels in this range are not used commercially [7,9]). Therefore they are installed into electric or hybrid-electric vehicles, in industrial applications that control power conditioning such as Uninterruptible Power Supply (UPS) [9], in satellite applications replacing the first generation of space batteries, and in spacecrafts replacing nickel-hydrogen batteries to improve efficiency and

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reduce spacecraft mass and cost [6]. The hybrid devices simulated here involve low cost flywheels (200 $/kW and 350 $/kW) that would compromise the initial system costs.

In this study, effort has been made for advanced technologies (such as flywheels) to be integrated into everyday systems, to aid their further commercialization. Our simulation was based on a specific load (for a typical house), while Naxos Island was selected, as the installation location, due to its high RES-potential [10]. All the systems considered were assumed to simultaneously utilize solar and wind energy and use a stack of batteries in combination with flywheels for the plant energy storage.

FESS advanced technology is substantially an Electro Mechanical Battery (EMB). This battery-type consists of a rotor suspended by bearings inside a vacuum chamber to reduce friction, and is connected to a combination electric generator [2]. Initially, flywheels used a rotating mass by steel on mechanical bearings but nowadays such systems are constructed from materials like carbon-fiber and the bearings have been replaced by magnetic bearings. This advanced approach on the construction of a flywheel energy storage system can be considered very promising because it offers high tensile strength during the rotation of the flywheel's axle while it also reduces friction effects on moving parts [8].

2. Theory

2.1. Technological aspects

Technological achievements that take advantage of wind and solar energy are generally known: photovoltaic panels (PV) transform solar radiation into DC current, and wind turbines (WT) convert kinetic wind energy into electrical power. The electric power produced by a typical photovoltaic array is given as [11,12]:

$$P_{\text{solar}} = P_{\text{STC}} f_{\text{der. PV}} \left(\frac{\overline{G}_T}{\overline{G}_{\text{STC}}}\right)\left[1+\alpha_P\left(T_C - T_{C,\text{STC}}\right)\right] \tag{1}$$

where P_{STC} is the output power of the panels in standard test conditions, $f_{\text{der. PV}}$ is the derating factor, $\overline{G}_T$ is the solar radiation incident, $\overline{G}_{\text{STC}}$ is the radiation in Standard Test Conditions (1000 W/m^2) and α_P is the temperature coefficient of the PV's power. The last brackets represent the performance of the PV cells which is influenced by the temperature, T_C, to which the photovoltaic array is exposed, in real time conditions.

Using mass flow-rate instead of mass, air density is included in the well-known expression of kinetic energy, thus wind power can be calculated as [13,14]:

$$P_{\text{wind}} = 0.5\,A^2 \rho_{\text{air}} u^3 \tag{2}$$

where A is the swept area of the turbine's rotor, ρ_{air} is the air density of the air, assumed to be constant, and u is wind velocity. It should be noted that only 30–40% of the wind power can be converted into electrical energy by horizontal axis turbines because of the mechanical losses of the construction [13].

The EMB is charged by spinning its rotor to maximum speed using the electrical load offered by a diesel generator and the grid in the majority of cases. For the present study, this electrical load is offered by the over-production of the RES-technologies used, and discharge occurs by slowing the spinning mass. In accordance the stored energy in a flywheel can be obtained as [8]:

$$E = \frac{1}{2} I \omega^2 \tag{3}$$

where I is the rotor inertia.

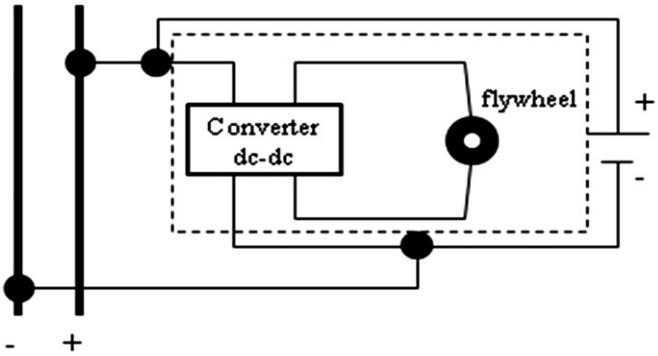

Fig. 1. The innovative storage system.

As shown, the most efficient way to increase the stored energy is to speed up the flywheel, but the speed limit is generally set by the tensile strength due to inertial loads and the materials used. This limitation can be partially overcome by using composite materials with low density and high tensile strength, which develop inertial loads and store kinetic energy more efficiently. The maximum kinetic energy per unit mass is given by [2]:

$$E_m = K \frac{\sigma}{\rho_{\text{met.}}} \tag{4}$$

where K is the shape factor and σ is maximum stress of the construction's flywheel metal.

2.2. Economical aspects

The performance analysis of a hybrid stand-alone system, where flywheels are used to store energy in combination with electrochemical batteries, is a very important step for the commercial use of FESS. However, a comparison with batteries in terms of economics is essential for an efficient decision on whether an advanced system can be proved feasible. Note that the capital and the net present cost of a RES-based stand-alone system are both quite high, and costs therefore one of the crucial parameters in designing such a system. In this study, the economic analysis is finalized by comparing the Net Present Cost (NPC) of the systems, representing the total cost for the investor at the end of the project lifetime, and is given as [15]:

$$C_{\text{NPC}} = \frac{C_{\text{an. tot}}}{\text{CRF}\left(i, R_{\text{proj.}}\right)} \tag{5}$$

Table 1
Scenarios for RES-based power plants.

Systems	Desirable load (kWh)	PV (kW)	Wind (kW)	Batteries	New batteries
PV, Wind and Hoppecke batteries	7775	1	1 × 5	4 (Hoppecke 3000 Ah)	–
PV, Wind and Surrette batteries		1	1 × 5	6 (Surrette 1900 Ah)	–
PV, Wind and Vision batteries		1	1 × 5	58 (Vision 55 Ah)	–
PV, Wind with flywheel and Hoppecke batteries		1	1 × 5	–	2 (Hoppecke 3000 Ah)
PV, Wind with flywheel and Surrette batteries		1	1 × 5	–	5 (Surrette 1900 Ah)
PV, Wind with flywheel and Vision batteries		1	1 × 5	–	10 (Vision 55 Ah)

Table 2
Operational characteristics of the new storage devices.

Operational characteristics	Flywheel + Hoppecke	Flywheel + Surrette	Flywheel + Vision
Round trip efficiency (%)	75.2	75.2	75.2
Nominal capacity (Ah)	4250	2525	263.33
Nominal voltage (V)	2	4	12
Minimum state of charge (%)	30	40	40
Float life (years)	30	30	30
Max charge rate (A/Ah)	3.926	3.856	3.606
Max charge current (A)	610	67.5	16.5
Lifetime throughput (cycles)	150,000	150,000	150,000

where $C_{\text{an. tot}}$ are the total annual system costs, and $\text{CRF}(i, R_{\text{proj.}})$ is the capital recovery factor, obtained by [15]:

$$\text{CRF}(i, R_{\text{proj.}}) = \frac{i(1+i)^{R_{\text{proj.}}}}{(1+i)^{R_{\text{proj.}}} - 1} \tag{6}$$

where $R_{\text{proj.}}$ is the project lifetime in years, and i is the real interest rate, given as [15]:

$$i = \frac{i' - A.I.R}{1 + A.I.R} \tag{7}$$

For the numerator in Eq. (5), the total annual cost of a system is the sum of total replacement, operational and maintenance costs and the salvage value of each component. The replacement costs are different for each component and are given by [15]:

$$C_{\text{an. rep.}} = C_{\text{tot. rep.}} f_{\text{rep.}} \text{SFF}(i, R_{\text{comp.}}) - S \quad \text{SFF}(i, R_{\text{proj.}}) \tag{8}$$

where $C_{\text{tot. rep.}}$ is the total replacement cost for each component at the end of its lifetime, $R_{\text{comp.}}$ and $R_{\text{proj.}}$ are the lifetime in years for a component and for the whole project, respectively, and $f_{\text{rep.}}$ describe the difference between component and project lifetime. For the scope of the present work, the second term of expression (8) does not equal zero because of the salvage value of some components at the end of the project's lifetime, given therefore as [15]:

$$S = C_{\text{tot. rep.}} \frac{R_{\text{rem. comp.}}}{R_{\text{comp.}}} \text{SFF}(i, R_{\text{proj.}}) \tag{9}$$

where $R_{\text{rem. comp.}}$ is the remaining years of life for each component and the sinking factor SFF is a ratio representing the future value of cash flows. SFF is calculated by [15]:

$$\text{SFF}(i, R_{\text{comp.}}) = \frac{i}{(1+i)^{R_{\text{comp.}}} - 1} \tag{10}$$

For the above-mentioned integrated mathematical model, the successful selection of different variables is crucial to obtain the appropriate results.

3. Simulations

For the needs of the present study, Naxos Island was chosen for the typical case-study, while the most efficient RES-based hybrid stand-alone system, studied elsewhere has been simulated here [10]. Moreover, an extensive study on the selection of electrochemical batteries took place during the system design stage. The present study is organized as follows: the first step was the construction of a hybrid photovoltaic-wind system which will cover the load of a typical house for one year. The second step was the choice of three different types of electrochemical batteries of different categories as a backup system for the energy produced in the system (powerful Hoppecke 3000 Ah batteries, deep cycle discharge Surrette 1900 Ah batteries and low power Vision 55 Ah batteries) as backup system for the energy produced at the established system. The same batteries were used for the simulations of the innovative storage system incorporating the flywheels. Finally, including flywheels to store energy in the hybrid system was achieved by constructing a new system, equivalent to a battery-type storage unit, combining a flywheel, a DC–DC converter and a battery. More precisely, the flywheel is permanently connected to a DC–DC converter for voltage regulation purposes between the devices (this is necessary due to the chosen DC current and parallel connection), as shown in Fig. 1.

The parallel connection of a flywheel and an electrochemical battery is an innovative approach for energy storage systems, therefore the results of these simulations are compared with those of conventional batteries to investigate if such a system is feasible in terms of energy and economy. A 10 kW high voltage flywheel was used in these scenarios and the main characteristics, arising from the advanced combination of the components, are the round trip efficiency and the maximum charge rate (A/Ah) that is higher than the most powerful commercial battery [16]. The values used in the simulations are presented in Table 2. Specifically, the hybrid battery banks using flywheels with batteries (named Flywheel + Hoppecke and Flywheel + Surrette) operate under

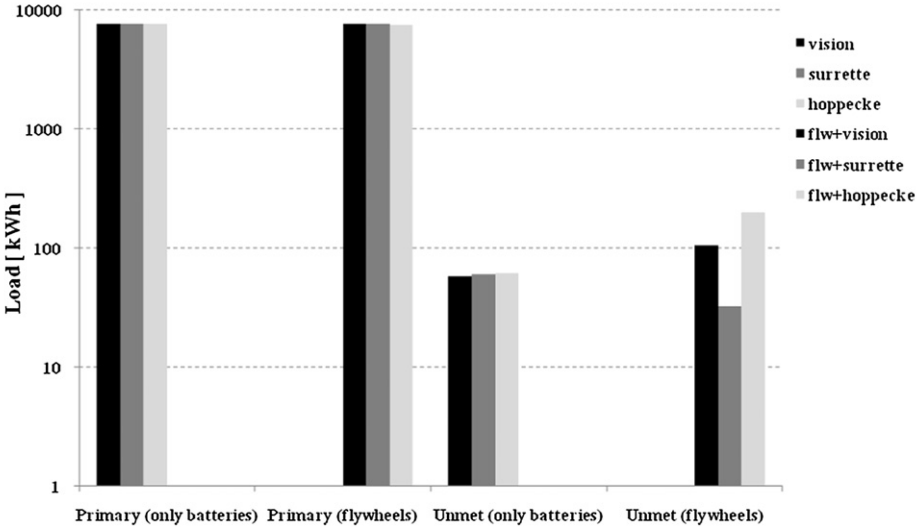

Fig. 2. Produced and Unmet load of each system.

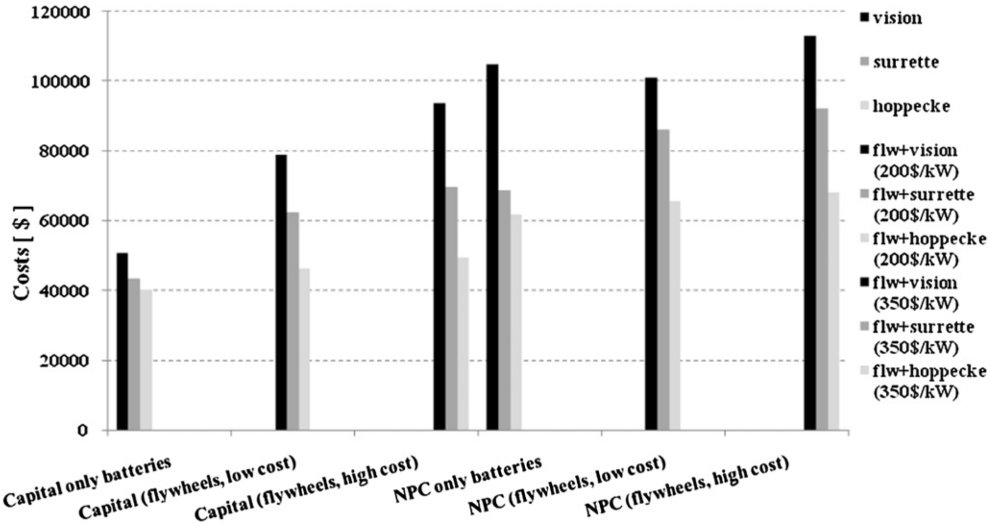

Fig. 3. Capital and Net Present Costs of each system.

a very low nominal voltage 2 V and 4 V, respectively, in accordance to the characteristics manufacturers provide. In order to adjust this low voltage with the standard 12 V outputs by PV and/or wind turbines, the use of DC–DC converters is essential for the balance of the whole system.

Regarding the economic issues of this innovative product, attention should be given to the lifetime of every component because it differs between flywheel, converter and battery. Therefore the economic study was finalized without the HOMER software tool which was used for the energetic optimization of the system [17]. The costs are calculated separately for each component and are added to the project's final budget. The lifetime of each battery, converter and flywheel were chosen to be 10, 15 and 30 years, respectively. Moreover, the nominal interest rate and annual inflation rate were chosen to equal those of the Euro zone, i.e. 4% and 1.6% respectively. During simulations, two different initial costs were used for the established flywheels: 200 $/kW and 350 $/kW, equivalent to the low and medium price [7,9].

4. Results and discussion

All possible scenarios of the different combinations of storage systems were designed and implemented in the HOMER software tool. The energy part of this optimization procedure was performed using HOMER but the economic study was finalized by hand using the mathematical model presented above. The main drawback, faced using HOMER, was that the specific simulation software tool incorporated flywheels in the form of load to be covered, rather than an energy, storage device. For this reason, the generation of the new storage system was considered essential for the incorporation of flywheels into a hybrid stand-alone system.

In accordance with the above-mentioned points, the scenarios were designed as presented in Table 1. Through system optimization, it can be seen that each accomplishes the requirements to cover the desirable load of a typical house, (=7775 kWh/year). The desirable load (primary) and the unmet load both, produced by the stand-alone RES-based systems, are presented in Fig. 2 which shows that the unmet load fluctuates at low levels. Furthermore,

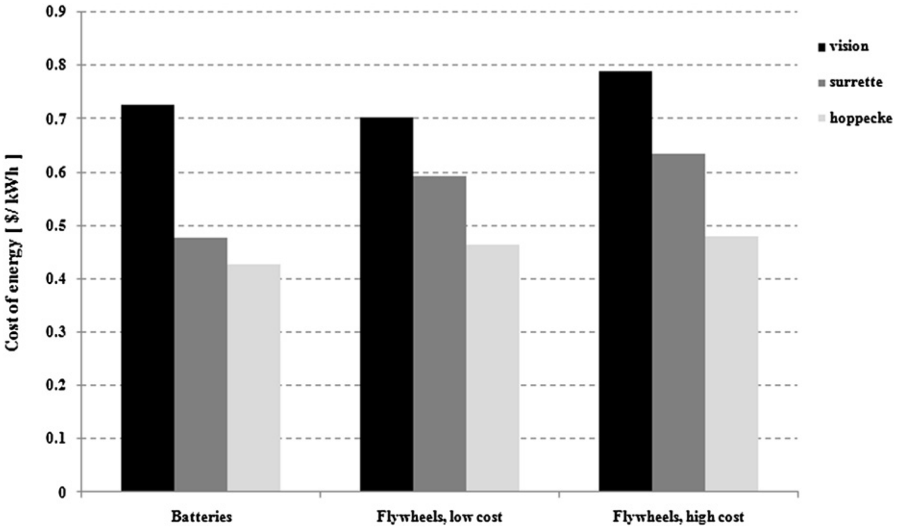

Fig. 4. Levelized Cost of Energy of the systems.

the lowest unmet load is present in systems with flywheels combined with Surrette batteries, and the highest appears in systems with flywheels and Hoppecke batteries. Although Hoppecke batteries are the most powerful, the economic optimization forces the system to operate without an extra new battery because the cost will increased greatly and, at the same time, the gain in energy level will be limited.

The optimization of a system is always related to economic issues, thus a stand-alone RES-based system with FESS as backup energy can be profitable, as depicted in Fig. 3. Initially the capital costs of systems with electrochemical batteries are lower than systems with flywheels because the materials used for both low and mid-cost flywheel construction are very expensive regarding their performance. However, the final decision on a profitable investment has to take into account the NPC of the systems. An investor can take advantage of the higher flywheel lifetime and Fig. 3 shows that the NPC of the systems with flywheels is comparable to this with the simple storage technologies. Moreover, Fig. 3 shows that the low price flywheels used (200 $/kW) corresponds to systems with NPC strongly comparable to that of more conventional systems using stacks of batteries for energy storage.

Finally, the cost of the produced energy is one of the main criteria for an investor to decide the best scenario for building a hybrid RES-based stand-alone system, based on advanced technologies like flywheels. This cost is presented in Fig. 4 for all the scenarios simulated. The above results are confirmed since all the combinations are comparable while systems with low price flywheels are found equivalent to those with electrochemical batteries. For the case of Vision batteries combined with flywheels, the produced energy cost (0.703 $/kWh) is lower than the simple system with 58 Vision batteries (0.725 $/kWh).

5. Conclusion

In the present study, nine different RES-based scenarios were simulated on Naxos Island, Greece. Three of them used electrochemical batteries as backup energy while the other six used a combination of electrochemical batteries and flywheel systems. Simulations were carried out using a modified hand-made calculation system and HOMER software. Electrochemical batteries as storage devices can be considered the “standard” solution for continuous operation of the RES-based stand-alone systems. The use of flywheels in combination with classic batteries is proven to be feasible here, where it is shown that all the hybrid systems could cover the desirable load of a typical house. Moreover, it is observed that although the initial costs of systems with simple batteries are much lower, systems combining flywheels can be competitive because the NPC of the different systems are equivalent. This is further strengthened by the Levelized Cost of Energy for the systems, which is comparable and in some cases, when using flywheels is lower. Finally, this innovative method of energy storage shows that flywheel systems could be commercialized in the near future.

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Glossary

Latin Symbols
A: Surface Area (m^2)
A.I.R: Annual inflation rate
C: Cost (€)
CRF: Capital recovery factor
E: Energy (J)
f: Factor
G: Solar radiation (W/m^2)
i: Real interest rate (%)
I: Inertia of the rotor ($kg\ m^2$)
i': Nominal interest rate (%)
K: Shape factor
R: Lifetime for each component (yr)
P: Power (W)
r: Radius of the rotor (m)
S: Salvage value (€)
SFF: Sinking factor
T: Temperature (°C)
u: Velocity (m/s)
x: Distance (m)

Greek Symbols
α: Temperature coefficient (%/°C)
ρ: Density (kg/m^3)
σ: Stress in the rotor of flywheel (N/m^2)
ω: Angular flywheel's speed (m/s)

Subscripts
air: Atmospheric air
an. rep.: Annualized replacement costs
an. tot.: Total annualized costs
C: Photovoltaic cell
comp.: Component
der. PV: Derating photovoltaic factor
m: Unit mass
met.: Metal of construction
NPC: Net present cost
Oper: Operational
P: Power
proj.: Project of establishment
rem. comp.: Remaining component's lifetime
rep.: Replacement component's years
solar: Solar potential
STC: Standard test conditions
T: Temperature
tot. rep.: Total replacement years
wind: Wind potential