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**COMPARISON OF FLYWHEEL WITH ELECTROCHEMICAL BATTERIES FOR ENERGY STORAGE IN
DECENTRALIZED APPLICATIONS**

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Abstract

In developing countries like India, with rapid growth in the economy, the demand for electricity is also increasing. As the renewable energy percentage increases in the total energy mix, the inherent intermittency and variability of renewable energy sources poses a challenge when these energy sources are integrated. This is where energy storage becomes very critical as it improves the dispatch rate of the electricity generated by renewable energy resource. With the rising demand for reliable, cost-effective, and environmentally friendly energy storage, the Flywheel Energy Storage System (FESS) is quickly coming into its own. This study presents an analysis which shows that using an FESS is a promising alternative in mitigating energy storage problems in decentralized electricity generation projects where an uninterrupted power supply (UPS) is required. With the help of HOMER simulations, we have tried to establish that energy storage through flywheel is a viable option.

Key words: FESS, BESS, Decentralized System, UPS, HOMER, NPC, COE and RES hybrid.

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1. INTRODUCTION

Renewable Energy Sources (RES) are characterized by their unpredictable behavior and their intermittent nature. Therefore during their non-availability or during peak load demand, energy storage plays an essential role for an uninterrupted power supply, especially for decentralized electricity generation projects^[1]. There are many energy storage technologies at different stages of technical and commercial development. Previous case studies and literature reviews show us that electrochemical battery energy storage system (BESS) have always been the first preference and hence extensively used for energy storage in decentralized electricity generation projects.

But, our learning at The Energy and Resources Institute (TERI), New Delhi, India brings out various issues that are encountered in the service, operation and supply of batteries. Challenges are faced at the technological front regarding problems of deep discharge, low lifecycle and low shelf life amongst many others, and on the management side with proper scheduled maintenance and training at end users level. In decentralized projects, the use of electrochemical batteries requires replacements after every 2 to 4 years, which leads to high battery maintenance and replacement costs for the end users. Secondly, the issue of the batteries' recyclability is another factor increasing logistic costs.

Flywheel Energy Storage systems (FESS) using advanced technology have come up as a promising alternative to the traditional electrochemical battery^[6]. The amount of energy storage depends on the mass, flywheel shape, and rotational speed of the rotor^[2]. A FESS can have energy fed into the rotational mass of a flywheel, store it as kinetic energy, and release it upon demand. FESS's have several significant advantages over conventional electrochemical batteries. In comparison to the latter, FES systems have a longer lifespan and a considerably shorter charge time – usually of less than 20 minutes. Apart from this, the high energy efficiency of up to 90% and better energy densities stands out, as well as the comparatively low maintenance requirements. Also, FES systems offer a huge variety of protection from sudden load fluctuations to power plants at different levels^{[5], [6]}.

Flywheels are considered to be a part of green technology as their raw materials are completely recyclable and they do not involve any toxic chemicals for their operation. However, they have some drawbacks as well, which include a limited storage time of 5 seconds to 15 minutes for the majority of FESS commercially available^[5], and 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^{[8], [9]}.

FESS technology is not used commercially due to its high capital cost. The cost of an FESS directly depends on the target storage time. It can cost from around \$200 to \$500 per kW for several minutes and \$1000 to \$3000 per kW for 1 hour. However, flywheels in this range are not used commercially^{[8], [10]}. In this paper, low cost flywheels within the range of \$300/kW to \$700/kW have been considered for our analysis^[1].

Applying National Renewable Energy Laboratory's (NREL) software "Hybrid Optimization Model for Electric Renewable (HOMER) version 2.68 beta" this study presents an analysis for choosing the most techno-economically viable energy storage system along with the best hybrid of renewable energy technologies for a given case. The energy costs of both FES system and conventional batteries in the given case are determined and compared with the help of a life cycle cost analysis; the result being that the inclusion of an FESS as a storage device can reduce the cost of energy to a significant extent. The inclusion of an FESS would also lead to a decrease in the number of power

disruptions. In the end, the conclusion will be reached that both regarding energy and economic feasibility, power generation systems with low price FES are equal to those with conventional batteries and thus decentralized projects can be carried out being based solely and completely on “green” technologies.

2. LITERATURE REVIEW

George et al. did simulations of techno-economic feasibility between BESS and FESS and found that an off-grid project using advanced and totally “green” technologies is possible and comparable [1]. Islam et al. used HOMER for sizing and simulation on FESS for an isolated wind-hydrogen-diesel hybrid. Their work showed that an addition of FESS to the system reduces the voltage and frequency fluctuations and number of generator switching over a period of time [2]. Okou et al. designed a rotor to manufacture for rural energy storage in sub-Saharan Africa. On this they did a life cycle cost analysis to compare the energy costs between a lead acid battery system and a flywheel rotor system. It was found that a saving of 37% per kWh for rural system installations could be achieved by integrating the FESS into Solar Home Systems [3].

Khan and Pillay accessed the potential impact of small scale FESS technology on Uganda’s energy sector [4]. Reed and Malcom did a comparison of high-speed flywheels, batteries, and ultra-capacitors on the bases of cost and fuel economy as the energy storage system in a fuel cell based hybrid electric vehicle. Their results showed that with consideration of both cost and fuel economy, high speed flywheels were a better option to batteries and ultra-capacitors [13]. Carrillo et al. did a comparative study of flywheel systems with constant speed flywheel, a variable speed one based on a power electronic converter, and the proposed system is made by means of simulations in order to evaluate the behavior of this configuration for an isolated wind plant [14].

Liu and Jiang said with the aid of new technologies the cost of FES can be lowered and the FES will play a significant role in securing global energy sustainability [15]. Jerbi et al. developed a fuzzy logic that established control over the FESS operation and the DC bus voltage in order to smooth the active power fluctuations due to the random wind speed variations [16]. Bai et al. developed an FESS with active magnetic bearings and provided an important direction for the application [17].

The predominant parts of prior studies have been directed towards optimizing mechanical issues whereas the electro technical parts now seem to show great potential for improvement.

3. METHODOLOGY

In this paper, the life cycle analysis has been considered to compare the levelized cost per unit of energy and the net present cost for the entire evaluation period of the project, reflecting upon the capital costs and the operating cost for different systems. This is envisaged to give a more realistic cost of energy evaluation. HOMER software is used to design the system and for the suitable sizing of the FESS. For this analysis on HOMER, certain assumptions were made; the project lifetime was

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taken to be 20 years with the discount rate of 10%. Two separate simulations were done, scenario 1 with FESS and scenario 2 with BESS. The technical specifications and all types of costs of all the components in the system – except for the battery and flywheel components – were assumed to be the same in both scenarios, thus allowing for a better comparison between the two scenarios.

The daily load of a decentralized system for uninterrupted power supply was assumed based on our learning of various projects at TERI, secondary sources and end user consultations, for this analysis is shown in figure 3.1. It has an average daily energy demand of 170kWh/day with a 22kW peak load.

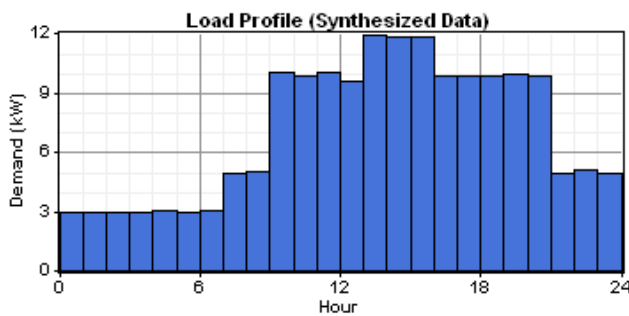


Fig 3.1. Load profile for the decentralized system with uninterrupted power supply

The system designed in HOMER to serve this UPS load in both the scenarios is shown in figure 3.2a and 3.2b below. These figures show the system architecture of scenario 1 with a SE25 flywheel as FESS and scenario 2 with a BESS for serving the decentralized load.

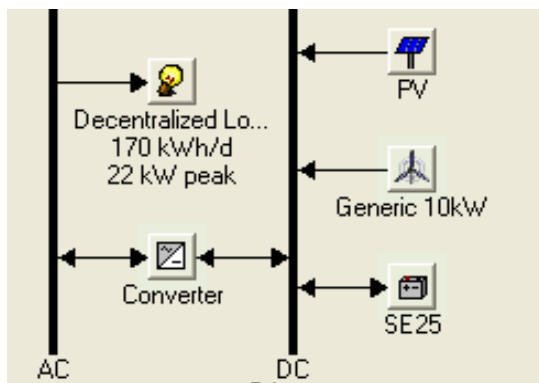


Fig 3.2a. System architecture for scenario 1

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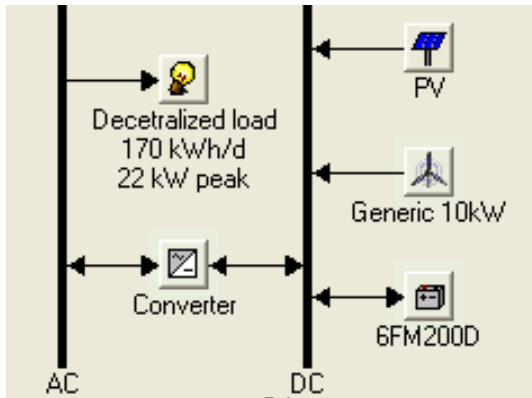


Fig 3.2b. System architecture for scenario 2

In scenario 1, a 25kWh rated capacity flywheel of 120V, 208Ah with a lifetime throughput of 100,000kWh was selected. A Smart Energy (SE25) flywheel from Beacon Power Corporation is used for this system, which has a highly cyclic capability, smart grid attributes, 20-years design life and is considered a sustainable technology ^[2]. In scenario 2, batteries of 12V, 200Ah with a lifetime throughput of 917kWh were used.

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Figure 3.3 show the Monthly average solar insolation at the selected location of 29o50'N, 79o59'E. The scaled annual average solar insolation was 5.24kWh/m²/d.

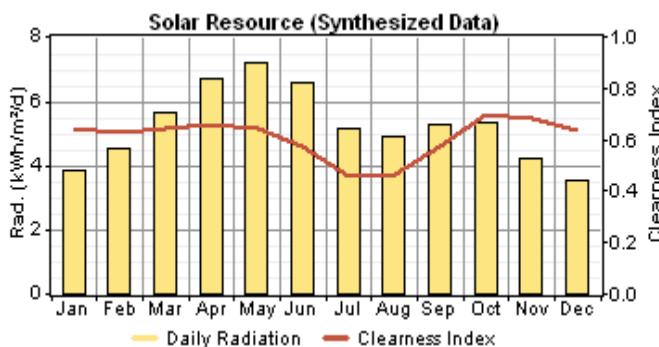
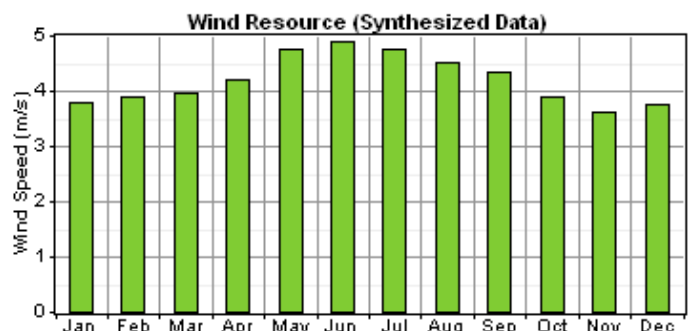


Fig 3.3. Monthly average solar insolation at the selected location. (Source: - NASA website)

Fig 3.4. Monthly average wind resource at the selected location. (Source: - NASA website)



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The scaled annual average of wind resource was 4.2m/s. Figure 3.4 show the monthly average wind resource of the selected location.

As the focus of the analysis in this paper is more on energy storage, therefore we would not go into detail of RE resource and RE technology analysis. The techno-economics of the resources and technologies in both the scenarios have been kept the same, so that an exact comparison can be done between FESS and BESS.

The cost analysis done with HOMER in scenarios 1 and 2 do not consider any subsidies and cash inflows for the cash flow calculation. It is merely based on capital costs, operation and maintenance cost, replacement and fuel costs. For the FESS, the capital cost was considered to be of \$500/kWh, the replacement cost to be 100% of the capital cost and the expenses for operation and maintenance to be 1% of the capital cost. For the BESS, in contrast, the capital cost was considered to be \$300 per battery, the replacement cost to be 75% of the capital cost and the operation and maintenance expenses to amount to 5% of the capital cost (*the prices considered in this analysis for all components and equipment's are an interpolation of data from TERI, (quotations) obtained from manufacturers, distributors and previous published literatures*).

4. RESULTS AND DISCUSSION

Simulations in HOMER were carried out and it was found the technical configuration of the RES hybrid system with energy storage selected by HOMER for scenarios 1 and 2 consists of 40kW of Solar-PV, a 10kW wind turbine, 20kW of converters with five numbers 25kWh flywheels in scenario1 and 200 numbers of 12V, 200Ah batteries in scenario2 are required to meet the assumed decentralized demand load of 170kWh/day at 22kW peak.. A life cycle cost analysis of an FESS and a BESS is shown below in figure 4.1a and 4.1b.

The levelized cost of energy (COE) for the system using BES was found to be \$USD 0.555/kWh and for the FESS was \$USD 0.436/kWh. The net present cost (NPC) of a BESS was found to be \$USD 276,408 and for the FESS was \$USD 226,118. The results screens of the HOMER simulations for the different energy storage systems are shown in Figures 4.1a and 4.1b below.

Sensitivity Results		Optimization Results															
Sensitivity variables																	
Wind Speed (m/s)	5	Diesel Price (\$/L)	0.8	Simulation Time Step (min)	10	Min. Ren. Fraction (%)	30										
Double click on a system below for simulation results.																	
System	PV (kW)	G10	DG (kW)	SE25	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	DG (hrs)	Batt. Li. (yr)		
Scenario 1	40	1		5	20	CC	\$ 201,500	2,892	\$ 226,118	0.436	1.00	0.05			16.4		

Fig 4.1a. Life cycle cost analysis of scenario 1

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Fig 4.1b. Life cycle cost analysis of scenario 2

The optimization of a system will always be based on economic considerations; investors will always be considering the profitability of their investment as of the utmost importance.

The results found in the HOMER simulations and depicted above show that the use of an FESS as backup for a decentralized RES hybrid system can be profitable, even though the initial capital costs of BESS's will be lower. The reason for these higher costs is the use of very expensive materials both in low- and mid-cost flywheels.

However, crucial factors to determine the different systems' respective profitability and main criteria for an investor's decision for the best scenario to build a hybrid RES-based decentralized system with UPS are the NPC and COE. Here, the higher lifetime of flywheels offers considerable advantages. In the end, both the COE and NPC of systems employing low price flywheels will be even lower than the COE and NPC of systems using stacks of electrochemical batteries for energy storage.

5. CONCLUSION

Using two different scenarios, the life cycle costs of the traditional electrochemical battery storage system and a flywheel energy storage system have been compared for a hybrid RES-based decentralized system with UPS.

In the long run, an FES system has been found to be more cost effective than the conventional electrochemical battery. Furthermore, even though the initial capital cost of a BESS will be lower, FESS's have the crucial advantage of an NPC and COE that is lower than that of a BESS. In the analysis carried out, the use of an FESS instead of a BESS in the given system design lead to a reduction of the NPC by 18.19% and a reduction of the COE by 21.44%.

Though this analysis was done for the given assumed case, even then it is very much replicable, even with changes in load profile and RES, this concept of FESS with RES-hybrid is still applicable with upscaling and downscaling of the flywheel's rated capacity and quantity.

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Apart from the above technical and economical benefits, the use of FESS would also mitigate the environmental problems associated with electrochemical battery disposal. These systems can also be used in health centers and telecommunication base stations as they fall within the energy range of UPS.

These advantages of flywheel energy storage argue strongly in favor of a commercialization of flywheels in the near future.

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OASYS South Asia project

The Off-grid Access Systems for South Asia (or OASYS South Asia) is a research project funded by the Engineering and Physical Sciences Research Council of UK and the Department for International Development, UK. This research is investigating off-grid electrification in South Asia from a multi-dimensional perspective, considering techno-economic, governance, socio-political and environmental dimensions. A consortium of universities and research institutes led by De Montfort University (originally by University of Dundee until end of August 2012) is carrying out this research. The partner teams include Edinburgh Napier University, University of Manchester, the Energy and Resources Institute (TERI) and TERI University (India).

The project has carried out a detailed review of status of off-grid electrification in the region and around the world. It has also considered the financial challenges, participatory models and governance issues. Based on these, an edited book titled “Rural Electrification through Decentralised Off-grid Systems in Developing Countries” was published in 2013 (Springer-Verlag, UK). As opposed to individual systems for off-grid electrification, such as solar home systems, the research under this project is focusing on enabling income generating activities through electrification and accordingly, investing decentralised mini-grids as a solution. Various local level solutions for the region have been looked into, including husk-based power, micro-hydro, solar PV-based mini-grids and hybrid systems. The project is also carrying out demonstration projects using alternative business models (community-based, private led and local government led) and technologies to develop a better understanding of the challenges. It is also looking at replication and scale-up challenges and options and will provide policy recommendations based on the research.

More details about the project and its outputs can be obtained from www.oasyssouthasia.dmu.ac.uk or by contacting the principal investigator Prof. Subhes Bhattacharyya (subhesb@dmu.ac.uk).

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