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Long-Discharge Flywheel Versus Battery Energy Storage for Microgrids: a Techno-Economic Comparison

Eugene Agusan Esparcia Jr.[a], Michael Tan Castro[a], Roger Evangelista Buendia[b], Joey Duran Ocon[a,*]

[a]Laboratory of Electrochemical Engineering (LEE), Department of Chemical Engineering, College of Engineering, University of the Philippines Diliman, Philippines
[b]Energy Engineering Program, National Graduate School of Engineering, University of the Philippines Diliman, Philippines
jdocon@up.edu.ph

The energy storage deployment becomes necessary as more renewable energy sources are being installed to achieve sustainable energy access in off-grid areas. Battery prices, however, still hinder massive deployment. One of the energy storage technologies being developed for microgrid applications are flywheels, which stores energy through rotational kinetic energy and are typically suited for high power applications. With the advent of long-discharge flywheels, such as those being marketed by Amber Kinetics® and Beacon Power®, they can be used in microgrids, which are dominated by batteries. This study provides a techno-economic comparison with sensitivity analysis between long-discharge flywheel and utility-scale lithium-ion battery for microgrid applications. The results show lowest levelized cost of electricity (LCOE) for flywheel-based hybrid energy system with 0.345 USD/kWh and renewable share of 62.4 % among tested configurations. The competitiveness of long-discharge flywheel over lithium-ion battery in the microgrid market depends on the diesel prices, expected reduction in lithium-ion battery prices, and improvements in lithium-ion battery lifespan.

1. Introduction

Energy storage deployment is increasing in recent years due to the increasing integration of renewable energy (RE) sources and increasing microgrid deployment. Microgrids have a huge potential to provide sustainable energy access and resiliency especially in off-grid areas such that various sectors have come up with different optimization and simulation techniques, and test appropriate energy system component combinations. For example, there are studies that incorporate advanced optimization and simulation techniques for microgrids such as chance-constrained programming (Lu et al., 2017), mixed-integer linear programming (MILP) with task interruption (Silvente and Papageorgeiu, 2017), and Power Pinch Analysis with uncertainties (Norbu and Bandyopadhyay, 2017). The viability of different energy system combinations is also being studied such as wind-pumped hydro configuration in China (Lee et al., 2018), and solar-biomass hybrid energy system in United Arab Emirates (Ghenai and Janajarah, 2016).

For microgrids, electrochemical energy storage technologies such as lead-acid, lithium-ion, sodium-sulfur, and vanadium redox-flow batteries are used to support RE sources. They are typically modular, scalable, with high energy density, and with low self-discharge (Moseley and Garche, 2015). However, the battery cost especially for lithium-ion battery is still prohibitive for widespread microgrid deployment (Schmidt et al., 2017).

One of the energy storage technologies being considered for microgrid applications are flywheels, which stores energy through rotational kinetic energy. The maximum rotational kinetic energy of flywheel is highly dependent on the maximum tensile strength of the flywheel material and rotor shape (Amiryar and Pullen, 2017). The key advantages of flywheels over batteries are safer, wider operating temperature, lower supply risks, and higher ease of recyclability. Flywheels are typically used for applications requiring high power applications and high cycle frequency (Moseley and Garche, 2015) such as uninterruptible power supply (UPS), power smoothening, and frequency regulation for microgrids (Arani et al., 2017).

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In recent years, companies such as Amber Kinetics® and Beacon Power® are promoting long-discharge flywheel for applications where batteries traditionally operate such as microgrids. So far, there are no publicly available academic study that tackled the use of long-discharge flywheel for RE support in microgrids. The applicability of long-discharge flywheel energy storage for microgrid application is explored by assessing its techno-economics when using solar photovoltaic (PV)-based energy systems. For this work, Busuanga Island, located north of Palawan Island, Philippines, is arbitrarily chosen for case study. A comparison between flywheel energy storage and battery energy storage is elucidated with sensitivity analysis on diesel price, lithium-ion battery price, and lithium-ion battery lifespan.

2. Data and methods

The Island Systems $LCOE_{min}$ Algorithm (ISLA) application (Castro et al., 2018), which is validated using HOMER^{TM} Pro (HOMER Energy, 2017) software, is used for microgrid simulation and optimization. The main economic parameter used for optimization is levelized cost of electricity (LCOE), which accounts for the total cost of the energy system per energy generated within the project lifespan. The following equation describes the equation for LCOE:

$$LCOE=\frac{\left[\frac{i(1+i)^{t_s}}{(1+i)^{t_s}-1}\right]\left[C_{NPC,total}\right]}{E_{served}} \tag{1}$$

where $C_{NPC,total}$ is the total net present cost (includes capital expenditure (CapEx), operations and maintenance (O&M) cost, replacement cost, and fuel cost), E_{served} is the electricity served to the load demand [kWh], i is the inflation rate, and t_s is the project lifespan. Projected future cost of lithium-ion battery is already incorporated in the calculations (Schmidt et al., 2017) while projected future cost of flywheels were not accounted due to lack of reliable pricing data appropriate for microgrid applications.

Table 1 summarizes of the techno-economic assumptions used throughout this work. Note that the depth of discharge (DOD) is the ratio of allowable capacity to be discharged to the total capacity in fraction values.

Table 1: Techno-economic assumptions used for optimization and simulation

Resource	Parameter	Unit	Value	Resource	Parameter	Unit	Value
Load (Busuanga)	Total	GWh	21.8	Flywheel	Roundtrip efficiency		0.86
	Peak	MW	4.4		Max. DOD		1.00
Solar PV	CapEx	USD/kW	1,200	Diesel	CapEx	USD/kW	500
	OpEx	USD/kW/y	25		OpEx	USD/kWh/y	5
	Lifetime	y	20		Fuel Cost	USD/dm^3	0,9
Li-ion	CapEx	USD/kWh	300		Fuel inflation rate		0
	OpEx	USD/kWh/y	3		Lifetime	H	15,000
	Lifetime (max)	y	10		Efficiency		[0.30, 0.40]
	Roundtrip efficiency		0.90	Project	CapEx	USD	0
	Max. DOD		0.80		OpEx	USD/y	0
Flywheel	CapEx	USD/kWh	600		Lifetime	y	20
	OpEx	USD/kWh/y	6		Inflation		0.1
	Lifetime (max)	y	20		Operating reserve		0.10

The renewable energy (RE) share, which is the total energy generated by renewable energy generators and discharging energy storage directly serving the load per total energy generated by all generators, is also calculated. For this work, the RE share is not optimized. The load-following method is used as the dispatch algorithm where the excess solar PV power generation during day-time is used to charge the battery. The battery will be used to power the load in the night-time. If the battery and/or solar PV cannot supply the load demand, the diesel generators will run to meet the load demand. Despite current installations of diesel and bunker fuel generators in Busuanga Island, the diesel generator size is assumed to be 110 % of the peak demand for demonstration purposes and to account the 10 % stability criterion. The normalized load profile is based from previous work (Ocon and Bertheau, 2019) and adjusted based on the peak load of the area.

For the flywheel model, the behaviour is derived from the Amber Kinetics Model 32 (Amber Kinetics, 2018). The following equation is used for modelling flywheel operation for microgrid applications (Blechinger, 2015), which is an idealized energy storage equation:

$$\mathrm{SoC}(t+1) = \mathrm{SoC}(t) - \frac{P(t)\Delta t}{S_{\mathrm{flywheel}}} \tag{2}$$

where SoC(t) is the state of charge (i.e. the available capacity at time t, in fraction values), P(t) is the power at timestep t [kW], Δt is timestep [h], and S_{flywheel} is the flywheel size [kWh]. The C-rate (C_{rate}), which is the rate where total storage capacity is fully discharged in a given time, used for flywheel is 0.25 (i.e. the total storage capacity will be fully discharged in 4 hours) to reflect the general behaviour of Amber Kinetics Model 32. The power output is restricted using the following equation:

$$|P(t)| \leq C_{\mathrm{rate}} S_{\mathrm{flywheel}} \tag{3}$$

3. Results and discussion

The optimal energy system configuration and component sizes in Busuanga Island were evaluated with selection based on the lowest LCOE possible. The LCOE of the hybrid energy systems and 100 % RE energy system configuration were compared to a diesel-only system. The sensitivity of LCOE towards diesel prices, lithium-ion battery prices, and lithium-ion battery lifespan were also evaluated in order to have a better understanding on the effects of externalities toward the economics of microgrids.

3.1 Comparison of energy systems

Table 2 shows the different energy system configuration with their optimal component sizes, LCOE, and RE share for Busuanga Island. Among tested energy systems configuration, the solar PV / diesel / flywheel configuration yielded the lowest LCOE. This result can be attributed to the reduced diesel fuel use and high lifespan of flywheels. It is worth noting that the LCOE of the solar PV / diesel / flywheel configuration is comparable to the solar PV / diesel / lithium-ion configuration. If these energy configurations were compared based on their RE share, then the solar PV / diesel / flywheel configuration yields the higher RE share. The higher RE share is due to the high depth of discharge (DOD) by flywheel. For 100 % RE scenario, the LCOE of solar PV / flywheel and solar PV / lithium-ion battery are higher than the current grid price (i.e. diesel only system). This is due to oversizing of energy systems components to meet the load demand. The flywheel size is smaller than lithium-ion battery due to its high DOD. However, the LCOE for 100 % RE scenario using flywheel is higher relative to the lithium-ion battery due to higher flywheel cost relative to lithium-ion battery.

Figure 1 compares the power flows of the hybrid energy systems using either lithium-ion battery or flywheels for a representative seven-day period in the reference year. The results validate the typical operation in load-following algorithm where excess generation is used to charge the energy storage, and then energy storage is used during night-time operation. Flywheels displace more diesel operation time than lithium-ion battery due to high DOD, which correspondingly results to a higher RE share.

Table 2: Optimal Energy System Configuration for Busuanga Island

System Configuration	Generation Component [MW]	Storage Component [MWh]	LCOE [USD/kWh]	RE Share [%]
Diesel	4.81		0.434	0.0
Solar PV / Diesel	9.80 (Solar PV); 4.81 (Diesel)		0.371	38.0
Solar PV / Diesel / Lithium-ion battery	11.51 (Solar PV); 4.81 (Diesel)	11.63	0.349	50.5
Solar PV / Diesel / Flywheel	13.72 (Solar PV); 4.81 (Diesel)	15.81	0.345	62.4
Solar PV / Lithium-ion battery	34.42	86.38	0.467	100.0
Solar PV / Flywheel	33.44	67.86	0.492	100.0

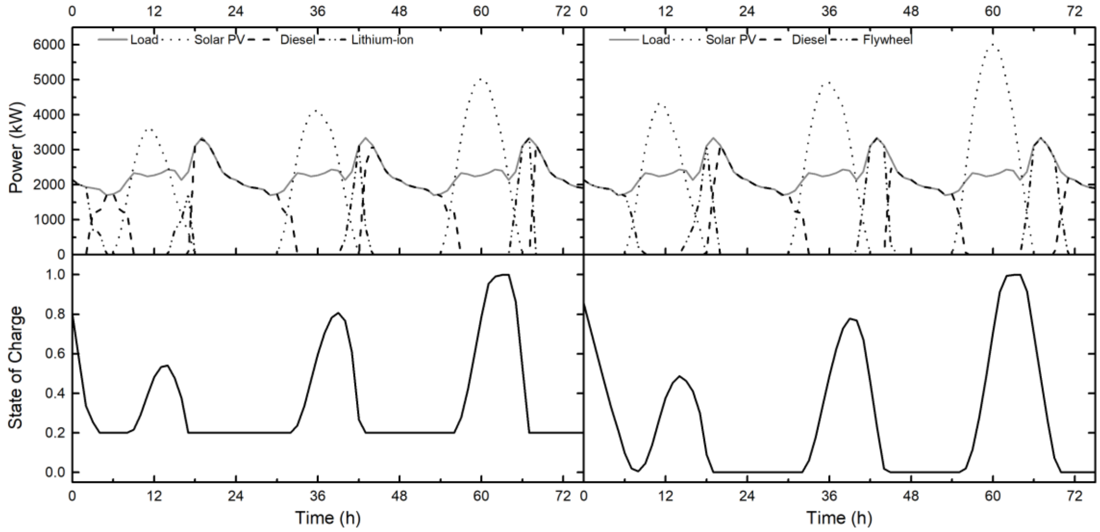

Figure 1: Power and energy storage state of charge curves of solar PV / diesel / flywheel energy system (left side) and solar PV / diesel / flywheel energy system (right side) in Busuanga Island.

3.2 Sensitivity Analysis

Figure 2 shows the LCOE sensitivity of different energy systems configuration towards diesel price (base price of 0.90 USD/dm^3). This is generated by doing the same methodology for LCOE optimization but changing the diesel prices while other parameters are held constant. The results suggest that solar PV / diesel / flywheel configuration is preferred when diesel price is between 0.90 (1.0 x) to 1.20 (2.0 x) USD/dm^3. When diesel price is below 0.90 USD/dm^3, the solar PV / diesel / flywheel configuration is still preferred but comparable to the solar PV / diesel / lithium-ion battery configuration due to increased diesel fuel use. The solar PV / lithium-ion battery configuration is preferred when diesel price is above 1.20 USD/dm^3, enabling 100 % RE scenario. As discussed earlier, the low cost of lithium-ion battery relative to flywheel enables the preferred deployment of solar PV / lithium-ion battery configuration over solar PV / flywheel configuration.

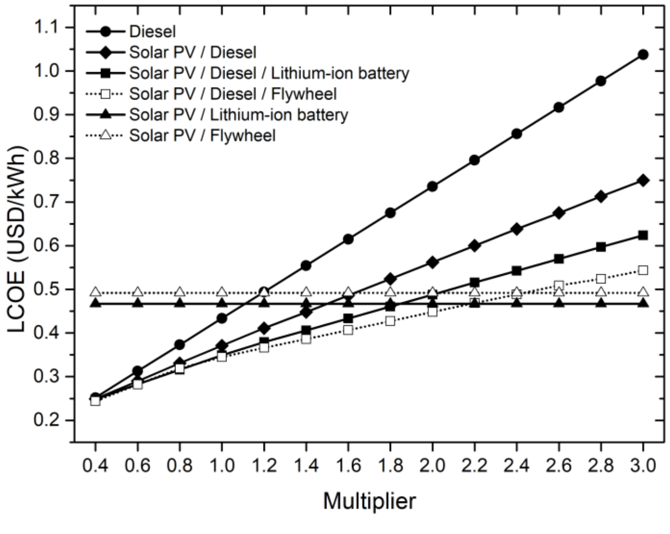

Figure 2: Sensitivity analysis of LCOE to the diesel prices in Busuanga Island

Figure 3 shows the LCOE sensitivity of different energy systems configuration towards Li-ion battery prices (base: 300 USD/kWh). This is also generated by doing the same methodology for LCOE optimization but changing the lithium-ion battery prices while other parameters are held constant. The results suggest that the solar PV / diesel / flywheel configuration is preferred when lithium-ion battery prices are above 300 USD/kWh.

Slight decrease in lithium-ion battery price will prefer solar PV / diesel / lithium-ion battery configuration. This scenario is likely since future forecast suggests that lithium-ion batteries will decrease rapidly in short to medium-term covering wider applications (Schmidt et al., 2019). This outlook implies that the LCOE advantage of solar PV / diesel / flywheel configuration may be short lived.

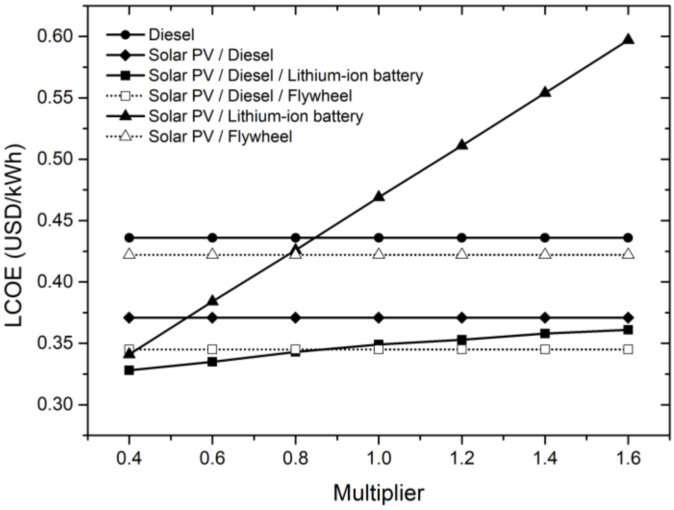

Figure 3: Sensitivity analysis of LCOE to Li-ion battery price in Busuanga Island

Figure 4 shows the LCOE sensitivity of different energy systems configuration towards Li-ion battery lifespan (base: 10 years). This is also generated by doing the same methodology for LCOE optimization but changing the battery lifespan while other parameters are held constant. The results suggest that solar PV / diesel / flywheel configuration is preferred as battery lifespan increases but its LCOE is comparable to solar PV / diesel / lithium-ion battery. The LCOE change of solar PV / diesel / lithium-ion battery configuration is relatively small due to low diesel cost. The LCOE curve of solar PV / lithium-ion battery configuration follows a non-linear behavior relative to battery lifespan due to the change in periodicity of battery replacements within the project lifespan. However, the LCOE of solar PV / lithium-ion battery configuration with 20-year battery lifespan is lower compared to the solar PV / flywheel configuration and diesel-only configuration. This imply that improvements of lithium-ion battery lifespan pose a threat to flywheels in enabling 100 % RE scenario.

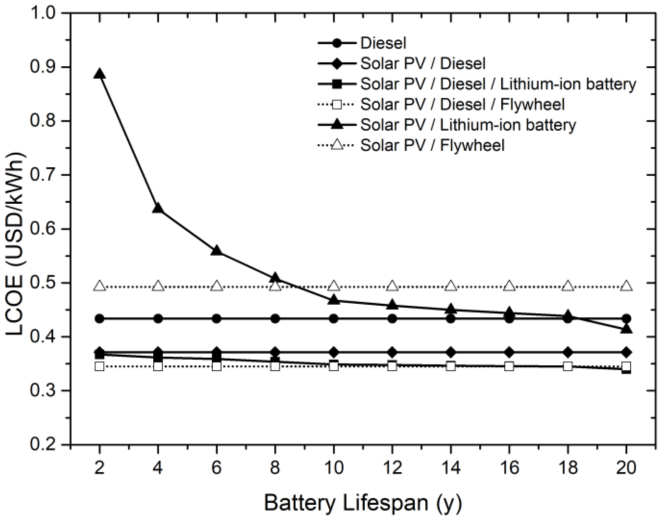

Figure 4. Sensitivity analysis of LCOE to Li-ion battery lifespan in Busuanga Island

4. Conclusions

Long-discharge flywheel energy storage provides a promising alternative energy storage technology for microgrid applications, especially in the Philippines due to potential electricity cost reduction. In particular, solar PV / diesel / flywheel energy configuration for Busuanga Island yields the lowest levelized cost of electricity (LCOE) with 0.345 USD/kWh and 62.4 % RE share. Flywheels in hybrid energy system configuration offer higher RE share relative to lithium-ion batteries. The power flow of solar PV / diesel / flywheel energy configuration validates the microgrid operation in load-following dispatch algorithm. Flywheels in hybrid energy configuration are preferred at diesel price regime of around 0.90 to 1.20 USD/kWh. The LCOE advantage of long-discharge flywheel is threatened if lithium-ion battery prices fall below 300 USD/kWh. In addition, improvements in lithium-ion battery lifespan to 20 years pose a threat to the LCOE advantage of flywheels, especially in enabling 100 % RE scenario. This work hopefully offers a realistic ballpark perspective for flywheel developers in order to come up with sound techno-economic strategies to capture the microgrid market. For future works, more robust analysis and case studies will be done to evaluate the techno-economic viability of flywheels for microgrid applications and looking at its competitiveness with respect to other storage technologies in other storage applications (e.g. frequency response, ancillary services, etc.).

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References

Arani A.A.K., Karami H., Gharehpetiana G.B., Hejazi M.S.A., 2017, Review of Flywheel Energy Storage Systems structures and applications in power systems and microgrids, Renewable and Sustainable Energy Reviews, 69, 9-18.

Amber Kinetics, 2018, A Revolution in Energy Storage <www.energy-cast.com/assets/amberkinetics_2018.pdf> accessed 31.03.2019.

Amiryar M., Pullen K., 2017, A Review of Flywheel Energy Storage System Technologies and Their Applications, Applied Sciences, 7, 286-296.

Blechinger P., 2015, Barriers and solutions to implementing renewable energies on Caribbean islands in respect of technical, economic, political, and social conditions, PhD Thesis, Technical University Berlin, Berlin, Germany.

Castro M., Cruz S.M., Esparcia E.J., Bertheau P., Blechinger P., Ocon J., 2018, Development of Battery Energy Storage System Models for an Off-grid Island Simulator, 13th SWEDES Conference, SDEWES2018-0173.

Ghenai C., Janajarah I., 2016, Design of Solar-Biomass Hybrid Microgrid System in Sharjah, Energy Procedia, 103, 357-362.

HOMER Energy, 2017, HOMER Pro <www.homerenergy.com/products/pro/index.html> accessed 31.03.2019.

Moseley P., Garche J., 2015, Electrochemical Energy Storage for Renewable Sources and Grid Balancing, Elsevier, Amsterdam, Netherlands.

Lee J.-Y., Lu Y.-C., Aviso K.B., Tan R.R., 2018, Mathematical Programming for Optimal Design of Hybrid Power Systems with Uncertainties, Chemical Engineering Transactions, 70, 67-72.

Lu J., Li R., Wang J., 2017, Effect of Collaborative Utilization of Energy Storage and Wind Power on Wind Power Grid-connected and Carbon Emission, Chemical Engineering Transactions, 62, 1117-1122.

Norbu S., Bandyopadhyay S., 2017, Power Pinch Analysis for optimal sizing of renewable-based isolated system with uncertainties, Energy, 135, 466-475.

Ocon J., Bertheau P., 2019, Energy Transition from Diesel-based to Solar Photovoltaics-Battery-Diesel Hybrid System-based Island Grids in the Philippines – Techno-Economic Potential and Policy Implication on Missionary Electrification, Journal of Sustainable Development of Energy, Water and Environment Systems, 7, 139-154.

Silvente J., Papageorgiou L., 2017, An MILP formulation for the optimal management of microgrids with task interruptions, Applied Energy, 206, 1131-1146.

Schmidt O., Hawkes A., Gambhir A., Staffell I., 2017, The future cost of electrical energy storage based on experience rates, Nature Energy, 2, 17110-17117.

Schmidt O., Melchior S., Hawkes A., Staffell I., 2019, Projecting the Future Levelized Cost of Electricity Storage Technologies, Joule, 3, 81-100.