Lifecycle Carbon Footprint Analysis of Batteries vs. Flywheels

White Paper 209

Revision 0

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Executive summary

Flywheel energy storage for static UPSs is often thought to be the “greener” technology when compared to batteries. This paper presents a lifecycle carbon footprint analysis to show that the opposite is often true, primarily because the energy consumed to operate the flywheel over its lifetime is greater than that of the equivalent VRLA battery solution, and the carbon emissions from this energy outweighs any carbon emissions savings in raw materials or cooling. A tool is presented to help demonstrate these carbon tradeoffs.

Introduction

The majority of UPSs that support data center loads today are static UPSs with lead-acid batteries. However, there has been growing interest in flywheel energy storage as a replacement for the more common battery energy storage. There are varying reasons for considering flywheels as an alternative, and the pro's and con's, as well as descriptions of each approach, are described in White Paper 65, *Comparing Data Center Batteries, Flywheels, and Ultracapacitors*. **Table 1** provides a summary of the key differences.

Table 1

High level comparison of VRLA batteries vs. flywheels for energy storage

Attribute	VRLA batteries	Flywheels
Runtime	5 minutes to 8 hours	1 second to 1 minute
Operating conditions	Narrow temperature range	Wide temperature range
Maintenance	Preventive maintenance, battery replacements every 3-5 years	Preventive maintenance, bearing replacement (dependent on vendor)
Space	Larger footprint	Smaller footprint
Energy consumption	Energy to float charge batteries = lower losses	Energy to maintain flywheel rotation = higher losses
Carbon footprint	Lower lifecycle carbon footprint	Higher lifecycle carbon footprint

Flywheel and Rotary are not the same

The terms flywheel UPS and rotary UPS are often used interchangeably, however they are NOT the same.

- A **"Flywheel" UPS** is a static UPS that replaces the DC battery string(s) with DC powered kinetic flywheel energy-storage
- A **Rotary UPS** is called "rotary" because rotating components (such as a motor-generator) within the UPS are used to transfer power to the load. Energy storage for rotary UPSs may be flywheels or batteries.

White Paper 92, *Comparison of Static and Rotary UPS*, explains the differences in greater detail.

This white paper provides an in depth look at the carbon footprint of flywheels vs. VRLA batteries as static UPS energy storage alternatives, to provide clarity on how the two approaches compare.

Flywheels are often presented as a "greener" alternative to batteries, primarily because of three factors:

- the materials used in flywheels vs. batteries
- a greater temperature tolerance and therefore no need for cooling of the flywheel(s)
- greater life expectancy

Lead acid batteries, on the other hand, are often presented as environmentally UN-friendly because of hazardous materials, and the amount of lead used. People paint a picture of landfills filled with batteries and the associated harm it's causing our environment. But the reality is that the majority of lead in VRLA batteries is recycled. In fact, according to Battery Council International, more than **98% of battery lead is recycled**.[1]

An analysis is presented in this paper, demonstrating the carbon footprint of VRLA batteries vs. flywheels over the entire data center lifecycle. The analysis shows that raw materials, service replacement life, and cooling are *not* the driving factors to the "greener" technology. In fact, **it is the difference in operating energy over the data center's life that leads us to the conclusion that, in general, VRLA batteries have a lower lifecycle carbon footprint than flywheels.**

[1] http://batterycouncil.org/?page=battery_recycling

Lifecycle carbon footprint

In comparing the carbon footprint of alternative energy storage approaches, it is important to consider the carbon emitted over their life cycle. The analysis in this paper considers the carbon emitted from "cradle to grave" (**Figure 1**), sometimes referred to as the "embodied" carbon. This includes the extraction of the raw materials, the manufacturing process, delivery to the site, the energy used in operating the systems and support systems (cooling in the case of the UPSs), and disposal, which includes recycling of materials.

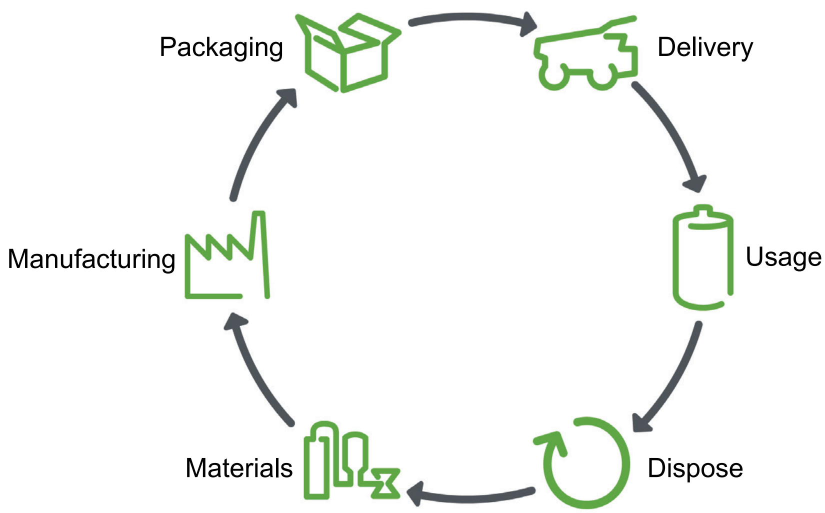


Figure 1

"Cradle-to-grave" Carbon footprint

Analysis methodology

VRLA batteries and flywheels were modeled with the following life cycle phases considered. Of these, some were excluded from the total carbon footprint, either because they were determined to be insignificant drivers to the overall carbon footprint, OR they were determined to be the same or very similar for the two energy storage approaches.

1. **Materials** – We identified the typical chemical composition of VRLA batteries and flywheels from various product specification sheets. This provided a percentage breakdown of the materials. A report by the University of Bath, and supported by MIT, was used to gather the embedded carbon rates (kg of carbon per kg of weight of the raw material) of each of the raw materials. The carbon emissions rates included the values for extraction of the virgin raw materials as well as the recycled materials, based on typical recycling rates of each of the raw materials.[2] Total raw material carbon emissions were then calculated as a weighted average, based on expected weight of each raw material. The "Raw materials comparison" section of the paper provides more details and demonstrates this analysis for the 1 MW data center scenarios.

2. **Manufacturing & packaging** – The carbon intensity of the manufacturing and packaging processes of flywheels and batteries are similar, and have a minimal impact on the overall lifecycle carbon footprint. Therefore, in the analysis presented, this has been excluded from the results.

3. **Delivery** – The further away the end destination is for the systems, the greater the impact this has on the overall carbon footprint. We assumed a default value of 322 kilometers (200 miles), but the model can be adjusted to any desired value. A typical tractor trailer fuel efficiency of 2.6 kilometers/liter (6 miles/gallon) with a carbon emis-

This is an energy storage comparison, not UPS topology

Energy storage and UPS topology are sometimes blended in discussions and analyses of the alternatives to show one as the greener or more efficient approach.

If you choose an efficient energy storage method with an inefficient UPS, and compare that to a less efficient energy storage method with a more efficient UPS, it becomes very difficult to isolate the real differences of the energy storage systems.

The analysis presented in this paper is NOT a comparison of UPS types and assumes identical UPS losses for both flywheels and batteries.

[2] University of Bath, Hammond, G.P. and C.I. Jones, Inventory of Carbon Energy (ICE) Version 2.0, http://web.mit.edu/2.813/www/readings/ICEv2.pdf.old

sions rate of 0.73 kg/liter (2.77 kg/gallon) was used to calculate the carbon impact of transportation for a full truck load of 19,958 kg (44,000 lb)[3]. To account for the difference in weight, we unitized the carbon emissions per kg of shipment and then multiplied by the appropriate weights. It was assumed that neither technology offered an advantage in terms of distance between manufacturing facilities and data center locations.

4. **Installation** – The carbon impact of site installation of batteries and flywheels are assumed to be similar in terms of both labor hours and installation equipment involved. Therefore, in the analysis presented, this has been excluded from the results.

5. **Operational energy** – The energy consumption during operation often has the most significant impact on the total carbon footprint. In the case of a UPS with VRLA batteries, the tare losses represent the energy consumed to trickle charge the battery so it is available during an outage as well as inefficiencies in the charger. Flywheel tare losses represent the power required to keep the wheel spinning in normal operation. Vendor information on the losses associated with keeping a flywheel spinning is not well documented, but measured data validated how much it consumes compared to batteries. Typical flywheel tare losses are around 1-2%, and come from components such as vacuum pumps or magnetic bearings. A typical value for battery tare loss is 0.2%. The UPS system is assumed to be the same in both cases (equal UPS losses), so it has been excluded from this analysis. The "Operational energy comparison" section demonstrates the results for a 1 MW energy storage system with a 20 year data center life, operating in the United Kingdom. The carbon emissions rate per kWh is dependent on the source of the utility power, which varies from one location to the next. The model includes average carbon emissions rates for countries across the globe.

6. **Cooling operational energy** – An advantage often cited about flywheels over batteries is their wider temperature tolerance. While a battery is generally specified to operate 0 – 25°C (32 – 77°F), a flywheel can tolerate -20 – 40°C (-4 – 104°F). With the flywheel's greater temperature range, we assumed no additional cooling was required. The battery room, on the other hand, was assumed to require supplemental cooling, with a partial PUE (power usage effectiveness) of 1.3.

7. **Maintenance** – VRLA batteries typically have a design life of 5 years. This means that over a 20 year data center life, they would be replaced 4 times. For each replacement required, we added the raw materials and transportation carbon emissions values. Semi-annual maintenance visits are also common for VRLA batteries, to ensure the batteries are safe and reliable. Flywheels can vary in maintenance requirements, but ones with magnetic bearings need no bearing replacements and have a typical design life of 20 years. We therefore assumed no replacements were necessary over the lifetime. Annual maintenance is needed and includes tasks such as changing out oil on the vacuum pumps. For both battery and flywheel maintenance visits, a service personnel vehicle with a fuel efficiency of 12.7 kilometers/liter (30 miles per gallon) was assumed.

8. **Disposal** – The carbon impact of disposing of the batteries and flywheels at the end of the data center's life was assumed to be similar in terms of labor hours involved. This represents a small percentage of total carbon footprint over the life cycle. Therefore, in the analysis presented, this has been excluded from the results. Note, when batteries are removed from service, the UPS/battery vendor should replace batteries as part of a service and provide a document such as that in the **Appendix**, stating that the obsolete batteries are being recycled in accordance with local and national regulations and recommendations.

[3] http://www.chemicaltransportation.com/transportation-resources/how-to-calculate-your-trucking-carbon-footprint

The greatest differences in carbon emissions between flywheels and VRLA batteries occur with the raw materials and usage/operation, including the operating energy of the battery or flywheel, and the cooling system needed to support them. In the following two sections, detail is provided on the carbon analysis of each.

Raw materials comparison

The primary raw material of a VRLA battery is lead, followed by sulfuric acid. **Figure 2** provides a sample data sheet with a breakdown of the chemical composition of a VRLA battery, including the concentration of each ingredient.

US Office: B&B Battery USA, Inc.
Address: 6415 Randolph Street, Commerce, CA 90040
Tel: 323-278-1900
Fax: 323-278-1268

SECTION 2: INFORMATION ON INGREDIENTS

Product name: Valve Regulated Lead-Acid Rechargeable battery

Ingredient	CAS No.	Concentration	Hazardous Label
Inorganic Lead/Lead Compounds	7439-92-1	~ 72%	T
Sulfuric Acid	7664-93-9	~ 20%	C
Fiberglass Separator	65997-17-3	~ 2%	/
Container Plastic (ABS or PP)	9003-56-9 (ABS)	~ 5%	/
	9003-07-0 (PP)		/

Figure 2

Sample data sheet with chemical composition of VRLA battery

Table 2 shows the embedded carbon emissions (kg CO2/kg) of the VRLA battery raw-material make-up. The calculated weighted average is 1.14 kg CO2/kg of battery weight.

Table 2

Raw materials carbon emissions of VRLA batteries

VRLA make-up	Concentration	kg CO2/kg
Lead / Lead compounds	72%	1.33
Sulfuric Acid	20%	0.00
Fiberglass Separator	2%	1.35
Container Plastic (ABS or PP)	5%	3.10
	Weighted average	1.14

The majority of a flywheel's weight is in its rotor hub, which is made primarily of high strength steel. **Figure 3** provides an example of the chemical composition of AISI 4340 alloy steel, which was used in the analysis to represent flywheel raw materials.

Chemical Composition

The following table shows the chemical composition of AISI 4340 alloy steel.

Element	Content (%)
Iron, Fe	95.195 - 96.33
Nickel, Ni	1.65 - 2.00
Chromium, Cr	0.700 - 0.900
Manganese, Mn	0.600 - 0.800
Carbon, C	0.370 - 0.430
Molybdenum, Mo	0.200 - 0.300
Silicon, Si	0.150 - 0.300
Sulfur, S	0.0400
Phosphorous, P	0.0350

Figure 3

Sample data sheet with chemical composition of high strength alloy steel used in flywheels

Table 3 provides the embodied carbon and overall weighted average carbon emissions for alloy steel.

Table 3

Raw materials carbon emissions of flywheels

Element	Content (%)	Assumed (%)	Embodied CO2 (kgCO2/kg)
Iron, Fe	95.195 - 96.33	95.5%	1.91
Nickel, Ni	1.65 - 2.00	1.83%	12.4
Chromium, Cr	0.700 - 0.900	0.80%	5.4
Manganese, Mn	0.600 - 0.800	0.70%	3.5
Carbon, C	0.370 - 0.430	0.00%	0
Molybdenum, Mo	0.200 - 0.300	0.25%	32.2
Silicon, Si	0.150 - 0.300	0.20%	13.5
Sulfur, S	0.04	0.00%	0.0
Phosphorous, P	0.035	0.00%	0.0
		Weighted average	2.2

The calculated values illustrate that batteries have a lower carbon emissions rate *per unit of weight*, than flywheels. When you consider that 72% of a battery is highly recyclable (the lead), this shouldn't come as a surprise.

When you look at a battery solution vs. flywheel (see **Table 4**), the battery solution does weigh substantially more, which leads to a higher embedded carbon footprint. The magnitude of the difference, however, is insignificant in comparison to the amount of carbon emissions that result from the operational energy (discussed in the next section).

Table 4

Raw materials carbon comparison

Energy source	Weight of 1MW solution	Carbon emissions / kg	Total (kg CO2)
Battery	11,700 kg	1.14	13,349
Flywheel	2,748 kg	2.2	6,115

Operational energy comparison

The typical losses associated with float charging (aka trickle charging) VRLA batteries is around 0.2%. This is well documented on UPS/Battery specification sheets. **Finding published flywheels loss data (energy to keep the flywheel spinning), on the other hand, is very difficult to find.** Measured data demonstrated 1.5% of additional losses on a UPS when batteries were replaced with a flywheel solution. While this value may vary from vendor to vendor, **flywheels are expected to exhibit a minimum of 1% losses.**

This difference in losses may seem like a small number, but when considered over a data center life of 15-20 years, proves to be substantial. **Table 5** illustrates this for a 1MW data center located in the United Kingdom.

Table 5

Carbon emissions from operational energy over lifetime

	Flywheel	VRLA
Losses	1.00%	0.20%
Load (kW)	1000	1000
kW losses	10	2
London carbon emissions rate (kg CO2/kWh)	0.475	0.475
kW-hrs of losses in 1 yr	87,600	17,520
kW-hrs of losses in 20 year life	1,752,000	350,400
Carbon footprint (kg CO2)	832,200	166,440

For this UPS example, **VRLA batteries resulted in 80% less carbon emissions from operational energy than flywheels**. This absolute difference in kg of CO2 will vary considerably from location to location, since the source of energy from the utilities varies. **Table 6** illustrates the differences in carbon emissions for utility energy sources.[4]

Table 6

Carbon emissions for varying electricity sources

Electricity source	g CO2/kWh of electricity generated
Hydroelectric	4
Wind	12
Nuclear	16
Biomass	18
Solar thermal	22
Geothermal	45
Solar PV	46
Natural gas	469
Coal	1001

[4] http://en.wikipedia.org/wiki/Life-cycle_greenhouse-gas_emissions_of_energy_sources

Since battery solutions generally have a tighter operating temperature tolerance, and because this is often stated as a reason flywheels have a lower carbon footprint, our analysis assumed an additional 30% cooling overhead for the battery (cooling partial PUE of 1.3), and no additional cooling for the flywheel (cooling partial PUE of 1.0). This resulted in additional carbon emissions of approximately 50,000 kg over the lifecycle (see **Table 7**), but this is a fraction of the carbon emissions that result from the additional energy required to operate (spin) the flywheel over its lifetime (**Table 5**).

Table 7

Carbon emissions from cooling overhead

	Flywheel	VRLA
Cooling partial PUE	1.0	1.3
Cooling kW	0.00	0.60
Cooling kW-hrs in 1 year	0	5,256
kW-hrs cooling in lifetime	0	105,120
Carbon footprint (kg CO2)	0	49,932

Some additional "green" considerations that were not factored into this comparison, but that do have an impact on the data center as a whole are:

- **Generator fuel consumption / exhaust emissions** – with a flywheel, the generator activates more frequently, resulting in greater fuel use and exhaust.
- **Generator noise** – with a flywheel, a more active generator means more noise.

Analyzing the carbon tradeoffs

Since we know that assumptions are key to any model, and that specific values used in the analysis above impact the carbon emissions calculated, we developed a TradeOff Tool that allows data center decision makers to adjust the assumptions based on their own data center conditions to see the impact these choices have. Users can enter their location, specify losses for the battery and flywheel, assign cooling losses, and choose the maintenance and replacement frequency.

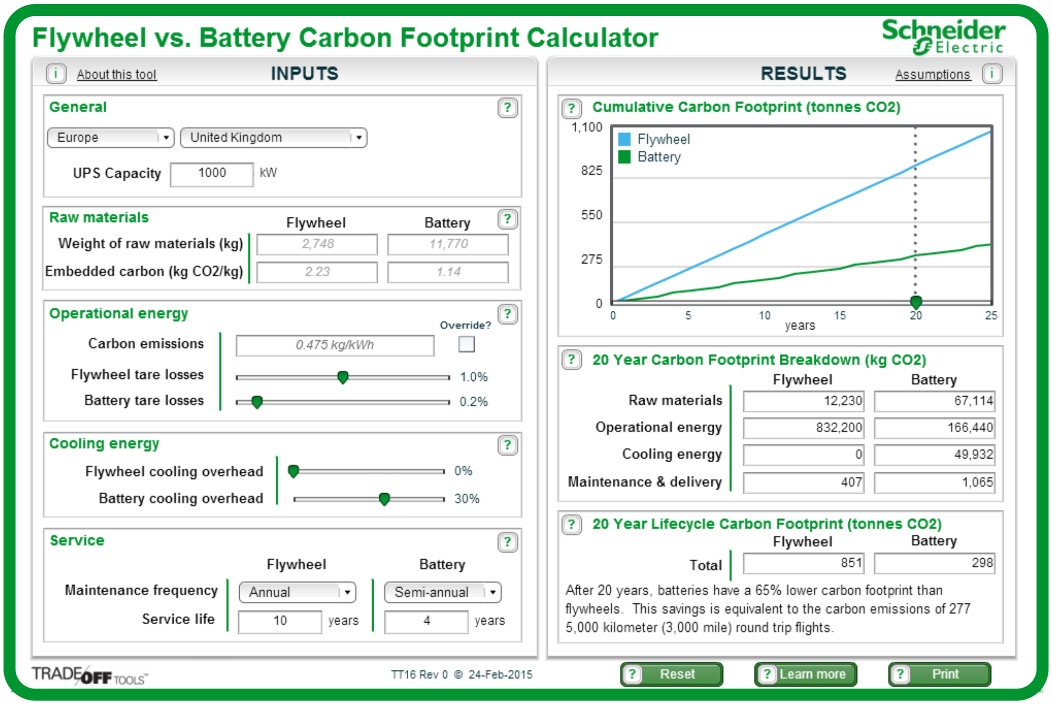
The biggest drivers to the results are:

- **Location** – Carbon emissions vary substantially from country to country (and even from utility company to utility company) based on the mix of sources for power generation. United Kingdom's estimated emissions rate was 0.475 kg/kWh, whereas France is 0.083 kg/kWh, and China is 0.83 kg/kWh. The "cleaner" the energy source for the system, the less of an impact the operational energy has on the overall lifecycle carbon footprint.
- **Tare losses for flywheel** – Flywheel loss data is extremely hard to find in published materials, most likely because the numbers are not favorable. When comparing these technologies for a specific data center project, it is a good practice to ask the vendor(s) to provide specific operating loss data.
- **Tare losses for batteries** – Battery loss data is easier to come by and is generally well documented.

Figure 4 illustrates TradeOff Tool 16, *Flywheel vs. Battery Carbon Footprint Calculator*. With the default settings (location = United Kingdom, flywheel losses = 1%, VRLA losses = 0.2%), batteries exhibit a lifecycle carbon emissions savings of 65% compared to flywheels.

Figure 4

TradeOff Tool comparing carbon of flywheels and batteries



Conclusion

When analyzing flywheels and batteries, a case can be made for either approach to be “greener”. The answer lies in the definition of “green” used, and in the assumptions and scope of the analysis. Flywheels are generally presented as greener because of the raw materials used, the reduced (or no) need for cooling, and the life expectancy/reduced service needs.

In this paper, we focus on the carbon footprint of the systems over their life cycle, and demonstrate that while there is some carbon savings in raw materials, cooling, and maintenance for flywheels, VRLA batteries result in a lower overall carbon footprint for the majority of locations throughout the globe. This is because the flywheel emissions savings over batteries are an order of magnitude smaller than the battery emissions savings over flywheels from operational energy over a lifetime.

A TradeOff Tool was developed and is available online to help decision makers understand the carbon differences of the two technologies, given their specific requirements and assumptions.

About the author

Wendy Torell is a Senior Research Analyst at Schneider Electric’s Data Center Science Center. In this role, she researches best practices in data center design and operation, publishes white papers & articles, and develops TradeOff Tools to help clients optimize the availability, efficiency, and cost of their data center environments. She also consults with clients on availability science approaches and design practices to help them meet their data center performance objectives. She received her Bachelor’s of Mechanical Engineering degree from Union College in Schenectady, NY and her MBA from University of Rhode Island. Wendy is an ASQ Certified Reliability Engineer.

Resources

Comparing Data Center Batteries, Flywheels, and Ultracapacitors
White Paper 65

Comparison of Static and Rotary UPS
White Paper 92

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Data Center Science Center
dcsc@schneider-electric.com

If you are a customer and have questions specific to your data center project:

Contact your Schneider Electric representative at
www.apc.com/support/contact/index.cfm

Appendix : Example certificate of battery recycling

Figure A1 provides an example of a certificate detailing the recycling commitment from Schneider Electric for batteries. This type of documentation provides assurance to the end customer that their obsolete products are being disposed of properly to minimize carbon impact.

Figure A1

Certificate detailing commitment to recycle batteries

SCHNEIDER ELECTRIC CERTIFICATE OF RECYCLING

This is to certify that Schneider Electric Critical Power and Cooling Service is recycling their scrap and obsolete batteries through the Fortune Group.

Fortune Groups is a full service precious and non-precious metal recycler. Fortune operates facilities in Rhode Island, New Jersey, Illinois, Florida, Texas and California. All batteries that are received are recycled through a licensed recycling facility. All proprietary materials are de-manufactured for the recovery of plastic and metal value

This Certificate is awarded to (Insert Customer's name) for all materials received from (Insert customers business) to any Fortune Group Facility.

Schneider Electric Critical Power and Cooling Services