Citation: Pullen, K. R. (2019). The Status and Future of Flywheel Energy Storage. Joule, 3(6), pp. 1394-1399. doi: 10.1016/j.joule.2019.04.006

Article

The Status and Future of Flywheel Energy Storage

Keith R Pullen[1*]

[1] City University of London, Department of Engineering, School of Mathematics, Computer Science and Engineering, London EC1V 0HB

* Correspondence: k.pullen@city.ac.uk

SUMMARY

Flywheels, one of the earliest forms of energy storage, could play a significant role in the transformation of the electrical power system into one which is fully sustainable yet low cost. This article describes the major components that make up a flywheel configured for electrical storage and why current commercially available designs of steel and composite rotor families coexist. In the process, design drivers, based on fundamentals are explained in a clear and simple manner inclusive of approaches to safety. The robust characteristics of flywheels deem them highly suitable for applications requiring fast response and high daily cycles, a need that is growing as grid inertia reduces. Lithium Ion batteries are currently the technology of choice for fast response but suffer from limited cycle and calendar life. This can be mitigated by having sufficient energy capacity to limit depth of discharge during short duration cycles whilst using this capacity to earn revenue for provision of other services. Now, as other mechanical, thermal to electric and renewable fuel based storage technologies develop, these will provide storage at a lower cost, greater duration and in a more sustainable way than Lithium Ion. However, the need for fast response storage will remain and steel flywheels are well placed to provide this given potential for low power cost and their sustainability credentials. In order to obtain cost estimates for flywheels in volume production, the cost of the power and storage elements were separated out with costs for each based on similar technologies in volume production. These indicate significantly lower costs than given for current commercially available flywheels, none of which are in volume production relative to Lithium Ion. Finally, some areas of research with potential to improve performance are described but, to be worthwhile, these developments must not lead to increased costs.

INTRODUCTION

The core element of a flywheel consist of a rotating mass, typically axisymmetric, which stores rotary kinetic energy E according to;

$$E = \frac{1}{2} I \omega^2 \quad [\mathrm{J}] \qquad \text{(Equation 1)}$$

where E is the stored kinetic energy, I is the flywheel moment of inertia [kgm^2], and ω the angular speed [rad/s]. In order to facilitate storage and extraction of electrical energy, the rotor must be part of a system as shown in Figure 1.

Electrical power is normally transmitted from a nominally constant voltage DC link to and from the motor-generator via a power converter. This converter generates a 3 phase input from the DC supply in charging or converts the AC generated back to DC during discharge. The motor-generator (MG) is either connected directly onto the flywheel rotor [1] or is sometimes directly integrated with the flywheel rotor [2]. As with any storage technology, it is desirable to provide a constant power level P irrespective of state of charge and this implies MG torque, T_{MG} [Nm] follows an inverse relationship with speed since:

$$T_{MG} = {}^{P}/_{\omega} \qquad \text{(Equation 2)}$$

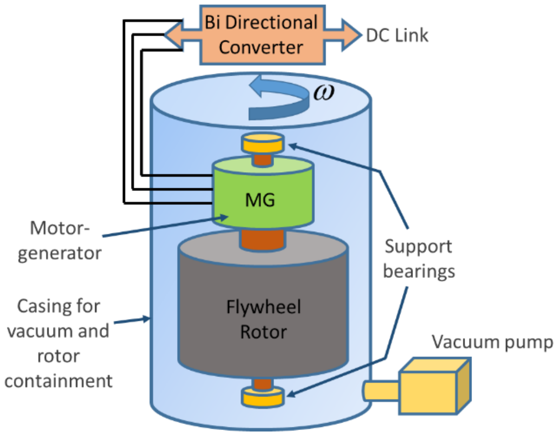

Figure 1. A flywheel system configured for electrical storage [3]

In order to avoid high T_{MG}, a minimum value of speed ω_{min} is set between $^1/_2$ to $^1/_3$ of maximum $\omega_{\max}$, itself limited by structural integrity of the rotor. The useable energy of a flywheel is therefore given by:

$$E_{Useable} = \frac{1}{2} I ({\omega_{\max}}^2 - {\omega_{\min}}^2) = \frac{1}{2} I {\omega_{\max}}^2 \left(1 - \frac{{\omega_{\min}}^2}{{\omega_{\max}}^2}\right) \quad [\mathrm{J}] \qquad \text{(Equation 3)}$$

Electrical flywheels are kept spinning at a desired state of charge and a more useful measure of performance is standby power loss, as opposed to rundown time. Standby power loss can be minimised by means of a good bearing system, a low electromagnetic drag MG and internal vacuum for low aerodynamic drag. Given the electric flywheel does not need a shaft seal, a hermetically sealed casing can minimise the operation of the vacuum pump. The casing must also contain the rotor in the event of a mechanical failure which could be a bearing failure or, more seriously, breakup of the rotor.

FLYWHEEL COMPONENTS AND RESULTING DESIGNS

The Rotor and containment

The choice of rotor dominates the design philosophy but consideration of this in isolation would be an error since it affects all other components and their cost. It is also vital to consider safety from the outset since all designs must either ensure rotor failure likelihood is either extremely unlikely or guarantee containment in the case that probability of rotor failure is significant. The starting point is equation 3 which shows ω_{max} and I should be maximised for a given rotor mass. ω_{max} is limited by the allowable rotor stress σ_{max}, this increasing also with the square of speed so maximum energy is proportional to allowable stress. Rotor stress is function of rotor shape but the value of I is also dependant on rotor shape and shapes giving low σ_{max} tend to have high I and vice versa. Due to this interaction, it is common to calculate a factor K for a particular shape which takes into account how the distribution of mass affects both I and σ_{max}. The maximum energy stored per unit mass or unit volume can then then given by;

$$\frac{E}{m} = K\frac{\sigma_{\mathrm{max}}}{\rho} \quad [\mathrm{J/kg}] \qquad \text{(Equation 4)}$$

$$\frac{E}{V} = K\sigma_{\mathrm{max}} \quad [\mathrm{J/m^3}] \qquad \text{(Equation 5)}$$

where m is the rotor mass, ρ the material density and V, rotor material volume. Values of K for common shapes are just over 0.3 for a thick hollow disc or cylinder with central hole, 0.6 for a disc or cylinder with no hole. Other shapes are possible but lead to less compact designs with high rotor surface area, increasing aerodynamic drag. These equations are very helpful in understanding why two materials and these shapes have been adopted almost exclusively in commercial designs, one not having a clear advantage over the other.

Starting with the term σ_{max}/ρ, the specific strength, Equation 4 teaches that maximising this would be desirable for a flywheel. Indeed, the development of high strength, low-density carbon fibre composites (CFC) in the 1970's generated renewed interest in flywheel energy storage. Based on design strengths typically used in commercial flywheels, σ_{max}/ρ is around 600kNm/kg for CFC whereas for wrought flywheel steels it is around 75kNm/kg. The values for σ_{max}/ρ are cannot be based on ultimate strengths since the allowable stress is reduced in order to give high or infinite fatigue life and greatly reduce the chance of rotor burst. Now with an advantage of factor eight, how can a steel rotor compete with CFC? Returning to equation 4, an effective shape is a disc or cylinder with no hole (K=0.6) hence steel designs mainly use this shape. Since CFC material is orthotropic, developing strength in one direction, it must be wound in the shape of a hollow cylinder, halving the value of K so the advantage is now reduced to four. Looking now at equation 5, with allowable strengths for steel 60% of CFC, taking into account K, CFC has 20% larger volume. However, the volume in Equation 5 is material not volume defined by the outer envelope of the rotor. For a CFC rotor with inner radius $^2/_3$ of the outer radius, the rotor envelope is 80% greater than the material volume. These two factors multiply to make the CFC rotor more than twice the external volume of a steel rotor for a given energy.

Considering rotor containment, the mechanism of failure for steel rotors is by fatigue crack growth to a critical size causing fast fracture. Typically, the rotor will break into three large chunks and release considerable momentum. Containment is possible by underground bunker installation such that the surrounding earth will absorb the impact forces if burst occurs [4]. It then makes sense to make such flywheels large for economies of scale. Another approach is to reduce stresses sufficiently that rotor failure is so improbable that burst containment is unnecessary, examples shown in [1]. Another approach is to laminate the rotor to limit the maximum amount of material released [3]. It was initially believed that CFC rotors exhibited only the benign failure mode by gradually breaking up into small debris and dust rather than chunks as typical for metal flywheels. This offered a major advantage for CFC rotors regarding the size and weight of the safety containment. However, a second explosive failure mode became known to industry specialists but nothing has been published on this to date. This explosive failure mode occurs as an instantaneous break-up of the CFC flywheel into small debris and dust and leads to very high tri-axial pressures putting more severe demands on the safety containment for CFC than for metal flywheels. This type of failure can be also mitigated by either bunkering [5], very heavy or sophisticated containment [1]. Since the containment needs to be substantial, and the casing needed to contain what is a higher external volume CFC rotor, the high specific strength advantage of CFC rotors is eroded further. This partly explains why steel and CFC designs co-exist, competing in the same applications.

The containment also maintains the vacuum needed to keep windage losses down. In principle, the windage losses can be eliminated but the vacuum level must be balanced against pumping costs.

The motor-generator and converter

In theory, any size of motor-generator (MG) can be added to the flywheel rotor to tailor power and duration to the application, minimising conversion losses dominating if cycles are very high, standby drag dominating if there are long idling periods. The MG must be structurally capable of operating to maximum design speed, transfer power efficiently and have minimum standby loss torque. The MG is almost certainly classified as high speed, operating in the 10’s thousands rpm unless the flywheel is particular large or low energy density. The MG must be brushless with AC current generated by the inverter for motoring and converted back to the DC in generator mode. In most cases, the MG is connected directly to the flywheel rotor and so operates in the vacuum which makes rotor cooling a challenge.

The main choices of MG are permanent magnet synchronous, switched reluctance, induction asynchronous and homopolar. More information in the comparison of each is given in [3]. In some designs, the MG is formed as part of the flywheel rotor which helps reduce volume but at the expense of needing a bespoke design. It is typical to place the MG inside the flywheel if it has a CFC construction since there is an obvious hollow space. Such a design may also be “inverse” with magnets on the outside and an internal stator, feasible since there is little windage loss given the vacuum. For steel rotors, the MG has to go to the side of the flywheel rotor but a standard design can be used of any type. There are some designs in which the steel flywheel itself forms the MG rotor, having advantages in using the same part for two purposes. However, this rotor must have good mechanical and electrical properties leading inevitably to compromise.
Round trip efficiencies of 85-90% are typically achievable with well designed MG and power electronics.

Bearing systems

The bearings support the flywheel rotor and MG whilst offering minimal frictional drag. Given air bearings are not possible with vacuum, losses too high for oil hydrodynamic bearings, the choices are mechanical rolling element and magnetic. Both types are used in commercial machines and losses are relatively low. Mechanical rolling element bearings (MREB) are typically oil lubricated with oils operating in vacuum conditions being readily available [6]. Passive magnetic bearings (PMB) can be used to offset the weight of the rotor with no energising requirement. Oil free solutions can be achieved by replacing mechanical bearings by active magnetic bearings (AMB), but care must be taken to minimise energising power and system cost. A bearing solution based purely on PMB is not possible due to the Ernshaw's theorem. There is a tradeoff in lower cost for MREB but likely requiring maintenance during the life of the flywheel verses the added cost of AMB but elimination of maintenance. The frictional loss in MREB and AMB energising power are similar. Both types are bearing system are found in commercially available flywheels. Losses for an MREB with PMB are in the order of 0.1 - 0.3 W per kg supported but will vary according to design specifics.

FLYWHEELS IN THE STORAGE LANDSCAPE

Interest in energy storage has grown exponentially with penetration of weather dependant renewables, particularly solar voltaic and wind, replacing large coal fired steam plant. Not only is renewable generation intermittent, the inertia of the grid has reduced, weakening frequency stability. Large steam plant provides substantial mechanical inertia, in a similar way to flywheels, reacting instantly if the frequency is pulled up or down by supply and demand imbalances. This inertia must be replaced and the solution currently adopted is to use sub-second response energy storage to create synthetic inertia. The storage technology mainly deployed for this is Lithium Ion (Li-Ion) batteries having the added advantage of storage durations of 1-2 hours, allowing additional revenue stacking steams by providing other services. The technology is in mass production, guaranteed by manufacturers for a defined operating duty and key reports [7] on Levelised Cost of Storage (LCOS) showed Li-Ion to out compete flywheels on cost. However, a more recent and comprehensive study, accounting for degradation and other effects has shown flywheels to be the most cost effective technology for fast response [8]. Although the analysis shows Li-Ion gaining by 2040, this depends on predictions for performance and costs.

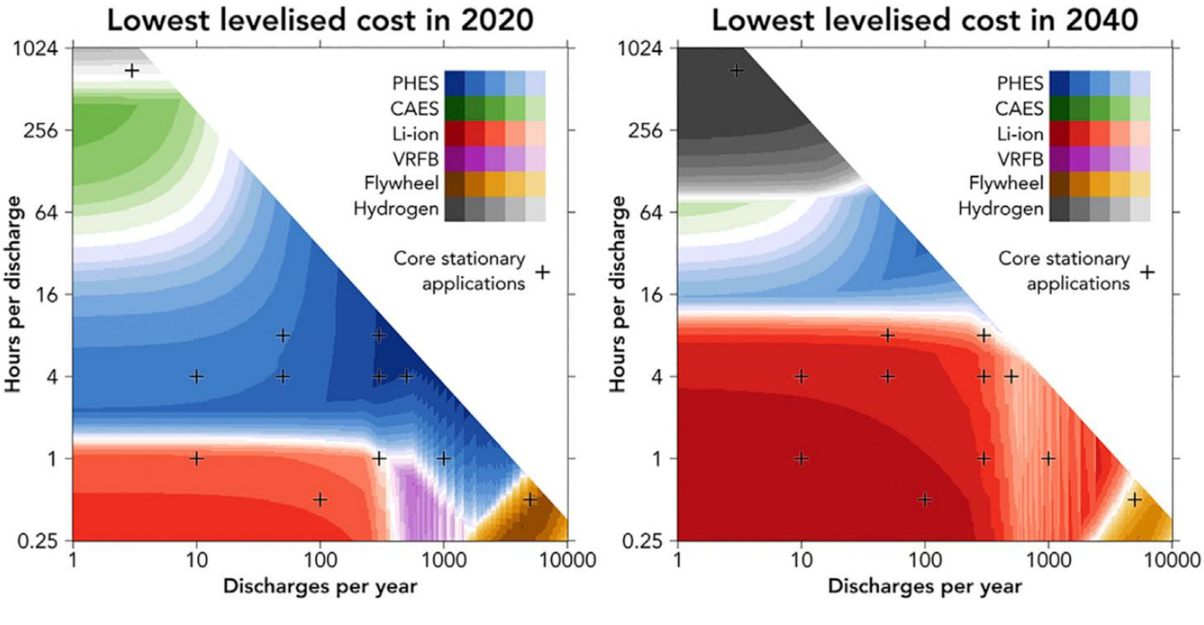

Figure 2. Lowest levelised cost of storage [8]

Some issues with Li-Ion have incentivised the development of alternatives including:

- Supply of key raw materials and ethical issues concerning their sources
- Inherent difficulty of recycling with current rates being very low
- Cycle and calendar life is limited to around 10 years, lower for applications with high cycles
- Thermal environment must be controlled, power is drawn for heating and cooling

It is also noted that Energy Storage on Investment (ESOI) for Li-Ion at 10 is low [9], versus around 100 for steel flywheels and 200 for compressed air and pumped hydro. The concern here is to promote technologies which maximise sustainability in the energy transition.

Another effect is the overlap of storage system characteristics in terms of duration and response. There is no storage system which is able to cover all timescales needed from fast response all the way to seasonal storage. Interestingly, most storage systems with durations greater than that which Li-Ion provides have response times in the order of 10's seconds due to fundamental mechanical or thermal inertias. The consequence is that at least two systems will always be needed, one for fast response and one for long duration. Since the long duration technologies such as pumped hydro, compressed air, heat-to-electric or engines running on renewable fuels are able to provide power within one minute, all that is needed from the fast response technology is a low minute duration. The best technology is then one with lowest power cost with the energy cost being less important. It is here that flywheels or other fast response technology with lower power cost than Li-Ion can compete. The issue of flywheel standby losses is often cited as a problem but in a well designed flywheel, for a given power, this may be no higher than the ancillary power needed for thermal management of Li-Ion needed to maximise life. The conclusion is that the 1-2 hr duration provided by Li-Ion overlaps with that already provided by the other long duration technologies so this redundancy may squeeze out Li-Ion if long duration, slow response technologies are deployed. An example of a hybrid system of fast and long duration technologies along the lines described is reported [10] in which flywheels and supercapacitors are being trialled with liquid air storage.

Supercapacitors are a mature and established technology with potential to challenge flywheels in fast response applications. They have low power cost but presently insufficient duration to bridge the response time gap of long duration technologies. Also, unlike flywheels, they degrade with time, temperature and age and, for grid voltages, must be connected in long series strings compromising reliability.

In summary, flywheels excel in short duration, high cycle applications and another measure of value is cost for a given total energy throughput, virtually unlimited due to high cycle life. A value for this can be quantified if the application duty cycle is also known.

FLYWHEEL COSTS AND FUTURE DEVELOPMENTS

The most important factors affecting market uptake for flywheels is cost reduction, particularly power cost. This can be achieved by a combination of design for low cost and large-scale manufacture. The cost of a flywheel can be broken down into two almost independent elements; a) the flywheel rotor with bearings, casings and ancillaries such as the vacuum pump (FW), and b) the motor-generator with the power electronics including grid tied inverter (MGPE). If the specific cost of the FW is $C_{\underline{fw}}$ \$/kWh and the cost of the MGPE is $C_{\underline{mgpe}}$\$/kW then the cost of any flywheel is given by;

$$\text{Cost (\$)} = EC_{\underline{fw}},\ + PC_{\underline{mgpe}}$$

where E is the capacity in kWh and P power in kW.

Based on the quality and grade of steel needed for rotor and casings, mass manufacturing costs and ancillaries, $C_{\underline{fw}}$ has been estimated to be \$800-1000 per kWh, conservative given material costs of \$600/tonne and approximately 200kg of steel are needed per kWh (rotor and casing). Costs are for a steel rotor design which avoids bunkering. For MGPE, $C_{\underline{mgpe}}$ can be taken from cost for electric motors and inverters in mass production and costs of \$50-100/kW are achievable in on the assumption that speeds and drive frequencies are not excessive. Although MG physical sizes fall with increased speed reducing materials, laminations have to be thinner and more expensive materials employed. Specific costs can now be related to full power duration or C rating as shown in Table 1;

Duration (sec)	C (kW/kWh)	Specific Power Cost $/kW	Specific Energy Cost $/kWh
60	60	63-117	3780-6960
120	30	77-133	2300-4000
180	20	90-150	1800-3000
300	12	117-183	1400-2200

Table 1: Cost estimates for steel flywheels varying with duration

It is immediately apparent that the power cost is dominated by the MGPE cost not the flywheel so cost reductions here have the greatest impact. The greatest potential is developments in power electronics with higher voltage MOSFETS leading to reduced costs and lower losses. As the automotive industry has pushed Li-Ion costs down so this industry will also reduce the cost of electrical machines and inverters. The values in Table 2 compare to the mean cost values used in [8] for preparation of Figure 2 of 641 $/kW and 5399$/kWh, reasonable for the current relatively small-scale flywheel industry but not production at scale. The investment required to scale up production should not be high given established methods are used in manufacture and no special materials or processes are required. The values table 1 can also be compared to Li-Ion costs given in [8] as $687/kW and $802/kWh which are greater in $/kW but lower in $/kWh, the comparison not taking degradation into account of course, an issue with higher cycle applications.

In terms of breakthroughs on rotors, much research has been focussed on composites in order to increase specific energy. The mass and volume of the entire flywheel including the full containment must be always be considered and significant gains could be made if the failure models of composite rotors can be fully understood allowing burst containment to be reduced without compromising safety. New ultra strength materials listed in [2,11] could bring benefits as long as system costs are not increased at the expense of better performance. Another issue is increasing speed needed to exploit high strength properties is likely increase the cost of the MGPE.

Standby losses the often cited as a major disadvantage for flywheels although in in terms of loss as a percentage of rated power, losses are similar to Li-Ion which needs power for environmental control. Given flywheels need to be used in applications with high daily cycles, self-discharge tends to become less of an issue in any case. In spite of this, reductions in cost and energisation power of AMBs will help reduce overall costs, in particular maintenance cost. Super conducting magnetic bearings [12] also offer the potential for a breakthrough in standing loss reduction as long as costs are kept within limits.

DECLARATION OF INTERESTS

The author is also a non-executive director of Dynamic Boosting Systems Ltd and is an author of patents relating to flywheels and related technologies.

REFERENCES

1. Lafoz, M., Santiago, J. and Etxaniz I (2013) Kinetic Energy Storage Based on flywheels: Basic Concepts, State of the Art and Analysis of Applications, European Energy Research Alliance JP ENERGY STORAGE Mechanical Storage Sub-program Ref 2013-05 CIEMAT., 22. 28040. Madrid
2. Hedlund, M., Lundin, J., Santiago, J., Abrahamsson, J. and Hans Bernhoff, H. (2015) Flywheel Energy Storage for Automotive Applications Energies 8, 10636-10663; doi:10.3390/en81010636
3. Amiryar, M.; Pullen, K. (2017) A Review of Flywheel Energy Storage System Technologies and Their Applications. Appl. Sci., 7, 286

4. Flywheels support energy grids of the future PC Control 02, (2015) https://www.ethercat.org/download/documents/Canada.pdf (accessed 5 February 2019)

5. Beacon Power LCC. Beacon POWER's Operating Plant in Stephentown, New York. http://beaconpower.com/system-safety/ (accessed on 5 February 2019).

6. DuPont™ Krytox® FG Vacuum Pump Oils http://www2.dupont.com/Lubricants/en_US/assets/downloads/new/H-96096,-Krytox-FG-Vacuum-Pump-Oils.pdf (accessed on 5 February 2019).

7. Lazard. (2016). Lazard's Levelized Cost of Storage Analysis, [2.0. version]. https://www.lazard.com/media/438042/lazard-levelizedcost-of-storage-v20.pdf

8. Schmidt, O., Melchior, S., Hawkes, A., and Staffell, I. (2018). Projecting the Future Levelized Cost of Electricity Storage Technologies, Joule 3, 81–100 https://doi.org/10.1016/j.joule.2018.12.008

9. Barnhart C. and Benson, S. (2013) On the importance of reducing the energetic and material demands of electrical energy storage, Energy Environ. Sci., 2013, 6, 1083

10. Williams, D., (2017) Highview energy storage system aimed at UK frequency response, Power Engineering International https://www.powerengineeringint.com/articles/2017/10/highview-energy-storage-system-aimed-at-uk-frequency-response.html (accessed 5 February 2019)

11. Buchroithner, A., Haidl, P., Birgel, C., Zarl T. and Wegleiter, H., (2018) Design and Experimental Evaluation of a Low-Cost Test Rig for Flywheel Energy Storage Burst Containment Investigation. Appl. Sci., 8(12), 2622; doi: 10.3390/app8122622

12. Strasik, M., Day, A., Johnson, P. and Hull J. (2007) Energy Storage Systems with Superconducting Bearings for Utility Applications Final, Report Cooperative Agreement No. DE-FC36-99GO10285 for Department of Energy, USA.