WP Report

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Investigation on Storage Technologies for Intermittent Renewable Energies: Evaluation and recommended R&D strategy

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STORAGE TECHNOLOGY REPORT
ST6: FLYWHEEL

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With the participation of network members

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1. Overview of the Storage Technology

Flywheels are kinetic energy storage devices, and store energy in a rotating mass (rotor), with the amount of stored energy (capacity) dependent on the mass and form (inertia), and rotational speed of the rotor. An accelerating torque causes a flywheel to speed up and store energy, while a decelerating torque causes a flywheel to slow down and regenerate energy.

The earliest applications of flywheels include potters wheels, and grindstones used for sharpening tools. Since the industrial revolution, flywheels have been used in most rotating engines and machines for very short-term energy storage, for example to smooth the torque pulses in internal combustion engines, and deliver smooth power. Flywheels are simple and effective in applications where the flywheel is directly mechanically coupled to smooth the shaft speed of rotating machinery. In such cases the kinetic energy storage provided by the rotor inertia requires no further interface to the mechanical system, although a mechanical gearbox may be used to increase the effective capacity.

A new application of flywheels is in the storage of electrical energy, which is achieved by the addition of an electrical machine and power converter. The electrical machine may be integrated with the flywheel, and operates at variable speed, and the power converter is usually provided by a power-electronic variable speed drive.

The main feature of flywheel energy storage (FES) systems generally is that they can be charged and discharged at high rates for many cycles. Typical state-of-the-art composite rotor designs have specific energy of up to 100 Wh/kg, with high specific power. The state-of-charge is easily assessed as a function of angular velocity, which is readily measured. The main drawbacks of flywheels are the high cost, and the relatively high standing losses. The lowest self-discharge rates currently achieved for complete flywheel systems, with electrical interface powered, are around 20% of the stored capacity per hour.

Flywheel energy storage technologies broadly fall into two classes; low speed flywheels, which are commercially available; and high-speed flywheels, which are just becoming commercial. Low speed flywheels, with typical operating speeds up to 6000 rev/min, have steel rotors and conventional bearings. For example, a flywheel system with steel rotor developed in a collaborative project at CCLRC in the 1980's had energy storage capacity 2.3 kWh @ 5000 rev/min, and rated power 45kW. (rotor specific energy 5 Wh/kg, specific power 100 W/kg).

High-speed flywheels, with operating speeds up to 50,000 rev/min, using advanced composite materials for the rotor, are under intensive development to increase the energy storage density and reduce unit cost. The high speed flywheel concept originated in the early 1970s at Lawrence Livermore National Laboratory (LLNL), when Post wrote an article in Scientific American recommending that flywheels be made of composite materials instead of metal, and presenting a new approach to rotor design. The LLNL developments reached commercial stage in 1994, with the technology being licensed to Trinity Flywheel for manufacturing. Composite materials are suitable for flywheel rotors due to their light weight and high strength. Lightness in high speed rotors is good from two points of view, viz., the ultra-low friction bearing assemblies are less costly, and the inertial loading which causes stress in the material at high rotational speeds is minimized. High strength is needed to achieve maximum rotational speed. Therefore, advanced composite rotors enable the storage of greater amounts of energy on a specific weight basis, in comparison with other materials. An further important consideration is that fibre reinforced composite rotors fail in a less destructive manner than metallic rotors, and are thus intrinsically safer.

A few high-speed flywheel systems have been installed in field trials, and are now being commercialised. Currently the main stationary applications are in uninterruptible power supplies (UPS), power quality (PQ) systems, and trackside support in traction (rail) systems. Several manufacturers foresee possibilities of applications in peak shaving in electrical power systems, and for power smoothing in renewable energy systems.

The main developers of flywheels which are commercially available or close to market include Active Power (and Caterpillar), Acumentrics Corporation, AFS Trinity Power Corporation, Beacon Power, Flywheel Energy Systems Inc., Pentadyne, Piller, Tribology Systems Inc., and Urenco Power Technologies. Active Power is one of the few manufacturers using steel rotors, most manufacturers use composite rotors. There are a number of technology developers, for example Argonne National Laboratory and Boeing are collaborating in the development of a low-loss flywheel using high temperature superconductor (HTS) bearings. The other main development areas include rotor materials, and rotor manufacturing techniques.

A recent survey (European Emerging Energy Storage Technology Markets, Frost & Sullivan, 2003) reports that only a few manufacturers share most of the European market, and Piller is the market leader with 47% of the market. The European market for new energy storage technologies (SMES, Supercapacitors, and Flywheels) is expected to rise from $104 million in 2002 to $215 million in 2009, representing a compound annual growth rate of around 11%. Currently flywheels represent 96% of new energy storage technology sales, and sales are expected to grow by around 8% annually. The key factors driving the market include the expected growth in utilisation of renewable energy, as well as regulatory aspects of electricity supply, and requirements for Uninterruptible Power Supplies (UPS) and power quality.

2. Technical characteristics and applications of the storage technology

2.1 Components and materials of the technology

2.1.1 Rotor technology

The kinetic energy stored in a rotating mass is:

$$E = \frac{1}{2} J\omega^2 \qquad (1)$$

where J is the moment of inertia, and ω is the angular velocity.

The moment of inertia is a function of the mass and shape of the flywheel :

$$J = \int x^2 dm_x \qquad (2)$$

where x is the distance of the differential mass dm_x from the axis of rotation.

In the case of a flywheel where the mass m is concentrated in the rim at radius r, then the moment of inertia is given by:

$$J = m\, r^2 \qquad (3)$$

Substituting equation (3) in (1) gives:

$$E = \frac{1}{2} m\, r^2 \omega^2 \qquad (4)$$

which shows that high angular velocity is more important than mass to achieve high stored energy.

The tensile strength of the material defines the upper limit of angular velocity. For example in the case of an imaginary flywheel with mass concentrated at the rim at radius r, the tensile stress in the rim at angular speed is

$$\sigma = \rho\, r^2 \omega^2 \qquad (5)$$

thus defining the maximum angular velocity ω_{max} for a maximum tensile strength of the material σ_{max}

The maximum stored energy is then

$$E = \frac{1}{2} m \frac{\sigma_{\max}}{\rho} \qquad (6)$$

which shows that the maximum energy that may be stored for a given mass is achieved by a flywheel made from a material which combines high tensile strength with low density. Therefore to achieve high specific energy (at high speeds), composite materials are better than metal, see Table 1.

	Density [$kg.m^{-3}$]	Strength [$MN.m^{-2}$]	Theoretical maximum specific energy [$Wh.kg^{-1}$]
Steel (AISI 4340)	**7800**	**1800**	**32**
Alloy (AlMnMg)	**2700**	**600**	**31**
Titanium (TiAl6Zr5)	**4500**	**1200**	**37**
GFRP Glass fibre reinforced polymer (60 vol% E-glass)	**2000**	**1600**	**111**
CFRP Carbon fibre reinforced polymer (60 vol% HT Carbon)	**1500**	**2400**	**222**

Table 1. Specific strength of rotor materials
(Material properties taken from Aspes Engineering AG website)

The specific energy per unit mass E_m is

$$E_m = \frac{1}{2} r^2 \omega^2 \qquad (7)$$

The minimum operational speed of the flywheel is mainly limited by the drive system torque, since

$$P = T\omega \qquad (8)$$

where P is the power, and T is the torque.

Therefore the torque increases as speed is reduced, while the power is maintained constant. The torque limitation, and the fact that flywheels store most energy at high speeds, means that the ratio of minimum to maximum operational speeds $s = \omega_{min}/\omega_{max}$ is usually not less than 0.2. The useful stored energy is then $E = E_{max}(1-s^2)$. When s = 1/3, the useful stored energy is nearly 90% of E_{max}.

2.1.2 Rotor Bearing

The rotor bearing design is important to achieve low losses and to minimise maintenance. The bearing losses achieved are usually small, especially when compared with other losses when driving the flywheel. Most flywheels operate at high speed and use high specification bearings. For example, the Active Power flywheel uses a combination of ceramic ball bearings in a steel race, with magnetic lift to increase bearing life substantially. The Urenco flywheel uses a low stiffness self balancing concept, and the bearing system consists of a passive magnetic bearing at the top, and a low loss pivot bearing at the bottom of the vertical axis. The bearings require no maintenance and have losses of only 168W.

Argonne National Laboratory has developed techniques for a high-temperature superconductor (HTS) bearing with extremely low rotational loss. These bearings have a rotational drag more than two orders of magnitude lower than that of a conventional magnetic bearing and several orders of magnitude lower than that of mechanical bearings. With this bearing, an energy-efficient flywheel could be constructed with a bearing loss of < 2%/day (including parasitic power to cool the HTS). In a separate project, Argonne is collaborating with Boeing and others to develop a FES with HTS bearings. Argonne has developed an Evershed-type HTS bearing, i.e., an HTS bearing in which most of the levitation is accomplished by an attractive force between a stationary permanent magnet and the permanent magnet rotor, while the HTS is used to provide stiffness and stability

2.1.3 Containment technology

The container for high speed flywheels is evacuated or helium filled, to reduce aerodynamic losses (windage) and rotor stresses. Provided the containment pressure is reduced to < 1mbar the losses due to windage are negligible. Safety is an important consideration, and the developers have carried out extensive safety testing.

2.1.4 Power interface

The power interface includes the motor/generator, a variable-speed power electronics converter, and a power controller.

The motor/generator is usually a high speed permanent magnet machine, integrated with the rotor. This is usually known as an integrated synchronous generator (ISG).

The power electronics interface is usually a pulse width modulated (PWM) bi-directional converter using insulated-gate bipolar transistor (IGBT) technology. The power electronics interface can achieve a full-load efficiency of greater than 90%, however this falls off at low loads. The converter may be single-stage (flywheel ISG a.c. ⇔ d.c. bus), or double stage (flywheel ISG a.c. ⇔ d.c. bus ⇔ a.c. network), according to the application requirements.

Finally, a power controller is required to monitor the flywheel and control the power flow. The controller operation will depend on the application, for example where the system is interfaced to an a.c. network, reactive power as well as active power will be controlled.

2.2 Data and performance characteristics

The data and performance characteristics of flywheel systems produced by the main manufacturers are summarised in the Annex Section 8.3. The data has been taken from manufacturers' websites and from information provided by some manufacturers in response to a questionnaire.

2.2.1 System voltage

A power electronic interface is always required and can be configured to suit any desired system voltage. The basic interface to the variable speed flywheel motor/generator is variable frequency and voltage a.c., and at least a converter to d.c. is always necessary. However in addition a bi-directional inverter may be included to provide an a.c. interface to the application. Manufacturers provide interfaces that are suitable for the target market or marketing strategy. For example, a system designed for UPS applications may have a d.c. or standard a.c. line voltage interface, or alternatively the flywheel module may be provided with a d.c. interface to allow the customer to choose the power electronics interface. Beacon Power offers a range of d.c. interface voltages, 36, 48, or 96V d.c. compatible with battery banks.

Voltage fluctuation in a.c. systems can be limited to less than 2%. Some voltage fluctuation is expected in d.c. UPS systems where power control is achieved by monitoring the voltage level, i.e. as the d.c. voltage falls, the flywheel system regenerates power to support the load.

2.2.2 Range of capacities

The capacity of single rotors range from 0.25kWh to 6kWh. In principle multiple rotor modules can be paralleled in a common d.c. bus, for example Active Power can provide paralleled systems with capacity and power up to around 7kWh at 2000kW using 8 rotors, and URENCO can provide 25kWh at 2.1MW for traction applications using ten modular systems.

The capacity available in the rotor is directly proportional to the square of the rotational speed and is unaffected by discharge rate or temperature. A key advantage of flywheels is that capacity is always clearly indicated by rotational speed. As already mentioned in Section 2.1.1, a flywheel is operated between a design minimum and maximum speed, which defines the useful stored energy or available capacity. In principle the available capacity could be increased at low discharge rates by lowering the minimum speed, at reduced torque and power, however this may reduce the cycling lifetime.

Various losses in the system, including bearing losses, and electrical losses (stator losses, power converter losses), contribute to the overall conversion efficiency. The power electronics switching losses usually dominate the total losses, and the overall efficiency is a function of power, usually > 80% for power in the range 10% to 100% rated. The maximum efficiency quoted by some manufacturers is 96%. This gives rise to a typical maximum in-out efficiency of 92%.

2.2.3 Energy and power density

Steel rotors have specific energy up to around 5 Wh/kg, while high speed composite rotors have achieved specific energy up to 100 Wh/kg. These specific energies are clearly much lower than the theoretical maxima for the materials used, as discussed in Section 2.1.1 and Table 1. The specific power is mainly a function of the flywheel hub, the electrical machine, and the power electronic interface, and figures up to around 1600 W/kg have been quoted. However the specific energy and power of the complete system may be reduced by at least a factor of 10 when the weight of the complete system, including containment, vacuum system, and electrical interface, is taken into account.

2.2.4 Cycling service and lifetime

The high cycling capability of flywheels is one of their key features, and is not dependent on the charge or discharge rate. Full-cycle lifetimes quoted for flywheels range from in excess of 10^5, up to 10^7. The highest cycling lifetimes would only be exceeded after 20 years with continuous cycling at the rate of one full charge-discharge cycle every 100 minutes. The limiting factor is most applications is more likely to be the standby lifetime, which is quoted as typically 20 years.

2.2.5 Faradic and energy efficiency

The overall system has typical in-out energy efficiency at rated power of over 90%. This falls off at low discharge rates, mainly as a function of the power electronics efficiency. However the relatively high self-discharge rate means that in-out efficiency falls rapidly when cycling is not continuous, for example when energy is stored for a period between charge and discharge.

2.2.6 Self-discharge.

The self-discharge losses could be analysed in two modes; open-circuit, where the power interface is switched off and the losses are those associated with the rotor including the bearings; and standby, where the power interface is switched on (perhaps intermittently) to maintain a constant speed. Flywheels are never operated for long periods in ‘open-circuit’ mode, and manufacturers generally specify average losses in ‘standby’ mode only. The average power supplied in standby mode is assumed to be equivalent to the total losses (rotor + power interface). An equivalent self-discharge rate in units of nominal capacity C per hour can be calculated from manufacturers’ data, as the ratio of losses to capacity C. Standby self-discharge rates are found to be in the range 0.18 to 2.0 times stored capacity per hour. These high self-discharge rates confirm that flywheels are usually not a suitable choice for long-term energy storage, other than to provide reliable standby power.

2.2.7 Temperature

Many manufacturers quote a wide operating range of –20°C to 40°C, however any of the system components (including the power electronics interface) can restrict the operating range. The operating temperature range may depend on system configuration and installation, for example operation at low temperatures can be extended when a small flywheel and associated power electronics interface are contained within a single enclosure, or where the flywheel is installed underground. The limited information published by the manufacturers regarding the influence of temperature on lifetime or losses suggests that any dependence is likely to be minor.

2.2.8 Possible degradations during operation

Provided the flywheel is operated within its specified speed range, then any speed (or state-of-charge) can be maintained indefinitely without degradation. The controller normally prevents operation outside this speed range, other than when the system is first started from rest. The input power during start-up is limited such that torque and current limits are not exceeded, until the minimum normal operating speed is achieved. Operating at speeds greater than the specified maximum implies a controller malfunction, however fail-safe features in the controller and power interface design can make this extremely unlikely. The ability to withstand continuous cycling for up to 10^7 cycles at high power, is one of the key advantages of flywheels. However operation over a wider speed range (lower minimum speed) can reduce the number of cycles (for example see URENCO data in Section 8.3). This means that a higher capacity at reduced power can be offered for applications such as UPS systems, where a high cycling lifetime is not required.

2.2.9 Recommended practices

The requirements for transportation and installation do not appear to be difficult. For example Active Power describes a simple installation procedure where the cabinet is bolted to the floor or other solid structure, the bearing retainers are removed, electrical power is connected, and the flywheel can be fully charged within 7 minutes. One manufacturer (Beacon Power) recommends underground installation.

2.3 Present situation of the storage technology

2.3.1 Technology developers and manufacturers

The main manufacturers include Active Power, Acumentrics Corporation, AFS Trinity Power Corporation, Beacon Power, Flywheel Energy Systems, Pentadyne, Piller, TSI (Tribology Systems Inc.), and Urenco Power Technologies.

Most manufacturers have developed high-speed composite flywheels. While most companies offer standard products targeted at a range of applications, a few companies aim to design solutions in response to customer-specific requirements. Steel flywheel manufacturers are in the minority. Active Power (and Caterpillar) are actively marketing UPS systems using a steel flywheel. Piller has a well-established dynamic UPS product using inertial storage, and incorporating a unique electrical machine, designed to provide support from loss of power until a diesel generating set can be started and brought on-line. This is a high-security system solution designed specifically for UPS applications.

Many other organisations and research centres with various technical specialities have flywheel R&D programmes. These include Boeing, Lawrence Livermore National Laboratory (LLNL), Argonne National Laboratory, Oak Ridge National Laboratory, Pennsylvania State University, The Center for Electromechanics at The University of Texas, NASA Glenn Research Center, The Office of Transportation technologies (OTT) of the US Department of Energy (DOE), ASPES AG, and European Universities.

2.3.2 Constructional features and manufacturing methods

The details of construction and manufacturing methods are usually proprietary to each manufacturer, and therefore only a generalised description is possible here.

The manufacturing process for steel flywheels includes casting, forging, heat treatment, machining, and balancing. Some early designs used several steel disks welded to a shaft, however this is only suitable for low speed operation because of problems related to welding and of balancing the overall rotor. The cost of steel is cheaper than fibre by at least a factor of 10, however composite fibre rotors can be operated at much higher speeds with specific energy up to 15 times that of a steel flywheel.

Composite flywheels are constructed using two basic methods. In the filament-winding process, fibre filaments first pass through a resin bath to become impregnated, and are then wound on a rotating mandrel. Multi-layer rotors using different fibres can be manufactured in a continuous process. In the resin-transfer moulding process (RTM), mats or weaves of fibres are first arranged in a mould, then low-viscosity resin is injected into the mould. RTM offers the possibility of cheaper mass-production, however current techniques mean that material properties of rotors are not as good as those made using the filament-winding process.

Pennsylvania State University, Composites Manufacturing Technology Center, is engaged in research aimed at developing a cost-effective manufacturing and fabrication process for advanced composite rotors.

2.3.3 Main conventional applications

Flywheels are suitable for applications requiring:
- continuous cycling
- high reliability (the state-of-charge is a direct function of rotor speed, and is known with certainty)
- high power
- low storage time up to several minutes (ratio of capacity to power)
- capacity in the kWh range
- short term storage

Examples of applications targeted by manufacturers include:
- UPS (during diesel generator start-up time)
- power quality (power injection, mitigation of voltage dips / sags)
- acceleration & regenerative braking (rail or traction, HEV)
- power system stability

The main applications at present are UPS systems, load following and peak power supply, telecommunications, power quality improvement, and traction (rail) support. Many manufacturers have an interest in renewable energy systems, and some trials are in progress.

Industrial processes often require a stable and reliable supply quality, otherwise dips and sags can cause shut-down with loss of product and considerable time lost starting up the process again. An example of this is described by Boyes in a paper presented at IEEE PES 2000, Seattle, where a company had a problem due to sags and momentary outages of the electrical supply to a production process line. A 250kW flywheel system was installed on one process line, which was then successfully protected.

2.3.4 Present R&D actions

The main activity is in the US, where most manufacturers are located. The main activities are aimed at reducing the overall cost of flywheel systems, and reducing the losses and extending the life of bearings.

Lawrence Livermore Laboratory, where pioneering work was begun by Post in 1973, continues the development of passive magnetic bearings, which have a long lifetime, do not require maintenance or lubrication, and have reduced frictional losses. Passive bearings are favoured because they are self-contained, unlike active magnetic bearings that require external electronics and electric power.

Current research in the Composite Manufacturing Technology Center at Pennsylvania State University is aimed at developing a cost-effective manufacturing and fabrication process for advanced composite rotors. This includes the development of a rapid filament winding process for GRP and CRP, the measurement of strain in high-speed rotors using opto-electronics devices, and the determination of fatigue behaviour of composite rotor material using coupon tests.

The NASA Glenn Research Center has an Aerospace Flywheel Development Program that aims to achieve a 5-fold increase in the specific energy of existing spacecraft batteries, and to achieve a 2-fold increase in battery life in low-earth orbit applications. A flywheel has been developed and has achieved full-speed operation at 60000 rev/min, and although this is targeted at spacecraft, it is possible that there will be technology transfer for other applications.

The US DOE HEV program is considering flywheels for hybrid electric vehicle (HEV) applications. Flywheels could be used in HEVs in ways that exploit the ability to deliver very high power pulses. One concept combines a flywheel with a standard engine, providing assistance during acceleration, and absorbing braking energy. Another concept uses flywheels to replace chemical batteries, although the energy density of a flywheel system is generally considered to be too low.

The Center for Electromechanics (CEM), University of Texas are involved in Flywheel and Alternator Development for the Advanced Locomotive Propulsion System (ALPS), and leads the US Flywheel Safety and Containment Program, a consortium of several leading flywheel developers. Advances in high strength materials, rotor dynamics, containment, non-destructive evaluation, and thermal management, provides a technology base for much of the commercial development that is underway. In addition, the CEM believe that compact flywheels are feasible with megawatt power and about 500MJ (~140 kWh) stored energy, levels which are of interest for electric utility line stabilisation.

Some recent EC-funded projects have concentrated on the application of flywheels to renewable energy generation, particularly the smoothing of power fluctuations generated by wind turbines. One project includes the development of magnetic bearings.

- Flywheel energy storage for wind power generation JOR3-CT97-0186 (co-ordinator KEMA)
- Low-cost, zero maintenance flywheel storage JOR3-CT96-0035 (co-ordinator Sigma)
- Power converters for flywheel energy storage systems JOR3-CT95-0070 (co-ordinator RAL)
- Hydrogen generation from stand-alone wind-powered electrolysis systems JOU2-CT93-0413 (co-ordinator RAL)
- Wind powered generators and high energy, low speed flywheels running in hybrid magnetic bearings JOR3-CT98-0238 (co-ordinator University of Sussex). The development is concerned with large diameter (1.0 to 1.5m diameter), 100 kg to 150 kg flywheels, at speeds of the order of 5000 rev/min in hybrid magnetic bearings. The hybrid approach involves using a combination of permanent magnets in conjunction with active suspension using d.c. electromagnets. These are being developed for use in flywheels operating in parallel with renewable energy generators. This work involves rotor dynamics, finite element modelling, simulation, secure containment for remote locations, and overall system control.

3. Economic issues

3.1 Cost of the storage technology

The cost of composite rotors is dominated by the cost of carbon fibre, rather than by the equipment or time used in manufacture. Composite rotors use carbon fibre (CFRP) for highly stressed parts of the rotor, as well as glass fibre (GFRP), which enables the mass to be reduced and the speed to be increased for a given energy stored. The cost of steel is around $1 per kg, while the cost of S-glass and high-strength carbon fibre ranges from $10 per kg up to $30 per kg or even more depending on specification. Although composite materials are much more expensive than steel, the additional cost can be offset by the reduced mass required. For example, although the cost of a composite rotor material per kg is up to 15 times more expensive than steel, the rotor can be operated at higher speeds, for example 29000 rev/min instead of 7000 rev/min, and the mass required for the same storage capacity can be reduced by a factor of up to 15. Therefore the material cost of the rotors for a given capacity is roughly similar at around $700 - $800 per kWh.

	Steel rotor	Composite rotor
Diameter [m]	0.64	0.46
Height [m]	0.23	0.20
Weight [kg]	555	32
Max. speed [rev/min]	7000	29000
Useful energy [kWh]	0.8	0.6
Material cost [$/kg]	1	15
Capacity cost [$/kWh]	690	800

Table 2. Comparison of steel and composite rotors
(from report by Taylor)

However these costs do not include the cost of a hub for the composite rotor, nor do they include the cost of manufacturing. Taylor reports that the bearings represent an additional cost of around 30% to 70% of the material cost of the rotor. The resulting cost of around $1000 per kWh seems expensive compared with a lead-acid battery, however flywheels may be competitive in applications such as power quality improvement, which require low capacity and high power. A good example is the Active Power system with 1kWh capacity and 250kWh power, equivalent to a storage time of 14 seconds. Most manufacturers offer flywheels with storage times in the region of 5 – 30 seconds, where the capacity is low, the power requirement drives the cost, and the most significant component cost is the power electronics drive.

A cost analysis model developed by Sandia [Taylor et al.] predicts the total cost of a flywheel system with 5-second storage time to be in the region of $200 to $500/kW. Here the power requirement drives the cost, and although the equivalent cost per kWh capacity is very high, additional capacity can be added with low incremental cost. Power electronics technology and IGBT devices have developed rapidly in the last decade, and it is likely that there will be future cost reductions.

The Sandia cost analysis model [Taylor] predicts the total cost of a system with a 1-hour storage time to be in the region of $1000 to $3000 per kW. Systems with this storage time are not manufactured at this time, however reduced losses using HTS bearings and cost reductions of the rotor and bearing assembly may make systems with longer storage times competitive.

3.2 Installation, operating and maintenance cost

The cost of energy throughput of a flywheel energy storage system operated for its full cycling lifetime is potentially low. Assuming a cycling lifetime of 10^6 cycles, a system with 5-second storage time has a potential cost of energy throughput of $0.14 to $0.36/kWh. Systems with longer storage times have very low energy costs, for example a system with 1-hour storage time would have a potential cost of energy throughput of $0.001 to $0.003.

Flywheel systems can be economically competitive with battery-based UPS systems. The Sandia model [Taylor et al.] predicts that a flywheel system (capital cost $800/kW, parasitic load of 4% of rated power, and O&M cost 2% of capital per year), could compete with a battery-based UPS (initial capital cost $450/kW, and battery replacement costs $525/kW).

4. Environmental Issues

4.1 Current knowledge on environmental issues of the storage technology

4.1.1 Hazardous materials

The materials used in flywheel systems are generally non-hazardous, and mainly consist of steel, aluminium, copper, glass and carbon fibre, epoxy resin, silicon (power electronics), and NdFeB rare earth magnets.

The rotor is manufactured from either steel or composite fibre. Resins used in the composite rotor have special handling requirements, but are non-hazardous when cured. The containment vessel is usually made from steel. The power electronics interface includes silicon semi-conductors, and heat-sinks, which may contain beryllium oxide (beryllia), which is only hazardous if dust is released from filing or machining.

4.1.2 Emissions and Safety aspects

There are no significant emissions during normal operation. In the case of a composite rotor failure, there are gases given off, however analysis by Urenco Power Technologies (UPT) has shown these are no more harmful than the exhaust from a diesel engine. The UPT rotor is intrinsically fail-safe, and is fully contained in the event of a failure.

The levels of electrical radiated and conducted emissions are likely to be similar to any standard power electronic drive, and are limited by international standards.

Acoustics noise levels are generally low, Urenco quoted less than 60dBa at 1 metre (the main noise source being the power electronics drive cooling fans and the vacuum pump), while Active Power and Piller quoted 72dBa at 1 metre.

Manufacturing of the rotor requires care in handling the fibre and resins to avoid contact with the skin. The manufacture of electronics devices requires the use of potentially dangerous materials and processes, for example the gas used in doping the silicon semi-conductor material. However the electronic devices used are no different to those in any other power electronic drive.

The main hazard during operation is the possible fatigue failure of the rotor and the sudden release of the stored energy in heat and flying debris. All manufacturers have actively considered the safety of rotors and their containment during operation, and consortia to consider safety have been assembled in both Europe and US. In Europe, the EC has funded the Flysafe project. The US Defense Advanced Research Projects Agency (DARPA) has assembled a Flywheel Safety and Containment Consortium to address the issue of flywheel safety. The DARPA Consortium includes Trinity Flywheel Power, US Flywheel Systems, SATCON, the University of Texas Center for Electromechanics (UTCEM), and Beacon Power, as well as various national laboratories.

4.1.3 Disposal

Flywheel systems present no particular problems for disposal at end-of-life. Steel and other metal parts can be recycled. The rotor can safely be disposed of in a land-fill site. The power interface is no different to any other power electronic drive, and recycling / disposal procedures are the same.

The Urenco system includes only 120kg composite material in the rotor, which is currently disposed of in land-fill. Practical techniques for recycling the rotor materials have been demonstrated, but more development is required on equipment for recovering the valuable fibres and rare earth magnetic material. The remainder of the Urenco total system weight of 1400 kg comprises steel, copper, and aluminium, which can be recycled easily using standard techniques.

4.2 Improvement options

The materials used in complete flywheel energy storage systems are not hazardous, and much can be re-cycled after the end-of-life.

Information on the usage of energy during the manufacturing process has not been found, and it would appear that this has not been analysed by manufacturers or researchers. The energy usage during operation is relatively high mainly due to bearing losses, together with power electronics conversion losses. As mentioned in Section 6, reduction of standing losses in the bearings is a key development objective. Many commercial flywheel products have a high power to capacity ratio, where the power electronics losses are significant. Although the interface losses may seem high, the a.c. power electronics losses would be comparable with interfaces at the same power level to any other storage technology.

Methods have been demonstrated for recycling composite rotors, to recover the valuable carbon fibres and rare earth magnetic materials, however it is not known whether these processes will become economic.

5. Application of the storage technology for Renewable Energy Systems

5.1 Existing applications

Flywheels are becoming well established as an attractive technology in UPS and traction applications. However installations in renewable energy systems are still relatively rare. Existing applications include autonomous hybrid systems (e.g. synchronous flywheel in a wind-diesel system, Punta Jandia, Fuerteventura), and smoothing wind power fluctuations from a single wind turbine (e.g. Urenco 100kW system at Fuji, Japan). The wind-diesel system including flywheel energy storage at Denham in Australia is probably the largest application, where three Enercon E-30 wind turbines have total rated power of 690kW. All existing renewable energy applications for flywheels are operating with wind turbines for rural electrification in remote locations, or for desalination on islands.

5.2 Operating characteristics

Generally the installation of a flywheel system presents no particular problems. A system may be transported in parts to remote applications if necessary, although this is unlikely to be an additional problem where a 300kW wind turbine has an associated 100kW flywheel system installed.

Maintenance intervals for the flywheel itself are infrequent or nil for some designs using maintenance-free bearings. The auxiliary systems require some routine maintenance, for example, the air filters for the power electronics drive, and the vacuum pump mineral oil. Therefore maintenance procedures are infrequent and easy to complete, even in remote installations. Flywheel control systems continuously monitor critical parameters and provide fail-safe shutdown in the event of critical problems, and provide remote signalling of warnings and alarms.

5.3 Assessment of the storage technology in these applications

The ability to cycle continuously at high power, with a relatively low capacity (ratio of capacity / rated power of the order of tens of seconds), and the high cycling lifetime, are the key advantages of flywheels in the wind power smoothing application. However the level of standing losses is potentially a drawback.

5.4 Potential future applications

Potential applications to renewable energy systems include:

- power smoothing, avoiding rapid voltage fluctuations & flicker (continuous cycling)
- power system stability (high power cycling and injection)
- grid reinforcement (peak lopping, distributed storage)
- bridging power until a diesel generating set in a hybrid stand-alone power system is started and ready to be brought on-line.

6. Needs for R&D on the storage technology for an extended use in Renewable Energy Systems

The key issues include:

- cost of materials and manufacturing processes
- reduction of operational losses
- optimum control strategies (application-specific)
- cost-benefit analysis
- safety and certification

Research and Development proposals include:

- Improvement of rotor materials (tensile strength, stability), and manufacturing technology
- Improvement in magnetic and mechanical bearings (fail-safe, reduction of standing losses)
- Safety and Certification
- Power electronics interface & control (losses, pulsed power techniques, storage modules, response time)
- Hybrid storage topologies (e.g. with battery)
- Control strategies (application-specific)
- Instrumentation, condition monitoring, lifetime prediction

7. Conclusions and Recommendations

Flywheel systems using steel or composite rotors have been successfully developed and are being produced by several manufacturers. The technology is already highly developed, and standard products are on the market.

Most standard flywheel systems have storage times in the region of 5 to 30 seconds, where the power electronics interface is the most significant capital cost. Despite this, current development is aimed at rotor cost reduction by achieving higher specific energy and reduced rotor mass. Advanced bearings are being actively developed including the use of HTS magnetic bearings, to provide reduced losses, higher efficiency, reduced running costs, and longer bearing life. Both these developments are particularly significant to systems with longer storage times of greater than 1 hour, where the rotor and bearing costs become the most significant system cost. Successful reduction of rotor losses and costs would make flywheel systems attractive to a wider range of applications.

The main markets for flywheel systems are UPS systems, power quality improvement, and traction applications. Analysis by Sandia has indicated that flywheels can be cost competitive with batteries in some UPS applications. There are already some applications of high power (low energy) flywheel systems for smoothing wind power fluctuations in weak networks, and new requirements are emerging for stability improvement and protection of wind farms against network voltage dips. These applications are ideally suited to high power cycling capabilities of flywheels. The development of lower loss and reduced cost systems with longer storage times could make flywheel systems competitive with batteries in stand-alone renewable energy systems.

8. Annexes

8.1 Glossary of terms and abbreviations

CFRP	Carbon Fibre Reinforced Plastic
FES	Flywheel Energy Storage
GFRP	Glass Fibre Reinforced Plastic
HEV	Hybrid Electric Vehicle
HTS	High Temperature Superconductor
IGBT	Insulated Gate Bipolar Transistor
ISG	Integrated Synchronous Generator
MLC	Magnetically Loaded Composite
PQ	Power Quality
PWM	Pulse Width Modulation
RTM	Resin Transfer Moulding
UPS	Uninterruptible Power Supply

C	capacity	[kWh]
E	kinetic energy	[Joule]
J	moment of inertia	[$kg.m^2$]
P	power	[W]
T	torque	[N.m]
m	rotor mass	[kg]
ρ	rotor material density	[$kg.m^{-3}$]
σ	tensile strength	[$N.m^{-2}$]
ω	angular velocity	[$rad.s^{-1}$]

8.2 Links to manufacturers, developers, and information sources

Manufacturers:

Active Power (and Caterpillar)	http://www.activepower.com/ http://www.cat.com/
Acumentrics Corporation	http://www.acumentrics.com/
AFS Trinity Power Corporation	http://www.afstrinity.com/
Beacon Power	http://www.beaconpower.com/
CCM (Centre for Concepts in Mechatronics)	http://www.ccm.nl
Flywheel Energy Systems	http://www.magma.ca/~fesi/index.html
International Computer Power	http://www.rotoups.com/
Magnet-Motor	http://www.magnet-motor.de/
Optimal Energy Systems Inc.	http://www.optimalenergysystems.com/
Pentadyne	http://www.pentadyne.com/
Piller	http://www.piller-gmbh.de/
Powercorp	http://www.pcorp.com.au/
RPM	http://home.earthlink.net/~fradella/homepage.htm
SatCon Power Systems	http://www.inverpower.com/
Tribology Systems Inc.	http://www.tribologysystems.com/
Urenco Power Technologies	http://www.uptenergy.com
US Flywheel (Note: US Flywheel ceased business in 2003)	http://www.us-flywheel.com/
rosseta-Technik	http://www.rosseta.de

Developers:

Boeing http://www.boeing.com/
http://www.boeing.com/news/releases/1998/news_release_980217c.html

Lawrence Livermore National Laboratory (LLNL)
http://www.llnl.gov

Argonne National Laboratory http://www.anl.gov/
http://www.et.anl.gov/sections/te/research/flywheel.html

Oak Ridge National Laboratory http://www.ornl.gov/
http://www.ornl.gov/publications/labnotes/mar94/flywheel.html

Pennsylvania State University http://www.psu.edu/

The Center for Electromechanics, The University of Texas
http://www.utexas.edu/research/cem/

NASA Glenn Research Center http://space-power.grc.nasa.gov/ppo/
http://space-power.grc.nasa.gov/ppo/projects/flywheel/techdet.html

The Office of Transportation technologies (OTT) of the US Department of Energy (DOE)
http://www.ott.doe.gov
http://www.ott.doe.gov/hev/flywheels.html

ASPES AG http://www.aspes.ch/

University of Newcastle http://www.ncl.ac.uk/
http://www.ncl.ac.uk/eece/research/groups/drives/drv-proj.htm

University of Sheffield http://www.shef.ac.uk/

University of Sussex http://www.sussex.ac.uk/
http://www.sussex.ac.uk/press_office/bulletin/30jan98/item2.html

Politecnico di Torino http://www.polito.it/index.en.html

Industry associations:

Flysafe http://www.flysafe.ch

Electricity Storage Association http://www.electricitystorage.org/

Energy Storage Council http://www.energystoragecouncil.org/

Sources of Information:

Energy Technology Data Exchange http://bia.osti.gov/etdeweb/

8.3 Data and performance characteristics

At least twelve flywheel manufacturers have been identified, offering products at various stages of development and commercialisation. Their web-sites provide useful information during the compilation of this report. However the project required more wide-ranging information, and a questionnaire was compiled and sent to ten flywheel manufacturers (Active Power, Acumentrics, AFS Trinity Power, Beacon Power, Flywheel Energy Systems, Pentadyne, Piller, Urenco Power Technologies UPT, US Flywheel). Since then US Flywheel has been closed. Tribology Systems Inc (TSI), part of the World Flywheel Consortium, Magnet-Motor, rosseta-Technik, and RPM could be added to this list. Unfortunately only four manufacturers (below) responded to the survey. The respondents offer fully commercial products, for UPS and traction (railway) applications, while the other companies may still be at the technology development stage.

Active Power markets systems with product names CleanSource UPS, Clean Source2, CleanSource DC; and the Cat UPS and GenSTART products marketed by Caterpiller. Fully commercial products are available for UPS applications, with over 3.5 million hours of operation in the field. The system configuration is a flywheel motor-generator that interfaces via power electronics to the d.c. link of a 3-phase a.c. UPS, providing ride-through energy for up to 2 minutes. Both a.c. and d.c. interfaces are provided. The rated power of a single rotor is 250kW, with capacity around 1kWh, and up to 8 rotors can be operated in parallel to provide 2000kW with capacity around 7kWh. The rotor is solid forged steel, and the bearings are a combination of ceramic ball bearings on a steel race, with magnetic lift to increase bearing life. The containment is provided by a cast iron enclosure, that also acts as the stator for the motor-generator.

RWE Piller Gmbh markets the POWERBRIDGE product in UPS systems, and for load levelling in local grids, such as d.c. railway systems. The product is fully commercial in series production, with over 500 installations worldwide in high reliability applications including UPS systems. The configuration is a steel flywheel operating at 1800 to 3400 rev/min, a synchronous generator, and power electronic converter. The rated power is 1300kW with capacity 4.6kWh. The rotor is a steel disc, with sealed ball-bearings. This is a high power machine, with 10kW losses at standby, and 60kW losses when operating at rated power.

URENCO Power Technologies Ltd offer the UPT KESS systems with two variants PQ250 and TR200, aimed at the power quality (250kW) and traction (200kW) applications. Multiples of the base units are combined to match the customer’s power and energy requirements, for example 12 machines can be combined to produce a 2400kW system. The rotor is a 110kg cylinder made from carbon and glass fibres, and Magnetically Loaded Composite (MLC) with 12-pole permanent magnets, and rotating at speeds up to 37500 rev/min. The bearings are a 20-year maintenance-free system consisting of a permanent magnet repulsion passive magnetic bearing, combined with a hydro-dynamic pivot bearing. The power electronics interface is d.c. for power quality and traction applications, and an a.c. interface is available. When operated at rated power, the capacity of 2kWh is available when operated over the speed range 37,800 to 27,000 rev/min, while operating at lower powers permits operation to a lower speed providing 3kWh. URENCO believe their product has significant advantages over competing products and quote the ability to cycle continuously at rated power; a very fast response (5mS to full power); a very high availability; the possibility of operating multiple units in parallel configurations with easy control interface; and a small footprint. The basic unit can be fitted through a standard door, thus avoiding building modifications.

Beacon Power offers products covering applications from telecommunications (BHE-6: 2kW, 6kWh) to PQ and UPS (BHP250: 250kW, 2kWh). Beacon has an exclusive agreement with Urenco to distribute high power products for the North American telecommunications UPS market.

Summarised data and performance characteristics, compiled from information provided by flywheel manufacturers and developers on their web pages, are summarised in Table 2 on the following pages.

	Active Power	**Acumentrics**	**AFS Trinity**	**Beacon Power**	**Flywheel Energy Systems**	**Magnet-Motor**
Product status	Commercial product available	Under development, available 2004	Pre-production 2004 Commercial 2005	Commercial product available	Rotors developed. Systems under development	Commercial product available, and under development
Product names	CleanSource DC CleanSource UPS CleanSource2 **Marketed by Caterpillar:** Cat UPS GenSTART	Power-Q (PQ100, PQ175, PQ250)	M3A 100kW M4A 200kW	Smart Energy series BHE-6 (2kW) Smart Power series BHP-250 (250kW) (UPT product, for which Beacon has distribution rights)	Series 45 rotors Emerging products for ACES, UPS, PQ/HEV	Magnetodynamic storage (MDS)
Rotor type	Solid forged 4340 steel	Composite	Carbon fibre composite	Composite	Composite	Carbon fibre composite
Bearing type	Ceramic ball in a steel race, with magnetic lift to increase life		Advanced	BHE: magnetic BHP: see UPT data	Mechanical	Bearings, plus magnetic support
Containment vessel	Cast iron, acting as vacuum housing and stator for the electrical system	Stainless steel (weatherproof)		Steel		
Power per rotor	250kW per rotor	80 kW 140 kW 200 kW (6kW typ. recharge)	100 kW 200 kW	BHE: 2 kW BHP: 250 kW	1.5kW (UPS) 50 kW (PQ/HEV)	5MW demonstrator
Capacity per rotor	1kWh approx.	0.44 kWh 0.56 kWh 0.55 kWh	0.42 kWh 2.0 kWh	BHE: 6 kWh BHP: 1.7 kWh min.	1.1kWh (PQ) 1.3kWh (PQ/HEV)	80 MJ (22.2 kWh) prototype
System maximum power and capacity	2000kW 7kWh approx. (8 rotors)	Paralleling possible	Paralleling possible	Paralleling possible Smart Energy matrix is based on 250kW, 25kWh units e.g. 10 units,		

				providing up to: 2500 kW, 250 kWh		
Rotor speed	2500 – 7700 rev/min		40000 rev/min	BHP: see UPT data	15000 – 45000 rev/min (UPS, Series 45 rotor) 17500 – 35000 rev/min (PQ/HEV, Series 39 rotor)	
Voltage interface	350 – 550 Vd.c. 380/400/415/480 Va.c. @ 50 or 60 Hz	480 V a.c. 3-ph. (option 208V a.c. on PQ100)	350-800 V d.c.	BHE: i/p 480 V a.c. 3-ph.; o/p 36, 48, or 96 V d.c. BHP: 480 V a.c. 3-ph.	3-ph	
Applications	UPS	UPS (industrial applications)	UPS Power quality & power management	BHE: Telecomms. UPS BHP: Power quality	Space. UPS Power Quality. HEV	Urban buses (since 1988) HEV UPS Pulsed power
Standby losses Self discharge rate Efficiency	1.5 kW at max speed initially 1.5 x capacity per hour	 Full load efficiency >95%	700 W (max) <500W typ 0.35 x capacity per hour	BHP: see UPT data		
Temperature: Operating Non-operating	 -20°C to 40°C -25°C to 70°C	 -20°C to 45°C -50°C to 65°C	 -20°C to 40°C	 BHE: -40°C to 46°C BHP: 0°C to 35°C BHP: -20°C to 70°C		
Lifetime	25+ years standby >10,000 cycles		> 100,000 cycles	BHE: 20 years BHP: see UPT data	Typ 100,000 cycles	

	Optimal Energy Systems	**Pentadyne**	**Piller**	**Tribology Systems Inc (TSI)**	**Urenco Power Technologies (UPT)**	**rosseta-Technik**
Product status	Under development	Commercial 2004	In series production, >500 installations world-wide	Commercial product available	Commercial product available	Under development Commercial 2004
Product names	FpoM FESM FPMM PCM	VSS-120	POWERBRIDGE	FLB-E 150Wh FLB-A 500Wh	UPT KESS PQ250 (power quality) TR200 (traction)	Rosseta T1 Rosseta T2
Rotor type	Graphite fibre composite	Carbon fibre composite cylinder, titanium hub	Steel disc	Composite	Composite 110 kg cylindrical carbon, glass, and MLC, with integral PM brushless d.c. motor/generator	Graphite fibre, epoxy resin composite
Bearing type		Magnetic	Ball bearings, permanent greased	Hybrid-ceramic ball bearings	Maintenance free for 20 years, passive magnetic and hydro-dynamic pivot bearings	
Containment vessel			Steel		800 kg steel	
Power per rotor		120 kW	1300 kW	40kW	250 kW max	150 to 300 kW
Capacity per rotor	0.9 kWh	0.67 kWh	4.6 kWh	0.5 kWh	2 kWh (min) 3 kWh (max)	2 to 6 kWh
System maximum power and capacity			para1leling possible		12 machines total: 2400 kW 36 kWh	
Rotor speed	60000 rev/min	55000 rev/min	1800 – 3400 rev/min	28000 rev/min	27000 – 37800 rev/min (high cycling) 18000 – 37800 rev/min (high	25000 rev/min

					capacity)	
Voltage interface		240 V a.c. 3-ph. 400 V d.c.	a.c. alternator		580-900 V d.c. 380 V a.c	550 – 1000 V d.c. 400 V a.c.
Applications	UPS, load levelling, 100 kW to 100 MW Space Pulsed power	UPS Power Quality HEV	Load-levelling in local grids. Efficiency improvements in traction systems	Surge power in HEV	Power quality. Traction. Cyclic loads. Island site generation.	Voltage stabilisation in railway systems. Regenerative braking in HEVs Peak load shaving
Standby losses Self discharge rate In-out efficiency at rated power		120 W typ. (idle) 0.18 x capacity per hour	10kW 0.46 x capacity per hour 95%		1.2 kW 1.67 x capacity per hour 94% (d.c. interface) 91% (a.c. interface)	
Temperature: Operating Non-operating		-20°C to 50°C -20°C to 80°C	0 to 40°C -30°C to 40°C		0°C to 40°C 0°C to 70°C	
Lifetime: Standby Cycles	200,000		25 years 10,000,000	20 years	20 years 10,000,000 (high cycling system) 500,000 (high capacity system, with lower minimum speed at lower power)	20 years 5,000,000 cycles

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