Energy and the Environment Capstone Design Project – Bass Connections 2017

Flywheel Energy Storage (FES): Exploring Alternative Use Cases

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1 Abstract

Each day, utilities struggle to delicately balance generation supply and consumer demand in electricity markets. Current market structures are highly inefficient, with costly power plants supplying power over overly congested transmission lines. Adding renewable energy sources to the grid only increases the complexity of the problem, because they create energy intermittently and unreliably. Recently, chemical batteries have been hailed as a potential solution to this problem, because they can lower peak consumption as the energy demand spikes - a process known as peak shaving. However, a more environmentally friendly option for peak shaving is a flywheel: a mechanical battery that stores kinetic energy that can be released as electricity. Although the flywheel is a net consumer of energy, it can also save money for both the consumer (and utility) by spinning up when electricity is at its cheapest and releasing the energy when the energy prices start to rise. Flywheels are typically used for frequency regulation; however, in this senior design capstone, we explored a use case for peak shifting and demand shaving in a commercial setting on the New York City electrical grid and engineered a proof of concept prototype. We used data analysis and real time electricity pricing to show that a 100 kW system of flywheels installed in the basement of a commercial building can induce monthly cost savings of up to $500, based on our July 2016 model. Furthermore, these flywheel systems could be coupled with renewables to assist with grid integration and yield economic and environmental benefits.

2 Introduction

2.1 Energy Markets

In order to understand one of the major drivers behind the need for energy storage systems, it is important to first explore the basic economics of power markets in the United States. In any regional grid, there are power generators producing electricity for the wholesale market and consumers paying for their electricity in the retail market [27]. In between the physical power producers and electricity customers are a variety of resellers, which often take the form of integrated utilities. Such utilities purchase wholesale electricity from generators (some utilities own their own generators) based on their overall cost to their customers. As resellers, utilities also manage the transmission and distribution of electricity to the costumer. In a deregulated state like New York, there are a myriad of utilities offering a variety of services and prices for customers to choose from.

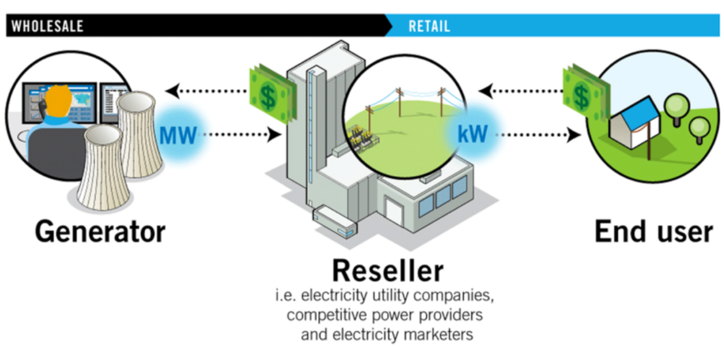

Figure 1: Power Market Basics

On a macro level, prices are set first by the New York ISO (Independent System Operator) in a Day Ahead Market, and are determined by a market auction system in which the ISO accepts electricity bids from all generators. Since ISOs are charged by state governments to take the cheapest available electricity prices, the NYISO will dispatch electricity in the wholesale market from generators on an increasing cost scale until all estimated demand can be met [10]. For example, cheaper electricity from renewables, nuclear, and coal will be set as base load power for the grid first, while more expensive natural gas bids will come online as demand ramps up. To set the most efficient locational based marginal prices (LBMP), NYISO also uses predictive algorithms that incorporate projected demand based on historical consumption patterns, weather forecasts, and other factors to calculate estimated demand. These wholesale electricity prices are similar to futures contracts; utilities can agree to lock in day-ahead power prices at a potentially cheaper rate than on the day of usage.

On any given day, there is also a Real Time spot market in which electricity is bought and sold based on actual supply and demand factors. Subsequently, the spot market is subject to a greater variance in electricity prices, but these prices better represent the real time dynamics of a given day. Often times, grid congestion, unexpected electricity demand, and power failures create a mismatch between the expected load profiles in the Day Ahead market and Real Time market. For example, the majority of New York's major electricity generators are located upstate, which leads to major line congestion when New York City requires huge amounts of power in the summer months [30]. Since electricity grids must perfectly balance supply and demand discrepancies in the in the Day Ahead market and Real Time market to avoid a system failure, small peaking plants must always be available match rapid or unexpected fluctuations in energy demand. During the hot summer afternoons, for example, numerous peaking plants are often needed to meet massive spikes in electricity usage. Running these plants is expensive, and many operate infrequency over the course of a year. As such, utilities that purchase power to meet pay a high premium to deal with unexpected consumption, which they pass onto the consumer to maintain a strong balance sheet.

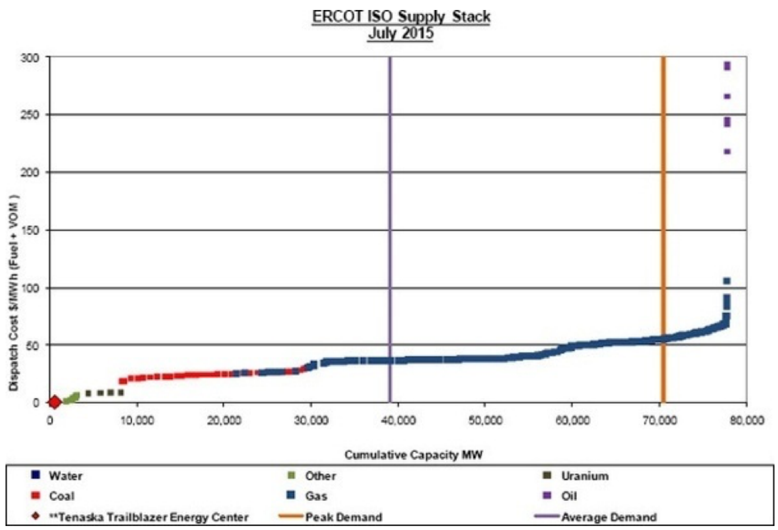

Figure 2: Regional ISO Supply Stack for July 2015

Utilities can charge their customers for electricity through a variety of rate structures. Historically, retail and some commercial customers have paid a flat KWh fee for their power usage regardless of their time of consumption. In charging their consumers a ubiquitous volumetric rate, monopolistic utilities could more easily lock in revenue streams and hedge against volatility. Flat rate pricing is also the least expensive or technologically sophisticated option for utilities to employ. Without massive amounts of data and a digitized grid, shifting to a more time or capacity based model could have been financially strenuous. While flat rates may have been effective for utilities in highly-regulated single markets, such price models are highly inefficient. If the marginal cost of electricity usage to consumers does not rise as they increase their consumption, customers will have larger demand profiles than they otherwise would have had if they had to bear the full cost of their additional consumption[12].

To improve economic signaling and better encapsulate demand profile changes, utilities have shifted to more dynamic fee models. One such model is called a Real Time Pricing structure, in which the price of electricity fluctuates hourly based on generation cost [32]. As demonstrated in the figure below, real time pricing models closely mirror a daily load profile by allowing the utility to charge hour specific rates [32]. Real Time Pricing structures have become popular for large commercial and industrial consumers, as they have the resources to meaningfully change their general consumption patterns. In fact, New York regulators mandated that utilities employ hourly pricing models for large commercial customers in the mid 2000s [18]. Time of Use (TOU) and Critical Peak Pricing (CPP) structures follow the same premise as Real Time Pricing models, but are less sensitive to the constant fluctuations of the market. TOU models are structured as a step function, with utilities designating particular time frames as off-peak, peak, and super peak over the course of the year. Customers using CPP pricing are not subject to time frame specific prices, but are instead notified before expected critical demand periods that their electricity rate is set to jump. Although RTP, TOU, and CPP rate structures approach power pricing differently, they are all used by utilities to send more efficient price signals to their customers.

Beyond the volumetric charge, many New York consumers will also pay two additional fees for their electricity. First, consumers are charged a fixed service fee, which covers utilities operational and management costs, as well as all of the costs associated with maintaining their complex distribution systems. Lastly, consumers are charged a demand charge, which is based on the highest 15-minute average usage recorded on the demand meter within a given month[33]. In order words, a demand charge is measured in kilowatts consumed (total consumption), whereas their flat rate charge is measured in kilowatt-hours consumed over a month (flow rate). Given that utilities are required to have the electrical capacity to meet all of their customers sudden needs, utilities charge their customers a demand charge to monetize their capacity infrastructure investments (ex. peaking plants) and encourage reductions in power consumption [12]. Demand charges are often expensive, and can make up a large portion of a commercial customers bill. By deploying energy storage technologies, companies can cut down on their peak consumption and significantly lower their demand charges.

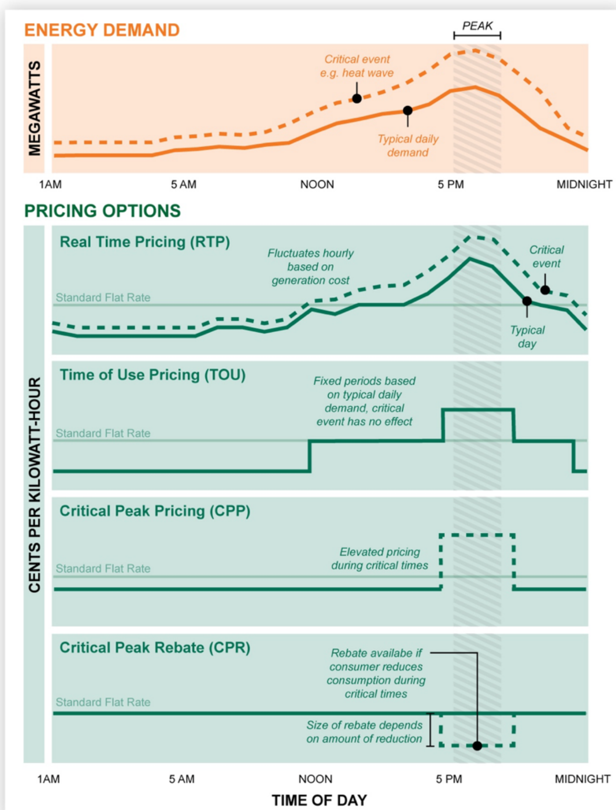

Figure 3: Dynamic Electricty Rate Structures

3 Concept Generation

3.1 Traditional Energy Storage Methods

Chemical batteries and flywheels aside, there are two main methods of grid energy storage in the United States: Pumped Hydro and Compressed Air Energy Storage. Both of these storage methods utilize potential energy in a way that can be later used to produce electricity.

Pumped hydro is the largest source of stored energy in the US, with a current capacity of 20.4 GW according to a 2016 US Department of Energy report. It has been used for over a century, with the first plant dating back to 1929 in Connecticut [1]. With a simple design, fast ramp up times, and low maintenance costs, Pumped Hydro is the industry standard for energy storage [19]. However, locations are geographically constrained because Pumped Hydro requires a large volume of water and an elevated reservoir. There are also other criticisms including high capital costs and negative impact on local ecosystems. However, innovations to the design such as constructing an underground reservoir. could lead to further Pumped Hydro expansion in the future.

Pumped Hydro works by pumping a large volume of water up to an elevated reservoir, storing the gravitational potential energy. The amount of energy stored is dependent on the volume of water as well as the height differential between the lower and upper reservoir. When electricity is required, the water runs through hydroelectric turbines and moves back down to the lower reservoir. The turbine is connected to a generator so that as the turbine turns, the connected generator produces energy. In many cases, the generator and motor are one and the same just running in the opposite direction. This process or pumping the water up and letting it flow back down is not 100% efficient in either direction, and therefore Pumped Hydro is a net consumer of energy. However, by assisting with peak shifting and peak shaving, it has the potential to save energy indirectly, preventing a peaking plant from turning on. For this reason, it saves money for both the utility and consumer [4]

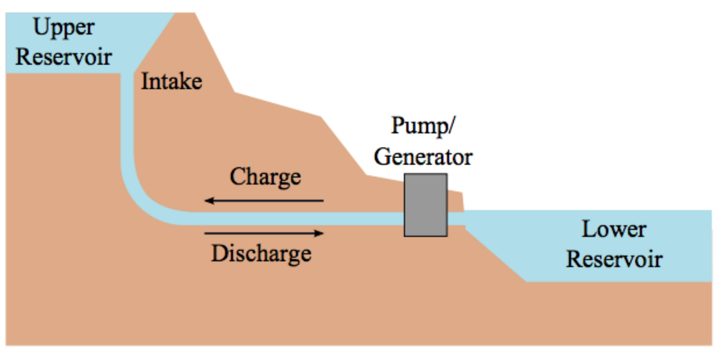

Figure 4: Illustration of Pumped Hydro System

Compressed Air Energy Storage (CAES) is similar to Pumped Hydro in its storage and output capacity, and performs the same functions of peak shaving and peak shifting. It is less widespread but CAES can be adapted anywhere because it doesnt have geographic constraints. Furthermore, CAES can be useful at any scale, even small non-grid applications such as propulsion of mine locomotives. CAES integrates well with existing grid systems because it is essentially a high-efficiency combustion turbine plant, with a ramp rate faster than traditional gas plants [6].

The way a CAES plant works is by storing and pressurizing a large volume of air in a confined space, typically a geologic formation such as a salt cavern or depleted oil well. To extract energy, the air is heated up, moving through an expansion turbine which drives a generator for power production. In a typical gas turbine, most of the energy provided by fuel goes towards compressing the air, so a CAES system uses significantly less fuel. The main efficiency limit of CAES is loss of heat, because not all of it can be used in the generator scheme. For a diabetic system, all excess heat from compression is dissipated, and in some cases an additional energy source such as natural gas is needed to make up for the wasted heat. The natural gas would help heat the gas for turbine expansion which would power the generator. In an adiabatic system, there is no transfer of heat so with perfect insulation it could have an efficiency of 100%. By utilizing the heat generated from compression, no combustion is involved so it becomes a zero-emissions system. However, an adiabatic system would be much harder to implement. None are currently in use, but one (the ADELE) is currently under construction in Germany [4].

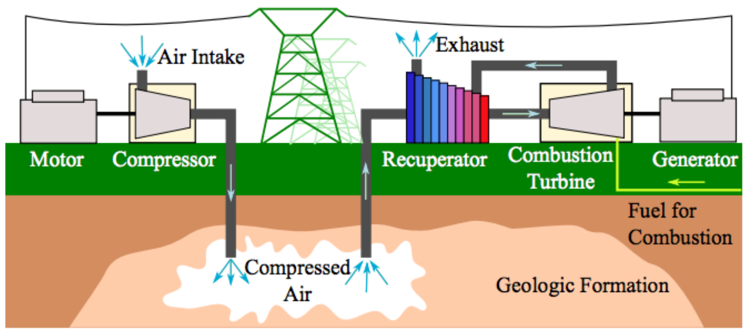

Figure 5: Illustration of Compressed Air Energy Storage System

In addition to Pumped Hydro and CAES, alternative methods of grid energy storage are being explored, utilizing chemical energy and thermal energy. However, for the foreseeable future, Pumped Hydro and CAES will be the dominating players in the grid energy storage market, for long term energy storage. Newer technologies such as batteries and flywheels are better suited towards a short term, high power storage application.

3.2 Decision Matrix

After researching energy storage technologies, energy markets, and current grid issues, we needed to choose an energy storage technology to prototype. Only existing energy storage technologies were considered. During a brainstorming session parameters were identified to evaluate the prototype options: cost, feasibility, efficiency, environmental impact, land use, scalability, and ability to innovate. Each prototype was scored for each parameter from 1-5, with 5 being the best outcome for our group. For example, for the cost parameter, 5 was for lowest cost because we wanted to minimize the prototype costs. The top three options were CAES, Pumped Hydro, and flywheels.

Consideration Metrics	**CAES**	**Pumped Hydro**	**FES**	**Spring**	**Phase Change**	**Chemical Battery**	***Weight***
Cost of prototype	3	4	3	4	2	3	*6*
Design feasibility	4	4	5	4	1	1	*5*
Efficiency	3	4	3	2	3	4	*3*
Environmental Impact	4	2	2	3	1	1	*5*
Land usage	4	5	4	3	4	5	*1*
Scalability	4	4	4	1	5	1	*3*
Ability to innovate	3	4	5	5	2	1	*4*
Total	95	99	98	91	58	52	

Table 1: Decision matrix highlighting strengths and weakness of the energy storage systems considered using key design metrics and a weight system to evaluate project fit

While pumped hydro had the highest score (99) through the decision matrix, we decided as a team that it was not a practical technology to pursue when considering application for peak demand cost savings perspective. While well-tested and a clear market leader, pumped hydro is incredibly geographically dependent due to the need for a large upper and lower reservoir and significant head. Additionally, pumped hydro is not a quickly dispatchable energy storage solution that can be utilized with short term peak shaving and demand shifting [4]. After this further analysis, we determined that pumped hydro would not a valuable technology to fit our use case of peak shaving in an high energy cost urban setting.

Flywheel Energy Storage had the second largest total score, and additionally is adaptable for an urban commercial building. FES also works well for peak shaving and peak shifting applications due to high power output.

4 Technology Background

4.1 Flywheel Past and Present

The use of flywheels dates back historically to the potters wheel, and has been critical to the industrial revolution as a component in the reciprocating steam engine and automotive engine. In this application, the increased moment of inertia serves to smooth the power output from the combustion cycle. In reciprocating engines, the combustion of the fuel results in a piston being driven down, exerting a torque on the shaft. However, in the other three of the four stages of the cycle, there is no torque exerted to increase the speed of the engine. This results in an engine with relatively discrete output. To make power output more continuous, flywheels are placed in-line with the shaft to increase the system's moment of inertia, effectively modulating the intermittency of power availability in engines. Additionally, the load may not be constant, flywheels more generally reduce noise in engine operation, supplementing governors in improving stability. Similarly, flywheels may be used to abate the mismatch of grid power supply and load demand, as discussed in the introduction.

There are many advantages to integrating flywheel storage technology into the power grid. Examples include cost efficiently meeting peak demand, providing a stable and dependable source of energy in case of emergency, and protecting the environment by incorporating renewables into the nation's energy portfolio. One further desirable quality is that flywheel technology is virtually independent of environmental factors such as altitude and proximity to underground caverns. This allows flywheels to be placed in close proximity to renewable energy sources, ranging from coastlines for tidal power to hotbeds of geothermal activity for geothermal power.

Additionally, the compact size of most flywheel energy storage systems, with some units as small as a mini-fridge, makes them easy to include in most building floorplans. Furthermore, flywheels are scalable; a single unit can be used in isolation, and multiple units can be placed in sequence for situations of much higher demand. As such, flywheels are a great fit for our market of commercial buildings in New York City. Termed the Mechanical Battery, flywheels store kinetic energy by rotating at high speeds. These storage devices are comprised of both mechanical and electrical components.

4.2 Flywheel Energy Storage Fundamentals

The flywheel itself is usually a weighted disk or hoop that stores energy as the angular velocity increases. The total energy storage capacity is dependent on the geometry of the flywheel, material density, and angular velocity, as presented in Equation 1.

$$E_{rot} = \frac{1}{2} I \omega^2 \tag{1}$$

$$I = \int mrdr \tag{2}$$

I is the moment of inertia, shown in Equation 2, and ω is the angular velocity. However, flywheels incur several types of losses, significantly air drag and frictional (rolling) drag. The retarding force from air drag is the result of interactions between air molecules and the object with some relative velocity. The rate at which energy is lost to air drag is determined by the air density ρ_a, its dynamic viscosity β_a, the angular speed ω, and the height and radius of the flywheel, as presented in Equation 3. The force of frictional (rolling) drag in a flywheel is largely from bearings, especially if using roller bearing elements. Any two components in contact with some non-zero relative velocity will add to this form of energy loss. The rate at which energy is lost to frictional drag is determined by the coefficient of friction μ, the mass m, the radius r, and the angular velocity ω, as shown in Equation 4. The net energy in a system, some time after t_1 when the flywheel is initially spinning at w_1, is presented Equation 5

$$P_{airdrag} = 0.04\rho_a^{0.8}\beta_a^{0.2}(r\omega)^{2.8}(2r)^{1.8}(\frac{h}{2r} + 0.33) \tag{3}$$

$$P_{rollingdrag} = \mu mg * r\omega \tag{4}$$

$$E_{net} = \frac{1}{2}C\rho hr^4\omega_1^2 - \int(P_{airdrag} + P_{rollingdrag})dt \tag{5}$$

C is the shape factor of the flywheel. For a hoop, this factor would be 1; for a disk, it would be $\frac{1}{2}$. ρ is the density, h is the height of the flywheel, and r is the flywheel radius. Geometrically, a flywheel's mass must be symmetrical radially to its center of rotation. Improper implementation of this would lead to vibrations, inducing additional stress, as will be discussed later.

4.3 Limiting Factors to FES Storage Capacity

From Equation 5, it may be concluded that maximizing the radius and angular speed are most effective at increasing energy capacity of a flywheel system. However, the maximum allowable radius and angular speed, and therefore also energy stored, is partly determined by the tensile strength of shaft. A flywheel system would fail if the hoop stress exceeds the tensile strength of the selected shaft material. Therefore, in designing a flywheel shaft, the engineer should be careful to ensure the condition proposed in Equation 6.

$$\sigma_t \geq \rho r^2\omega^2 = \sigma_{hoop} \tag{6}$$

The hoop stress in the shaft is proportional to the square of both the radius and the angular speed. This further supports the advantage of increasing the flywheel radius first to maximize energy, especially if the shaft tensile strength is the limiting quantity, as hoop stress is only proportional to the square of the radius, while rotational energy is proportional to the radius raised to the fourth power.

Additionally, in considering limiting factors to a design, if the mass of the flywheel is not placed symmetrically relative to the center of rotation, the flywheel would exert a radial force on the shaft, which, in excess, could overcome the shaft strength in bending. This unbalance force is presented in Equation 7 and Equation 8.

$$F = Uw^2 \tag{7}$$

$$U = mr = \int \rho\pi hdAr = \int \rho\pi rhdA \tag{8}$$

The unbalance, U, is calculated from the equivalent mass that is not offset. For example, the entirety of a 12" diameter flywheel is shown in Figure 4.3, however only the unbalanced subset of the total mass when offset 0.5" is exhibited in Figure 7. Only this subset of the mass is included in calculating U.

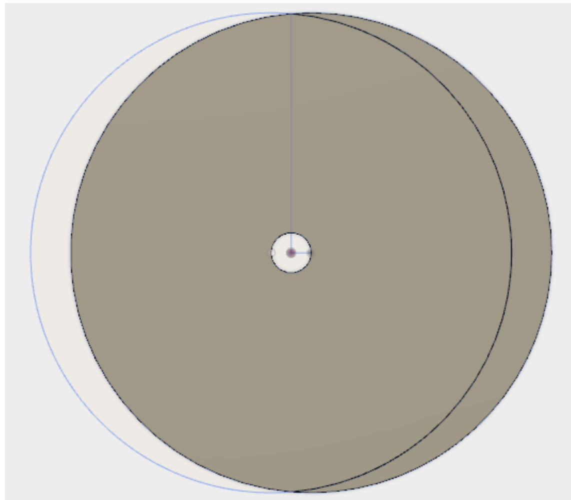

Figure 6: A Topview of a 12" Flywheel with 0.5" Shaft Offset

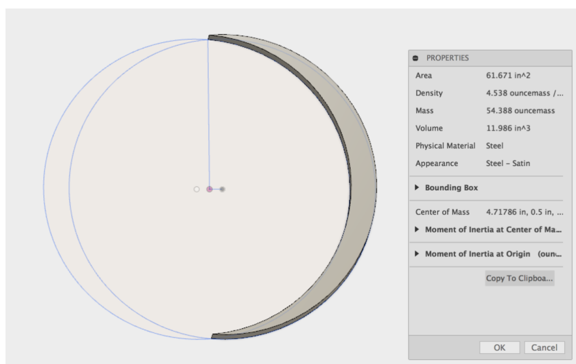

Figure 7: A Topview of a 12" Flywheel with 0.5" Shaft Offset, only showing the unbalanced mass

The applied unbalance force causes a moment, an approximation of which is shown in Equation 9, where L is the length of the shaft, and d is the distance from the end of the shaft to the flywheel.

$$M = F(6Ld - 6d^2 - L^2) \tag{9}$$

This moment then causes a bending stress, shown in Equation 10, determined by the distance from plane of stress symmetry c, the moment M, and the moment of inertia I.

$$\sigma = \frac{Mc}{I} \tag{10}$$

In the case of the shaft, c is the radius of the shaft. Ultimately, calculations reveal that the flywheel can safely operate up to approximately 24000rpm with $\frac{1}{64}$ of an inch of offset, and 18000rpm with $\frac{1}{32}$ of an inch of offset.

4.4 Additional Mechanical Components

Additional mechanical components include the bearings, the motor engagement mechanism and the housing. Housing acts as the anchor for the flywheel and as a secondary safety measure, in the case of failure such as described above. Therefore, the housing material should be selected to be sufficiently strong, such as aluminum or steel.

As the housing is stationary, and the shaft and flywheel rotate in tandem, bearings are the interface between the stationary and non-stationary components. Designs may include standard roller-element bearings, magnetic bearings or some combination of the two. Roller-element bearings typically have two concentric collars. The outside collar is stationary, and fastened to the housing. The inside collar is fastened to the ends of the shaft. Roller-elements, typically balls or cylinders, are placed between the two collars, allowing for smoother relative motion. Additionally these bearings support the weight of the flywheel and shaft. As described in the subsection titled Flywheel Energy Storage Fundamentals, these roller-element bearings are primary contributors to the frictional, or rolling, energy losses.

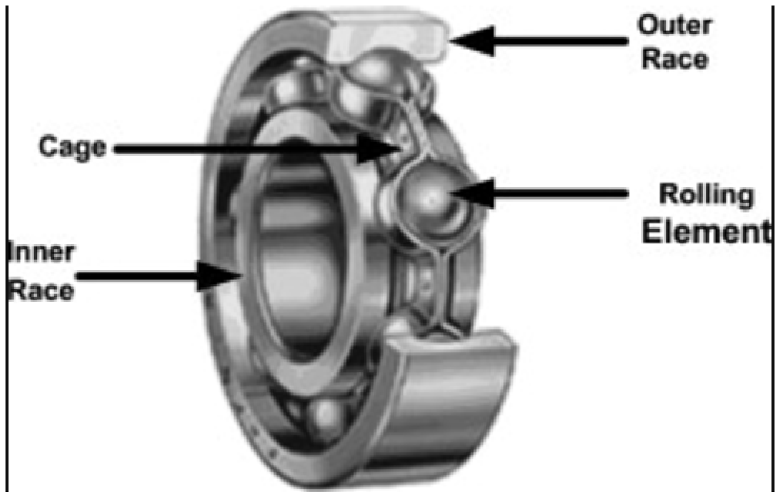

Figure 8: Schematic of Ball Bearing, a Type of Roller-Element Bearing.

Alternatively, magnetic bearings avoid any contact surface between two components with a non-zero relative motion, unlike roller-element bearing. This is advantageous, as it does not incur these frictional losses. However, their operation is more complex, requiring finely tuned sensors and controls. As shown in Figure 9, magnetic bearings work by running a current through a coiled wire to induce a magnetic field. As long as the shaft is made of some ferrous material, such as steel, this field can be directed such that it exerts a magnetic force on the shaft, opposing the gravitational force. Position sensors are placed in conjunction with the electromagnets, which send feedback to a control unit, which then dictates the direction and magnitude of the current, and with it, the direction and strength of the induced magnetic force on the shaft.

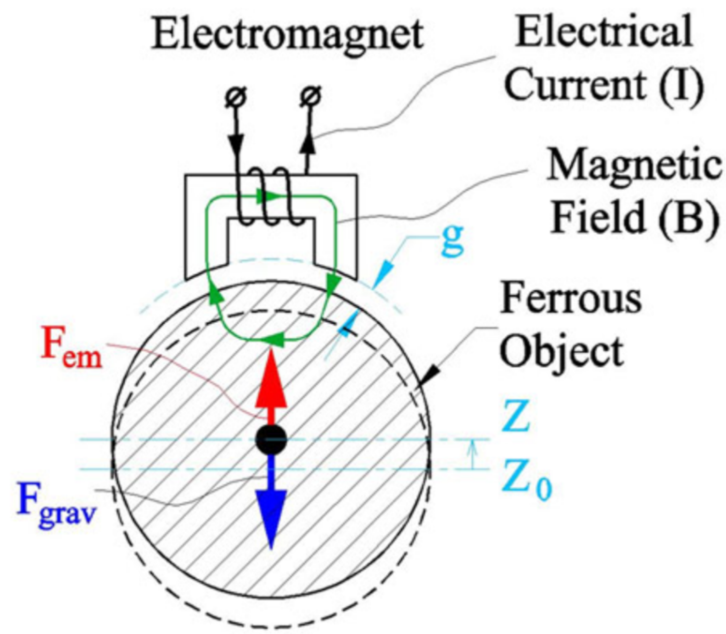

Figure 9: Schematic of a single electromagnet, the basic unit within magnetic bearings. This interacts with ferrous material, such as a steel shaft, to exert The electromagnetic force F_{em}, shown in red.

As shown in Figure 10, these bearings can be placed to either support the shaft radially or axially, but unlike roller-element bearings, cannot individually stabilize both radially and axially.

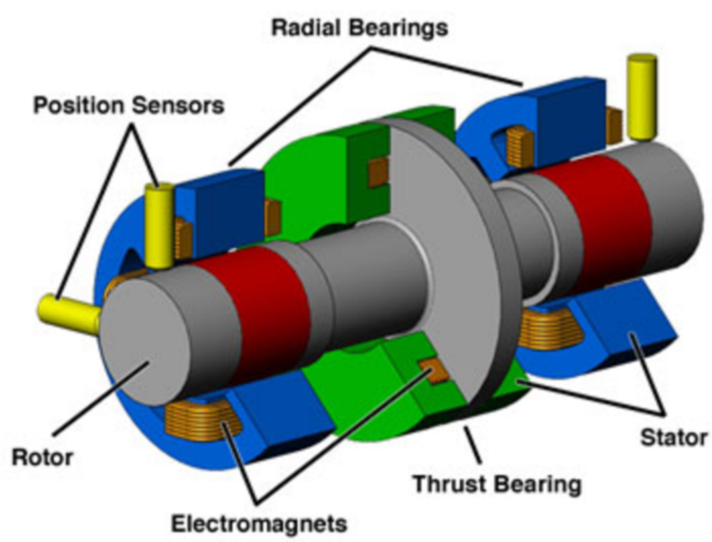

Figure 10: Magnetic bearings used in tandem for multidimensional stabilization. Each magnetic bearing is comprise of electromagnets, position sensors, and (not shown) a power source and control unit.

Failure of bearings can be catastrophic. Thus roller-elements may be used in conjunction with magnetic bearings, placed such that magnetic bearings resist loads, and roller-element bearings apply at most a stabilizing force, and perhaps carry little force unless the magnetic bearings fail.

In FES, there are broadly 4 stages of operation. The first stage is resting, when the flywheels are dormant. The second stage is spin-up, when the the angular speed is increasing. In the third stage, the flywheel is freely spinning, and is storing rotational energy. In the fourth stage, this "stored" rotational energy is converted to electrical energy.

The motor/generator is coupled with the rotation of the shaft in both the second stage, spin-up, and the fourth stage, spin-down. While the motor/generator could be continuously coupled with the shaft rotation, in the third stage, spinning the motor even with no load would require work from the system. This work, and therefore energy loss, can be eliminated by coupling the motion of the motor/generator with the shaft and flywheel only during stages 2 and 4 (coupling in stage 1 is optional).

The motor/generator may be coupled in several different ways. First, the motor/generator may be placed in-line with the shaft. This type of coupling results in the frequency of the shaft and flywheel matching the frequency of the motor, as shown in Figure 11.

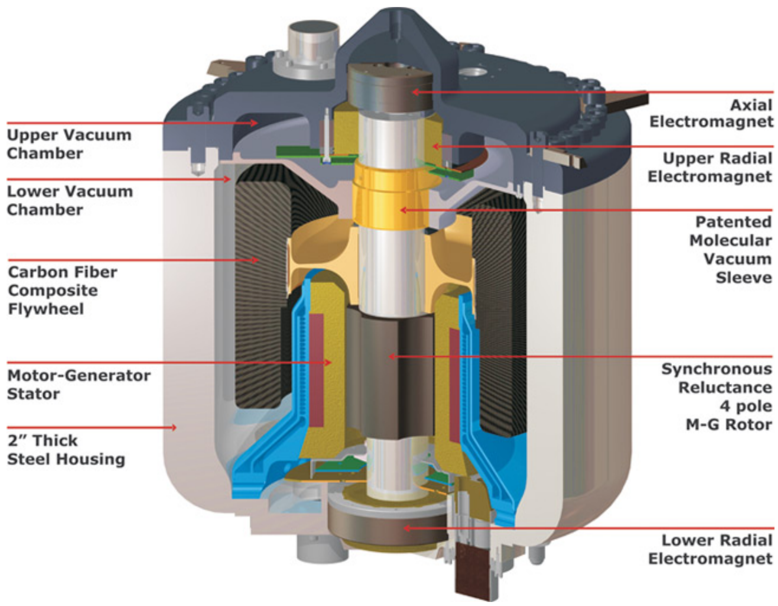

Figure 11: Example of a FES with the Motor Placed In-Line with the Shaft.

Alternatively, the motor/generator can be coupled through a friction wheel or a gear system. In the latter type, this is can be accomplished with a friction wheel or single gear connection. The frequency of the motor with a pair of gears or friction wheel is related to that of the flywheel by Equation 11.

$$f_{motor} = \frac{r_{shaft}}{r_{motor}} f_{shaft} \tag{11}$$

The two frequencies are inversely proportional to their radii. The larger the radius of the motor wheel in relation to that at the contact point with the flywheel system, the higher the flywheel frequency, and the higher the system energy.

The type of coupling also varies. For in-line configurations, the motor could be de-constructed such that the magnetic rotor is a part of the shaft, permanently fixed on. From here the stator would be fixed radially. The stator would shift axially to couple with the magnetic rotor, surrounding it, during either stage 2 or 4, or decouple by separating from and expose the magnetic rotor. However, this requires high precision and little to no system vibration, which is particularly challenging at high angular speed due to unbalance forces. A more forgiving choice is a clutch. Clutches generally are comprised of two adjacent plates, one on the motor and one on the end of the shaft. These engage or disengage through direct contact, hydraulic fluids, or electromagnetic interaction.

4.5 Electrical Components

While flywheels store rotational energy, the energy available from the grid is in electrical energy. Motors convert this grid energy to rotational energy, which can be transferred to the flywheel. Motors comprise of a rotor, with a nonzero rotational velocity, and the stator, which is stationary, fixed to its surroundings, and encompasses the rotor. The two have a non-zero relative motion due to electromagnetic induction.

A current running through a wire induces a magnetic field encircling that wire, according to the Biot-Savart Law. When this wire, and associated current, is coiled, the net induced field is normal to the plane of the coil. In the case of motors, these coils are generally placed on the rotor, with magnets on the stator. The induced magnetic field of the coils can then exert a net torque on the set of magnets, as shown in Figure 12.

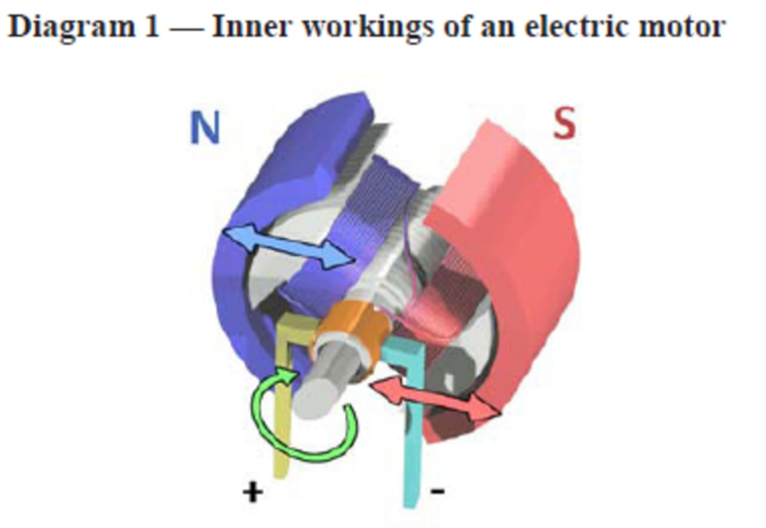

Figure 12: Schematic exhibiting how the force between induced magnets and permanent magnets in a motor exert a torque

Motors may be brushed or brushless, meaning the magnitude and direction current sent to each coil is controlled mechanically or electronically respectively. This will be explored further in 5.4, Motor Selection. Ultimately, in the case of a flywheel, the motor can act as either a generator or motor. While brushless motors are generally more efficient, these require a more complex, finely tuned electronic motor controller with hall sensors.

5 Prototype Design

5.1 Prototype Overview and Goals

Our goal for this project was to create a prototype to visually demonstrate the concepts behind flywheel energy storage, and to serve as a proof of concept. A small scale demonstration gives an audience the opportunity to see the spin up and spin down cycle as well as an visual output (in our case a LED array lighting up) in real time.

While we initially explored a number of layouts and orientations for the rotor and motor assembly, we ultimately decided on a horizontal shaft surrounded by a cage of 8020 aluminum extrusions.

5.2 Bill of Materials

Table 2: Costs for Prototype Materials

Item Description	**Category**	**Quantity**	**Cost / Unit**	**Total Cost**	**Description**
Flywheel Cylinder	Rotor	1	$ 230.00	$ 230.00	McMaster Part 9086K43
Rotary Shaft	Rotor	1	$ 44.68	$ 44.68	McMaster Part 1346K38
Steel Plates	Frame	2	$ 57.80	$ 115.60	McMaster Part 9019K55
8020 Rods	Frame	4	$ 3.79	$ 15.16	8020 Part 1010-S, each rod 8 in long
8020 Rods	Frame	12	$ 6.09	$ 73.08	8020 Part 1010-S, each rod 18 in long
8020 Rods	Frame	4	$ 7.47	$ 29.88	8020 Part 1010-S, each rod 24 in long
8020 Rods	Frame	4	$ 7.93	$ 31.72	8020 Part 1010-S, each rod 26 in long
8020 Gusset Connectors	Frame	40	$ 4.72	$ 188.80	8020 Part 4132-Black
8020 Bolts	Frame	175	$ 0.50	$ 87.50	8020 Part 3321
8020 Flat Plates	Frame	15	$ 7.35	$ 110.25	8020 part 4061
Rotor/Shaft Collar	Connection	3	$ 2.55	$ 7.65	McMaster Part 9414T19
Flange mounted bearing	Connection	2	$ 39.74	$ 79.48	McMaster Part 6494K33
Friction drive wheel 1" diameter shaft	Connection	2	$ 26.21	$ 52.42	McMaster Part 2474K67
Friction drive wheel for motor	Connection	1	$ 21.94	$ 21.94	McMaster Part 60885K56
Set Screws	Connection	1	$ 4.61	$ 4.61	McMaster Part 92311A422
Motor 1	Electronics	2	$ 148.35	$ 296.70	McMaster Part 6331K16
Alligator Clips	Electronics	10	$ 1.36	$ 13.60	McMaster Part 7236K88
Variable Resistance	Electronics	1	$ 57.69	$ 57.69	McMaster Part 6787K51
LEDs	Electronics	1	$ 6.44	$ 6.44	Amazon Part 60F3W-YT-6SE-6SE
Breadboard	Electronics	1	$ 6.96	$ 6.96	McMaster Part 1305N11
TOTAL				**$ 1,474.16**	

5.3 Material Selection

In order to create our prototype, we wanted to choose materials and parts that would be cheap and make the assembly process as easy as possible. It was also important to choose strong materials with consistent material properties (especially density) in order to keep the flywheel prototype balanced. Steel seemed to fit the bill so it is the material for the shaft, flywheel, and bearings.

For the frame of the prototype, it had to be designed for easy iterations while also acting as a cage to protect us in case the shaft somehow failed and the disk was tossed into the air. We chose to create the frame out of 8020, aluminum extrusions that are strong while soft to cut and drill. 8020 has a whole system of parts designed to make it easy to attach and hold rods together at a variety of angles.

5.4 Motor Selection

A given motor is characterized by its maximum power, maximum torque (or current), efficiency, size, and type of current control. The power of a motor is rate at which it can convert electrical energy to rotational energy. It is related to the torque T and angular speed ω.

$$P = T\omega = VI \tag{12}$$

The maximum power supplied by a motor does not dictate the actual energy capacity of FES, though it determines the time for the flywheel to spin up to that energy capacity. For a successful design, the flywheel should rotate at its preferred maximum speed after less than five minutes of spin up.

The voltage supplied to the motor is proportional to the angular speed. Therefore, if a motor is supplied by a battery with 24V rather than 12V, the eventual maximum angular speed of the flywheel will double, and the energy quadruple according to Equation 1. Each motor has a characteristic multiplier dictating the ratio of voltage to angular frequency. Given energy calculations, the desired flywheel speed was 3000rpm. While this value was initially much higher, for safety reasons, it was reduced. Therefore, given a 24V power source, the motor should spin up to 3000 rpm, or 800 rpm/V.

Just as the supplied voltage and maximum angular speed are proportional, so is the torque T and armature current I_a, as shown in Equation 13. The armature current is the sum of the current drawn to each coil of wire in the motor.

$$T = k\phi I_a \tag{13}$$

k is a constant characterizing a permanent magnet, ϕ is the magnetic flux. The maximum torque is limited by the permanent magnets, which can magnetic saturation at high torque, while the current limit is dictated by the voltage supplied. A given motor is built to have a characteristic maximum torque and current, which also limits the time to spin up to the ideal angular speed. At low speeds, this is particularly relevant, since, as exhibited by Equation 12, for a given power and at low angular speeds, the torque must higher.

Given that the motor must move in order to be engaged and disengaged, the motor had to be relatively lightweight and small volumetrically. Also, for motors with greater efficiency, industrial motors with unnecessary dust covers or motors with unnecessarily large maximum power output were avoided, as both result in lower efficiency operation.

Finally, motors are split into two distinct categories: brushed and brushless. A brushed motor has a commutator and brushes, which transmit electrical flow, as shown in Figure 13. On the contrary, a brushless motor uses a controller instead of a commutator and brushes, which alters the current of each coil independently according to the relative position of the permanent magnets.

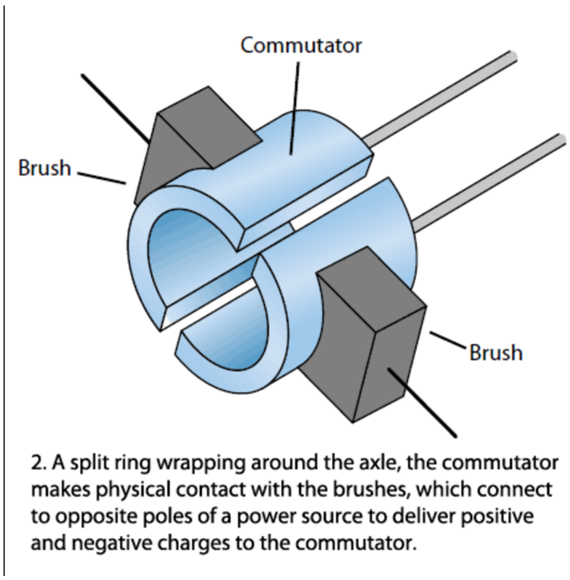

Figure 13: Schematic of a Commutator

Because brushless motors avoid the contact friction of the brushes and commutator, they avoid this type of energy loss. Additionally, as commutator can only determines the direction of the current flow, and not the magnitude, the current draw follows the shape of a square wave. On the contrary, a brushless motor, with electrical controls, can alter both the magnitude and direction of the current flow to each coil of wire. Consequently, the current flow in each coil of a brushless motor can follow a sine wave. This is preferable, as a coil can now maximize its current flow when permanent magnets are between coils, meaning the applied magnetic force translates to the greatest possible torque. Due to both the lack of friction and improved current control, brushless motors are significantly more efficient. However, the design of a sinusoidal control system can be very involved. Additionally, brushless motors also require a rectifier in order to operate as a generator, and even more involved electrical controls. Therefore, given the expertise of the engineering team being primarily in mechanical, civil, and environmental realms, a 200W brushed motor was selected.

5.5 Timeline

This timeline highlights the major milestones of our capstone project Spring 2017. We made this timeline in January and continued to refine it as new tasks came up, while holding ourselves accountable to upcoming deadlines.

Deliverable	Date Projected	Description
Progress Presentation	**2/6/17**	
Define end-user and measurable objective	1/30/17	Condensing and synthesizing problem scope
Brainstorm list of 5-10 possible designs	1/30/17	Focus on mechanical designs applicable in urban environments
Evaluate potential markets and baseline energy costs	2/4/17	Focus on urban areas, high energy costs, peak hours, commercial buildings
Select a concept design	2/4/17	Using our decision matrix and market analysis
Prototype Design Review	**2/27/17**	
Begin prototype design process	2/8/17	Sketch designs on paper and start 3D CAD models
Order parts for prototype	2/20/17	Create BOM, order parts via Pat
Finish prototype design	3/27/17	Using measurements and insights after prototype construction
Economic Research		
Acquire NYISO pricing and load data	2/16/17	Search for reliable data
Aggregate monthly data	2/20/17	Use software to format data
Identify specific ConEd plan and rate	2/20/17	Utilizing market research
Model peak shifting savings	4/5/17,4/17/17	First and second iteration for first and second poster
Model peak shaving savings	4/5/17,4/17/17	First and second iteration for first and second poster
Model cost of system and payback time	4/10/17	Create cost savings breakdown for peak shaving and shifting, also extrapolating from prototype budget
Environmental Analysis		
Research carbon outputs	3/27/17	Identify sources of data to compare peak and off peak emissions
Research pairing with renewables	3/28/17	Investigate opportunities to pair flywheels with renewables
Lifecycle analysis	4/5/17	Research comparative lifecycle of flywheel vs battery
Poster Presentation Mechanical Engineering	**4/5/17**	
Outline brainstorm	3/6/17	Make poster skeleton
Task assignments	3/6/17	Decide who is in charge of each section
Prototype Demonstration	**4/19/17**	
Rough flywheel testing	3/5/17	Testing flywheel and shaft for balance, spin up, free rotation
Receive parts	3/20/17	Find order on cart in Hudson
First prototype construction	3/27/17	Create frame, make additional part purchases, complete machining for assembly
Secondary prototype construction	4/3/17	Make additional iterations on frame, 3D print needed parts
Verification and Validation	4/10/17	Final flywheel testing with data aquision technology
Poster Presentation Bass Connections	**4/20/17**	
Outline brainstorm	4/17/17	Make poster skeleton
Task assignments	4/17/17	Decide who is in charge of each section
Final Presentation	**4/24/17**	
Outline brainstorm	4/17/17	Make powerpoint skeleton
Task assignments	4/17/17	Decide who is in charge of each slide
Final Report	**4/30/17**	
Outline brainstorm	3/13/17	Utilize past examples to make skeleton
Task assignments	3/20/17	Decide who is in charge of each section
First draft	4/17/17	Team members write full first draft for their section
Review and edit	4/24/17	Each member reads through paper and offers edits

Table 3: Energy Storage Team Timeline

5.6 Prototype Assembly

In creating our prototype, we ran into the issue of needing to develop custom pieces to fit our required design specifications.

One of these was the length of the 8020, because they were ordered in longer bars that we had to chop to length on a vertical band saw in the student machine shop.

In order to fit the friction wheel to the motor shaft, we created a custom aluminum press fit bushing to widen the shaft diameter. For this machined part, we used the lathe in the student machine shop.

Finally, we used two vertical metal plates to connect the bearing mounts to the 8020 and the shaft. In order to use these metal plates, we drilled a number of holes using the CNC mill in the student machine shop.

These experiences creating parts in the machine shop were valuable for both the mechanical engineers as well as the team as a whole for exposure to hands-on engineering experience.

5.7 Prototype Images

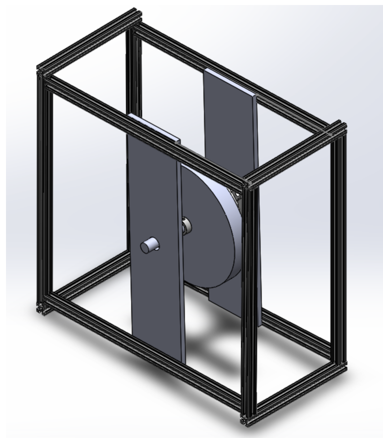

Figure 14: Isometric view of CAD model of flywheel prototype

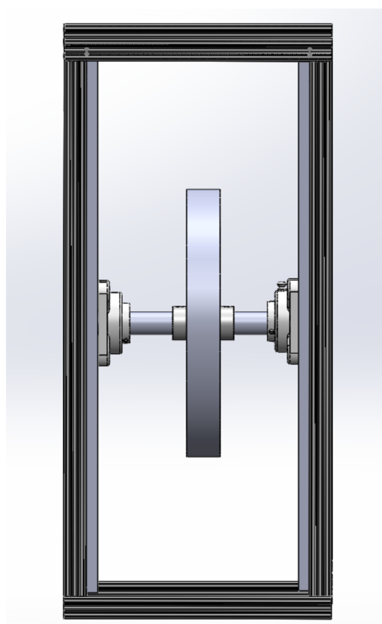

Figure 15: Top view of CAD model of flywheel prototype

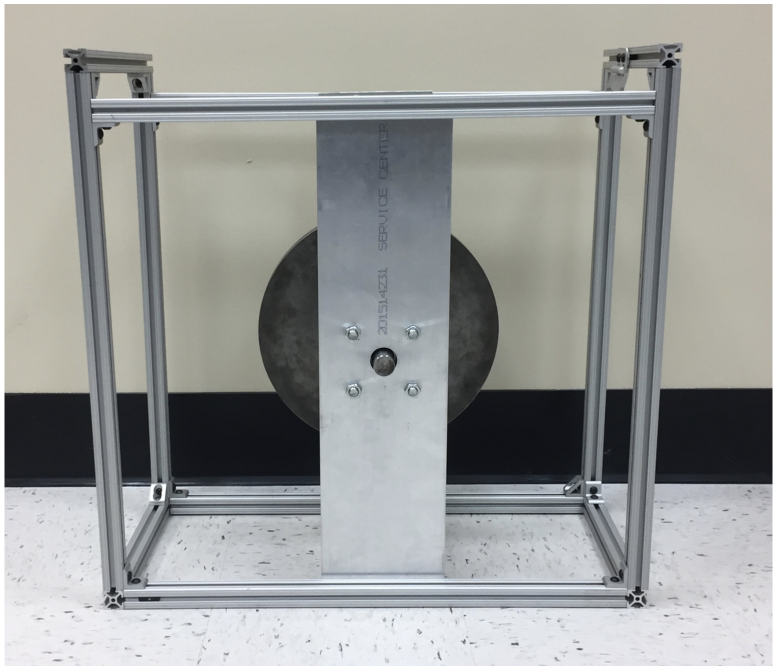

Figure 16: Image of finished flywheel prototype frame and rotor assembly

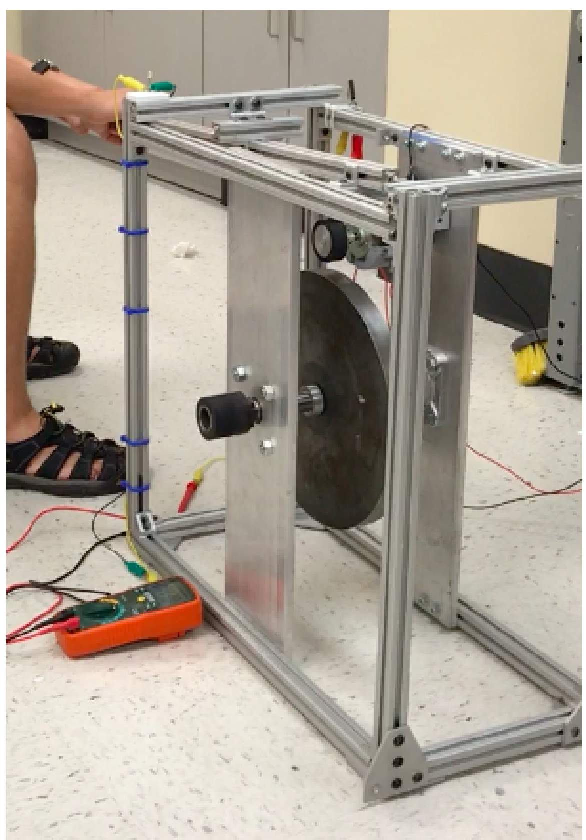

Figure 17: Image of finished flywheel prototype setup with motor arm and electrical components

5.8 Safety Analysis

To ensure safe operation, the design was analyzed using Finite Element Analysis in Fusion360 software and theoretical unbalance was modeled under various conditions. Figures 18 and 19 show the stress and displacement results of the FEA. Overall, the static factor of safety is over 100 which is more that satisfactory.

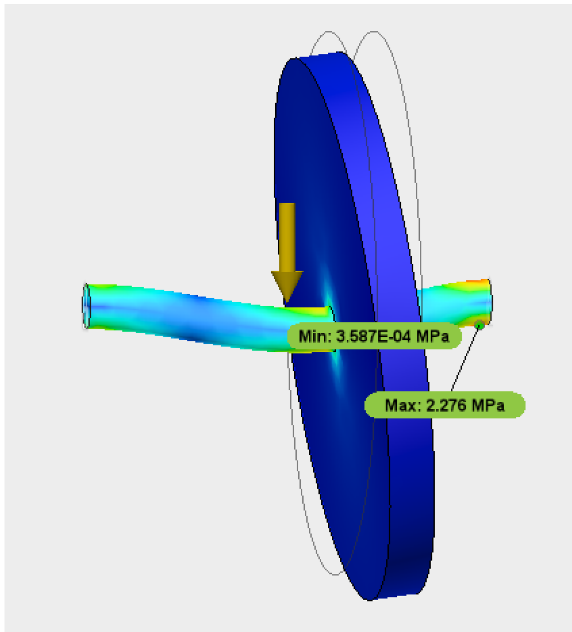

Figure 18: Screen Shot of Stress Results from FEA in Fusion360

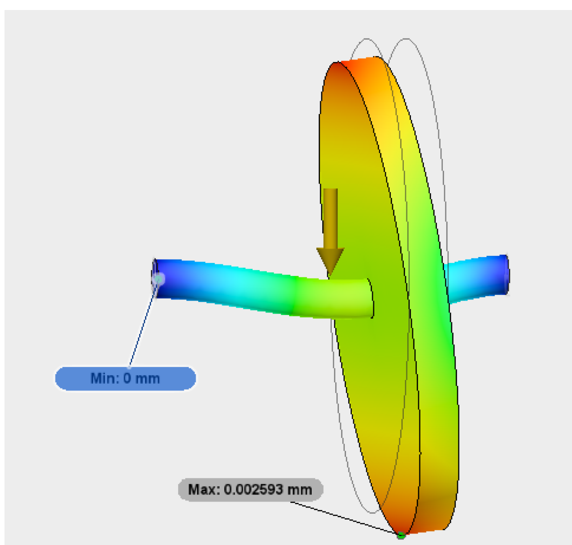

Figure 19: Screen Shot of Displacement Results from FEA in Fusion360

Additionally, the unbalance force given a series of angular speeds and flywheel mass offset from the center of rotation were calculated using Equations 8, 7 and 9.

Shaft Diameter	1"	Steel:	A36	AISI 4340		
Material	Steel	Yeild Strength (MPa)	250	1590		
Disk Diameter	10"	Shear Strength (MPa)	125	795		
		Offset (inches)				
		1	1/4	1/16	1/32	1/64
Angular Speed (rpm)	500	32.64	8.16	2.04	1.02	0.51
	3000	105.74	26.44	6.61	3.30	1.65
	10000	1174.94	293.74	73.43	36.72	18.36
	24000	6767.66	1691.92	422.98	211.49	105.74

Figure 20: Unbalance Calculation Results

According to the above Figure 20, the factor of safety for unbalance is over 100 for an offset up to $\frac{1}{32}$, and over 4 for up to an inch of offset.

5.9 Testing Description

The goal of the testing was to demonstrate the proof of concept for flywheel energy capture, storage, and release. To accomplish this goal, we created a circuit connecting the motor/generator unit to a variable voltage 24V DC power supply and to a Texas Instruments portable data acquisition (DAQ) system. The unit shifted between running as a motor (used for flywheel spin-up), as a generator (used for energy capture) and turned off via a three-state switch connected in the circuit (see schematic in Figure 21). A block diagram showing the energy transfer throughout this testing procedure can be found in Figure 22.

The DAQ system we used for this process was only able to read values $\leq$ 10V, so we created a voltage divider circuit using two 200 Ω resistors to divide the 20V supply in half. Next, to find the current draw both for the input and output tests (as the DAQ system could only read in voltages), we needed to use a known resistance (a 200 Ω resistor) in series with the input DAQ terminal.

$$Voltage/Resistance = Current \tag{14}$$

After conducting 3 tests to find both spin-up input voltage and current and spin-down output voltage and current (with respect to time), we began the data analytics process. Once the data was trimmed to a uniform time span and impractical noise from the motor/generator was ignored at the beginning and end of the tests, we used average data to calculate input and output power for our flywheel model.

$$Power = Voltage * Current \tag{15}$$

The resulting power output graph can be found in the Test Results section in Figure 23.

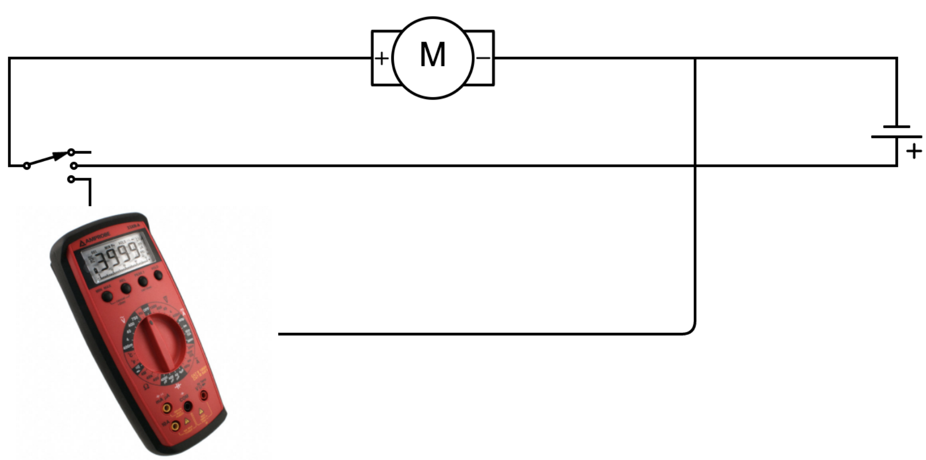

Figure 21: Wiring schematic during output generation testing

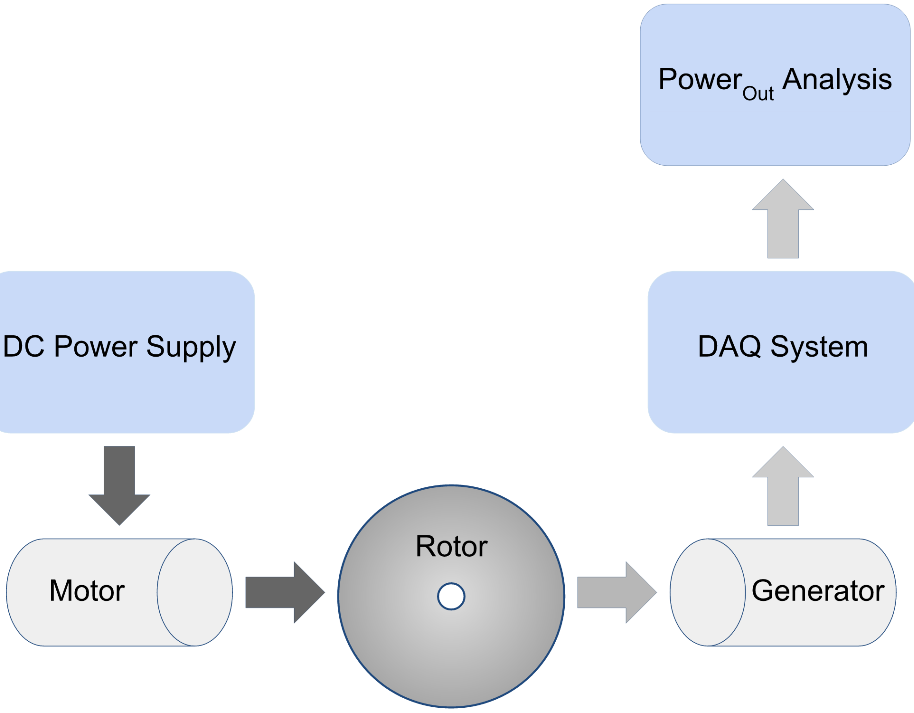

Figure 22: Block diagram depicting the direction and intensity (represented by arrow direction and color) of energy transfer in the FES prototype system

5.10 Test Results

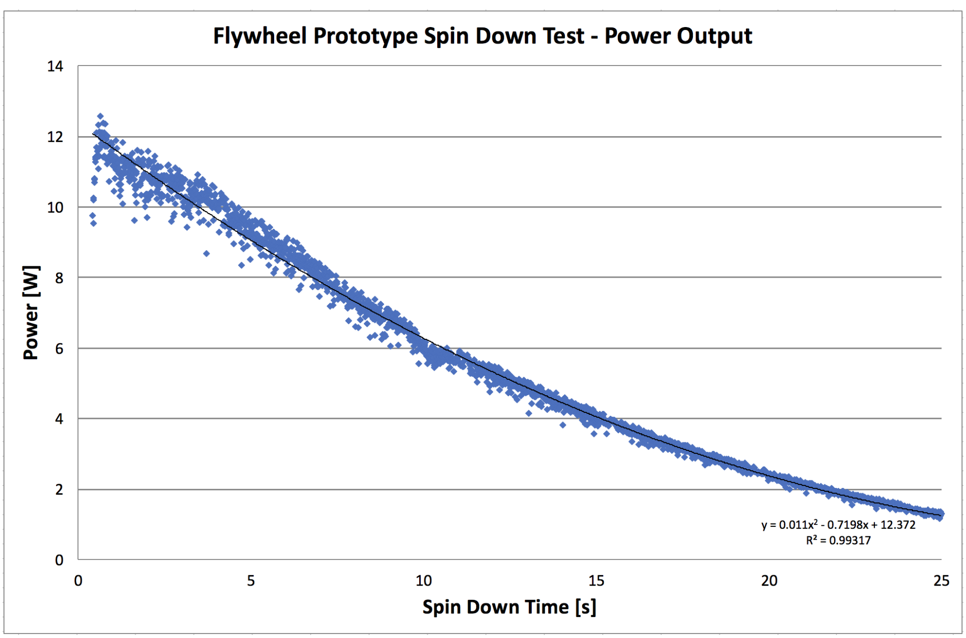

Figure 23: Graph showing prototype flywheel power output with time during the spin down process

The integral of this curve was used to calculate the energy leaving the flywheel system once the generator connected. Almost all of the energy is expelled within 25 seconds, which reinforces the idea that flywheels have a quick discharge time. It also shows that our max power output was about 12 Watts.

5.11 Prototype Conclusions

The prototype successfully met its initial goal of acting as a visual proof of concept to show how flywheels can be used for energy storage applications. The demonstration aspect of this project allowed us to share this technology with a wide audience. However, after the data collection testing we performed, we realized the large inefficiencies with our model, which only had an efficiency of 16.9%. After putting in 838.5 Joules, we were only able to retrieve 141.7 Joules. This inefficiency is primarily due to friction within and low-budget nature of our model. First and foremost, the bearings we chose (while advertised as low-friction) still heavily contributed to slowing down the rotor thus reducing the potential power output. Adding lubricant to the bearings may have helped in reducing some of this rolling friction. Next, any misalignment between the two bearing blocks led to significant friction between the shaft and bearings. We took caution in our initial alignment, but as the model moved and shifted while running, it is very possible additional misalignment occurred. Finally, air friction, while most likely not a major factor in reducing overall efficiency in our model, plays a role in the inefficiencies of flywheel energy storage. In total however, this model proved useful in demonstrating FES technology - we were able to charge and discharge our flywheel quickly, storing enough energy to light three 3 Volt LEDs for about 10 seconds.

6 Market Analysis

6.1 Model Overview

To test the economic feasibility of a flywheel in a commercial building in Midtown Manhattan, our group constructed a savings model designed to estimate savings from both peak shaving and peak shifting. For the purposes of this model, peak shaving is defined as reductions in hourly electricity usage level over the course of a given month for all hours above a chosen hourly usage threshold. Peak shifting is defined as reductions in hourly electricity consumption during hours in a given month where the gaps between the real time price for electricity in the hour in question and the preceding hour are greatest. Peak shaving savings are applicable for all consumers that face demand charges. While residential consumers rarely have demand charges, most commercial consumers use enough electricity to qualify, especially in our target market. Peak shifting savings only apply to consumers who use time-of-use pricing plans as opposed to flat-rate plans; therefore, our model focuses on commercial consumers in Midtown Manhattan with time-of-use plans. To construct the model, we used historical real time pricing data from the NYISO [28], Con Edison billing information and pricing data [2], and a building load profile for a large office in Manhattan created by the Office of Energy Efficiency & Renewable Energy (EERE) [37]. The model used data from July 2016 to calculate optimal savings, as July historically is New York Citys hottest month and has the highest monthly electricity consumption [5].

6.2 Projected savings

6.2.1 Peak shifting

To calculate peak shifting savings, the real time hourly price of each of the 744 hours in July was compared to the real time price of the previous hour. The hours were sorted by price differential from largest to smallest, and the top 10, 20, 30, and 50 hours were analyzed in the savings model. In order to account for the assumption that the flywheel system requires an hour to charge and then the subsequent hour to discharge, the top hours were controlled for sequential hours by removing the sequential hour with the lower price differential. In reality, one of the attractive qualities of flywheels as storage systems is their quick charge time, which could result in rapid partial charges and discharges between consecutive hours; however, potential partial charge applications were discounted to maintain manageable calculations. Once the optimal hours were properly calculated, they were inputted into our savings formula. The most effective way of explaining the logic behind the savings formula is to break it down into three iterations of increasing complexity. The first iteration is a simple savings formula comparing the original cost and the new cost; the second iteration takes into account friction loss and the size constraint imposed by the flywheel size; the third iteration accounts for additional size constraints by establishing an hourly consumption cap to avoid demand charge increases.

The simplest iteration illustrates that hourly savings is equivalent to the product of the original price ($/kWh) and kWh consumed minus the product of the new price (\$/kWh) and the kWh consumed. That equation is expressed as $(RTP_t * kWh_t) - (RTP_{t-1} * kWh_t)$. However, that equation fails to take into account the friction loss of the flywheel system over the course of the hour between charge and discharge, as well as the size of the flywheel, which constrains the number of kWh that can be offset. The second iteration assumed a system size of 100 kW and a round-trip efficiency of 85%, in line with conservative modern flywheel estimates [38]. Using these values, the most intuitive way to think of the friction component of the equation is to express it as $(RTP_t * 100kWh) - (RTP_{t-1} * 100kWh + RTP_t * 100kWh * 0.15)$. To compensate for the 15 kWh lost to friction, the consumer must buy those 15 kWh at the original hourly price of RTP_t. This equation can be rewritten as $(RTP_t * 100kWh * 0.85) - (RTP_{t-1} * 100kWh)$. However, this iteration fails to account for the potential impact of the 100 kWh increase in hour t-1 on the consumers monthly demand charge.

As stated in the previous section, the demand charge is based on the highest 30-minute kW usage at any period over the monthly bill cycle. In our model, there were several instances where shifting 100 kWh from an hour with a high price to the preceding hour would have increased the preceding hours building load usage enough to make it the hour with the highest consumption, resulting in an increased demand charge and monetary losses. To avoid this situation, we established an hourly consumption cap, set so that no hour went beyond this limit. In order to maximize the sum of the peak shaving and peak shifting savings specific to our model and building load data, this level was set at 1,640 kWh. This level could be optimized more efficiently using demand management software, but served as a reasonable estimate for our model. To capture the effect of this cap in the savings model, a new variable Size was created, where $Size = min(100kWh, (1640 - Load_{t-1}))$. The third and final iteration of our savings model was expressed as the following:

$$(0.85RTP_t * Size) - (Size * RTP_{t-1}) \tag{16}$$

Based on our fairly conservative model, savings of between \$142 and \$197 were achievable depending on the number of cycles run, as shown below in Table 5.

Number of cycles	10	20	30	50
Savings	\$142.55	\$167.92	\$180.66	\$196.81

Table 4: Table showing the projected savings for different number of run cycles

As the number of cycles increases, the per-cycle savings diminishes in conjunction with shrinking real time price gaps between the inputted hours. Figure 24 illustrates these diminishing returns and shows per-hour savings for the 30-cycle model. The bars correspond to the top 30 individual savings hours, while the orange line shows the cumulative savings of those hours.

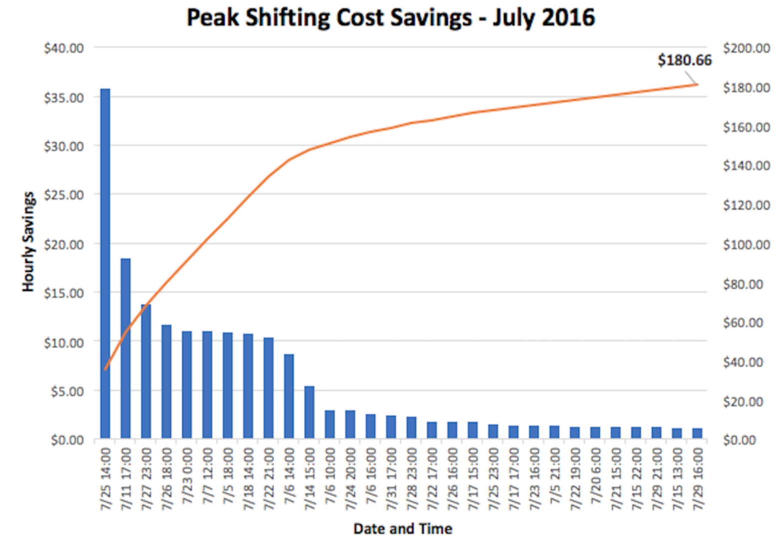

Figure 24: Graph showing peak shifting cost saving analysis for July 2016 in NYC

6.2.2 Peak shaving

As stated in the peak shifting methodology, the cap on hourly consumption was set at 1,640 kWh in order to maximize the sum of the peak shaving and peak shifting savings. Peak shaving savings were calculated using Con Edison pricing data and the large office building profile modelled by the EERE. For all 744 hours in July, hourly electricity usage was arranged from largest to smallest. In order to calculate savings, all hours above 1,640 kWh of consumption had to be reduced to the 1,640 kWh threshold. As shown in Figure 1, there were 28 hours with over 1,600 kWh of consumption, but conveniently only two above 1,640 kWh. In order to reduce these hours consumption below the 1,640 kWh threshold, the flywheel system was charged in their respective preceding hour by the difference of the hours load and 1,640 multiplied by the additional charge needed to account for friction loss. While this process results in the net consumption of electricity, the enormous premium tied to demand charge per kW prices vastly outweighs the additional per kW electricity charges paid in the previous hour. The full equation is as follows:

$$\frac{1}{2}[(Load_t - 1640) * Price_{DC} - ((Load_t - 1640) * (1/0.85) * RTP_{t-1} + (Load_s - 1640) * (1/0.85) * RTP_{s-1})] \quad (17)$$

In the above equation, $Load_t$ is the hourly consumption in the peak hour, $Price_{DC}$ is the demand charge price charged by Con Edison, RTP_{t-1} is the real time price of electricity in the hour preceding the peak consumption hour, Loads is the hourly consumption in the other hour with a consumption above 1,640 kWh, and RTP_{s-1} is the real time price for the hour preceding that hour. The friction loss is captured by (1/0.85) which is the extra charge needed to compensate for the ensuing 15% friction loss. The function is multiplied by one-half two because ConEd bases demand charges off of the highest 30-minute interval per month, not highest hour interval. Based on Con Edison rates from July 2016, a large commercial building operating on a time of use consumption plan would pay the Rider M rate of $13.31 per kW of load used. It is important to realize that while demand charge rates are assessed based on kW of load used and kW and kWh are not the same unit of measurement, kW and kWh are equivalent in this model since kWh of consumption are being measured in per hour increments. In other words, a building's highest hourly consumption in kWh in any given month must be met by an equivalent load in kW to stop the building from losing power, allowing us to treat the load profile as kW instead of kWh for this application.

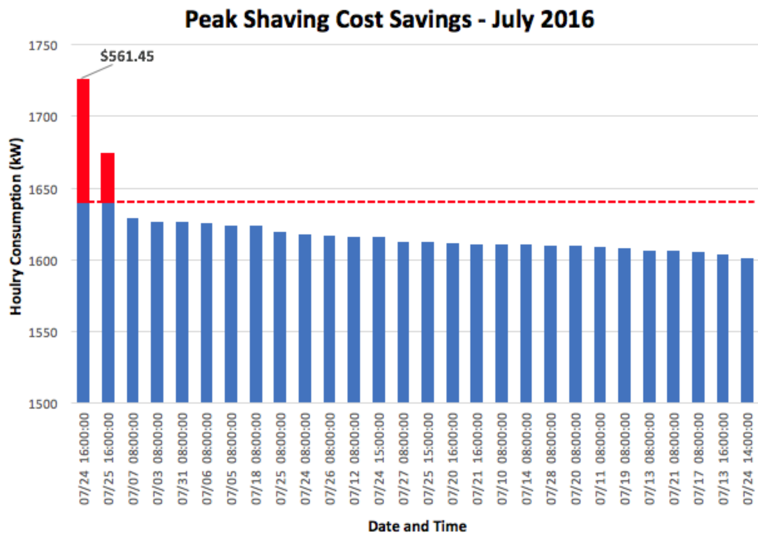

Figure 25: Graph showing peak shaving cost saving analysis for July 2016 in NYC

Based on our model, reducing the two highest hours below the consumption cap at 1,640 kW results in $278.80 worth of savings. When combined with the peak shifting savings, this would result in total monthly savings of $459.46.

However, it is important to realize that limitations of this model make this estimate fairly conservative. The building load data pulled from the EERE were averaged, aggregated building load estimates. As such, the data was fairly smooth over the course of a day and month, resulting in very few monthly consumption spikes. In practice, a single building would have a more variable consumption profile. The likelihood of one 30-minute window of time seeing a dramatic consumption spike would be far higher in a lone buildings profile than in smoothed, averaged estimates. In a hypothetical model where the full 100 kW system could be used, a maximum of 85 kW of peak load could be reduced after accounting for friction, as opposed to the current 42 kW reduction in our model. In this hypothetical, as depicted in Figure 25, savings from peak shaving would jump to $561.45, more than doubling our models estimate.

Additional limitations of the model were constraints in the charge-up window for the peak shifting estimates. In practice, companies could opt to charge and discharge the flywheel in less than one-hour cycles, given flywheels quick maximum discharge speed. Additionally, they could opt to charge the system more than one hour prior to discharge to take advantage of the lowest possible electricity prices when the opportunity presents itself. Several companies, such as the energy storage company Stem, offer predictive energy software that could be paired with our system to calculate the optimal cycle times and frequencies in order to maximize potential savings. Just as our flywheel design serves as a proof of concept with room for future improvement for a final product, this model serves as a proof of concept of the tangible economic benefits, with room for improvement in future iterations.

7 Environmental Impact Analysis

7.1 Advantages

One of the most significant barriers of the implementation of renewable resources is ensuring that generation of electricity will meet demand. This is because the stochastic changes of irradiation and wind velocity over time create a high level of uncertainty for future energy availability and generation [36]. Reliance on renewable generation if left in an unreliable form, can lead to power grid stabilization issues, requiring frequent assistance from conventional generators. These are expensive to maintain when left in standby mode for periodic use and burn limited fossil fuels. In order to avoid these unnecessary expenses, the United States uses a system known as the day-ahead Reliability Unit Commitment (RUC) process. This is a process where power plant companies, also referred to as Independent System Operators (ISOs), commit to a specific generation capacity 24 hours ahead of time [16]. A wind or solar farm cannot commit to higher generation without fear of failing to meet their requirement in the event the wind stops or a storm rolls in–even for only a few minutes. This decreases the amount of renewable energy that can be used as baseload or even a stable power source, thus increasing the amount of reliable non-renewable power generation. As shown in Figure 26, FES helps supply the power needed for those short intermittent breaks in wind speed and irradiation, improving the reliability of both wind and solar generation. FES can also improve the quality, by smoothing the net power flow onto the grid [14].

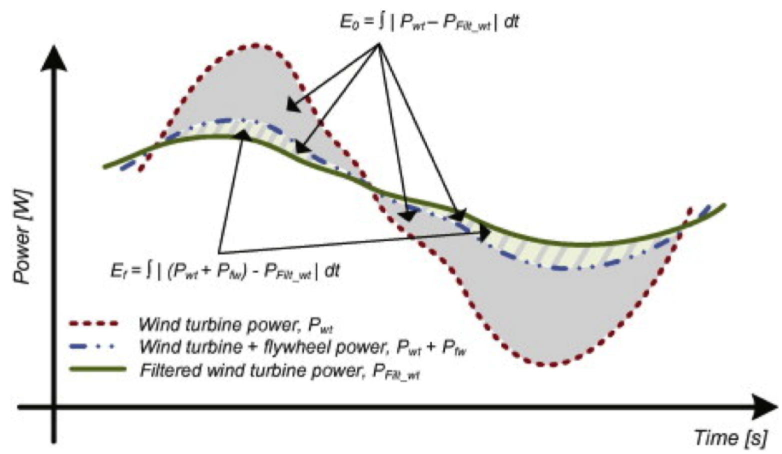

Figure 26: Power-time plot showing the potential for FES used for intermittency smoothing

However, it is not practical to rely on FES for extended periods in which wind or solar power becomes unavailable. The development of computer models to predict these occurrences is the best way to predict and plan for day-ahead RUCs [36].

Flywheel VS Battery Storage			
Category	Lead-Acid Battery	Lithium-ion Battery	Flywheel
Energy Density (Wh/l)	50-100	200-350	20-200
Cycle Life/Calendar life	500-2000/5-15 yrs	10,000-1,000,000/5-20 yrs	Millions/15-20 yrs
Depth of Discharge (%)	70	100	75
Self-discharge Rate (%)	5 per month	5 per month	2-5 per hour
Charging Time	Hours	Hours	Minutes
Operating Temperatures (°C)	0 to 40	-20 to 50	-35 to 40
Round Trip Efficiency (%)	75-80	83-86	80-95
Materials Required	Toxic	Toxic and Rare	Safe and Plentiful

Figure 27: Table highlighting key metrics in comparison between battery types

FES offers many benefits, including, high efficiency, long cycle life, wide operating temperature range, and freedom from depth-of-discharge effects [21]. In fact, most flywheels can be brought to speed in under a minute and can discharge their energy in the same amount of time. This is known as symmetric recharge. Chemical batteries, which constitute one of the most common means of power storage used today, take much longer to deliver power and to charge. The long cycle and calendar life, combined with safe and abundant materials makes flywheels environmentally preferable to lead-acid and lithium-ion batteries.

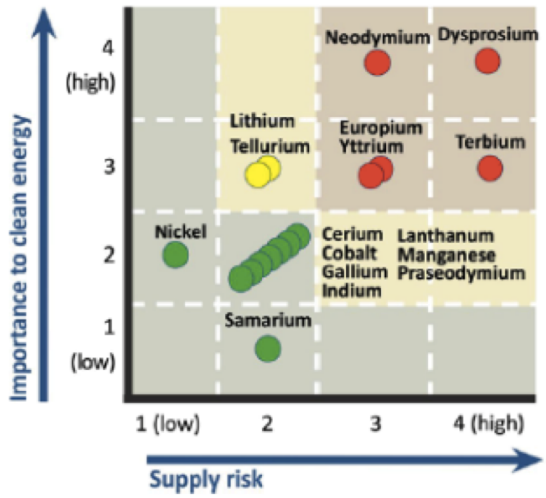

Figure 28: Graph showing the supply risk vs. the importance to clean energy for a number of metals used in batteries today

As Figure 28 shows, there is a high supply risk for the metals considered to be most important to the development of chemical battery storage. Furthermore, the process for mining the rare earth metals required for these batteries is detrimental to the environment. Because these metal exist in such tiny quantities in inconvenient places a lot of energy and chemicals are utilized, along with earth moved when they are mined [39]. In fact, in some places these metals only make up 0.2% of the earth that is mined, with the other 99.8%, now contaminated with chemicals, being dumped back into the environment.

7.2 Disadvantages

While implementation of FES would undoubtedly have several positive environmental impacts, there are also a few potential concerns that cannot be ignored. First, despite reducing energy use of during hours of peak demand, flywheels would actually increase overall energy consumption. As energy from the grid must be used for spin-up and an ideal system can achieve efficiencies in the range of 85 to 90 percent, a 10 to 15 percent increase in generation is necessary to account for these losses. In order to evaluate the effect this might have on a large commercial building in New York City, the extra hourly electricity was compared to the total demand. From this a 0.078 percent increase in electricity consumption was determined, which suggests that in the case being observed the negative effects of FES on overall energy use are negligible.

Additionally, implementing large-scale FES in the current energy landscape would not necessarily have a positive impact on greenhouse gas emissions. Flywheels, like most other storage technologies, do not produce any on-site emissions. Thus, their impact on emissions is almost entirely derived from which types of power plants are used in charging and which types are being offset when the energy is discharged. A 2015 study similar to the one presented here investigated how storage systems responding to price signals would charge and discharge. They found that most systems would charge coal electricity overnight and offset peaking natural gas plants during the afternoon resulting in a net increase of CO_2 emissions between 104 and 407 kg/MWh depending on the amount of information available [22]. This applies more directly to electrical energy storage as flywheels are generally used over a much shorter window and wouldnt necessarily employ the same plants for charging, but it is still enough to show that FES alone is not an effective method for reducing greenhouse gas emissions.

Finally, it is possible that widespread integration of energy storage could impede the progress of the ongoing transition towards cleaner energy. Storage systems afford power plants with several benefits such as improving power quality by providing frequency regulation and allowing plants to run at optimal efficiencies by storing excess generation. Endesa, the largest Spanish electric utility, has just invested in a $259 million electrical storage system to be paired with a 1,158 MW coal power plant designed to perform these exact functions [34]. Large-scale adoption of storage systems such as this could potentially prolong reliance on coal for baseload power while at the same time narrowing the market for cleaner peaking plants. Although continuously dropping natural gas and renewable generation prices make this unlikely, all sides should be considered if FES is to be presented as an environmentally friendly solution.

8 Impacts

8.1 Business Model

A flywheel energy storage (FES) system provides a valuable way to store electricity for hours at a time with the intention of helping consumers avoid exorbitantly high spot prices during periods of peak demand. During during periods of heavy electricity use, such as during the warmest part of the day in the summer months, real-time prices for electricity can jump to anywhere from five to ten times normal levels. While utility companies will send notifications to consumers when these prices are expected, not everyone is able to adapt their consumption to avoid paying these very high costs. An example of such a customer would be a large office building, which cannot simply cut off power consumption in the middle of the business day. However, when notified of an impending surge in the real time price of electricity, an office building equipped with a FES system could withdraw electricity during the preceding hours with lower costs of electricity and dispatch this stored energy during the periods of relatively expensive electricity.

While large commercial users of electricity are our primary market, an FES system would be incredibly valuable to other consumers as well. In developing nations where massive interconnected grids do not exist (as they do in the US), an FES system could help small, local micro-grids regulate frequency and store electricity obtained from intermittent sources. Areas such as South America, Sub-Saharan Africa and Southeast Asia are regions that could obtain tremendous amounts of electricity from solar panels, yet many of these regions have remote areas where grid connection is incredibly difficult. Coupling solar panels with an energy storage devices such as an FES system would accelerate rural electrification and provide a more cost effective way to do so than erecting miles and miles of transmission lines.

The flywheel energy storage market is still relatively young and as a result the capital costs have not yet benefited from economies of scale. A recent analysis performed by Lazard, the financial advisory firm, reported that the capital costs for a Flywheel system in 2015 were between $1,800 and $3,000 per kWh. To determine how much the system that we used in our deployment model would cost, we compared a similarly sized existing system installed by Beacon Power, one of the leading companies in the Flywheel market. The Beacon 400 Series Flywheel contains 25 kWh of usable energy at full charge and has a real power output of 100 kW for 15 minutes. We used a conservative metric of $2,500 per kWh to estimate a total capital cost for our system at $62,500.

Throughout the United States, various incentives are offered to companies and consumers that help to ensure grid stability. One particular incentive that would reduce the cost of our system is offered by the New York State Energy Research and Development Association (NYSERDA). NYSERDAs Performance Based Demand Response incentive offers $200/kW in ConEdision districts for equipment necessary to participate in demand response programs. This $20,000 incentive decreases the total capital cost of our system by 32% to $42,500. To estimate how much savings the Flywheel system would generate our consumer on a yearly basis, we annualized our July savings obtained from the deployment model. We assumed that savings in January would be approximately half as much as in July. We also assumed that the savings would increase as the months progressed towards July and would regress past July until it reached the January figure. Using this method of approximation we obtained annualized saving figure of nine times the July savings amount.

The tables below demonstrate the payback period a consumer could expect from using a Flywheel Energy Storage system. The first case demonstrates a scenario in which no subsidy or tax credit reduces the cost of the system. This is a conservative case that demonstrates the potential savings to any consumer, regardless of the local, state, or federal governments sentiments towards incentivizing new energy technologies. In this scenario, the consumer fully recoups the capital invested through purchasing the system in the 10th year of operation.

Assumptions	
System Size (kWh)	25
System Size (kW)	100
Flywheel Cost ($/kWh)	$ 2,500
Estimated July Savings	$ 731.34
Estimated Monthly Savings	$ 548.51
Cost of 100 kW System	$ 62,500
ConEd Subsidy	$ -
Discount Rate	3%

Figure 29: Scenario one (no subsidy or tax credit) assumptions

Year	0	1	2	3	4	5	6	7	8	9	10
Costs	$ 62,500	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Savings Estimate	$ -	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06
Net Savings	-$ 62,500	-$ 55,918	-$ 49,336	-$ 42,754	-$ 36,172	-$ 29,590	-$ 23,008	-$ 16,426	-$ 9,844	-$ 3,261	$ 3,321
Discounted Savings	-$ 62,500	-$ 54,289	-$ 46,504	-$ 39,126	-$ 32,138	-$ 25,524	-$ 19,269	-$ 13,355	-$ 7,771	-$ 2,500	$ 2,471

Figure 30: Table showing savings after each year of implementation for scenario one

In the second scenario, we included the $200/kW incentive offered by NYSERDA to decrease the cost of the system by $20,000. In this scenario, the consumer fully recoups the capital invested in the 7th year of operation. While the amount of subsidization of the system will vary depending on what grid it is operating on, this scenario demonstrates the importance of government and utility incentives in making new energy technologies financially feasible for consumers.

Assumptions	
System Size (kWh)	25
System Size (kW)	100
Flywheel Cost ($/kWh)	$ 2,500
Estimated July Savings	$ 731.34
Estimated Monthly Savings	$ 548.51
Cost of 100 kW System	$ 62,500
ConEd Subsidy	$ 20,000
Discount Rate	3%

Figure 31: Scenario two (with subsidy) assumptions

Year	0	1	2	3	4	5	6	7	8	9	10
Costs	$ 42,500	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Savings Estimate	$ -	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06	$ 6,582.06
Net Savings	-$ 42,500	-$ 35,918	-$ 29,336	-$ 22,754	-$ 16,172	-$ 9,590	-$ 3,008	$ 3,574	$ 10,156	$ 16,739	$ 23,321
Discounted Savings	-$ 42,500	-$ 34,872	-$ 27,652	-$ 20,823	-$ 14,368	-$ 8,272	-$ 2,519	$ 2,906	$ 8,018	$ 12,829	$ 17,353

Figure 32: Table showing savings after each year of implementation for scenario two

We performed a sensitivity analysis on our projections to determine how much changes in system cost and estimated savings would affect the estimated return on investment. To examine this we created a sensitivity table on the discounted savings in the 10th year assuming the $20,000 subsidy. The results were very reassuring as all combinations of cost and estimated savings yielded a positive value for discounted savings other than the least optimal case. In this case, when the cost of a flywheel system is $3,000/kWh and when monthly savings are $365.67, which is one half of the estimated July savings, the system would not fully return the consumers invested capital for a few more years.

Year 10 Discounted Savings		Estimated Monthly Savings		
	$ 17,353	$ 365.67	$ 548.51	$ 731.34
Flywheel Cost ($/kWh)	$ 1,800.00	$ 14,049	$ 30,375	$ 46,700
	$ 2,500.00	$ 1,027	$ 17,353	$ 33,678
	$ 3,000.00	-$ 8,274	$ 8,052	$ 24,377

Figure 33: Table showing estimated monthly savings based on flywheel system cost ($/kWh)

8.2 Future Improvement and Scaling

In the future, flywheels will have to limit their frictional losses to become more widespread and make an impact with incorporating renewables into the grid. According to some estimates, even the most efficient flywheels lose ten percent of their energy to friction each hour. If flywheels could hold onto their energy for longer, the implications for grid energy storage as well as cost savings from arbitrage would be huge.

One way to lower this friction is to replace fluid or ball bearings with magnetic bearings. Bearings, which inherently create friction in flywheels, hold the shaft in place for the motor and generator while also allowing for rotation. However, magnetic bearings are costly and require a lot of maintenance because they can cause hazardous failure. Another way to lower the friction would be housing the flywheel in a vacuum chamber. Although costly, this would render the role of air friction negligible. Both of these methods will be will need to become more ubiquitous for the flywheel market to grow in the future. As the demand for energy storage technology increases, hopefully the low-friction technology will improve and the cost will come down.

As the flywheel technology advances, there are quite a few companies to watch, including Beacon Power, Amber Kinetics, Active Power, and Power Thru. These companies currently dominate the flywheel market, which is projected to be worth $477.8 Million by 2024 according to a report by Grand View Research, Inc [15]. Demand for flywheels is growing because they provide high power output and ensure uninterrupted power supply. The area facing the most growth is within the commercial and industrial sectors, especially in data centers because they are energy intensive and require uninterrupted power. If millions of dollars of flywheels were paired with solar or wind like in the case studies, the emissions implications would be huge.

Within the flywheel market, as well as the energy storage market overall, distributed storage is projected to outpace grid storage for the near future [24]. The value proposition, in conjunction with renewables, is that a building generating renewable energy on-site can utilize flywheels to mitigate intermittency issues and minimize grid dependency. Furthermore, the political climate around net metering is becoming more favorable for distributed storage because utilities pay very little to energy producers adding excess renewable energy to the grid. Instead of consuming energy as it is generated on site, or transmitting it to the grid, the commercial or industrial building can be smarter and save the energy on-site to use it when the grid prices are highest. This increases the cost savings for the consumer while still saving money for the utility via peak shaving and peak shifting.

In the end, the enabler for growth in the flywheel market is going to be data science [7]. Software can enable users to charge and discharge their flywheels or other grid storage technologies to achieve the highest cost savings. For example, J C Penney installed batteries in six of its Southern California stores and was able to create annual savings of over $6,000 in price arbitrage for each store using Stem Software [35]. As more of these stories are shared, market demand will continue to grow.

9 Conclusion

9.1 Project Summary

Utilities constantly struggle to match electricity demand with generation supply. This problem is further complicated as more stringent environmental regulation and decreasing generation prices lead to increased renewable integration. Energy storage systems such as chemical batteries capable of mitigating the inherent issues of uncertainty and intermittency have been proposed as a potential solution. Another storage system commonly used for frequency regulation, the flywheel, was examined here for its potential application in a commercial building in New York City for the purpose of peak shifting and peak shaving.

Over the past year the feasibility of a commercial-scale flywheel system was evaluated based on its technical performance, economic viability, and environmental impact. First, a scalable flywheel prototype with a round trip efficiency of 16.9 percent was developed to prove the system could in fact quickly store and discharge electrical energy. Additionally, it was shown that a 100 kW flywheel system could save the consumer up to $500 per month through analysis of real time electricity pricing data. Finally, a comparative life cycle analysis demonstrated why flywheels are preferable to chemical batteries from an environmental perspective. Future iterations should focus on: (1) minimizing friction and no-load losses by implementing magnetic bearings or a vacuum chamber and (2) integrating software to automate flywheel spin up and spin down in order to maximize overall savings.

9.2 Bass Connections Review

The Bass Connections in Energy program provided a great experience for the Energy Storage team. From the beginning, we were able to explore a plethora of topics related to energy and the environment from natural gas flares to energy access in developing countries. This developed a broader understanding of some of the most pressing issues facing society today. Once we had selected a project focus we were required to work through the process by first identifying a specific problem, then evaluating potential solutions, and eventually assessing the feasibility of the system we selected. Furthermore, we were able to do this with an interdisciplinary group of students working simultaneously on several different aspects of the project. Familiarity with this process will undoubtedly prove to be useful as we enter the workplace. Overall, we are all thankful for this opportunity and proud of everything we have accomplished over the last year.

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