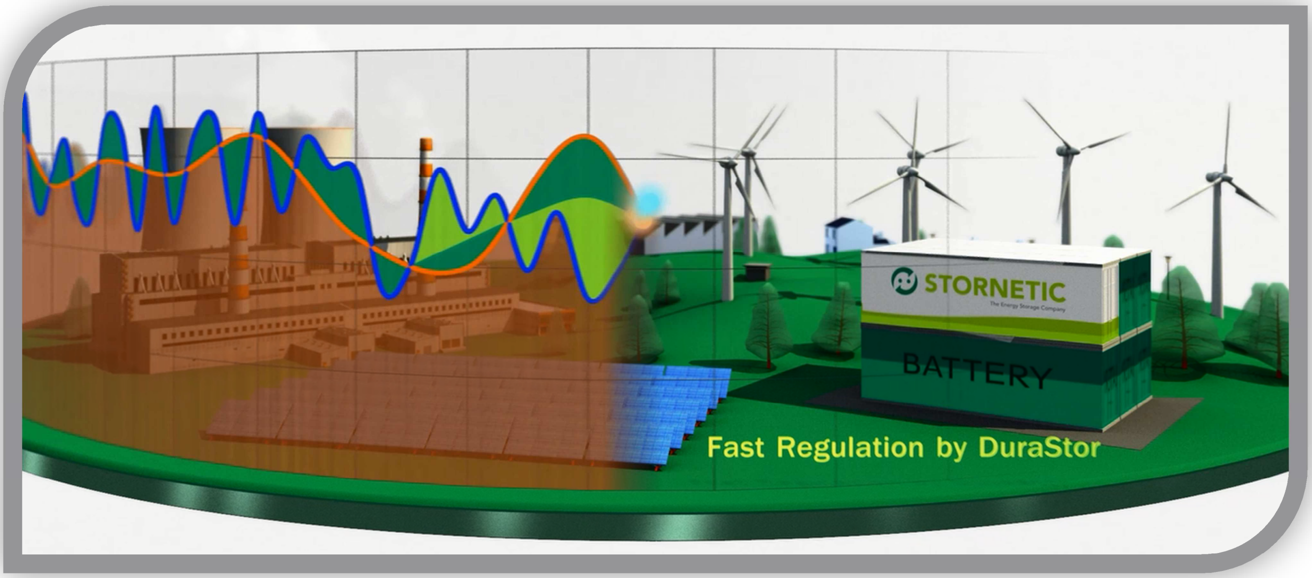
White Paper

Benefits of Hybrid Storage System with Flywheels



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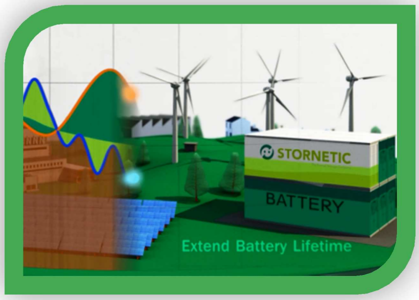
Summary

Energy storage solutions have become more and more demanding and complex. Falling energy prices as a result of general overcapacity are leading to less attractive storage business cases, especially in larger distribution and transmission grids. To justify investments into storage, as illustrated in the RMI (Rocky Mountain Institute) report, a combination of revenue streams is required to achieve reasonable rates of return. Multiple services that energy storage systems can monetize, range from energy shifting solutions up to fast dynamic grid services like frequency regulation, black start, T&D deferral, etc.



However, providing multiple grid services through a single energy storage system poses technical challenges not only on the physical battery capabilities, but also on the control design architecture of the system. This can be compared to a single design storage system of a typical Li-ion or Flow Battery which services a single grid function, such as energy shifting. Load curves are less predictable and more demanding when analyzing multiple grid services and require high bi-directional load gradients. This makes the design of the energy storage system more complex.

Hybrid energy storage solutions combine battery systems for mid and long term energy storage with flywheel systems for short dynamic response. The battery systems store the excess produced energy and shift it into the time it's needed, while the flywheels handle the majority of the short term grid imbalance's, such as grid frequency or voltage droops, as well as high power gradients.

The hybrid system is engineered by analyzing load curves and modelling current flows thru the batteries to maximize battery life, while supporting multiple grid functions. The design architecture of the control system allows for optimal operation of the energy storage system, whereby the strengths of both long duration batteries and flywheels are leveraged.

This white paper attempts to illustrate that hybrid energy storage systems can provide multiple grid services cost effectively and can provide attractive returns to investors.

Content

Introduction

Energy storage systems are widely used today to support the implementation of renewables. Battery technologies have become mature, bankable, state of the art technology. Their prices have fallen significantly in the last few years due to overcapacity and improved manufacturing technologies. They have reached a price level where material costs are <50% of the system costs (1) (2) (3). Li-ion modules are sold today at the edge of, or below sustainable pricing at approximately 300$/kWh for larger quantities (4) resulting in storage container costs around 500$/kWh (excluding power conversion costs). These systems are typically designed for:

- Shifting energy production to meet demand
- Reducing the impact of volatility on grid stability (firming of renewable generation)
- Avoiding CO_2 pollution

Business cases have been mainly determined by the difference between renewable generation costs and the purchased energy cost at the meter. They are especially attractive where energy costs at the meter are high, such as in islands, countries or states with high grid fees or power taxes. On the other hand, many large scale storage projects serving the wholesale energy markets are under threat because market prices are falling and the historical mid-day price peak has been eliminated due to solar power generation.

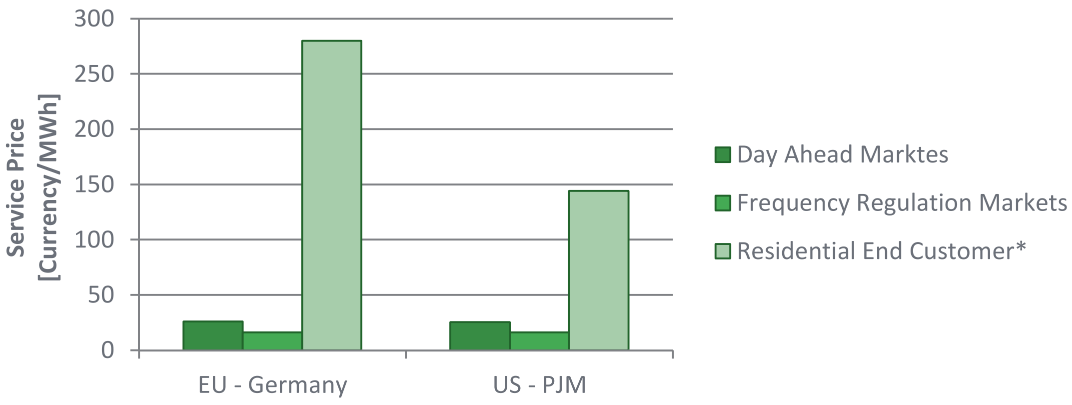


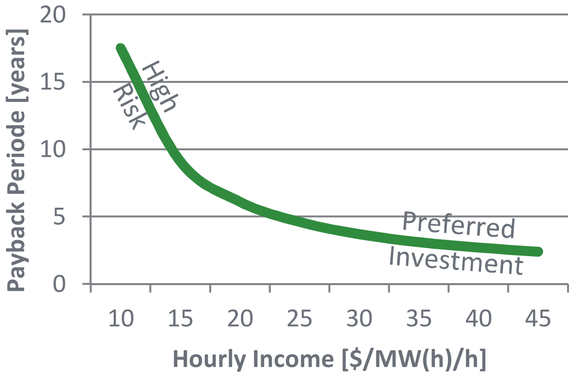
Figure 1: Q1 2016 Energy Prices for Day Ahead Energy Auctions and Primary Frequency Regulation Service in wholesale markets compared to end customer prices (Data from EEX Spot and PJM Data Portal, Eurostat, EIA, Regelleistung.net and May 2016 Pennsylvania consumer prices)

Additionally, storage systems have been successfully used to balance grids. Studies have shown that the fast response time of flywheel and battery storage systems compared to conventional generators has a positive influence on grid stability and ancillary service costs (5) whilst also reducing the CO_2 pollution (6). Unfortunately, the market prices for ancillary services have come under pressure in many markets due to overcapacity in conventional generation as a result of renewable growth. This makes business cases less attractive today for energy storage in the wholesale markets.

However, the need for grid stabilization in general is increasing, because:

- More and more fossil power plants have been decommissioned due to environmental concerns and compliance. This leads to a lack of system inertia and increases the need for fast dynamic responding energy sources like storage (7), (5)
- The volatility of new renewable power generation increases grid instabilities (8) (9)
- The increased power flows at the distribution level require additional decentralized voltage stabilization increasing the responsibility of Distribution System Operators (DSO) for grid security and stability (8) (9)

Remote islands grids create another market for energy storage. Typically, energy costs in island markets are very high compared to large scale wholesale markets due to the remote location and the need for diesel power generation. This creates attractive win-win business cases integrating renewable energy like solar or wind using the diesel gen sets as back-up. Storage systems are mainly used to shift energy. Voltage and frequency stabilization becomes an issue as volatility of demand and generation is higher than in larger grids. This creates additional challenges for power conversion and storage systems concerning robustness and lifetime (10), (11).
From an investor's perspective, in order to have an acceptable rate of return while mitigating revenue stream risks, system warranty, etc., it becomes essential to have multiple revenue streams by providing multiple grid services. The following simplified example shows the sensitivity of the payback based on hourly income.



Assumptions	Value	Unit
System size	1	MW
Project investment	800	$/kW
Availability	98%	
Annual operating costs	5%	of the invest.
Investment	800000	$
Annual operating costs	40000	$

Figure 2: Calculation of the impact of hourly income on the simple payback period of a storage investment

As shown by this example, bankable projects require an hourly income ≥ 25$/MW(h)/hr neglecting the additional cost for siting, interconnection and permitting. Significant financial risk exists if the income is ≤ 15$/MW(h)/h. A long payback time increases market, as well as, technical risks such as the lifetime of the storage technology. This underlines the need to collect income from various streams to reduce project risks. Multiple services help to (12):

- Increase the number of operating hours and thus the annual income
- Increase the hourly income by combining services

Rocky Mountain Institute has determined which storage services can be combined into useful business cases from both a commercial and technical perspective. Services like self-consumption or excessive solar storage can be effectively combined with regulation services like frequency regulation, voltage support or UPS. Preferably those applications should be combined which achieve a combined hourly income larger than 30-35$/MW(h)/h assuming that the costs of siting, project management and/or financing costs are included. Typically, these projects are closer to the end customer at the meter. The significant spread between energy generation costs and energy purchasing costs are used to deliver additional services like frequency regulation and voltage control. Using the data from Figure 1 hourly turnover of 115€/kW(h)/h[1] for Germany or 60$/kW(h)/h[2] in the California is possible. On distribution level, benefits are typically decreased by the last mile distribution grid fees.

[1] Based on 0.19ct/kWh solar power production costs in Germany (19)

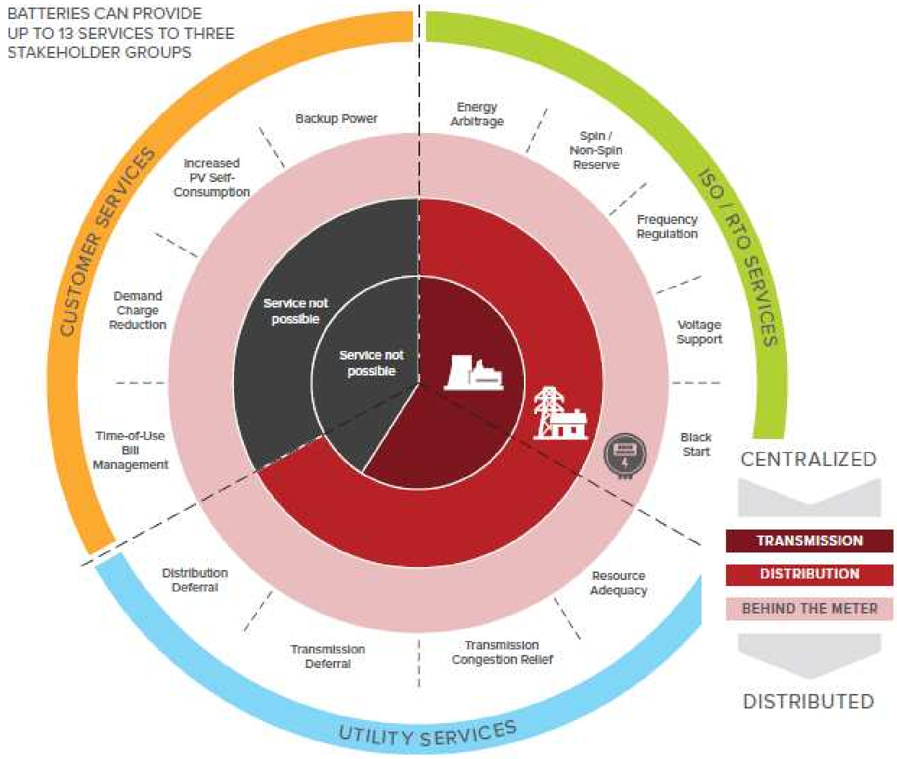


Figure 3: RMI evaluation of possible storage services for different stakeholders offering income for a storage project (12)

Market Challenges

In the current market environment different challenges exist for storage project profitability.

- Storage Projects with income lower 30$/kW(h)/h have to increase the guaranteed operational service life to reduce the technical and operational risks and allow a reasonable return on investment beyond a 5 to 7-year period.
- Projects with combined applications have a more complex technical design, including control and management systems. They are more challenging and less predictable due to demanding load curves, thus increasing the difficulty to determine conditions for long warranty period.

Figure 4 gives an overview of typical challenges concerning more complex storage projects.

[2] Based on 0.09ct/kWh solar power production cost in US (18)

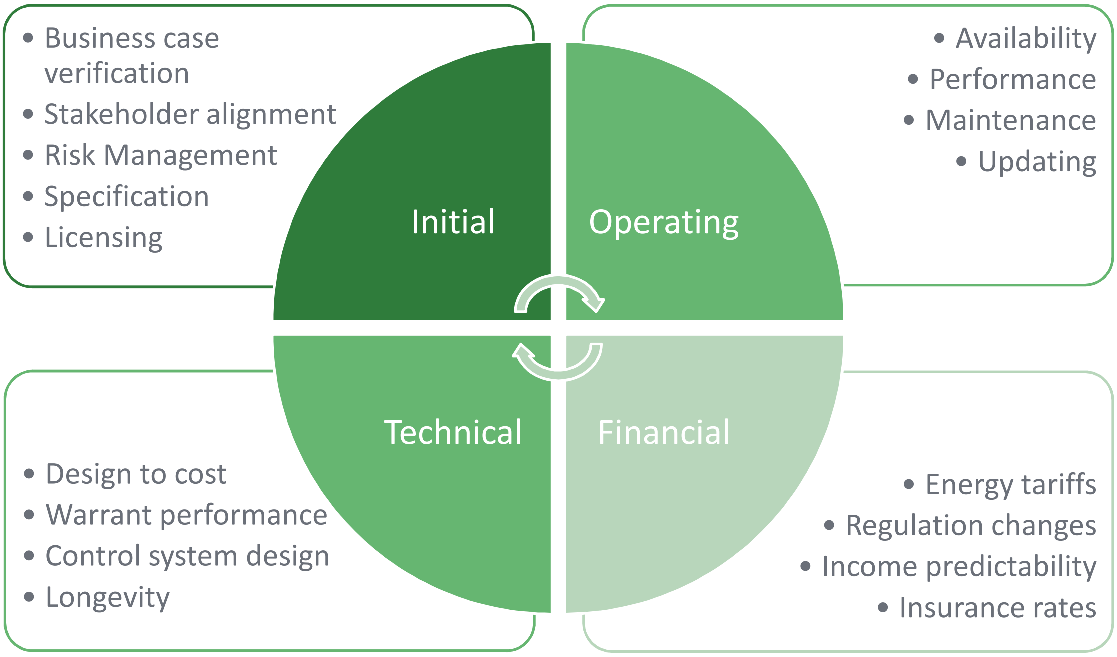


Figure 4: Challenges and Risk of combined storage applications or applications operating at lower income

To cover the long term risks, it is important that the storage solution offer a broad application portfolio to the end user, as well as, robustness and longevity. Both features directly increase the salvage value and the capability to deal with market changes. This allows the end customer to be more flexible and have lower asset risks. Both features also raise questions on the battery technology employed, typically designed today for service life of around 10 years. This is caused by heat and temperature restrictions and limited load cycle capability for Li-ion technologies.
Alternatively, project cost can be reduced by using flow batteries or other lower cost cell chemistries, as long as durability, responsiveness and power costs are reasonable.

High Level Solution

Hybrid storage systems, such as shown in Figure 5, offer an economic and technical solution for these challenges. Synergies created by the combination of the strength of each technology, allow to build a system which is more efficient and more robust than a stand-alone battery solution.
It is important to combine the right technologies and to have a smart control technology supporting the strengths of each technology. The smart controller should find the optimum solution delivering the customer service with high accuracy and responsiveness whilst protecting the systems from more harming load cases.

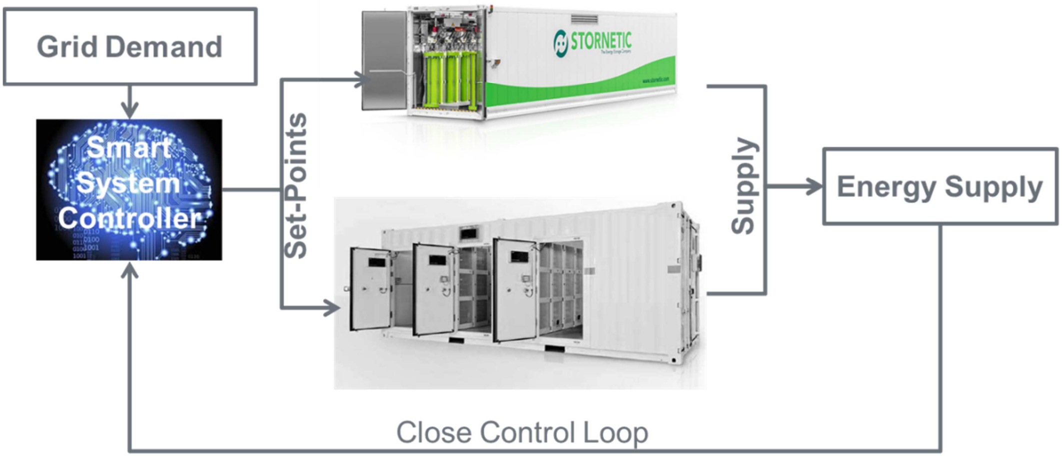


Figure 5: Hybrid storage system

For hybrid systems made with Lead or Li-ion batteries in combination with flywheels, flywheels, because of their excellent cycling behavior, should act as a filter to reduce battery cycling and provide enough time for battery cells to cool when switching from charging to discharging, thus extending system lifetime. Additionally, they can provide ultra-fast response to load changes in applications that require UPS functionalities.
Flow batteries are typically not as responsive as Li-ion batteries (13). Sometimes they only allow lower c-rates during charging. This disqualifies this technology for some applications like frequency regulation. On the other hand, they have superior properties in long term storage offering better business cases for solar or wind energy shifting. Flywheels can fill the gap making hybrids more competitive, for example in micro grids.
Both cases require different smart system and control designs to provide maximum service at minimum initial investment and operating costs.

System Design

Storage demand signals are typically a combination of long and short term signals, see Figure 6. Renewable firming or generation leads to relatively long term trends. The best example is PV producing over the day and not producing after sunset. Winds produced by solar heating during the day are another example where daytime overproduction exists which slowly fills storage with excess produced energy. This results in one long daytime period where the storage is filled and then discharged overnight. Storage times from 3 to 6 hours are common. Typically, Li-ion or flow batteries are used with flow batteries becoming more popular.
Additionally, small generation/consumption deviations lead to short term load changes. Grid frequency or voltage changes are a typical indicator for short term generation/consumption changes. The cycles lead to a frequent number of smaller cycles, requiring the storage to switch from charging to discharging and changing the storage energy content (State of Charge) of the batteries. These cycles stress the battery on top of the larger cycle from renewable firming. Tests at the Transmission System Operator (TSO) grid level in Italy have shown that batteries are aging up to two times faster than expected compared to results from lab test cycles (14). Additionally, they are less predictable over time creating challenges for warranty agreements.

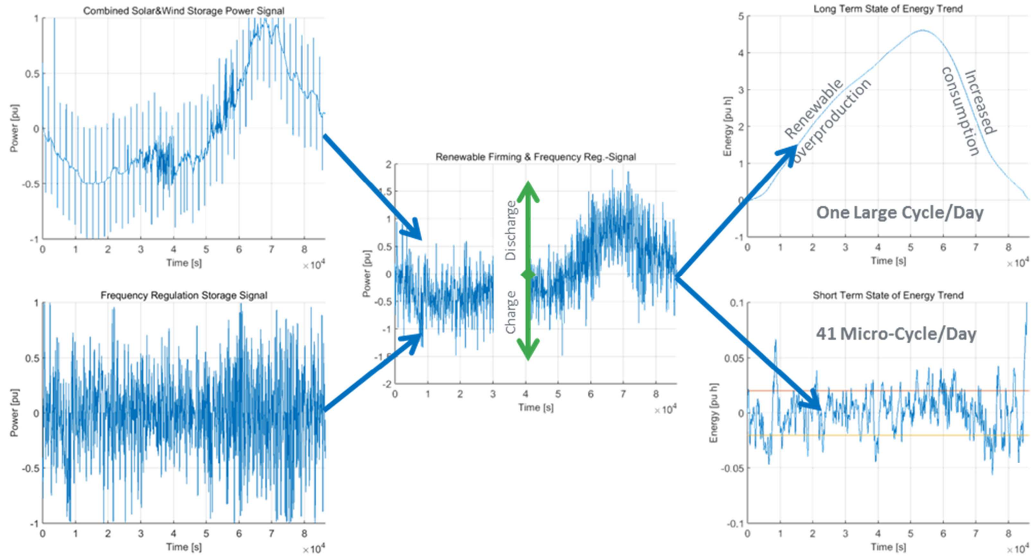


Figure 6: Power profiles of a grid with Solar- + Wind-Firming and Frequency Regulation and the impact on the energy state of the storage system. Data taken from (15) and PJM Data Center

In a hybrid system consisting of battery and flywheel storage, the micro-cycles are handled by the flywheel system. This can be achieved by having cascaded control loops in the Smart System Controller, see Figure 7. The flywheel systems acts as a filter and the its state of charge is than used to operate the long term storage. Additional control loops can be added to add functionalities and improve system response.

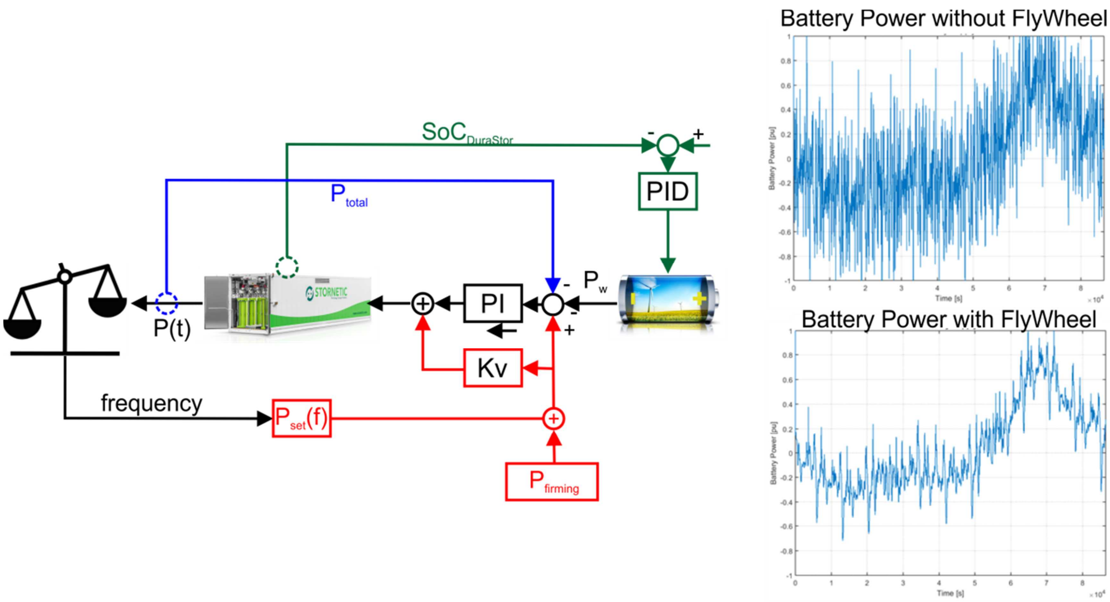


Figure 7: Example of a cascaded controller to operate hybrid storage systems in a Microgrid Application, Power data taken from PNNL (15)

The flywheel functioning as a filter allows an energy optimized battery container design. In case of multiple applications, the SOC corridor which can be effectively used is reduced. Because the system needs to provide power at any time for ancillary services extremely low or high SOC cannot be used, as explained in Figure 8. Because of the cell impedance any current flow in or out of the cell changes the terminal voltage of the cell. If the terminal voltage is lower than 2.5V or higher than 4.2V, the battery management and protection system will disconnect the cell and the battery is not operational anymore. To avoid this, the system needs to be designed taking into account its SOC limits. In the case of flywheel use, these limits can be broadened reducing the investment into the battery container. Additionally, lower cost energy cells could be used, because of reduced need to have low cell impedance.

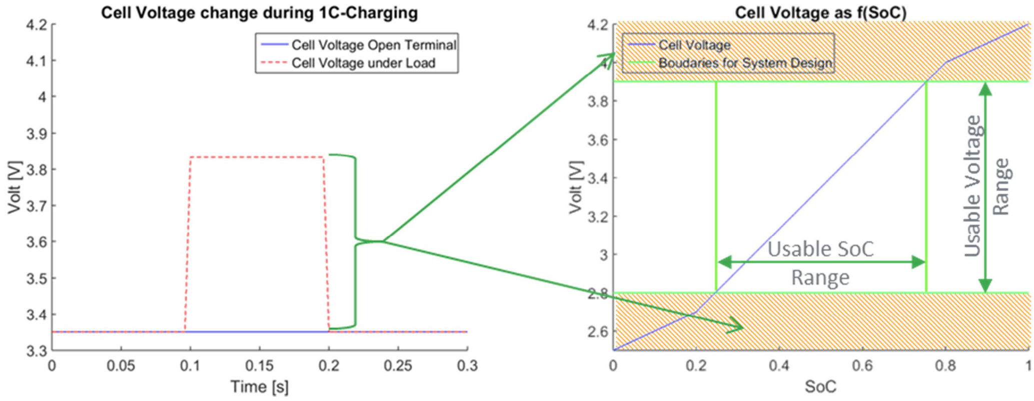


Figure 8: Example how a 1 C-Charge request changes the cell voltage and the impact of this on the usable SoC corridor using a 68Ah cell with 0.05ohm impedance

Successful tests in Germany with a Stornetic DuraStor 500 system show the easy integration of flywheel systems. The Smart controller is external, operating in a virtual power plant, delivering, for example, secondary frequency control to the German grid. Communication is done via internet. The DuraStor system is locally integrated into a production and research facility (16).

The impact on the battery performance is significant. Cycles are reduced and even more important the average cell temperature is reduced as less power flows through the cell, see Figure 10. The cyclic impact on system life is described in (14), (17), and (18),see Figure 9. Literature data is spreading and field-experience shows significant deviation from lab testing, (14).

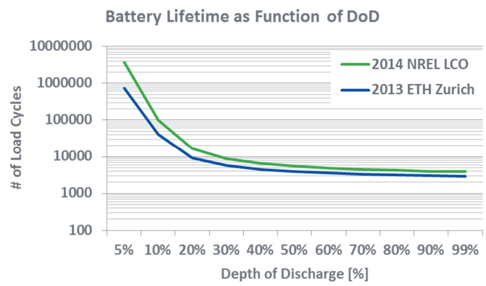


Figure 9: Impact of DoD cycles on Battery life (17)

Effective cooling of battery cells has a strong impact on lifetime explaining the variations in results (19). Typically cell lifetime is reduced by a factor two to four per 20° Celsius temperature increase (18) (20). The comparison of the two power plots in Figure 6 show the significant difference in power flow for a battery doing firming or firming plus frequency regulation. This directly impacts cell temperature which increases based on cell impedance. Simulation with these results show that micro-cycles impact the system by up to 30% mainly caused by temperature driven aging. The results are strongly dependent on the cooling design and on the resistance of the cell. Both typically increase with cell life (19), (21).

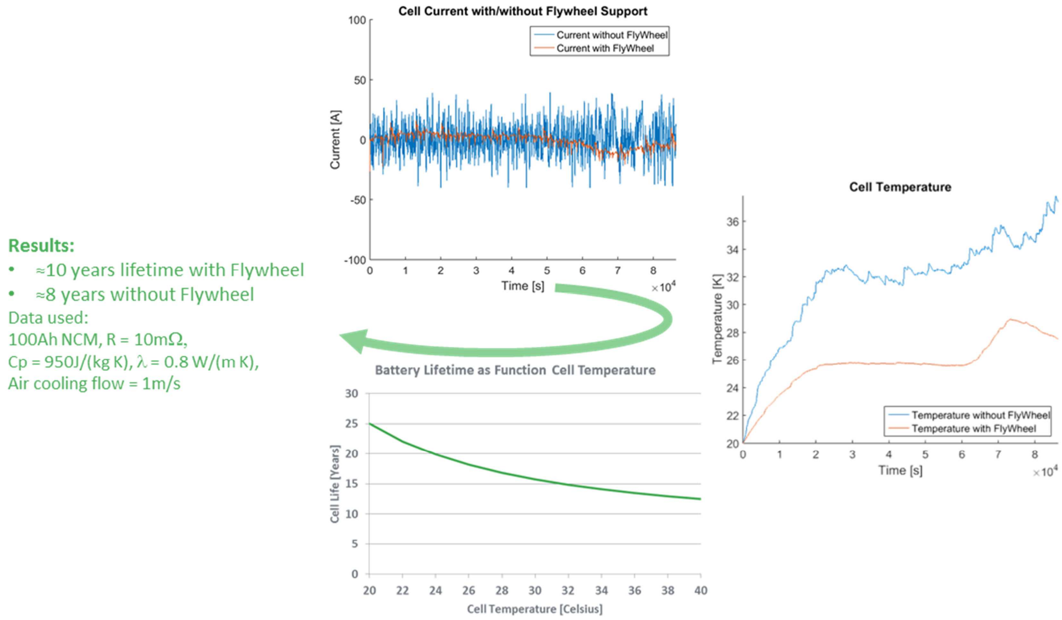


Figure 10: Impact of cell current and cell temperature on cell lifetime for a renewable firming application including frequency regulation @ 98% yearly operating time (Data taken from (18), (22), (23), (19), (20))

Business Benefits

As shown the technical benefits of battery – flywheel hybrid systems are important. Extended project lifetime, improved responsiveness, simplified conditions for warranties together with using less and lower cost cells are the main technical benefits. On the other hand, providing multiple grid services increases the turnover possible.

Containerized flywheel systems like DuraStor are especially easy to combine with battery systems as they offer the same modularity and flexibility. To a certain extent power conversion systems, control systems and auxiliaries can be shared. Project installation is also simplified, as is on site installation effort, as well, civil engineering costs are reduced. All three act to reduce overall project costs.

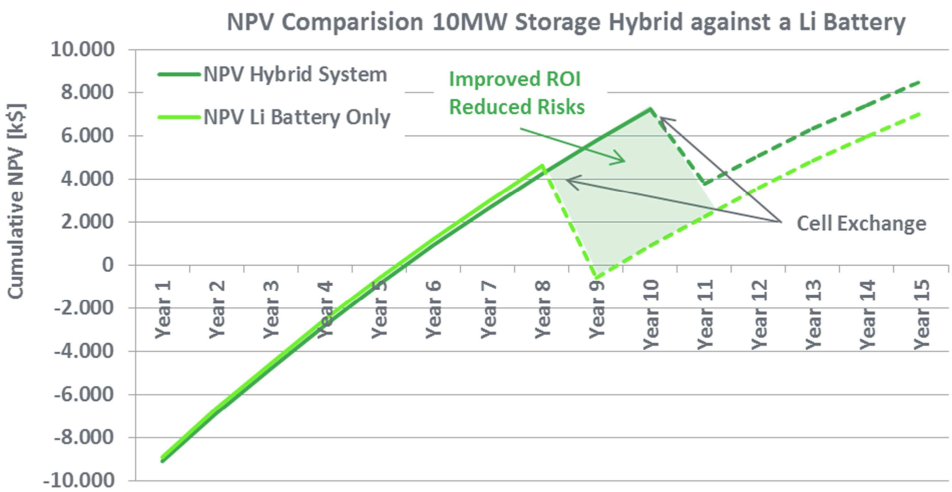


Figure 11: Payback and NPV of a 10MW installation for combined services assuming 35$/kW/h income @ operating costs equal to 7% of Capex.

The results show that at almost comparable investment costs and payback times, a hybrid solution can offer a significantly higher Return on Investment while reducing project financing risks.

Summary

As energy storage becomes more main stream beyond the pilot stage at many utilities, it is important to leverage all the services an energy storage system can provide to extract full value for the investor in these projects. Today the majority of installed storage projects provide a single grid function, either energy shifting to deal with the duck curve issues in the California market, or frequency regulation in the PJM or ERCOT markets.

But as witnessed in PJM, though Reg D pricing was quite attractive in the beginning, the market quickly saturated and prices have deteriorated, affecting financial results for the investor. As other ISO markets evaluate and introduce Reg D type mechanisms or other fast frequency regulation services, it is important for the storage developer or investor to evaluate the projects thru multiple revenue streams rather than servicing a single grid function. As traditional base-load coal generation plants are retired and replaced with renewable generation, ISO operators will look to replace the missing system inertia thru distributed resources that solve multiple grid imbalance issues.

In order to provide multiple grid services as noted in the RMI report, it is essential to design and select an appropriate storage technology. The typical Li-ion system designed for energy shifting currently in the market are not suited or might not be appropriate to provide multiple services cost effectively. Hybrid systems, a combination of long discharge battery technology with fast response flywheels can provide multiple grid services more effectively.

An important aspect of a hybrid energy storage system is not only the pairing of the appropriate battery chemistry with fast response systems such as flywheels, but also having an effective control system architecture that makes appropriate decisions when to charge, discharge, what part of the hybrid systems provides the energy and which grid service provides the most revenue, i.e. the control system must analyze both technical aspects of the storage system, as well as, make appropriate commercial decisions for effective operation of the storage system.

Stornetic GMBH, a Germany based containerized flywheel energy storage systems supplier, is introducing hybrid energy storage to service multiple grid services.

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