

University of Bristol

Faculty of Engineering



ARUP

Design Project 4 - Final Report

Investigation of the Use Energy Storage Technologies to Reduce Peak Demand Charges for the University of Bristol

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Acknowledgements

A paragraph should be written in place of this text, acknowledging all persons who have helped or contributed towards your project. All formally allocated supervisors should be acknowledged first followed by other university staff, representatives of external companies and people not falling in those categories such as peers and PhD students. The acknowledgement should indicate the nature of the assistance received, for example "I acknowledge Paul Rowe of OnAxis Ltd for providing the linear motors used in section 4 and Dr Simon Richards for help in writing the source code for the controller."

Declaration

The accompanying research project report entitled: "Investigation of the Use Energy Storage Technologies to Reduce Peak Demand Charges for the University of Bristol" is submitted in the fourth year of study towards an application for the degree of Bachelor of Engineering in Engineering Design at the University of Bristol. The report is based upon independent work by the candidate. All contributions from others have been acknowledged above. The views expressed within the report are those of the author and not of the University of Bristol.

I hereby declare that the above statements are true.

Signed (author)

.....

Full Name

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Date

1st March 2017

Executive Summary

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List of Acronyms

ESS:	Energy Storage System
DUoS:	Energy Storage System Distribution Use of System
TNUoS:	Transmission Network Use of System
SQP:	Sequential Quadratic Programming
ROI:	Return On Investment
VRB	: Vanadium Redox Batteries
PHS:	Pumped Hydroelectric Storage
CAES:	Compressed Air Energy Storage
CES:	Cryogenic Energy Storage
TES:	Thermal Energy Storage
SMES:	Superconducting Magnetic Energy Storages

1 Aims and Objectives

The announcement of the new £300million University of Bristol Campus in Temple Quarter [1], presents an exciting new opportunity for digital innovations in sustainable energy. The government's 2020 smart meter rollout, is the first step for creating a smart energy grid, key to achieving a low-carbon, sustainable and efficient energy for the UK [2]. The UK's vision corresponds to the University of Bristol's new strategy, seeking to boost its world-class research capacity and promote innovation in policy to increase sustainability [3]. The creation of a world-leading sustainable digital campus is an attractive means for the University to achieve its vision. Consequently, the aim of this group project is to bring a explore of new digital technologies reducing both energy costs and energy usage, uniting these themes to set a new frontier in campus's sustainability.

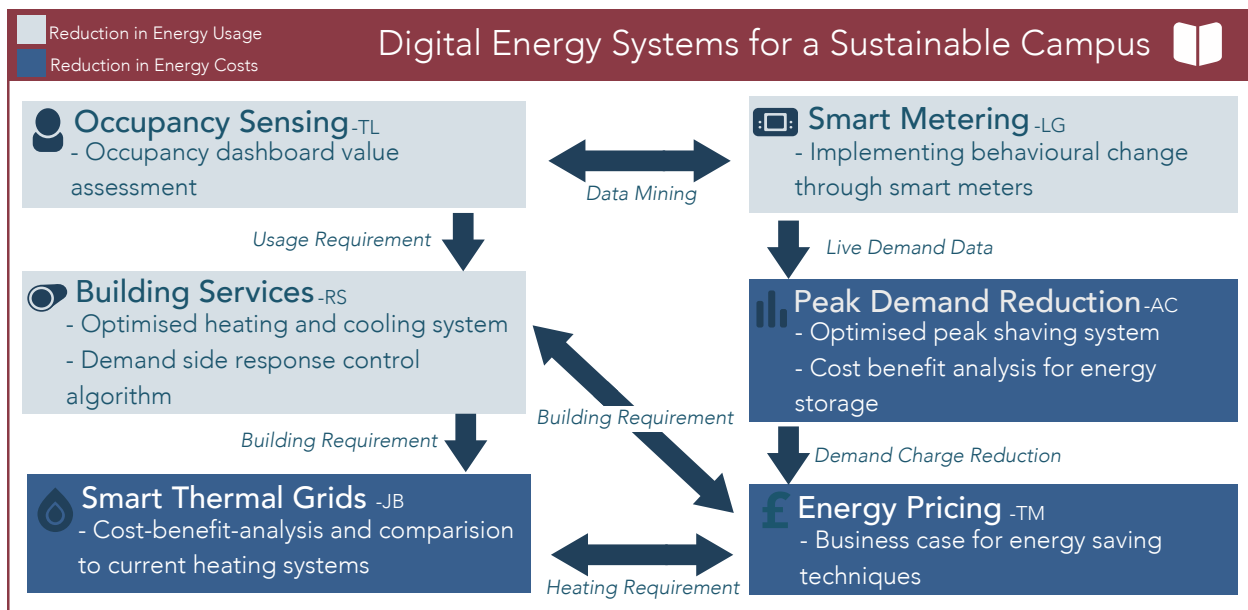


Figure 1: Group Design Project Diagram Showing Relationships Between Individual Projects

Figure 1 shows how the separate subjects of the project are split, where research in Occupancy Sensing, Smart Metering and Building Services will evaluate how energy usage in the new campus can be optimised. Smart Thermal Grid, Energy Pricing and Peak Demand Reduction, all analyse methods of reducing the University's energy costs. Where new energy pricing structures coupled with peak demand reduction technologies, can reduce the load on the grid, helping support sustainable energies. The 5th year group project will unite these themes, creating a smart "brain" through combining usage data with new technologies and strategies, providing a business case to develop sustainable energy services on the new campus, pushing the University to meet its carbon neutral 2030 goal [3].

1.1 Individual Project Aim

The aim of this individual project is to investigate the feasibility of using an energy storage system (ESS) to reduce charges related to peak energy demand for the University of Bristol, implemented in the new Temple Quarter campus. Within the project, the University's peak demand charges will be analysed and simulated, modelling the

bespoke energy requirements of the campus. Different peak-shaving system architectures will then be modelled against this usage and charge data, finding an optimum solution for the system's design concerning the system's capital cost against savings made from energy bills. This model will provide a comparison between using a decentralised system, for room by room use, or a centralised system, being applied to the whole building. The outputs of the project for 5th year will be a flexible model which produces an optimum peak-shaving system architecture for a given University scenario, providing a cost benefit analysis of using energy storage.

1.2 Objectives

Literature Review

1. Perform a detailed literature review, and market analysis of energy storage systems used to reduce peak energy demands, highlighting relevant modelling techniques and limitations.
2. Investigate different energy storage solutions, looking at their applicability to a University peak-shaving system, comparing parameters such as; power-ratings, discharge times, charge times and costs.

Definition of System Architectures

3. Define peak-shaving system architectures, establishing the key performance variables. This objective will include an investigation of peak demand sensing, smart metering usage, energy storage health monitoring, energy conversion, methods to split supply between an energy storage system and the mains and a comparison between decentralised and centralised energy storage models.

Modelling and Analysis

4. Analyse the University's current peak demand charges; understanding the University's current demand charge structure and collecting typical energy usage data. Parameters such as time of day and sources of energy peaks will be incorporated.
5. Produce a simulation to optimise the peak-shaving system, comparing metrics including; unit cost and reduction in peak kWh charges based on University billing structure. This model will provide a comparative analysis of the different system architectures. The model will detail savings against the University's current peak demand charges, being comprised of three stages:
 - (a) A simulation of the University's a normal energy use case and peak demand charges, for use as a datum.
 - (b) Inclusion of energy storage systems, simulating logic and detailing any prediction methods.
 - (c) An assessment of the use of peak load shedding, supply levelling and forecasting to improve the performance of the model.

Evaluation

6. Evaluate results of the simulation, concluding on the effectiveness of different peak-shaving system architectures against particular scenarios. A cost-based analysis will be used to measure the feasibility of the different energy storage systems for the University.

2 Background and Summary of Key Work and References

The following literature review provides a comprehensive overview of current research towards using Energy Storage Systems (ESS) to reduce peaks in energy demand and lower utility costs for the consumer. Peak demand reduction is synonymous with peak shaving; the ability to control energy usage from a supplier during intervals of high demand, to limit or reduce demand charges [4], [5]. As this project is investigating reducing the peak demand charge for the University of Bristol, section 2.1, provides an overview of the University's energy bill, detailing which charges are effected by peak demand. Section 2.2 evaluates traditional methods of peak shaving, covering a brief look at ESSs current usage. Section 2.3 includes a broad range of research of ESSs in different case studies, optimising the system architecture and analysis on ESSs financial return on investment (ROI). This research will help in define system architectures for modelling. Finally section 2.4 analyses the applicability of different ESSs, down-selecting to leave a shortlist of ESSs to be modelled.

2.1 Peak Demand Charges

The University of Bristol's infrastructure, spans across three sites; the City Centre, Stoke Bishop and Langford. Across these locations, the majority of facilities receive separate energy bills, allowing a high degree of granularity in the understanding energy charges [6]. The University receives charges bundled together under four distinct themes [6], these have been ranked below based on the effect a peak-shaving system could have on the charge.

1. **Distribution Use of System (DUoS)** - This bill includes the capacity charge; where the customer pays for a maximum demand level in kW [7]. The capacity charge is set higher than the actual maximum demand, reducing the risk of breaching this threshold. If breached, the customer incurs substantial penalties, and the supplier increases the threshold for the next billing period. By levelling off peaks in energy demand, the capacity charge threshold can decrease. The capacity charge will be the key focus for the proposed peak-shaving system.
2. **Transmission Network Use of System (TNUoS)** - These come from three half-hour periods when the UK's National Grid demand is greatest, referred to as Triads. These dates lie between November and February and must be separated by at least ten days during the financial year [8]. The average max peak demand across the three Triads [9], is multiplied by a tariff for the respective zone in cost per kW [10]. Combined they become the TNUoS charge, added to the customer's end of year bill. The University has become quite good at forecasting these periods [6], making it possible to schedule ESSs to reduce peaks during these periods.
3. **Unit Charge** - Unit charges come at three different rates, green, amber and red^a, depending on the time of day. Energy costs during red periods are significantly higher (between 5pm-7pm). For Western Power (University's current supplier), there is a 17000% increase in price during these periods^b. The unit charge will decrease as a consequence of reducing peak demand, where an ESS should only charge in green periods.

^aSee page 27 of [11].

^b25.405 p/kWh in red periods against 0.147p/kWh in green periods [11].

4. **Feed-In Tariff (FIT)** - Based on feeding back energy to the grid. Peak-shaving will not be applicable.

2.2 Current Peak Demand Management Methods and Energy Storage Systems Usage

Traditionally there are two methods for reducing peak demand for industrial complexes [4]. These are:

- **Load Shedding:** This is reducing energy usage, by switching off certain systems during periods of peak demand [12]. An intelligent scheduling system or a simple forecasting tool can be used to execute load shedding [13], where systems can be switched off autonomously or manually. Often load shedding is calculated daily using a schedule to set a fixed maximum energy limit [14].
 - *Limitations:* Forecasting errors can significantly reduce the effectiveness of this system, where reactive methods are often better [14]. Due to the free flow of staff and students at the University's facilities, predicting peak demands accurately can become a greater challenge.
- **On-site Generation:** Adding off-the-grid capacity to the consumer [4]. The University currently uses some generators to reduce red zone unit charges, supported by [15] showing that fuel costs of running a diesel generators are lower than energy purchased in red zone rates. If a good return on investment is found from purchasing the asset, a diesel generator may be feasible to be used alongside an ESS during these periods.
 - *Limitations:* The University currently has 0.5MW of PhotoVoltaic (PV) installed using nearly all available space [6]. These PV's provide only 0.5% of the total energy demand, meaning the use of on-site generation to offset peak demand has a negligible effect in flattening the University's demand if used directly.

In addition to these limitations, statistics such as "40% of energy use in the campus comes from 5% of the space, predominantly labs" [16], make the University campus a unique case study for peak demand shaving, where energy storage systems appear more attractive than traditional techniques.

There are a limited number of peak shaving ESS solutions available commercially. ABB offers energy-storage, smart-grid products, which perform load levelling at grid level [17]. These systems are designed primarily for supply levelling, using forecasting methods and large ESSs to offset excess energy supply produced from renewable energies [18], rather than focusing on reducing its customers energy bills. One Cycle Control have created technologies to regulate peak-load and mitigate peak demand charges for commercial/industrial facilities using Li-ion batteries [19]. The technologies proved effective at reducing peak demand charges, but highlight that the steep cost of the ESSs reduces the system's financial feasibility [20]. Being able to sense peak loads and respond actively will maximise the performance of the system, while the ESS chosen will have the greatest effect on the systems cost. Section 2.4 evaluates these two different technologies.

2.3 Peak Shaving Systems Literature Review

Acknowledging limitations in commercial peak-shaving ESSs, understanding current research is crucial to designing efficient system architectures. Research is grouped, highlighting each section's significance, identifying areas for further research in work package 2.

2.3.1 Forecasting and the Use of ESS in Load Shifting

Using energy pricing forecasts, an ESS can be switched on to shift energy costs; purchasing energy at a cheaper rate, using this energy during peak times. Looking at the gap in energy prices, demand charges and investment costs for an ESS, NaS, Li-ion and Flow batteries, a basic on/off algorithm to shift energy purchasing from peak to off-peak times does not produce a viable return on investment (ROI) [21]. [22] highlights that billing peak periods were directly correlated with peak demand, requiring an even larger ESS to offset this demand. [23] used real hourly spot prices to decide the best times to turn on and off Vanadium Redox Batteries (VRB) and Polysulfide Bromide Batteries (PSB). Through sequential quadratic programming (SQP), battery sizes were optimised, finding PSB's had a better business case for load shifting. The fundamental differences between [21] and [23], were energy bills targeted and the granularity of the pricing data used. [14] evaluated different control strategies combining many forecasts to reduce errors in peak shaving over a monthly period. Weighted and lowest error forecasts were the best strategies for an energy management system and should be added to the system architecture if forecasting is used. [24] added a real-time operator to create an intelligent scheduling system based on a house to forecast. This system significantly improved the state of charge of the battery, freeing more energy for use in reducing peaks, highlighting that forecasts combined with real-time information can increase the performance of the system further. Work-package 2 will, therefore, look at using weighted and lowest error forecasts for an ESS, further understanding the implications of battery health, whilst work-package 3 will determine if the Universities energy usage data is responsive enough for a real time intelligent scheduling system.

2.3.2 Supply Levelling

Supply levelling is the most common use for ESS [25], using large batteries to reduce power fluctuations brought by the use of renewable technologies [26], [27]. Supply levelling works by storing excess supply, reducing peaks in the grid rather than in demand. The technology is, therefore, similar to peak shaving. [28] looked at improving supply for a residential home. Shiftable water heating was identified to account for 50% of household electricity use, being modelled as the primary storage device. Excess load from wind turbines was used to heat water in excess supply periods bypassing an inverter significantly improving energy losses. This research is supported by [29]. Minimising conversion through inverters makes a large difference in the efficiency of the system. An investigation into energy conversion and, using heat as a secondary storage method will be performed in work-package 2.

2.3.3 Battery Sizing and Financial Modelling

Numerous studies, analysing the business cases for ESSs have been conducted. [21] and [22] model the use ESSs broadly, to reduce the cost of all energy charges, revealing that the ROI is unlikely to be feasible beyond 2020. Papers including [30] and [31] evaluated financial models for particular case studies, showing that bespoke solutions achieved greater peak shaving reductions than returns promised by current generic products [17]. [21], [22], [30], [31] and [32] all present a strong arguments that a bespoke solution for the University will provide a better business case for ESS than generic commercial technology.

Investigating the benefits of a decentralised system, reducing peaks on a small scale rather than using one

large central ESS, [33] analysed both peak shaving and battery longevity for a large data centre. Through both experimentation and modelling, [33] showed that when regarding the batteries lifespan, the ability to regulate load through a series of batteries can be more favourable than a centralised system. Reaserach conducted by [34] and [20] also both support using a decentralised system. A simulation of the impact of lithium-ion batteries operated under a peak-shaving control algorithm identified cost-optimal battery configurations and their impact on grid demand, revealing that small short duration batteries were more favourable and cost effective for the customer, further supported by [32]. The model for this project will assess if this is also the case for a University facility understanding that a few rooms such as labs contribute to the majority of peak loads.

[35], [36] all [37] all show alternate ways of optimising the battery sizing configurations. [37], used a non-numeric modelling method, focusing on ultra-capacitors to find the optimal ESS. The results emphasised the constraint of storage capacity, showing an exponential decrease in value gained after a particular size of ESS. Finding this size for different University scenarios will be the primary focus of this project's model. [36] created an analytical model, using energy bands to regulate peak load, giving an optimum storage size for a given system; this was a straightforward and efficient method of modelling battery usage. [35] looked specifically at Vanadium Redox Flow Batteries (VRFB) arguing it benefits over other ESS methods, producing a MATLAB/Simulink for a residential use case, showing that VRFB can regulate its frequency efficiently, due to its fast response time, while still performing peak-shaving services. This project proposes using a similar modelling technique to [35], incorporating more ESSs.

2.4 Peak Shaving Technologies - Electrical Storage System (ESS)

The selected Electrical Storage System (ESS) will govern the cost and feasibility of a peak shaving system. An ESS converts electrical energy into a form stored for later use [38]. Electrochemical batteries characterise low maintenance, high round-trip efficiency, long cycle lives and high energy density's; arguably being the most appropriate technology for peak shaving [39], [40]. Batteries, therefore, have been chosen as the main focus for this study. The various storage methods can be characterised for different uses summaries below:

- **Energy Management:** for large scale storage, typically used by power plants for load levelling and ramping/load following.
 - Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES) and Cryogenic Energy Storage (CES) are the conventional technologies for high generation above 100MW. All these methods are on a scale too large to be considered for this project.
 - Large-scale batteries, flow batteries, fuel cells, solar fuels, CES and Thermal Energy Storage (TES) are suitable for medium-scale energy management with capacities of 10 -- 100 MW. These are appropriate for consideration for this project.
- **Power quality:** fast response times improve power quality allowing techniques such as the instantaneous voltage drop, flicker mitigation and short duration uninterrupted power supply
 - Flywheels, Batteries, Superconducting Magnetic Energy Storages (SMES), capacitors and ultra-capacitors have millisecond response time lower for storage sizes less than 1 MW - suitable perhaps in addition to large scale battery. Flywheel efficiency is too low for operational use, so has been

removed from this study.

- **Bridging power:** Relatively fast response (< 1 s) but also have relatively long discharge time (hours). The typical power rating for these types of applications is about 100 kW -- 10 MW.
 - Batteries, flow batteries [41], fuel cells and Metal-Air Cells[38], [42].

By removing energy storage methods that would not be appropriate for the system a table was created ^c comparing ESSs. Batteries along with capacitors provide the response time [43] and efficiencies required to make the system justifiable, where only rechargeable batteries were compared. From section 2.3.3 a model of a University peak demand reduction system will need to compare different battery parameters along with their cost, to optimise the model.

^cSee table 1, in the Appendices

3 Development Of Model And Background Research

3.1 Battery Model Definition

3.1.1 Battery Economics

NPV Calculation

3.1.2 Battery Costing

3.1.3 Discharge of Battery Modelling

3.2 New Campus Demand Model

3.2.1 Creation of Senate House Billing Model

Representative Bill Creation

Tax and Other Charges

3.2.2 Definition of New Campus Requirements/ Assumptions

3.2.3 Creation of New Campus Model

3.3 Definition of System Architectures / Strategies

3.3.1 Peak demand Sensing and Smart Metering

3.3.2 Energy Conversion

3.3.3 Centralised vs Decentralised

3.3.4 Strategies

Simple Red Peak Battery Usage

Advanced Strategies

4 Validation of Model

4.1 Sensitivity Check

5 Results and Analysis

5.1 Senate House Battery Strategy and Sizing

5.1.1 Simple

5.1.2 Advanced

5.2 New Campus Battery Strategy and Sizing

5.2.1 Simple

5.2.2 Advanced

5.3 Discussion of Results

6 Conclusions and Future Work

6.1 Conclusions

6.2 Future Work

7 Appendices

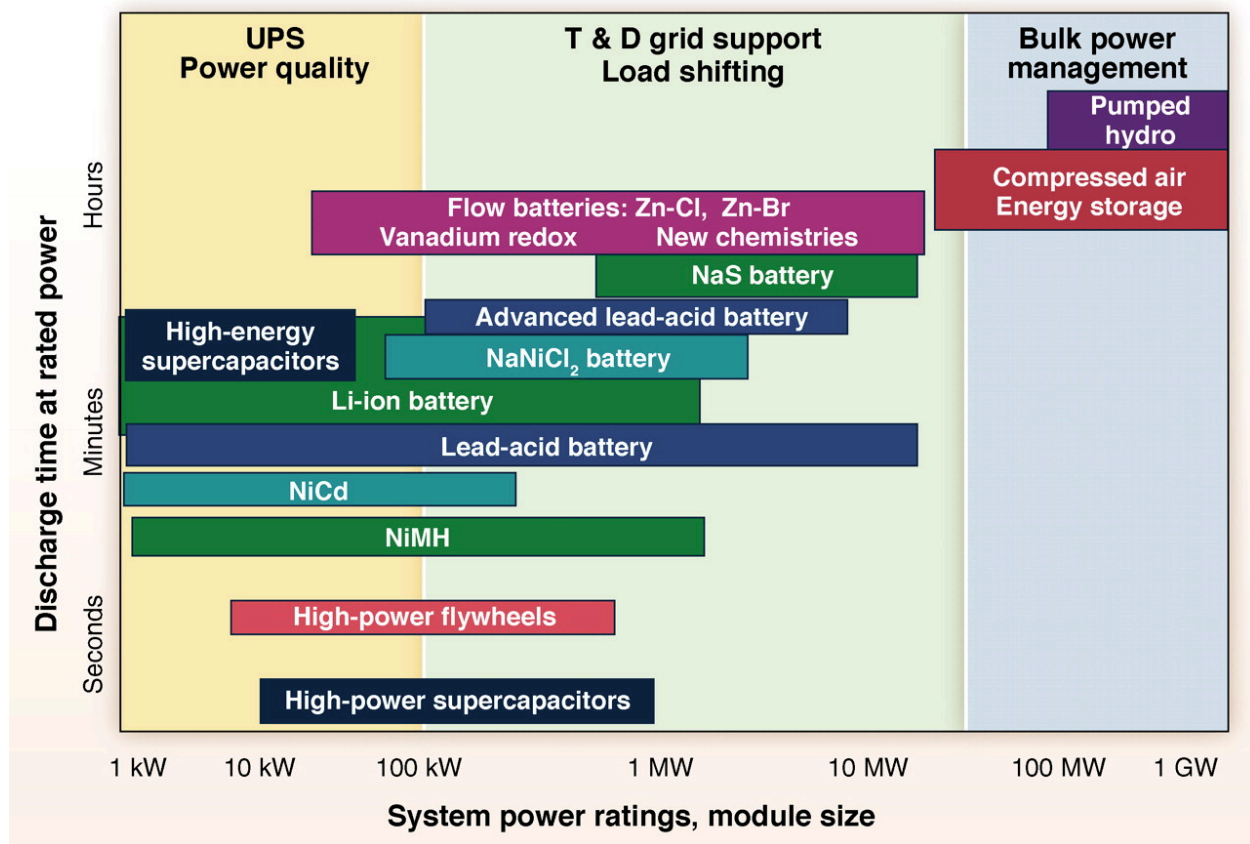


Figure 2: Diagram Showing Batteries Catorgised for Their Use Case [40]

Battery Characteristics Comparison Table											
Battery Type	Lead Acid	Nikel		Lithium Ion			Sodium	Flow		Capacitor	
Battery Compostion		NiCd	NiMH	Colbalt	Magnanese	Phosphate	NaS	VRB	ZnBr	Standard	Ultra Capacito
Degree of Maturity	High	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low	High	Medium
Cost \$/kW	300-600	500-1500	500-1500	1200-4000	1200-4000	1200-4000	1000-3000	600-1500	700-2500	200-400	100-300
Storage Cost \$/kWh	2-50	800-1500	500-550	600-2500	600-2500	600-2500	300-500	150-1000	150-1000	500-1000	300-2000
Cycle Life	500-1000	2000-2500	300-500	500-1000	500-1000	1000-2000	2500	12000+	2000+	50000+	100000+
Charge Time hrs	8-16	1-2	2-4	2-4	1-2	1-2	1-2	1-2	1-2	0-0.5	0-0.5
Specific Energy Whkg ⁻¹	30-50	45-80	60-120	150-250	100-150	90-120	150-240	10-30	30-50	0.05-5	0.05-5
Power Rating MW	0-20	0-40	0-40	0-0.1	0-0.1	0-0.1	0.05-8	0.03-3	0.05-2	0-0.05	0-0.3
Discharge Rate p Day %	0.1-0.3	0.2-0.6	1	0.1	0.1	0.1	20	0.01	0.01	0.4	20-40%
Discharge Time	Seconds - Hours	Seconds - Hours	Seconds - Hours	Seconds - Hours	Seconds - Hours	Seconds - Hours	Seconds - Hours	Seconds - 10hr	Seconds - 10hr	Milliseconds-1hr	Milliseconds-1hr

Table 1: Table Showing Battery Performance

Above were 3053 words.

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