5.0 Power Subsystem

The power system is necessary for the other CubeSat subsystems, such as the microcontroller and communication, to function. The design objectives of the power system include: providing sufficient power to the electrical subsystem, minimizing power drain from the batteries, ensuring efficient recharging of the batteries, and minimizing weight and volume. In addition, Satellite Solutions hopes to improve upon Sub-Orbital-Technologies' power system.

The preliminary design of Satellite Solutions' CubeSat power system implemented various power generation methods, a DC-to-DC boost converter, a battery charger, rechargeable batteries, and a DC-to-DC converter. Parts for that power system have been ordered; however, due to a back order of 8-14 weeks, a redesign of the system was necessary to provide parts faster. As a result, the power system has multiple design options due to different component specifications. Some of the design options change battery configuration (series or parallel) and the method of power delivery to the CubeSat subsystems. The redesign of the system also resulted in a new design strategy that examined the power system from the load to the source. The strategy is based on the idea that each component is dependent upon the component from which it receives power.

The following discussion presents a final design review of the power system by Satellite Solutions. First, the general operation and problems of the CanSat power system are given. Next, the CubeSat power system is divided into three main areas, which include: power generation, storage, and distribution. A general layout of the power system is presented in Figure 18, which provides a road map for discussing the areas of interest. Note that the power distribution and generation elements are explained first in order to define the requirements of the power storage element

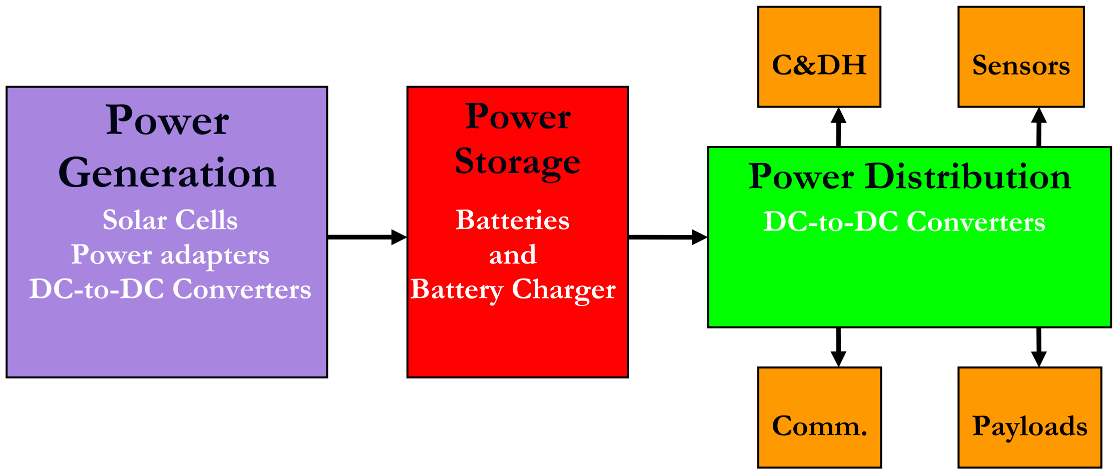


Figure 18: General Layout of the CubeSat Power System

Within each area, the component design, requirements, evaluation criteria, and best option(s) for a particular design are presented. The review of the power system provides general information about the components, but is mostly concerned with component evaluation. Last of all, final design options are presented based on the power system energy balance, cost, and future adaptability. A basic understanding of circuit theory is expected and assumed known for the following explanations.

5.1 Background

The CanSat power system is composed of two independent battery sources, a voltage regulator, and two capacitors, as seen in Figure 19. Despite its simplicity, the CanSat power system had some shortcomings: the dual battery sources added unnecessary weight, the batteries had to be replaced frequently, and the voltage regulator was incorrectly matched to the power supply (voltage drop out was too high).

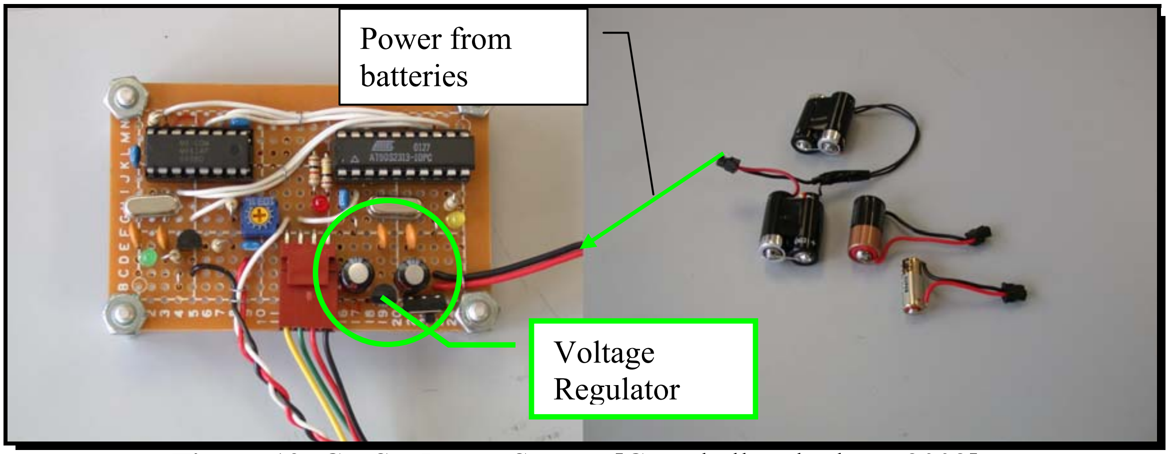


Figure 19: CanSat Power System [Campbell and others, 2002].

5.2 Component Theory

The principle idea of power system components is to adjust the respective output voltage and/or currents according to component and design needs. Components within a power system include linear regulators, DC-to-DC converters, charge pumps, and battery chargers just to name a few. Most power system components are made from diodes, transistors, and other electrical devices to obtain the desired outputs. A generalized block diagram of a power system component can be seen in Figure 20.

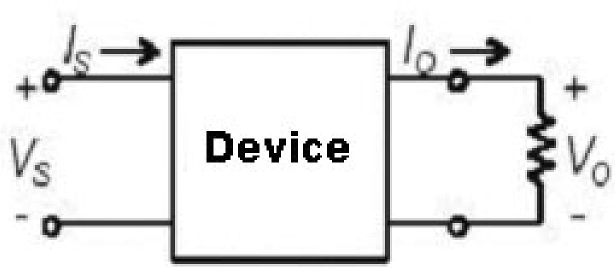


Figure 20: Representative Power System Component Block Diagram [Zulinski, 2003]

Although the current and voltage change from the input to the output in each device, ideally the power should remain the constant; however, this is not the case. The output power is always lower than the input power due to resistive losses [Zulinski, 2003]. As a result, the all power system components have an associated efficiency.

$$\eta = \frac{P_o}{P_s} = \frac{V_o I_o}{V_s I_s} \tag{1}$$

where

$$
\begin{aligned}
P_o &= Output\ \ Power \\
P_s &= Source\ \ Power \\
V_o &= Output\ \ Voltage \\
V_s &= Source\ \ Voltage \\
I_o &= Output\ \ Current \\
I_s &= Source\ Current
\end{aligned}
$$

Linear regulators are somewhat different because the current remains nearly constant, which means that the output voltage divided by the input voltage equals the efficiency. In addition, a constant current implies that a linear regulator can only step down a voltage because efficiency cannot be greater than 100%. On the other hand, converters and battery chargers allow for varying input and output currents resulting in step-up and step-down voltage applications, as well as much higher efficiencies. Note that linear regulators will receive little attention due to their high inefficiency.

5.3 Power Distribution

The power distribution element of the power system is discussed with respect to design, component requirements, and component evaluation criteria and selection.

5.3.1 Design

Design of the power distribution area centered around two options, seen in Figure 21. The first option assumes a low input voltage from the batteries, meaning a step-up device is required. The second option assumes a higher input voltage than the loads require, which means a pair of step-down devices are needed. The step-up/down device can be a charge pump, linear regulator, or DC-to-DC switch mode converter. The charge pump is not ideal for our application because it cannot produce the current output required. For our purposes, the inductor based DC-to-DC converters were examined. The only requirement for selection of various converters is that they meet the power needs of the CubeSat system load.

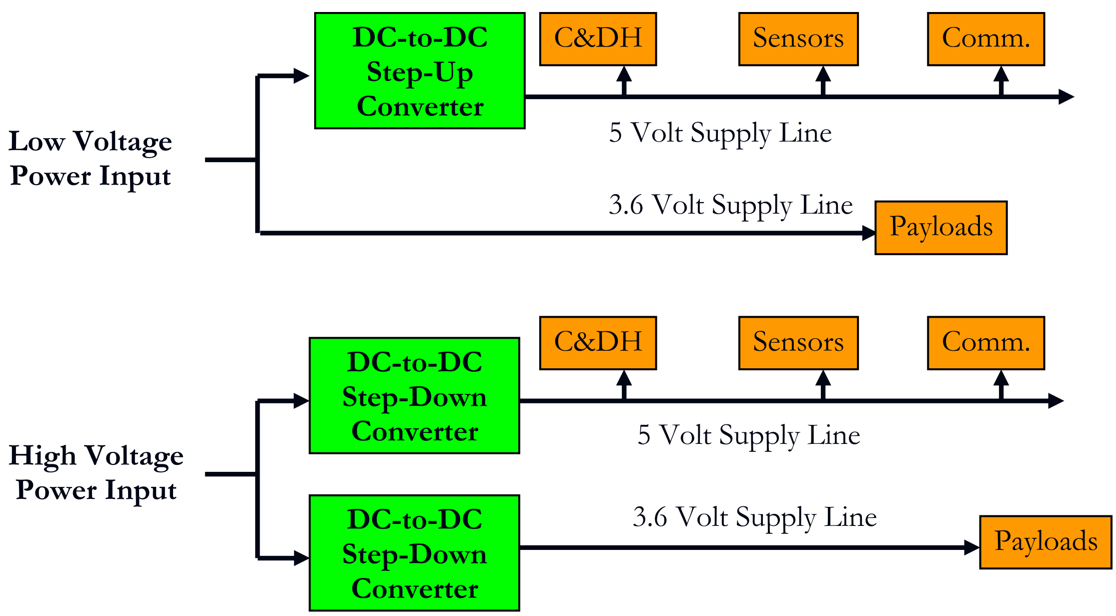


Figure 21: Power Distribution Design

5.3.2 Requirements

Manufacturers of the components within aforementioned subsystems provide voltage, current, and power requirements to operate each device. The chart in Figure 22 is a distribution of power based on the requirements of other subsystems, such as the C&DH, communications, sensors, and experiments.

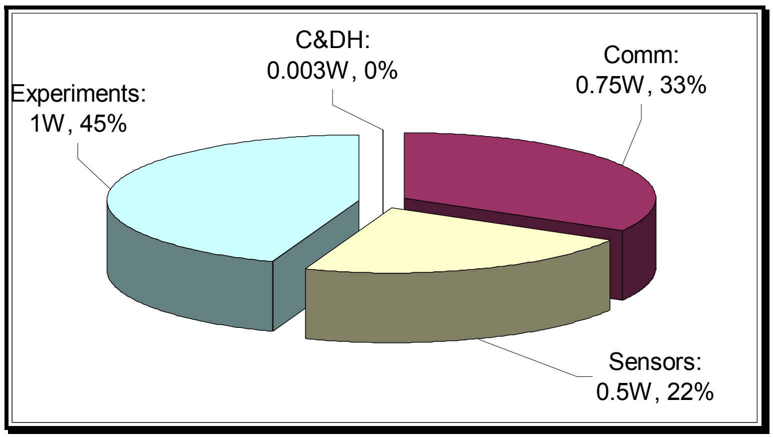


Figure 22: Power Requirement Breakdown by Subsystem.

The CSDT calculated the maximum power draw on the system to be 2.25 Watts. To account for future changes and additions to other subsystems, the power was assumed to increase to 2.5 Watts. In addition, manufactures of the communication system, microcontroller, and GPS provided voltage requirements, which were 3.6 or 5 Volts. Based on the maximum power requirements from each subsystem, approximately 56%, or 1.253 Watts, of the total CubeSat power is needed for the 5 Volt subsystems and 44%, or 1 Watts, for the 3.6 Volt subsystems. Therefore, the resulting minimum currents required for the 3.6 and 5 Volt supply lines are 0.278 and 0.251 Amps.

5.3.3 Component Evaluation Criteria and Selection

In addition to the power requirements, the efficiency of the converter is an important performance characteristic and should be as high as possible over a wide range of current. Figure 23 illustrates a good efficiency curve with respect to current draw.

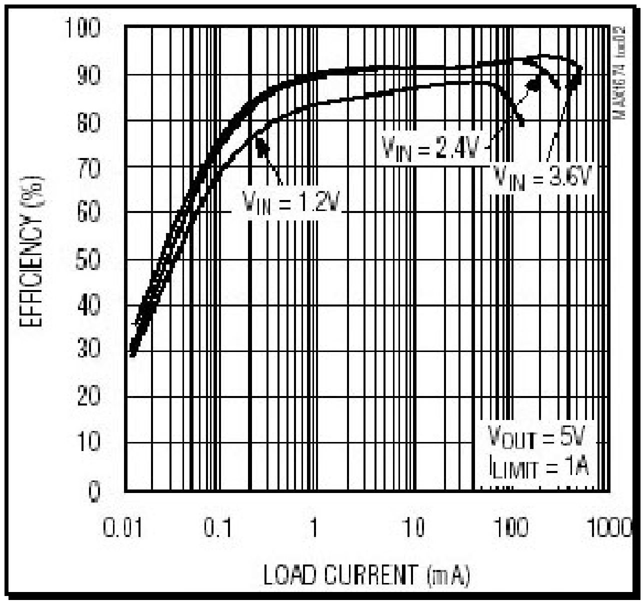


Figure 23: A Good Efficiency Curve for a DC-to-DC Converter [Maxim, 2003].

Other important characteristics include lowest possible input voltage, robustness, wide range of environmental temperatures, and cost. Research for converters uncovered numerous options by manufactures such as Maxim, Texas Instruments, National Semiconductor, and Linear Technology. Table 4 presents the chosen step-up and step-down converters for each design option and their specifications. All of the chosen components accommodate the necessary power requirements for the CubeSat system load.

Table 4: Converter Specifications for Power Distribution Design Options [Maxim, 2003], [National Semiconductor, 2003], [Texas Instruments, 2003]

Part Number	Type	Input Voltage (V)	Output Voltage (V)	Max Output Current (mA)	Max Efficiency (%)	Temperature Range (C)
MAX757	Step-Up	0.7 to 5.5	2.7 to 5	300 @5 Vout, 3.3 Vin	88 @5 Vout, 3.3 Vin	-40 to 85
MAX1795	Step-Up	0.7 to 5.5	2 to 5.5	300 @5 Vout, 3.6 Vin	95 @5 Vout, 3.6 Vin	-40 to 85
MAX1723	Step-Up	0.8 to 5.5	2 to 5.5	150 @5 Vout, 3.6 Vin	90 @5 Vout, 3.6 Vin	-40 to 85
TPS61130	Step-Up	1.8 to 5.5	2.5 to 5.5	200 @5 Vout, 3.6 Vin	87 @5 Vout, 3.6 Vin	-25 to 85
UCC2941	Step-Up	0.8 to 5	5	200 @5 Vout, 3 Vin	90 @5 Vout, 3 Vin	-55 to 150
LM2621	Step-Up	1.2 to 14	5	300 @5 Vout, 3.6 Vin	88 @5 Vout, 3.6 Vin	-40 to 85
LM2641	Step-Down	5.5 to 30	2.2 to 8	1000 @6.5 V	94 @6.5 V	0 to 125
LM1572	Step-Down	8.5 to 16	2.42 to 5	830 @5 Vout, 7.2 Vin	95 @5 Vout, 7.2 Vin	-40 to 125
TL497L	Step-Down	4.5 to 12	-25 to 30	N/A	>60	-60 to 150
MAX639	Step-Down	4 to 11.5	5	150 @5 Vout, 7.2 Vin	94 @5 Vout, 7.2 Vin	-55 to 125
MAX750A	Step-Down	4 to 11	1.25 to 11	600 @5 Vout, 7.2 Vin	93 @5 Vout, 7.2 Vin	-55 to 125
LM2655	Step-Down	4 to 14	1.238 to 5	500 @3.6 Vout, 7.2 Vin	96 @3.6 Vout, 0.5 Iout 7.2 Vin	-40 to 125
Max1761	Step-Down	4.5 to 20	1 to 5.5	600 @3.6 Vout, 7.2 Vin	94 @3.6 Vout, 7.2 Vin	-40 to 85

Often, setting the boost converter to its maximum output voltage results in degraded efficiency; therefore, the criteria for the efficiency and maximum output current were examined closely. The best step-up converter for the low voltage power input design is MAX1795. The selected step-down converter for the high voltage power input design is LM2655, which will be used on both the 3.6 and 5 Volt supply lines. Both of the chosen converters presented the best efficiency over a wide range of load currents.

The power input requirement for the power distribution element using MAX1795 and LM2655 are 2.4 and 2.51 Watts, which assumed 5% less efficiency than the maximum presented in Table 4.

5.4 Power Generation

The power generation element of the power system is discussed with respect to design, component requirements, and component evaluation criteria and selection. The solar cells were thoroughly researched to ensure that an eventual space application for the CubeSat is possible. However, solar cells are not required for the sounding rocket launches in August.

5.4.1 Design

The design of the power generation area includes solar cells, a power adapter, and DC-to-DC converter, as seen in Figure 24. The solar cells can be wired in two different configurations. In the first configuration, all the cells are wired together in series, which means that the voltage adds while the current remains constant. The second configuration has the cells wired together in parallel on each face; then, the combined cells on each face are wired in series. Note that if the output voltage from the solar cells and power adapter are within the input voltage of the battery charger, then a DC-to-DC converter may not be necessary.

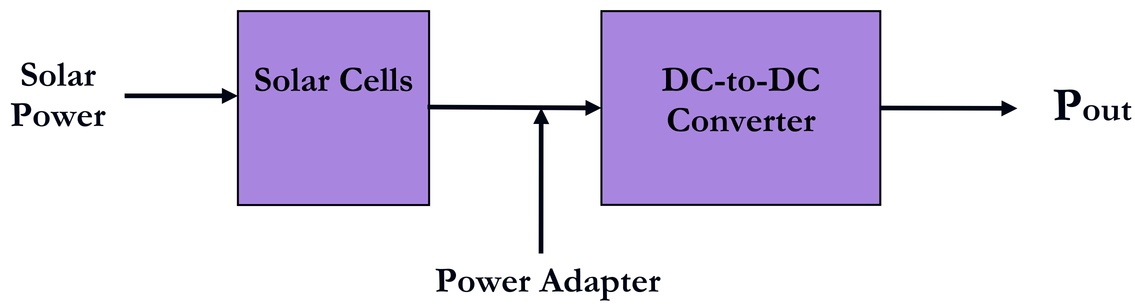


Figure 24: Power Generation Design

5.4.2 Requirements

Unfortunately, Satellite Solutions did not have the luxury of an unlimited budget; therefore, one of the major non-technical requirements for the CubeSat power system was the budget. The budget requirement mostly affects the solar cells because they are so expensive. The price of solar cells increases exponentially with increasing solar efficiency. Obviously, the highest efficiency and, therefore, most powerful solar cells are desirable; however, the solar cell expense was limited to $1100. In addition, surface area coverage was limited from a possible 600 cm^2 to 470 cm^2 because of antennas, data and power ports, and structural fasteners. Last of all, an external power source was a design requirement, set by our advisors. As a result, the power input from the power adapters had to be equivalent to the power input from solar.

5.4.3 Component Evaluation Criteria and Selection

The solar cells are a part of the flight hardware; therefore, the solar cells must be capable of withstanding deployment forces, vibration, and a wide range of operating temperatures. In addition, the solar cell best suited for our design should be light in weight and produce the greatest amount of power. The CSDT researched varying types of solar cells from three different corporations. All of the solar cells are space proven. Specifications for the varying solar cells are presented in Table 5.

Table 5: Specifications For Varying Solar Cells [Spectorlab, 2003], [Emcore Corporation, 2003], [Silicon Solar, 2000].

	Spectrolab	Emcore		Silcon Solar
	Dual Junction	Dual Junction	Tripple Junction	Single Junction
Supply Voltage (V)	2.05	2.08	2.57	0.51
Supply Current (mA)	230 to >286	427.50	427.50	3500 1300 250 75
Power (mW)	471 to >586	889.20	1096.54	1785 663 127.5 38.25
Energy Conversion Efficiency (%)	16.1 to >20	23.2	28.6	12.4
Size (cm)	3.12 x 6.91	3.72 x 7.61	3.72 x 7.61	10.3 x 10.3 6.25 x 6.25 1.7 x 6.25 2.6 x 1.7
Thickness (Microns)	140	155	155	N/A
Wieght (Grams)	N/A	2.4	2.4	N/A
Cost per Cell ($)	5.40 to 12.60 (Note: Must buy at least 50 cells)	260.00	260.00	6.00 3.00 1.50 1.00

In order to determine the maximum power and, therefore the best solar cell, the specifications must be examined with respect to efficiency and optimal surface area coverage. The efficiency is known, and the optimal surface area coverage for each manufacturer's solar cell was determined by assuming that a 0.5 cm minimum should be left uncovered from the surface of each edge of the CubeSat for structural fasteners. In addition, a minimum of a 6 cm² and 9 cm² sections were assumed uncovered for access ports and antennas. Furthermore, the solar cells were assumed to be in pure sunlight (solar constant = 0.1353 W/cm²) where about ¼ of the CubeSat surface area received direct sunlight. The maximum power the solar cells will produce when in the sun is based on the optimal solar cell coverage, efficiency, solar constant, and average area receiving direct sunlight. Therefore, Table 6 presents the power capabilities of each solar cell.

Table 6: Power Capabilities of Each Solar Cell

	Manufacturer	Efficiency (%)	Area (cm^2)	All Cells in Series	Cells on each side in parallel, each side in series
Power (W) Voltage (V) Current (A)	Spectrolab	16	388	2.10 9.13 0.23	2.10 1.52 1.38
Power (W) Voltage (V) Current (A)	Spectrolab	17	388	2.23 8.92 0.25	2.23 1.49 1.50
Power (W) Voltage (V) Current (A)	Spectrolab	18	388	2.36 8.85 0.27	2.36 1.47 1.60
Power (W) Voltage (V) Current (A)	Spectrolab	19	388	2.49 9.10 0.27	2.49 1.52 1.64
Power (W) Voltage (V) Current (A)	Spectrolab	20	388	2.62 9.27 0.28	2.62 1.55 1.70
Power (W) Voltage (V) Current (A)	Emcore	23.8	340	2.74 11.90 0.23	2.74 1.98 1.38
Power (W) Voltage (V) Current (A)	Emcore	28.6	340	3.29 14.30 0.23	3.29 2.38 1.38
Power (W) Voltage (V) Current (A)	Silicon Solar	12.4	444	N/A	1.86 0.99 1.88

The AC and DC power adapters for supplying power to the battery charger are not a part of the actual CubeSat design and, therefore, the criteria applied to the solar cells do not apply in this situation. The AC and DC adapters require more research, but the desired requirements are easily attainable.

In the power distribution section, converters were discussed because two explicit predetermined voltages were set to run the other subsystems of the CubeSat. In this case, a converter might be required to obtain the necessary battery charger power input (particularly voltage) criteria if the solar cells cannot produce the desired characteristics. Besides the aforementioned requirement, the other criteria include those mentioned in the power distribution section. The important specifications of each model are presented in Table 7.

Table 7: Power Generation Converter Specifications

Part Number	Input Voltage (V)	Max Output Voltage (V)	Max Output Current (mA)	Max Efficiency (%)	Temperature Range (C)
LT1301	1.8	12	120 @ 12 Vout, 3.3 Vin	87 @ 12 Vout, 3.3 Vin	-65 to 150
LT1303	1.8	25	200 @ 5 Vout, 2 Vin	83 @ 5 Vout, 2 Vin	-65 to 150
LT1305	1.8	5	400 @ 5 Vout, 2 Vin	78 @ 5 Vout, 2 Vin	-65 to 150
LT1316	1.8	12	50 @ 5 Vout, 1.8 Vin	82 @ 5 Vout, 1.8 Vin	-65 to 150
LM2623	0.8 to 14	14	300 @ 5 Vout, 2.1 Vin	78 @ 5 Vout, 2.1 Vin	-65 to 150
MAX629	0.8 to Vout	28	100 @ 12 Vout, 3 Vin	80 @ 12 Vout, 3 Vin	-65 to 165
MAX772	2 to 16.5	15	1000 @ 15 Vout, 9 Vin	94 @ 15 Vout, 9 Vin	-65 to 160
MAX1674	0.7 to Vout	5.5	150 @ 5 Vout, 1.2 Vin	88 @ 5 Vout, 1.2 Vin	-65 to 165
MAX1703	0.7 to 5.5	5.5	400 @ 5 Vout, 1.2 Vin	88 @ 5 Vout, 1.2 Vin	-65 to 160
MAX1709	0.7 to 5.5	5.5	1300 @ 5 Vout, 2.5 Vin	88 @ 5 Vout, 2.5 Vin	-65 to 150

Often, setting the converter to its maximum output voltage results in degraded efficiency; therefore, the criteria for the efficiency and maximum output current were examined closely. If a converter is used in the power generation element, then MAX772 provides the best performance characteristics with a wide range of output voltages.

5.5 Power Storage

The power generation element of the power system is discussed with respect to design, component requirements, and component evaluation criteria and selection.

5.5.1 Design

The battery charger receives power and energy from the power distribution element, and outputs power to the power distribution element. Generally, the battery charger is connected directly to the battery, which in turn, is connected to the system load, as seen in Figure 25. However, there are battery chargers that offer the capability to support the load and charge the batteries at the same time. Further research regarding load supporting battery chargers should be investigated by future semesters.

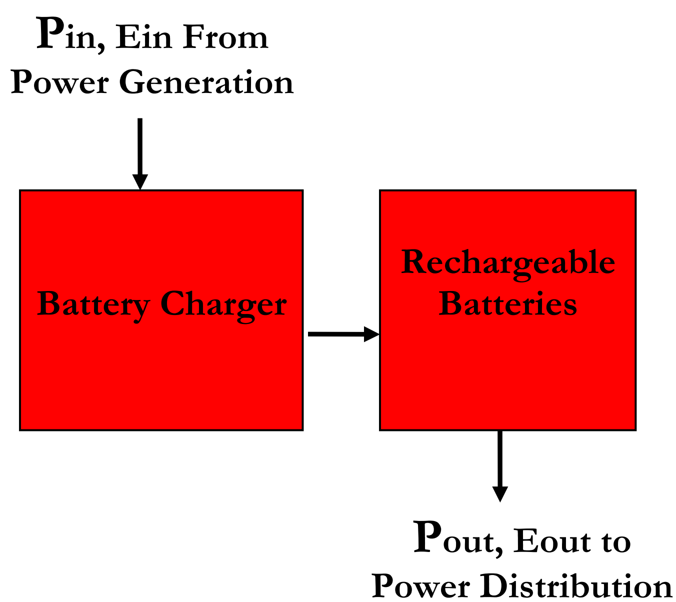


Figure 25: Basic Power Storage Design

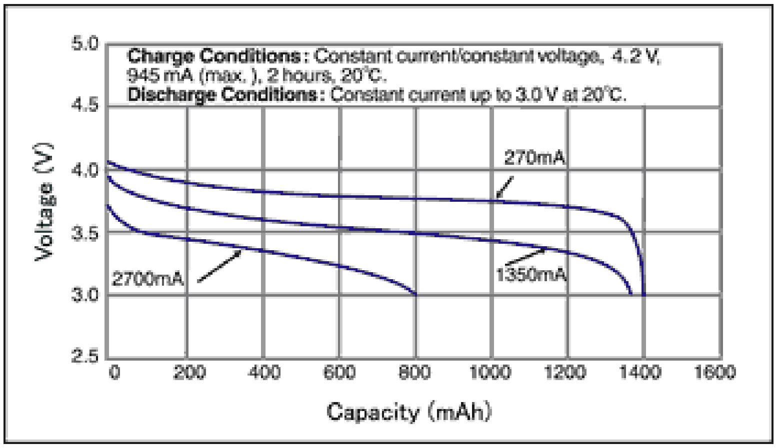
5.5.2 Requirements

The power storage element is required to support the system load (power distribution) and recharge the batteries. The output voltage from the batteries must be matched with the input voltage required for the power distribution element. Furthermore, the batteries should support the maximum power draw. Obviously, the battery charger must be capable of charging the selected battery chemistry. In addition, the input voltage of the battery charger must be matched with output voltage from the power generation element.

5.5.3 Component Evaluation Criteria and Selection

A battery is a device that converts chemical energy into electricity. All battery types derive power from electrochemical reactions. In order for a battery to be considered rechargeable, the electrochemical reactions must be reversible. But the fundamental difference between the two batteries, both rechargeable and non-rechargeable batteries discharge in a similar fashion.

The most important evaluation criterion for a battery is performance. The favorable performance characteristics of a battery include: high energy density, slow discharge (loss of voltage), and quick recharge capability. The energy density is defined as the capacity (Amps per hour) times voltage per weight (g) of the battery. A slow discharge means that battery voltage drops slowly with current draw. Graphically, a slow discharge curve is illustrated as shallow sloped curve over the discharge time of battery. Last, quick recharge means that the battery voltage increases rapidly with respect to time, as illustrated by a steep slope at the beginning of the charge curve. The general discharge and charge characteristics of a battery type are illustrated in Figure 26.



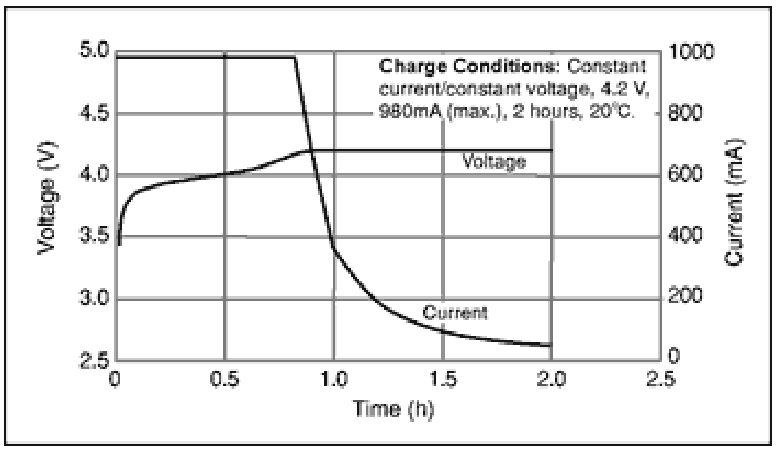


Figure 26: General Discharging (Top) and Charging (Bottom) Characteristics of Selected Battery Types [Matsushita Battery, 2003].

Also, rechargeable batteries are necessary for space application and help reduce maintenance time during ground testing. Other criteria used for comparison included: weight, volume, ease of use, charge cycles, environmental temperature range, and cost. Although theses characteristics are not essential criteria to the CubeSat design, they are extremely important and affect the CubeSat overall design. Typically, minimum battery weight and volume are desirable characteristics of a satellite. The ease of use refers to the complexity and difficulty in charging a particular battery chemistry. The charge cycles refers to how many times the battery can be recharged before a significant loss of memory. Typically, good batteries are costly, but extremely important to the performance of other subsystems. As a result, the CSDT is open to the idea of purchasing expensive batteries.

Research for batteries yielded three different battery types. The battery types are classified by their chemistry and include: Nickel-Metal Hydride (NiMH), Lithium Ion (Li Ion), and Lithium Polymer (Li Poly). The NiMH batteries have a positive electrode composed of nickel hydroxide, and a negative electrode made of a hydrogen-absorbing alloy. Both electrodes are exposed to an alkaline electrolyte. The metal casing is equipped with a safety valve to relieve excess pressure [Matsushita Battery, 2003]. Li Ion batteries have a negative electrode made of carbon and a positive electrode made of lithium cobalt oxide [Matsushita Battery, 2003]. Last of all, Li Poly batteries are the most technologically advanced and expensive. The difference between Lithium Ion and Lithium Polymer batteries lies in the electrolyte material. The polymer electrolyte of a Li Poly battery has a low intrinsic conductivity, which allows the cell to be very thin [Ultralife, 2002]. General specifications for NiMH, Li Ion, and Li Poly batteries are presented in Table 8.

Table 8: General Specifications for Various Rechargeable Battery Chemistries [Matsushita Battery, 2003], [Ultralife, 2002].

Criteria	Nickel Metal Hydride	Nickel Metal Hydride	Lithium Ion	Lithium Ion	Lithium Polymer
	Cylindrical	Prismatic	Cylindrical	Prismatic	Prismatic
Energy Density (mWh/g)	64	60	147	142	152
Charge Cycles	1000	1000	500	500	300
Difficulty of Charge	Easy	Easy	Difficult, due to safety concerns	Difficult, due to safety concerns	Difficult, due to safety concerns
Suseptible to Over Charge	No	No	Yes	Yes	Yes
Temperature Range (C)	0 to 45	0 to 45	-10 to 45	-10 to 45	-20 to 60
Cost per Cell ($)	$5	$8	$30	$30	$99

The battery configuration and the number of batteries are variable parameters, however, the best battery for the sole, series, and parallel design configurations where chosen by examining a multitude of characteristics, as seen in Table 9. The highlighted options indicate the preferred battery and configuration.

Table 9: The Best Options for Various Battery Configurations [Kokam, 2003], [Matsushita Battery, 2003], [Ultralife, 2002].

Part Number	Chemistry	Charge Current (mA)	Charge Time (min)	Configuration	Total Weight (g)	Total Volume (cm^3)	Total Capacity (mAh)	Total Voltage (V)
CGA633450A	Li Ion	980	120	Single Cell	24	10.8	1035	3.6
UBC433475	Li Poly	465	135	Single Cell	22.00	11.97	930	3.7
SLPB523462	Li Poly	980	70	Single Cell	20.50	11.58	1020	3.7
CGR17500	Li Ion	550	120	2 in Series	50.00	22.24	830	7.2
CGA523436	Li Ion	680	90	2 in Series	29.00	12.72	710	7.2
UBC383562	Li Poly	320	135	2 in Series	28.00	16.5	640	7.4
SLPB353452	Li Poly	540	70	2 in Series	24.00	13.2	560	7.4
HHR120AA	NiMH	1200	70	3 in Series	69	21.3	1150	3.6
HHF135T4	NiMH	1350	70	3 in Series	75.00	20.85	1350	3.6

Typically, a particular battery chemistry is required to be charged at a certain voltage, but the current can vary up to a certain limit. The higher the current the faster the battery(ies) will charge. If the voltage and current are known, then so is the power needed to supply the battery(ies). Like the converters, the power out is equal to the power in, but with some inefficiency. As a result, the charging current, efficiency, and input voltage are all important criteria. The power input comes from the previously discussed power generation element. In addition to the requirements and important criteria, battery charges were examined with respect to the number of batteries, monitoring options, and the environmental temperature range. Furthermore, the development of "home made" charges is often difficult due to chip size, equipment restrictions, and complexity. Accordingly, a prefabricated circuit board, seen in Figure 27, is advantageous for the battery charger because of the ease of installation. The only requirement of a prefabricated board, aside from those mentioned for the battery charger, is that it fit within the CubeSat structure.

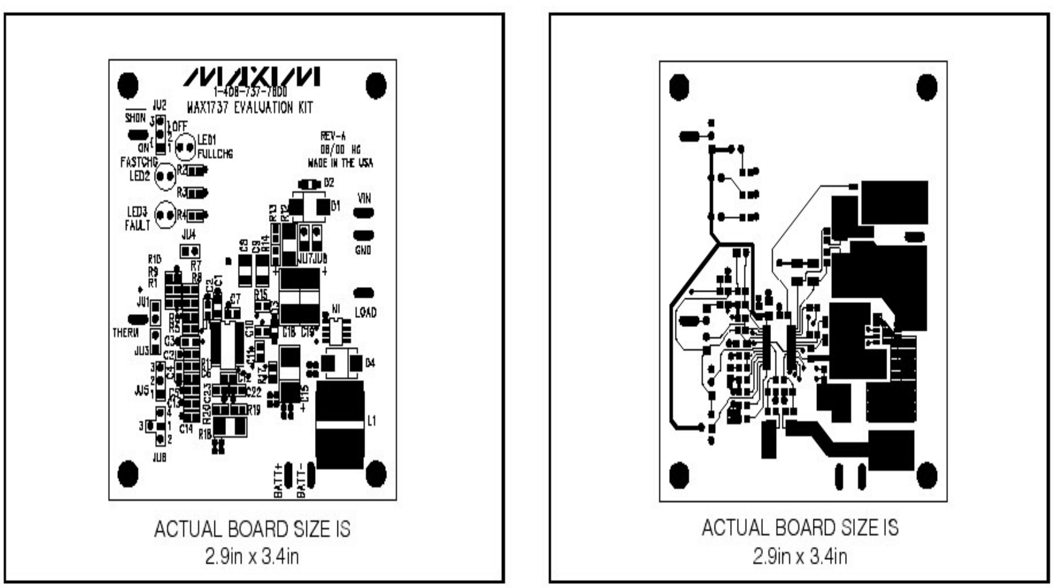


Figure 27: Prefabricated Battery Charger Circuit Board [Maxim, 2003].

The investigation of battery chargers has revealed a wealth of information at Maxim/Dallas Semiconductor Corporation. Other battery charger manufactures, such as Wes Tech, Kokam Engineering, Linear Technology, and Texas Instruments, also presented some competitive options. Ten different models of battery chargers were pre-selected as possible candidates for the final design. All ten models meet the aforementioned requirements for being able to charge one of the selected battery configurations. Furthermore, the chargers are stand-alone, which means the complicated charging logic does not need to be programmed into a microcontroller. Instead, the process is controlled by the chargers own microcontroller. The general specifications for each of the chargers are presented in Table 10.

Table 10: Specifications for Battery Charger Options [FMA Direct, 2003], [Maxim, 2003], [National Semiconductor, 2003], [Texas Instruments, 2003].

Part Number	Battery Type	Number of Batteries	Input Voltage (V) (note: min to max is given, but the min value increases with the number of cells)	Charging Current (Amps)	Temperature Range (Celsius)	Monitors Outputs	Cost ($)
LIPOCH102	Lithium Ion Li Poly	1	9 to 12	0.25	N/A	None	$30.00
LIPOCH202	Lithium Ion Li Poly	1 to 2	11 to 13.5	0.25	N/A	None	$30.00
Wes Tech	Lithium Ion Li Poly	1 to 3	11 to 26	Up to 1	N/A	None	$50.00
LM3621	Lithium Ion	1	3 to 5.5	Up to 1	0 to 70	N/A	N/A
BQ2057	Lithium Ion	1 or 2	4.5 to 15	Up to 1	-20 to 70	Temp and Current	N/A
MAX1737	Lithium Ion	1 to 4	6 to 28	Up to 4	-40 to 85	Voltage, Current, Temp,Time	$125.00
MAX1758	Lithium Ion	1 to 4	6 to 28	Up to 1.5	-40 to 85	Voltage, Current, Temp,Time	$125.00
MAX846A	Lithium Ion	1 to 2	6 or 10		0 to 70	Voltage and Current	
MAX712	NiMH	1 to 16	1.5V +(1.9V * # of cells)	Up to 4	-40 to 85	Temp, Time, and Voltage	$240.00
MAX1873	Lithium Ion Li Poly NMH	2 to 4 2 to 4 6 to10	9 to 28	Up to 4	-40 to 85	Voltage and Current	$60.00

Because of the variety of battery chemistries and configurations, four battery chargers have been selected: Wes Tech, LM3621, MAX1737, and BQ2005, MAX712. The exact charger is dependent on the battery chemistry and input voltage from the power generation element.

5.6 CubeSat Power Subsystem Design

Until now, the design process has concentrated on selecting components based on maximum power draw and generation. However, the most important requirement for the CubeSat power system, as a whole, is balancing the input energy with the output energy. The energy balance is crucial in the environment of space because the CubeSat has limited charging time per orbit, but will be continually using energy. The design theory is explained followed by a design option summary.

5.6.1 Design Theory

In order to support the load, the batteries must be able to produce the needed output energy for the period of one orbit. The output energy (to the power distribution element) is a function of power and operational percentage per orbit of each subsystem, the power distribution efficiency, and the orbital period.

$$E_{out} = \frac{T}{\eta_{pdc}} \sum_{i=1}^{n} P_i \beta_i \tag{2}$$

where

T is the orbital period

η_{pdc} is the efficiency of the converter in the power distribution element

P_i is the power draw from a particular subsystem

β_i is the active operational percentage per orbit for a subsystem

The orbital period is calculated based on the altitude the CubeSat is above the Earth's surface. From Kepler's second law, the orbital period is

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{3}$$

where

a is the radius from the center Earth

μ is the gravitational constant for the Earth

The energy out of the battery depends on the capacity and voltage of the battery setup, and always needs to be greater than E_{out}.

$$E_{batt} = CV \tag{4}$$

where

C is the capacity of the battery

V is the voltage

By equating 2 and 3, the capacity of the battery setup is determined assuming the other variables are known. The number of batteries, wiring configuration, and capacity of each individual battery are adjusted to satisfy the power system design objectives while maintaining the necessary design specifications.

Furthermore, the output energy must be less than the input energy in order for the battery charger to resupply the batteries with the energy lost. In this circumstance, the energy is dependent on the orbital time in the sun and the power generated by the solar cells.

$$E_{in} = P_{pg}T\phi = [A_{sc}\eta_{sc}\alpha\psi]T\phi \tag{5}$$

where

P_{pg} is the power from the power generation element

ϕ is the percentage of the orbit period that CubeSat is in the sun

A_{sc} is the surface are that the solar cells cover

η_{sc} is the efficiency of the solar cells

α is the coefficient of average area for the CubeSat

ψ is the solar constant $= 0.1353 \, {}^{W}\!/_{cm^2}$

To summarize, the aforementioned relations and equations govern the design process of the power system. Failure to satisfy the conditions presented will result in a defective, inoperable power system.

5.6.2 Design Option Summary

The design options of the optimal power system are based on the overall design objectives, which are dependent on numerous design variables, component requirements, and criteria. There are two types of operational parameters, orbital trajectory and subsystem characteristics. The orbital trajectory has a direct effect on the amount of time the CubeSat is in the sun and, therefore, the amount of time the CubeSat can recharge its batteries. The orbital trajectory is dependent upon the organization that launches the CubeSat; therefore, the eccentricity and orbital altitude were assumed to be 0 (circular orbit) and 400 km, which resulted in a period of 92.56 minutes. The CSDT assumed that the CubeSat is in the sun 60% of its orbital time, or 55 min and 32 sec. The subsystem characteristics include items such as power requirements and active operational percentages for each subsystem. Table 11 presents all the operational parameters and their assumed values.

Table 11: Operational Parameters

Orbital Trajectory		
Altitude (km)	Period (min)	Time in Sun (min)
400.00	92.56	55.53

Subsystem	Voltage (V)	Current (A)		Power (W)		Operation (%)	Energy (Wh)	
	Continous	Active	Stand-by	Active	Stand-by	Active	Active	Stand-by
C&DH	5.000	0.001	0.000	0.003	0.001	100.000	0.005	0.000
Communications	5.000	0.150	0.050	0.750	0.250	50.000	0.578	0.193
Sensors	5.000	0.100	0.100	0.500	0.500	50.000	0.386	0.386
Experiments	3.600	0.278	0.000	1.000	0.000	10.000	0.154	0.000

Based upon the assumed operational parameters presented above, the CSDT has selected three promising power systems that balance energy, minimize weight and volume, and adhere to all component requirements. The final design options are presented from the cheapest to the most expensive.

Table 12: Option 1

Energy Capability of the Battery				
Component	Part Number	Voltage (V)	Capacity (Ah)	Energy (Wh)
Battery	HHR120AA	3.6	1.15	4.14

Energy Available to Charge the Batteries				
Component	Part Number	Efficiency (%)	Cell Coverage (cm^2)	Energy (Wh)
Solar Cells	Spectrolab	17.00	388.00	2.07
Converter	None	0.00	-------------------------------	2.07
Charger	BQ2005	90.00	-------------------------------	1.86

Energy Required By System Load			
Component	Part Number	Efficiency (%)	Energy (Wh)
Converter	LM2655	92.00	1.85

Table 13: Option 2

Energy Capability of the Battery				
Component	**Part Number**	**Voltage (V)**	**Capacity (Ah)**	**Energy (Wh)**
Battery	SLPB523462	3.7	1.02	3.774

Energy Available to Charge the Batteries				
Component	**Part Number**	**Efficiency (%)**	**Cell Coverage (cm^2)**	**Energy (Wh)**
Solar Cells	Spectrolab	18.00	388.00	2.19
Converter	None	0.00	------------------------------	2.19
Charger	MAX1737	90.00	------------------------------	1.97

Energy Required By System Load			
Component	**Part Number**	**Efficiency (%)**	**Energy (Wh)**
Converter	MAX1795	90.00	1.89

Table 14: Option 3

Energy Capability of the Battery				
Component	**Part Number**	**Voltage (V)**	**Capacity (Ah)**	**Energy (Wh)**
Battery	SLPB523462	3.7	1.02	3.774

Energy Available to Charge the Batteries				
Component	**Part Number**	**Efficiency (%)**	**Cell Coverage (cm^2)**	**Energy (Wh)**
Solar Cells	Spectrolab	20.00	388.00	2.43
Converter	MAX772	90.00	------------------------------	2.19
Charger	Wes Tech	90.00	------------------------------	1.97

Energy Required By System Load			
Component	**Part Number**	**Efficiency (%)**	**Energy (Wh)**
Converter	MAX1795	90.00	1.89

Please note that the best design option is not known; therefore, future CubeSat design teams should investigate and test each option to determine the optimal power/energy characteristics, minimum weight, and minimum volume. Details of future work on the power subsystem can be found in the management section of this report.