Power Sources for Small Robots

Kevin Dowling

CMU-RI-TR-97-02

January 1997

Field Robotics Center
The Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

Abstract

This report is a discussion, evaluation and comparison of potential sources of electrical power for small mobile systems. Power sources are an inevitable challenge in the design of portable and small mobile systems, especially robotic systems. Power systems cannot be an afterthought and, if left to final design stages, can result in severe and adverse effects on the system, such as excess weight, size, heat and operational limitations. Power system alternatives include batteries, fuel cells and generators, thermoelectric generators, supercapacitors, flywheels and even non-storage options such as tethers. This report presents general principles and provides a means to compare and evaluate different technologies for their particular application. In particular, comparisons are provided in the context of Ragone diagrams to illustrate the capabilities of the different technologies.

Copyright 1997 Carnegie Mellon University

This research was sponsored by the Swedish Institute of Computer Science, MITI Real World Computing Partnership, NASA and the Robotics Institute at Carnegie Mellon University. Views are those of the author and should not be interpreted as representing the official policies, either expressed or implied, of the sponsors.

Power Systems for Small Robots

Kevin Dowling[1]
RWCP-SICS (NF)[2]
Swedish Institute of Computer Science[3]

Table of Contents

---

[1] Carnegie Mellon University, Robotics Institute, 5000 Forbes Ave. Pgh, PA 15213, <nivek@cmu.edu>
[2] Real World Computing Partnership, Novel Functions SICS Laboratory
[3] POB 1263, S-164 28 Kista, Sweden

1. Introduction

This monograph is a discussion, evaluation and comparison of potential sources of electrical power for small mobile systems. Power sources are an inevitable challenge in the design of portable and small mobile systems, especially robotic systems. The incorporation of power sources can be a frustrating activity that often seems a diversion from other, seemingly more important, issues such as configuration and control. However, selection and incorporation of power sources should be an early and primary design focus because of its impact on the rest of the system, including size, weight, packaging, mechanism and wiring. Power systems cannot be an afterthought and, if left to final design stages, can result in severe and adverse effects on the system, such as excess weight, size, heat and operational limitations. Quite simply, power sources are difficult and critical to small mobile systems.

Small mobile machines require small mobile power sources. Supplying power to small devices has primarily taken two forms: batteries, whose technology is maturing but has improved relatively slowly over the years and tethers which can supply unlimited energy but limit mobility. In general, power doesn't scale well for small mobile machines; to obtain hours of operation at power levels of tens of watts requires a power pack that adds considerable mass and volume to small systems.

Power system alternatives include batteries, fuel cells and generators, thermoelectric generators, supercapacitors, flywheels and even non-storage options such as tethers. This report does *not* provide a detailed look at the chemistry and physics of each technology. It does, however, present general principles and provides a means for the reader to compare and evaluate different technologies for their particular application. In particular, comparisons are provided in the context of Ragone diagrams to illustrate the capabilities of the different technologies.

The selection process is not easy or obvious. It is tempting to select that energy storage medium that provides the highest power or energy density, but a host of other issues have to be addressed as well. These issues include handling, cost, packaging, heating and cooling etc. It is also possible that the answer is not a single technology but a hybrid of more than one source to provide satisfactory overall power and energy levels.

1.1 General Requirements

This section provides general guidelines for small power sources. Later, using real examples, we will use firm numbers but for now consider only desirable general properties of such systems:

- **Power** Power systems we consider provide continuous power of under 300W. At the lower end, 30W or so, long term power sources are of special interest for mobile mechanisms. Batteries are the current choice in this regime but recharge cycles (assuming no replacement) take significant time and the batteries, by themselves, can be a considerable fraction of the mass of such systems.
- **Energy** Energy requirements are approximately 2-3 kWh. Note that Wh units are energy units and 3600 Joules = 1Wh..

- **Mass** The power system is for use in small mobile systems, so the desirable mass is on the order of a few kilograms or, at most, tens of kilograms.
- **Voltage** Working voltages for electronics is typically from 3-5VDC and motor actuator voltages are typically 12 or 24VDC. Other electronics typically use small dc-dc converters to provide the appropriate voltages.
- **Price** The cost of these power system will depend on the technology and the cost will depend on the application. In general, the cost should be 10-20% of the cost of the system and should not dominate system cost.
- **Maintenance** An ideal technology should require only simple recharging or refilling and require little maintenance.
- **Safety** The power technology should be environmentally safe. For example, some battery technologies that use heavy metals which are toxic. The power systems should be safe from fire, explosion and the technology should have low toxicity. Toxicity is not an issue during use, only upon disposal and this can be strongly mitigated through recycling.

A useful power technology should be self-contained and not depend on external components or energy. For this reason and others, solar power does not appear to be an option due to the long recharge time for battery systems, dependence on environmental conditions and the relatively large cross-sectional area required for appreciable power generation. For space-borne systems or immobile systems, however, solar is a viable option.

1.2 Comparisons and Metrics

The evaluation of appropriate technologies is critical for power system selection. In selecting a power source, it’s tempting to examine a table that shows energy capacity for a variety of power storage technologies and then simply select a technology at the required performance level. However, this does not show other attributes such as the ability to deliver power and the rate at which this energy can be drawn. In this section I will show a graphical technique for evaluating power systems.

Additionally, performance is but one consideration and there are other ramifications in selection that must also be examined. Potentially adverse effects and issues of any technology include noise, low shelf-life, cost, volatility, charging time, heat, lifetime and operating quirks.

Ragone Diagram

Power sources can be evaluated and measured by several different criteria. These include energy density, power density, volumetric density, or even force density when applied to actuation. A very useful graphic technique for comparing various power storage technologies is a Ragone diagram which plots specific energy versus specific power. [Ragone68] The diagram, as shown in Figure 1-1, is a log-log plot which allows a significant spectrum of power and energies to be plotted. The diagonal lines in the figure show the amount of time available for a constant discharge of the energy in the system. That is, for a given amount of power usage and a given amount of energy, this line indicates the amount of time available for operation. This can be thought of as the ratio of specific energy to specific power and the resulting dimensional unit is time. This is mostly useful for battery technologies whose ‘fuel’ is integral to the system.

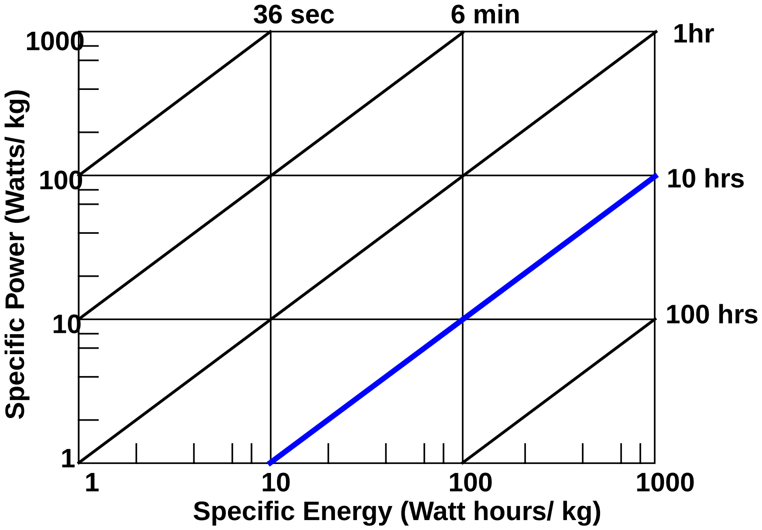

Figure 1-1 A Ragone diagram plots specific energy versus specific power. The 10 hour operating line is delineated in bold.

As shown in Figure 2, many different technologies can be shown to inhabit the spectrum of energy and power densities and we will discuss each of the general areas shown in the diagram. At the extremes of energy storage are sources based on radioactive decay such as radio-isotope thermo-electric generators, or RTGs, that provide a small amount of power for decades. At the extremes of power density are those systems that can release enormous amounts of energy but for only short periods of time such as supercapacitors and

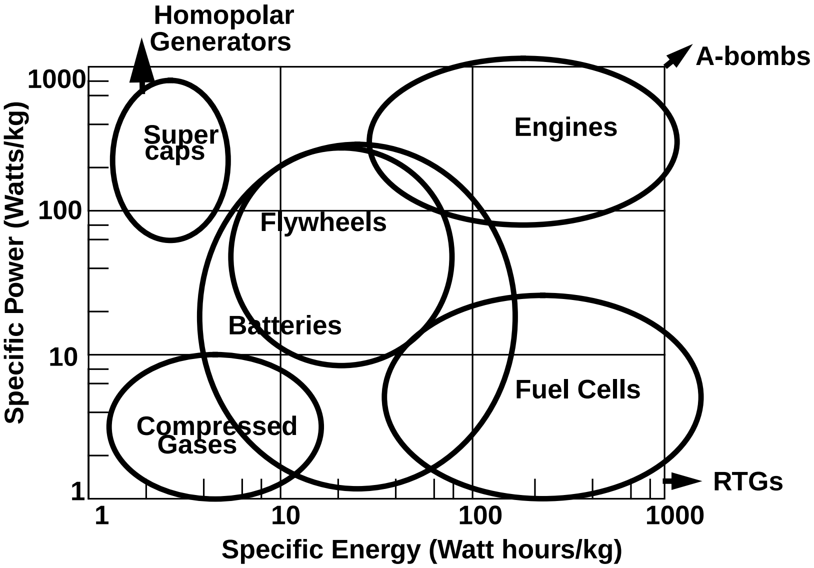

Figure 2 A general comparison of different technologies

homopolar generators[1]. Between these extremes fall all other power and energy storage technologies. Atomic bombs may seem fanciful but they have been seriously proposed as a means of propulsion, [Zubrin96], and for large excavation projects.

In summary, Ragone diagrams provide a convenient graphic form to compare technologies. When application power and energy requirements are known, this assists decision-making and provide a means to iterate design changes and see their effects.

While the Ragone diagram provides a useful form for selection it also useful to evaluate the meaning of the metrics themselves and their respective dimensional units. The next subsection examines these metrics, their dimensional units in power systems, and the physical interpretation of these units.

Energy to Weight Ratio

The dimension of energy to weight ratio is a length unit as shown below:

$$\frac{\text{energy}}{\text{weight}} = \frac{\text{joules}}{\text{newtons}} = \text{meters} \qquad \textbf{Eq. 1}$$

This is equivalent to how high an energy storage system can lift it's own weight in a 1g field. This gives an intuitive feel for energy capacity and the value is independent of the size of the system. For example, lead acid batteries have a specific energy value of 50Wh/kg. This value, in the energy/weight form, means they can lift their own mass 18,000 meters. Again, this is independent of the mass of the system; it's always 18,000 meters. See Appendix B. for more details on the calculation.

Power to Weight Ratio

The dimensional unit of power to weight ratio is a velocity:

$$\frac{\text{power}}{\text{weight}} = \frac{\text{joules/second}}{\text{newtons}} = \frac{\text{meters}}{\text{second}} \qquad \textbf{Eq. 2}$$

This has an interesting physical meaning; it represents how quickly a system can climb vertically, given its power to weight ratio in a 1g field. It is the terminal velocity the system could achieve if the system could devote all of it's power to vertical motion. For most applications, this has more pragmatic implications for climbing hills than cliffs, but it can be used to directly relate power limitations to velocity limitations in traversing terrain.

1.3 Scale Effects

Size and mass can affect power system selection and use. A technology that works at a 1 gram or 1 millimeter scale may not work at a 10 meter or 1000 kilogram scale. Suppose a

---

[1] A homopolar generator is a direct-current generator in which the poles are all of the same polarity. A pure direct current is produced without commutation. Units have been built to supply 9M Amps and 60M Joules.

1000kg system requires 10kW to travel at 10m/s and can travel for 10 hours over rough terrain. This is roughly equivalent to a small automobile with a standard gasoline-powered engine and is both feasible and practical. Now, scale everything down by a factor of 1000. This results in a 1kg vehicle that uses 10W and travels at 1cm/s. The vehicle should now operate for 10 hours and travel 360m during that time. However, at that scale it would be very difficult to obtain 10 hours of operating time from most practical power sources such as batteries. Even if the *entire* mass of the smaller system were to be used for a power source the energy density required would be 100Wh/kg. This is already at the edge of current, practical battery technology.

The larger scale example is not entirely relevant for automobiles; practical drag and rolling resistance coefficients result in power consumption of only about 3kW for vehicles traveling at 15m/s. However, this is over relatively smooth level roads. For small robotic systems smooth paved paths are not always available. Hence, the power requirements are higher.

Why can’t the power source scale down? There is a technology shift dependent on scale. For instance, hydrocarbon fuels such as gasoline pack far more energy per mass than batteries. Even when the engine/generator is taken into account, at larger scales the energy and power density of the total package is quite high. However, standard engine-generator designs are not often practical as electrical power sources for small systems due to noise and heat. Thus, there is often a necessary shift to technologies whose energy and power densities are less.

This example neglected air resistance although at higher velocities or smaller scales the effects of air resistance are significant. Air resistance is much worse at *smaller* scales as a percentage of energy output if velocity is constant. This is because surface and cross-sectional area increase as the square of the size whereas volume and mass increase as the cube. Thus, wind-drag, which is dependent on surface area, is proportionally smaller for a heavier and larger object than a smaller one of similar shape and composition. An everyday example is that of falling dust and rocks. They are the same shape and composition, yet the dust will settle much more slowly than the rocks. In general, the aerodynamic drag force is a function of the square of the velocity and power is a function of the cube of the velocity.

Since the power *needed* goes up as the scale squared but the power *available* goes up as the scale cubed then that means that the power required at larger sizes goes up inversely proportional to size. In effect, bigger things can go faster for the power available. In fact the velocity can increase as the cube root of the size as the system gets bigger.

For similar reasons, small things do more work against friction because surface friction effects are proportional to area. However, in some ways, small scale can assist the designer: small things have higher strength-to-weight ratios and require less structural mass. An excellent discussion of scale effects can be found in [McMahon83].

In summary, small scale often poses problems that are not issues with large scale systems. Power density due to technology limitations is one critical issue and other issues that work against small scale power systems include air resistance and friction. The key is that for smaller things we need technologies of greater energy density.

1.4 Hybrid Systems

Power sources can be power limited. This means that they can deliver small amounts of energy for long periods of time but be unable to deliver high power for short durations. When designing such a system, load fluctuations can force specifications well beyond average needs because of momentary high loads that occasionally occur. Automobiles are an excellent example of this: high-power is only needed for acceleration or hills but for most steady driving only a fraction of the available power is needed. For this reason, it may be practical to have a two-stage or hybrid power system where a first stage continuously feeds a second stage with energy or where two systems in parallel can deliver power as needed.

There are two types of hybrid systems: serial and parallel. In series hybrid systems, the first stage provides a small amount of energy continuously and the second stage delivers high power for short durations. An analogous system might be a trickle of water supplying a bucket which is being drained at varying rates. The trickle is the small continuous supply of power and the bucket becomes the second stage buffer. As long as the overall usage is below the overall supply rate then the system can continue to operate as long as the first stage is continually supplied with ‘fuel’. As shown in Figure 3, this can be organized as a hybrid serial configuration. However, significant losses can occur because of the pass-thru of the first stage feeding the second stage. The alternative, shown in Figure 4, is the hybrid parallel configuration where either source can be drawn upon at any time and the serial configuration losses are eliminated.

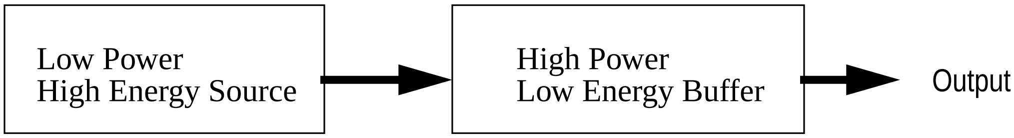

Figure 3 Hybrid serial power configuration.

For example, in electric cars, a parallel configuration provides a conventional mechanical connection between the engine and wheels as well as an electric motor to drive the wheels. With this configuration an electric motor could be used for acceleration and the mechanical power from the engine is used for highway driving where power output requirements are lower than for acceleration..

There are several advantages of the hybrid approach. In the serial configuration, the first stage can be sized to the average load and not peak loads - that is, the first stage can be optimized for constant power output. In the case of small engines this is a strong benefit and can double overall engine efficiency. The first source need not idle either, it may be possible to shut it off entirely for some period of time. For systems that need braking, the recovery of braking energy into the buffer store can also improve overall operating time.

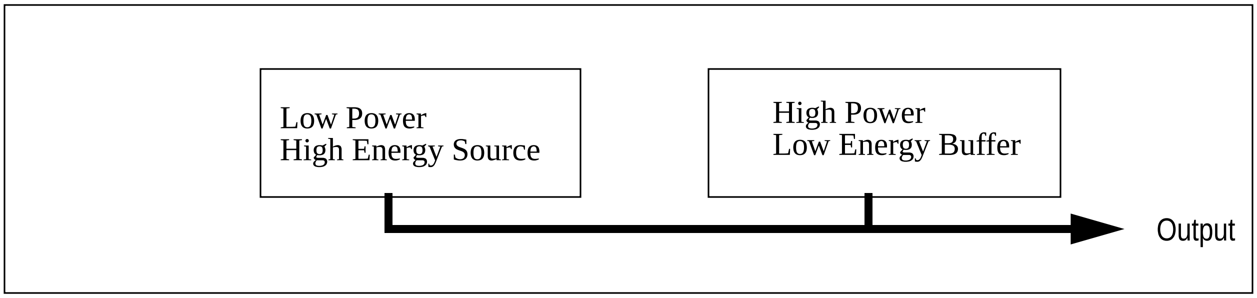

Figure 4 Hybrid parallel power configuration.

By carefully matching appropriate technologies, hybrid systems may offer specifications that are greater than either one of the technologies used.

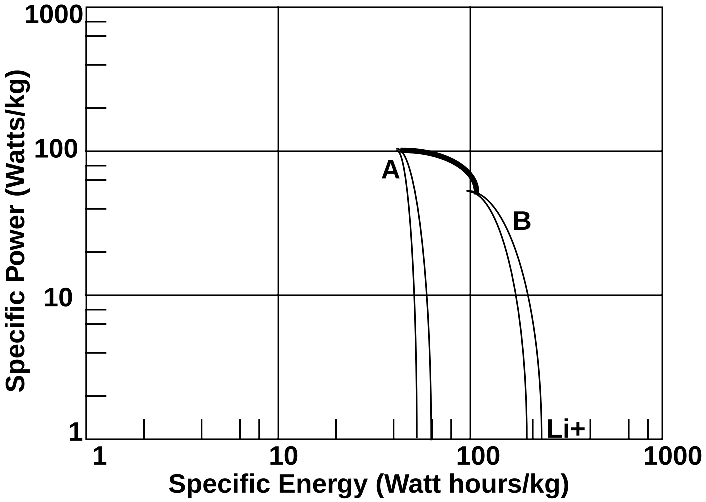

Figure 5 Hybrids can bridge the capabilities of different technologies

As shown in Figure 5, an hybrid power source can be shown in the Ragone diagram by connecting two technologies by a locus of points which provide energy and power maxima. A point along that locus can be selected to provide a specific energy greater than the less energy dense technology can achieve, source **A** in this case. The hybrid is a linear combination of the two technologies and thus forms a curve in log-log space.

The total energy for the series hybrid becomes the sum of the two individual energies but the power is limited by the technology that has the lower specific power. Here’s an example that uses two technologies with widely different specific energy and power density.

Table 1: Two technologies used to form a hybrid power source.

Technology	Specific Energy	Specific Power	Time at max power
A	50 Wh/kg	100W/kg	0.5hr
B	100 Wh/kg	50W/kg	2.0hr

Table 1 shows two technologies, **A** and **B**, with their respective energy and power densities. Source **A** can't provide high energy storage but can deliver lots of power and **B** is just the opposite. If you take a mass fraction of both source **A** and source **B** you'll end up with a hybrid. However, the maximum continuous power draw is still limited by the discharge time of the 'slower' battery technology, source **B**. That is, the point on the locus does not mean you can supply that power level *continuously* for that period of time given by the time line. It may need to be interrupted by a charging cycle from one source to the other.

For example if you have 0.5kg of source **A** and 0.5kg of source **B** you'll end up with a hybrid that can provide (0.5kg x 50Wh/kg + 0.5kg x 100Wh/kg)/1kg = 75Wh/kg of energy. The specific energy is then less than source **B** alone but greater than source **A** alone. The peak power is still limited by source **A** to 100W and, if drawn continuously, only for 15min. (0.5kg x 50Wh/kg / 100W/kg). Note that this is *peak* power. The maximum *continuous* power output is still limited by source **B** because of it's physical limits. The average max power is still just 75W/kg and, in the example given, can be provided for 1 hour.

As the mass fractions change, the locus of points will be a line joining the two technologies, but on a log-log plot this becomes a curve due to the non-zero intercept. Using the (y=mx+b) form in log-log representation gives log x = log (logmx + logb). To reiterate, this line represents the *power and energy maxima and not continuous power draw at that level*.

In summary, hybrids may complicate the overall system through increased part count and the incorporation of additional technologies, but the performance delivered for a particular application may be superior to that of any individual technology.

2. Rechargeable Batteries

In recent years, the development of products such as laptop computers, portable video recorders, personal digital assistants and communication devices have forwarded the need for batteries with greater energy-to-weight ratios, greater lifetimes and more consistent voltage outputs. Primary batteries are not rechargeable and are still used for a variety of these applications although secondary or rechargeable batteries are preferred for reasons of cost and ease of use. Rechargeable batteries can have electricity generating reactions reversed by passing a current in the opposite direction.

Nickel-cadmium batteries are currently the most prevalent in these applications but their cost has mostly limited them to small low-power applications. Lead-acid storage batteries, although less expensive, have low energy-to-weight ratios. New batteries with improved specific energy include lithium batteries that use electrolytes made of polymer film. These batteries are costly, however, because lithium is both difficult to work with and is highly reactive in air. There are also significant differences in power densities between the technologies.

2.1 Discharge Rate Effects

The amount of charge available in a battery for use depends on the *rate* of discharge as shown in Figure 6. That is, drawing high currents can actually *reduce* the total amount of energy available. The energy that is not put to work is dissipated as heat. Careful monitoring and use of a second stage in a hybrid system may be needed to minimize this effect.

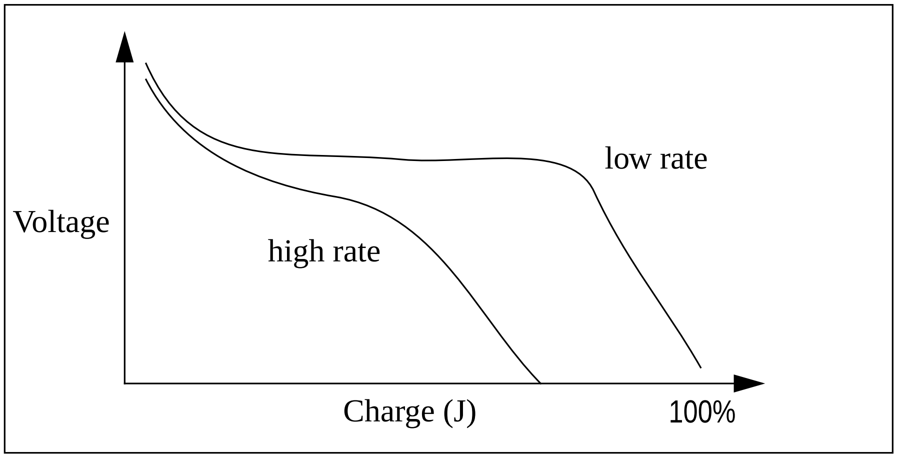

Figure 6 Battery capacity can depend on rate of discharge

2.2 Self-discharge

Self-discharge is the internal dissipation of battery energy over time due to the internal leakage of the batteries. NiMh batteries, for example, have relatively high leakage and can self-discharge over several weeks on the shelf. The self-discharge leakage, the one that reduces shelf life, is effectively a parallel resistance and is unrelated to the internal resistance. Batteries with high rates of discharge typically have high leakage rates which means that the effective series resistance is low. This limits the power at which the energy can be withdrawn from the battery. If the battery is thought of as a bucket of water (energy), the self-discharge is a leak in the bucket. This effect is important for applications where the power source sits idle for a long period of time before use.

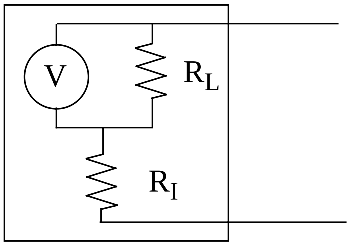

Figure 7 Simplified model of battery showing the series internal resistance, R_I, and leakage resistance, R_L.

The internal resistance and self-discharge do have a tendency to increase or decrease together, because it is possible to lower the series resistance by making the battery shorter and fatter, providing more area for current to flow and less length for the current to push its way through. The same geometry also facilitates the reverse flow of current through resistive leaks back through the battery during charging. A good example of this geometry effect can be seen in the flat batteries used by Polaroid in their film packs. These batteries have obvious packaging benefits but the primary benefit is their ability to supply high power for a short time.

The leakage paths back through the battery are separate from the normal electrochemical charge/discharge paths, as the different self-discharge characteristics of the different chemistries show. Most batteries for portable products have low internal series resistance. NiMH, as described above, also has a low parallel leakage resistance that reduces it’s shelf life on a full charge. If there are long standby times between use or charging, this self-discharge rate may be an important factor in technology selection.

2.3 Battery Technologies

There are a bewildering array of battery chemistries and types. In this section we summarize several mainstream technologies than have been in use for some time, and that are commercially available from several vendors. For the following sections, Table 1 Battery Comparison on page 15, provides a quick summary of the capabilities of the following technologies.

Lead Acid

Lead acid is the oldest and most mature of the battery technologies. Gelled lead acid batteries are safe, widely used and provide energy densities of up to 40Wh/kg. They also have an easily modeled linear discharge curve and a relatively long shelf life. The big drawback is that they are large and heavy relative to other battery technologies.

Nickel Cadmium (NiCd)

NiCd batteries are widely used in rechargeable applications where high current is needed. They typically have greater energy density and higher number of discharge cycles compared to lead acid batteries. They also have the highest specific power of any commonly available battery technology. Curiously though industrial quality NiCds can be heavier than their lead acid equivalents. NiCds are relatively inexpensive and widely available.

Nickel Metal Hydride (NiMH)

NiMH batteries provide a significant improvement in energy to weight ratios over NiCds. Additionally, the composition is of environmentally friendly materials with no heavy metals such as cadmium, lead, mercury or lithium. However, their self-discharge rate is higher than most other battery technologies making them unsuitable for long-term energy storage. Also, their power density is lower than NiCd's.

Lithium Ion (Li+)

Lithium batteries offer significantly increased energy density over NiCd and NiMh technologies. Their self discharge rates are low and their weight is very low for a given amount of energy compared to other technologies. However, the volume may be as high as NiMH for a given amount of energy. Li+ is also power limited and high currents are not usually possible with this technology. Lithium batteries have to also be carefully charged to avoid fire and burning because the heating effects during charging can ignite the Li+. This is because as Li+ charges it heats up and the internal resistance goes down drawing more current, thus creating a potential runaway condition. The solution is utilization of well-designed chargers that provide careful current limiting.

Intensive research and development in this technology may mitigate some of the concerns with Li+. Already, a large Japanese car manufacturer has recently announced a lithium-powered car to be sold in 1998.

Silver Zinc (AgZn) and Silver Cadmium (AgCd)

Silver Zinc and Silver Cadmium are used in applications where the high power density is critical and high price is acceptable as in space and military applications. Though they can be only 20% of the mass and volume of an equivalent lead-acid battery they can cost more than fifteen times as much. Additionally, the lifetimes are relatively short with typical lifetimes of 100-250 cycles. One useful feature of Silver-based technologies are stable voltages that are independent of state of discharge.

Sodium Sulfer (NaS) and Lithium Chloride (Li-Cl)

Both Sodium Sulfer and Lithium Chloride batteries offer high specific power and energy but require high temperature operation. Sodium Sulfer systems operate at 250C and Lithium Chloride systems operate at 350C. Both systems are potentially very dangerous in the event of a crash or accident.

Nickel Zinc (Ni-Zn)

Nickel Zinc provides an intermediate capablity in power specific energy and power but there are limitations in cycle life as compared to other technologies listed here.

Table 1 gives a comparison of various battery technologies. The figures are from many sources including manufacturers specification sheets and several articles. However, specifications varied from source to source, sometimes significantly. A consensus was formed by evaluating the figures and eliminating outliers in some cases and simply averaging results in others. Battery use, both charging and discharging, will often dictate the number of cycles and the amount of energy that can be drawn from them, so the estimate of number of cycles is based on full charge/discharge cycles.

Metal-air batteries are sometimes referred to as semi-fuel cells and are discussed in the following section.

Table 2: Battery Comparison

Type	Energy Density Wh/kg	Power Density W/kg	Self-discharge/ month	Cycles to 80%
Pb-acid	30-45	200	5%	200-1000
Ni-Cd	40-50	190	15%	500-1000
NiMH	50-60	180	25%	500-1000
Li+	130	800	5%	1200
Ag-Zn	140-200	100-330	4%	100-250
Ag-Cd	55-95	100-220	4%	300-500
Zn-Air	200-300	80-100		N/A
Al-Air	350	500-600		N/A

The data shown in Figure 8 shows the relative power and energy densities for several battery technologies.

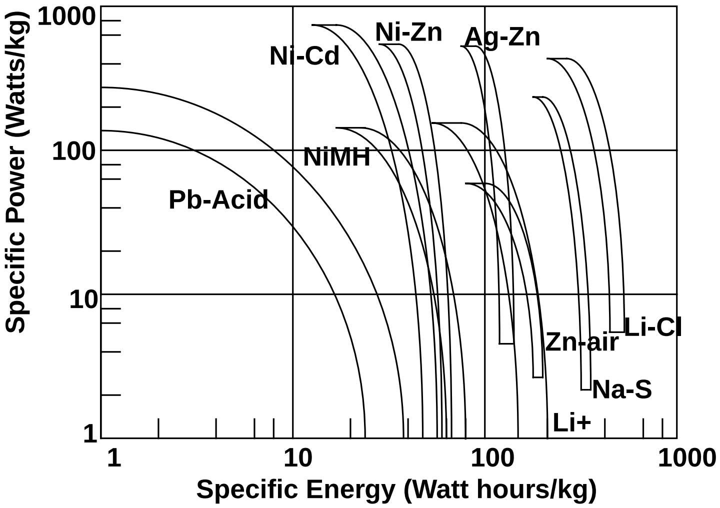

Figure 8 Several battery technologies plotted on a Ragone diagram

3. Fuel Cells

Fuel cells are considered similar to batteries except that fuel is continuously supplied as well as an oxidant, usually oxygen from the air. Fuel cells, like batteries, provide direct current through a non-combustion process. They derive power directly from a hydrocarbon source at higher efficiencies than combustion processes, up to 75%. Combustion processes typically can only extract 30-40% of the energy from such fuels. Because fuel cells are not a heat engine process, they are not limited by Carnot efficiencies. With fuel cells much of the heat and noise normally associated with combustion processes is eliminated.

It is sometimes difficult to tell batteries, fuel cells and semi fuel cells apart. In general, batteries, both rechargeable and non-rechargeable, utilize solid cathodes and anodes and contain all the chemicals used in the electricity generating reaction. Fuel cells use gas cathodes and anodes and fuel is supplied with reactants from an outside source. Finally, the relatively new breed of metal-air batteries utilize gas (air) cathodes and solid anodes and are considered semi-fuel cells.

Fuel cells contain two electrodes sandwiched around a conductive electrolyte as shown in Figure 9. At the anode a platinum catalyst causes the release of electrons from hydrogen gas. The hydrogen ions move across the membrane and the electrons released by the hydrogen thus can be used to form a current through a load. As long as there is a supply of fuel and oxygen flowing into the cell, it generates a steady electric current, heat and water. The efficiency can be increased to nearly 80% with cogeneration power generation utilizing the waste heat but this is viable only with large megawatt-sized systems.

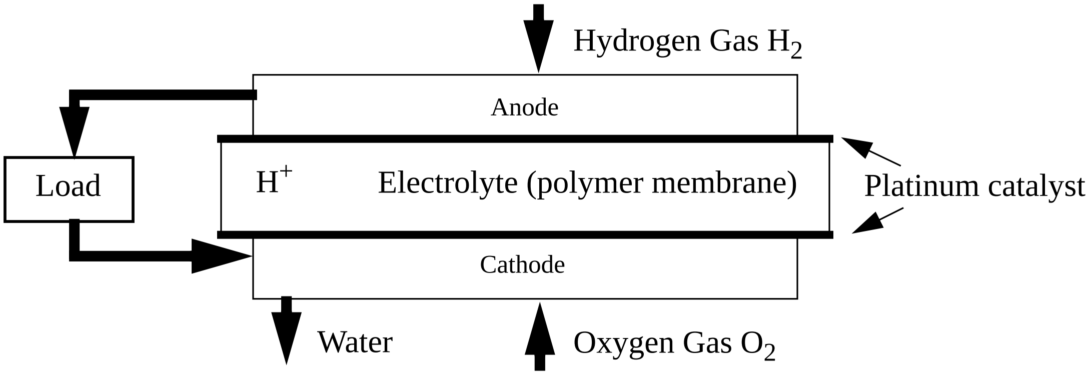

Figure 9 Components of a Proton Exchange Membrane (PEM) fuel cell

Some fuel cells can utilize any hydrocarbon and others are specialized to a specific fuel such as hydrogen. The hydrogen can be stored as a compressed gas or, more safely, as a metal hydride. Hydrides are safe and easy to store and ship. Interestingly, metal hydride’s energy per volume is greater than liquid H_2 and a far safer storage medium as well. In comparison to gasoline, which is not a hydride, hydrogen is more energy dense by mass. For example, 50kg of gasoline is equivalent to 20kg of H_2. However the 50kg of gasoline can be stored in 50 liters whereas the liquid hydrogen requires 250 liters.

A most promising fuel cell technologies is the Proton-Exchange-Membrane or PEM which uses a platinum catalyst on the anode and a polymer membrane in the electrolyte. Another fuel pursued by several companies for hydrogen generation is methanol. This is because the hydrogen can be stripped from the methanol molecules at much lower temperatures, 250 °C, versus other gases such as Propane which require temperatures of 600-800 °C.

Most fuel cell development is focused on large systems where power levels are in the hundred of kilowatts and there are not many commercial fuel cell systems available for low power applications. However, H Power, a US company, is developing much smaller units that can generate substantive power. Applications for these smaller units include laptop computers, cameras and military field applications. The smallest of H Power's production units generates 30W continuous and 40W peak at 15VDC. This unit weighs less than 2kg but is about 870cm^3 and gives 100Whr per hydride charge. Overall, this is equivalent to 50Wh/kg. Recharge time is 10 minutes and operating lifetime is 5,000 cycles and ten years minimum.

H Power claims to be able to provide custom voltages, from 5 to 180VDC, and power outputs from 5 to 360W. The unit consists of the metal hydride storage, control circuit, regulator and pump, and the PEM fuel cell itself. The present form of the fuel cell can also be modified extensively. According to H Power, all but the fuel cell itself can be repackaged into a more appropriate forms. An advantage over battery systems is the lack of self-discharge during periods of inactivity.

3.1 Semi-fuel cells

Semi-fuel cells utilize aluminum alloys and air cathodes and can provide energy densities of up to 500Wh/kg. The aluminum air battery uses aluminum as the anode and an air-breathing cathode, but underwater versions can utilize seawater as the electrolyte. These semi-fuel cells utilize metal anodes and air cathodes and an electrolyte (either alkaline or saline) is provided for the currents between the two. Specific power of these cells can be limited because of the air electrode. Some specifcations indicated specific power of only 30W/kg.

The semi-fuel cells, such as Yardney's (formerly Alupower) aluminum oxygen battery, offer long-duration power supplies that are actively used in autonomous underwater vehicles (AUVs). Like fueled generator systems they are 'mechanically' rechargeable meaning the anode must be physically replaced.

Yardney, has developed man-portable units that can supply 300W continuously for 12 hours at 12VDC. The units provide over 200Wh/kg - far more than alternative battery technologies. A new unit being developed will supply 3.0kWh at 12 or 24V and weighs only 6kg! Several other units have been in production and commercially available for use as reserve power systems for communication electronics.

These units offer one of the better power and energy systems with reasonable power and high energy storage.

4. Generator Systems

Gasoline and other fuels offer very high energy densities compared to batteries. The energy content of gasoline exceeds that of lead-acid batteries by a factor of 200 on a weight basis, not including the engine. Even taking new battery technologies into account, two orders of magnitude is an extraordinary difference to overcome if electric vehicles are to be comparable to vehicles powered by gasoline engines. [Kalhammer95]

The conversion of the gasoline energy to motive power is done through a combustion process in an engine. In ordinary applications this is a mechanical coupling of the engine output to motive power. The engine output is also used to drive an alternator that provides electrical power for a variety of applications, most notably spark ignition for several types of engines. The exception is the Diesel cycle which uses compression of air and resultant heat to ignite the fuel. Since the conversion of fuel energy to mechanical energy in engines is typically only 30-40% efficient in better systems, the remaining energy is lost as heat and must be shed for effective operation in any engine-based power source.

Engine generators are two stage systems that continually charge a battery during operation. Thus, even when the system is immobile, generator systems continue using fuel even under these no-load conditions. Perhaps an automatic starter-system using another technology and a small storage system could mitigate this problem. Elastic storage elements have also been demonstrated to provide this auto-start capability to eliminate idling periods. [Killgoar80]

However, even the smallest commercial generators are significantly heavier and larger than most small applications allow. For example, Honda’s lightest generator, the EX350, is a relatively quiet 300 watt unit that weighs less than 9kg and can run for two hours. Thus, this unit provides 5.4kWh and overall energy density is over 40W/kg for a two hour period and can be refueled for longer operating times. With a fill-up this is equivalent to an 80Wh/kg power source. Not bad compared to most battery technologies, but the unit is fairly large. By increasing the fuel tank, the total energy and energy to weight ratio of the system increases, but the power to weight ratio becomes worse. The limit, of course, is lots of fuel and a tiny engine which means little power but *lots* of energy.

Engine Types

There are several issues in the selection and use of engine generator systems. These include selection of the engine type, wrestling with several issues that are introduced with engine systems and scale issues.

There are an amazing and bewildering variety of engine types and sizes. Basic engine types are Otto cycle, two-stroke, Diesel, Wankel and Stirling. All but the last are internal combustion (IC) engines. A wide selection of IC engine types and sizes are available for car and aircraft modelers including two-stroke, four-stroke, twin and multi-cylinder units, and radial units; some of these miniature engines even have superchargers. While most are air-cooled, there are water cooled units as well. Power ratings are from 20W up to 1.8kW for these types of engines. Steam turbine generators, while still used for most power generation today in nuclear and fossil fuel plants, are not discussed here due to complexity and scale of such systems.

Small engines are surprisingly efficient for their size. [McMahon83] provides a comprehensive chart of various engines sizes showing that small engines and high performance aircraft engines exceed average power to mass ratios across the spectrum of engine sizes. The average power/mass ratio is about 750 W/kg in engines. High performance engines double this ratio but are not typically run for extended periods.

By coupling a small high-performance gasoline engine to a small motor generator, perhaps significant power can be generated at a small size and mass. These small gasoline engines are used in radio-control (R/C) planes and cars and provide significant power at high speed. Small motors built by OS, Saito, Kyosho, Zenoah and others offer power ratings above 1500 W. Some of these units provide nearly 5kW/kg, an extraordinary power to mass ratio. The power rating is, of course, the product of torque and rpm and the small engines run at very high rpm where the range is from 8000rpm up to 30000rpm for some units. The generator coupled to this would therefore have to run at these high speeds as well. [Kyosho96][OS96][Tiger96][Saito96]

One unit, the Model 1801 made by OS, is a Wankel engine with a round profile that may be useful for packaging. Many of the airplane engines are available in a radial form that can be useful for packaging as well.

Problematic issues with engine generators include sound, vibration, exhaust and the need for an air intake as well as heating and cooling. Another issue is the stability of electrical power from the system. The engine is a spinning mass and subject to angular velocity variation due to load changes. Therefore, some form of regulation is required for clean electrical power. Typically, in a larger generator a mechanical governor is used to regulate speed. This is often done via feedback to carburetor vane control. Since diesel engines don’t have carburetors their speed is regulated by fuel pressure from the injector pump and a mechanical governor that moves a linkage connected to the injector pump for speed control. This, in turn, can affect output frequency.

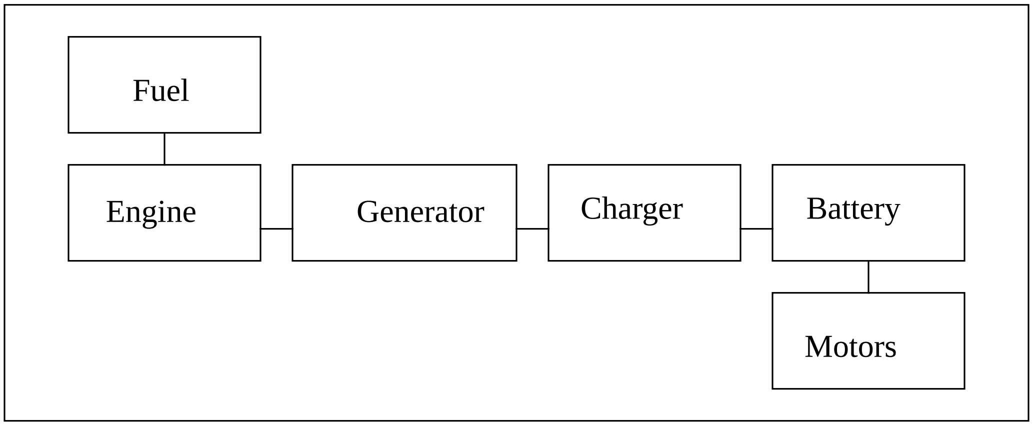

Figure 10 Layout of engine and generator system.

One concept is to run a small 400Hz synchro, like those used in military electronics systems. At 24000rpm, the engine drives the synchro at the appropriate speed to generate 400Hz power. At this frequency it is easy to recitify and regulate the output to supply a charging voltage for the second power stage such as a battery system.

However, the output power of such a system is likely to be noisy and subject to variation resulting from load changes. If the generator output is used to charge a battery pack, the overall system can provide clean DC power. This cleaner power is at the cost of overall conversion efficiency, but the hybrid system may still offer significant power-to-weight ratios. Again, this is primarily because the fuel, typically a gasoline and oil mixture, provides energy densities many times that of batteries.

While muffler systems are available for model engines, this type of power system is still likely to be the loudest of all alternatives. Refueling can be done with a small tank replacement or an external fitting but will still be likely more difficult than an electric connection. Conversations with small engine manufacturers indicate that the manufacturers do not think they would be suitable as engine-generators but there do not seem any fundamental technical reasons precluding this use. One accessory company does make a small magnetic ring that attaches to existing engines to provide a small amount of power for lights. [Sullivan96]

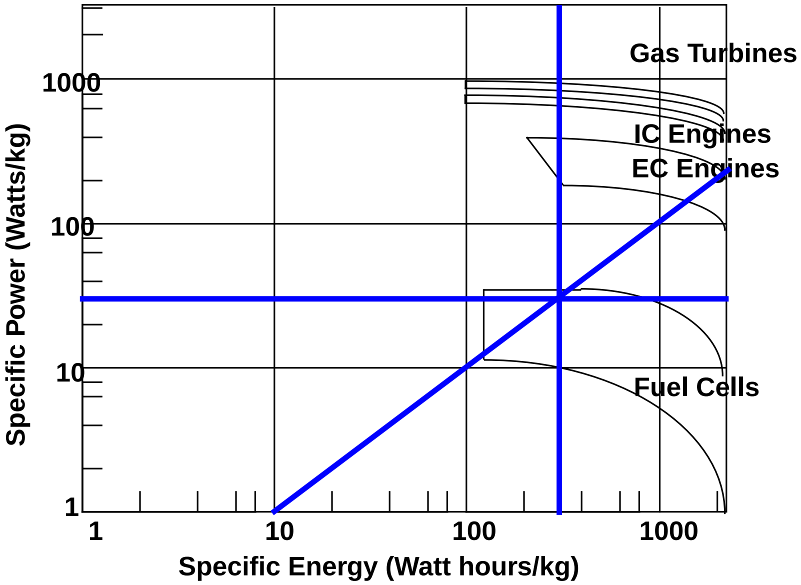

Figure 11 Engines and Fuel cells offer significant energy and power densities.

5. Thermoelectric

Thermo-electric devices convert heat directly into electricity through the Seebeck effect. For power generation, the Seebeck effect produces an electrical current or voltage in a circuit made of two different conducting materials if the two junctions are held at different temperatures. The Peltier effect is the inverse effect wherein an electrical current is used to produce cooling or heating. This type of power generation has several advantages over other alternatives that convert heat into electricity: no moving parts, silent, vibration free and can be scaled to very small sizes with no loss of efficiency. However, the efficiencies of thermoelectric conversion are only 5-10 percent. For power levels below a few kilowatts these levels are comparable to steam and internal combustion due to adverse scale effects on these other technologies.

A steady power level is produced by maintaining a temperature difference across a thermopile and an assembly of semi-conductor thermoelectric elements. It can utilize the combustion of a gaseous fuel, such as propane or natural gas, to provide the heat while natural convection provides the cooling required to create the temperature differential.

There are high initial costs due to the materials and fabrication, but thermoelectric power generation is used for remote terrestrial equipment with modest power requirements. These applications include remote telephone repeaters, lighthouses and buoys and arctic weather stations.

Thermoelectric generators do not have high specific power or specific energy. Global Thermoelectric, for example, manufactures a model 5015 unit which can supply 15W at 12 or 24VDC, but it weighs 21 kg, without fuel, resulting in 0.7W/kg, but larger units such as their 8550 can provide 550w in 103kg giving over 5.3 W/kg. The consumption of Propane for the 5015 is about 1.1 kg/day (2 liters) of operation.

The lower specific power and energy must be weighed off against the simplicity of operation of the units. Fuel and recharging is simple and there are no moving parts to the system.

6. Supercapacitors

Capacitors are commonly employed in electrical circuits to store energy as a charge built up on plates separated by a dielectric material. Supercapacitors, also called ultracapacitors, provide very high energy storage as compared with conventional capacitors used in electronics. In fact, supercapacitors can be thought of as high-power, low-energy batteries. They are typically envisioned as part of a hybrid power system with batteries. The battery satisfies average power demand and the supercapacitors handle relatively short duration power peaks during acceleration, regenerative braking, and hill climbing. This arrangement can provide improved performance, increase overall efficiency, battery life, and energy storage in the battery, and lower life cycle costs. Figure 12 shows a typical arrangement for a parallel plate capacitor.

Typically, the higher the value of the dielectric the greater the charge stored, but the breakdown voltage of the material tends to be the determining factor in energy density. Maximizing energy density requires materials with high breakdown voltage and an intermediate range of dielectric constants.

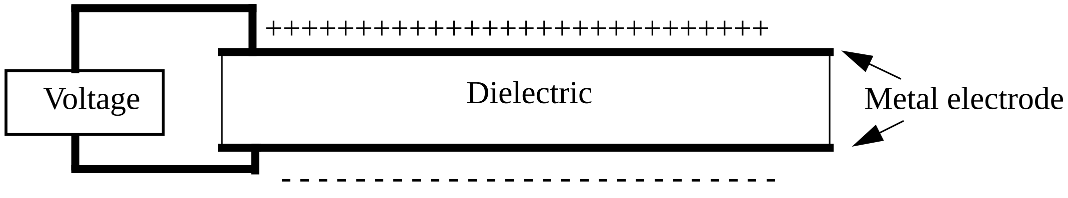

Figure 12 A typical parallel plate capacitor.

Supercapacitors offer the highest specific power of any of the power sources investigated in this report. Power densities are available to 7.5kW/kg. These tremendous values are offset by the short amount of time that the energy can be supplied. Thus, overall *energy* density is quite low, perhaps 1-2 Wh/kg.

Present and projected energy densities for devices are low compared to batteries, but the recharging of capacitors can be done very quickly. The use of supercapacitors as a energy storage device helps mitigate the discharge rate issue of batteries shown in Figure 6. This may make them suitable in a hybrid system for storing regenerative or braking energy as well.

Because of substantial interest in electric vehicles, supercapacitors have attracted a great deal of interest with a number of government and university research labs currently investigating new materials and configurations. SRI International is developing an ultracapacitor based on lithium polymer technology for hybrid and electric vehicle applications. Projected specific power and energy are up to 5 kW/kg and 49 kWh/kg [Calstart96]. Note in Figure 13 where this is in relationship to existing battery technologies. Even if commercially viable units reach only half this capacity there will be significant advantages in the incorporation of this technology for load leveling and energy storage.

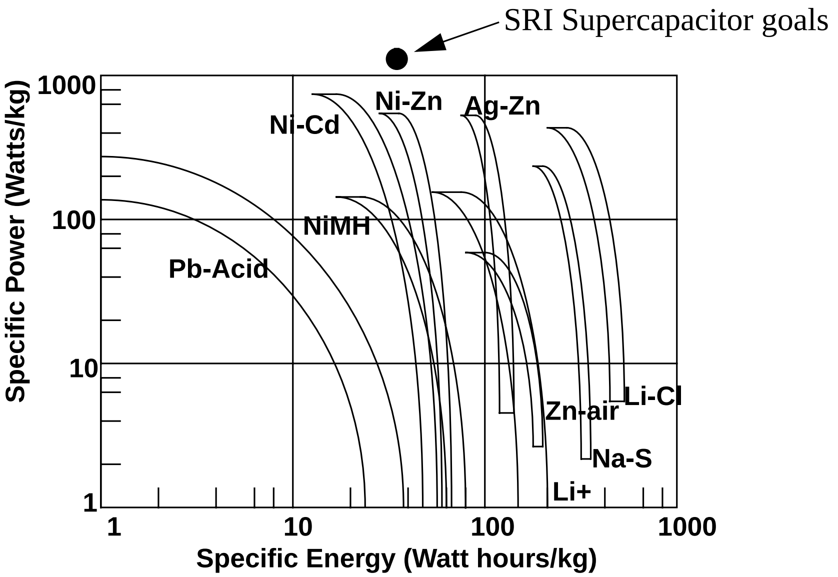

Figure 13 Supercapacitors are projected to provide highest specific power.

7. Mechanical Energy Storage

Storage of energy in a mechanical system might appear to be low tech and not viable for energy storage or power release. For these systems however, the use of new and stronger materials improves their effectiveness in many applications and the simplicity of some of the systems is also attractive. In this sections we will cover energy storage in flywheels, compressed gases and other forms of elastic storage.

7.1 Flywheels

The inertia of a rotating mass is often used to smooth out angular velocity variations of spinning systems such as engines and are also used to provide very high instantaneous power and force in large tools such as punches. Another proposed use for such spinning masses, or flywheels, is for energy storage and retrieval; flywheels can be a mechanical or electromechanical energy storage system.

Flywheels have been under active research for decades as an energy storage medium for electric and low-pollution/high efficiency vehicles. Conversion from electrical to mechanical energy and vice versa can be quite efficient using permanent magnets on the flywheel and a coil to generate current. Efficiency values greater than 90% have been reported and energy loss is minimized by keeping frictional losses low through the use of magnetic bearings and vacuum. [Hively96]

If a metallic flywheel failed under the high stresses, the energy in the wheel would turn the system into high speed, high energy shrapnel. Fortunately, proposed carbon fibre composites turn to a fine dust or a cotton candy-like material so that a relatively light shield, made from aramid fibers and other commonly available high-strength materials, can be used. Of course, this ‘cotton-candy’ is *hot* cotton-candy.

The energy in the flywheel is related to the square of the angular velocity and to the square of the radius, but only linearly with mass. Thus, smaller flywheels can only provide significant energies by increasing their rotational velocity. Surprisingly, the limiting factor to energy storage in a flywheel of any size depends only on the strength and density of the material. An increase in energy storage can be made by increasing mass, but the total energy is independent of radius.

Gyroscopic forces complicate movement of a rotating flywheel but two flywheels can be connected by a shaft to make the total angular momentum to be zero, thus making it easy to turn. The shaft must be strong in shear to transfer the appreciable torque and the wheels have to be accelerated in synchrony to avoid incurring net angular momentum. This may be difficult to implement for a small system, but perhaps a gimbal system can be used to offset the precession torques.

Technical challenges in flywheel system development include active magnetic suspensions, maintaining vacuum, flywheel materials, and dynamic models of flywheel stresses. Several companies are working on systems for automobiles at this time. U.S. Flywheel Systems, one of several companies developing flywheels, has reported flywheel systems with energy densities of 100Wh/kg and power densities of over 450W/kg with conversion efficiencies of up 96%. The power and energy figures, while not quite equal to that of engine technologies, are better than most battery technologies. Proposed vehicle use would entail up to sixteen 4.1kWh units to provide sufficient power and energy. [Hively96]

Flywheels have the advantage of relatively short re-charging times as compared to batteries and reportedly have longer lifetimes in terms of number of cycles and overall operating life.

7.2 Compressed Gas

Compressed gases can also be used to store energy and produce power. At larger scales they are often used to start other sources of power such as large diesel engines. In general though, the energy density of compressed gases is not very high, but is close to equaling that of lead acid batteries. Since we are concerned with mobile systems, the direct use of compressed gases for force actuation may make more sense instead of converting the work to electricity which is then used for motor actuators. [Binnard95]

Gases and other compressible fluids store energy which is the product of pressure and volume. For pressure cylinders an equivalent metric of energy-to-weight ratio is the product of pressure and volume divided by the weight or PV/W as shown below. This also results in a length unit which also equals distance the energy of the system can lift its own weight. See Energy Lift Calculations on page 37 for more details.

$$\frac{\text{pressure} \times \text{volume}}{\text{weight}} = \frac{\frac{\text{newtons}}{\text{meter}^2} \times \text{meters}^3}{\text{newtons}} = \text{meters} \qquad \textbf{Eq. 3}$$

This is equivalent to Eq. 1 in both meaning and units. Although this is a nice metric, it does tend to increase with absolute size and pressure due to the decrease in the ratio of pressure vessel liner weight with structural weight.

For electricity generation however, assuming you are not using the combustion of such gases, a tank of compressed gas, such as air, can be used to power a small turbine-generator with the escaping gas to produce electricity, similar to a turbocharger design in a car. The energy density of such air turbine generator systems seems to be equivalent to lead acid batteries, but does not provide much higher densities even with high-strength materials for the tank construction. Tank volume and weight are a considerable fraction of the density figure and the total energy is a function of the rated maximum pressure of the tank. As with other types of mechanical storage there are issues of systems inertias and acoustic propagation. Inertias are low in a compressed gas; it is after all, a fluid. However, energy can’t propagate faster than the acoustic limit in the fluid or material. This means a power limit for a unit volume and pressure of the gas.

As an example, compressed air systems are used for powering portable tools and paintball guns. They are constructed of reinforced aluminum and store air at pressures of about 3000 psi (2.07×10^7 Pa). A 1 liter tank weighs around 1 kg and is considered safe for general use. This gives a PV/W metric of over 2100 meters but assumes isothermal conditions. It’s unlikely that significant energy as compared to other technologies can be achieved, although the energy may be released rapidly to give short term high power. However, Lawrence Livermore National Labs has reportedly designed and built softball-sized, 655cm^3, composite spherical tanks with PV/W’s of over 25,000 meters[1]. This puts the energy storage capability well within the range of lead-acid batteries. [Whitehead95]

---

[1] This is about 1 million inches and LLNL has termed these units ‘minches’!

7.3 Springs and Elastic Storage

Springs are another energy storage device where potential energy in the form of strain in a material can be released to perform work. One of the most common and oldest uses of springs as an energy storage medium is that of mainsprings and balance springs in clocks and watches. The resultant torques and forces can be quite high, but the energy is typically released slowly through an escapement mechanism or governor. Mainspring design can be quite involved and many developments including isochronal and isothermal configurations and materials have been made for clock design.

In general, energy densities for springs are quite low. Specifications from commercial power spring manufacturers indicate max energy storage figures of 2.9×10^6 J/m^3 for steel. [Sandvik 94] Most power springs are designed to 50% volume for concentric pre-stressed units. Using density of steel as 7900kg/m3, and a Joule to Wh conversion, the 50% volume gives only 0.2 Wh/kg energy density. But, if released in a fraction of a second, the power density can be significant and the power released can be most impressive. The rapid acceleration of loose garage door springs or coil springs that pop from housings can be quite astonishing and dangerous.

The storage of energy in springs and through mechanical deformation can provide a energy metric where σ is tensile strength, ρg is unit weight, and E is the modulus of elasticity:

$$\frac{\text{energy}}{\text{weight}} = \frac{\frac{1}{2}\sigma^2/E}{\rho g} = \text{length} \qquad \textbf{Eq. 1}$$

Again, the elastic storage capability is expressed as a length dimension and provides an indication of energy-to-weight ratio.

For electrical power, as in flywheels, the mechanical output has to be harnessed to a generator. The additional infrastructure and the configuration of such a device make it impractical for power generation except perhaps in low, constant load power mechanical power output. The results show that springs are poor energy storage devices as regards specific energy, but they are in wide use in systems where mechanical output is required because they are simple, their cycle life is very long, and the storage of energy lasts significantly longer than other options.

There are many other materials that could be used for elastic strain storage. Rubber band engines sound toy-like but their storage efficiencies are higher than that of steel-based spring materials. The conversion of low human input power to high release power in such devices as crossbows and animal traps can provide amazing power levels. Theoretical limits for materials such as Nylon, Spectra and Kevlar are up to 5000 meters in energy to weight ratios. This height metric is less than other technology alternatives but is surprisingly high and these systems capable of releasing the energy very quickly and they can be coupled in a wide variety of mechanical means.

8. Human Power and Energy

These comparisons of technologies often prompt the question of how much power can a human deliver and how much energy do humans have? This is perhaps an incongruous topic and provided only for comparison purposes. Are there enabling technologies that allow or enhance the use of people as energy sources? We convert food into energy and power, so are there applications where this is useful? The answer is germane to such human powered systems such as bicycles, cars and planes. In the Daedalus Project, a human-powered plane recreated the mythic flight between a Grecian island and Crete. [Dorsey90] Ethan Nadel, a physiologist at Yale, led the human engine analysis by examining power and energy output of candidate pilots. They created a volumetric oxygen test to provide a maximum respiratory exchange ratio of CO_2 to O_2. At maximum oxygen intake they found that fit athletes could generate more than 4W/kg peak power output. They conjectured that, at 70% of this limit, a fit athlete could provide extended duration power outputs of 200-250W for four to five hours. The plane required athlete power-to-weight ratios that were above 3W/kg. Two examples given during the Daedalus project were:

Table 3: Human power output examples from Daedalus Project

Athlete	Power out	Mass	Power/Mass	70% level
A	235W	55kg	4.27W/kg	2.99W/kg
B	324W	73kg	4.43W/kg	3.11W/kg

Note that the heavier candidate is able to produce significantly more power but, on a per weight basis, does worse. Total energy output over several hours and using a median value of 3W/kg gives: 3W/kg x 4 hours = 12Wh/kg energy output.

The chemical energy conversion efficiency results in significant heating effects and the human working at this level of output is producing 600-1000W of heat. Without adequate cooling, the core body temperature at this level of exertion can go up 1 degree C every 5-8 minutes. Additionally, environment conditions should provide temperatures below 18C and below 70% relative humidity to prevent overheating and exhaustion. Human efficiency, the ability to turn O_2 into energy, is roughly 20-25%. However, although cooling affects energy output the human is not a heat engine, rather it is a type of chemical fuel cell. [Nadel88]

Another figure of interest is human peak *power* output. If we use world records in weightlifting as the measure of peak output power then we can make some general calculations regarding output power. For example, the world records for the snatch, lifting the weight from the ground to above your head, are at about 200kg in the heavyweight class. If we assume the weight is lifted 2m, then this gives 200kg * 9.8m/s2 * 2m = 3920J. If we also assume this takes about 1 second then this equals a power output of 3.9kW for 1 second. Specific power in this weight class gives about 36W/kg. Remember though, that this is for only about 1 second of activity.

These figures are directly proportional to height but without heights for weightlifters these are only rough numbers. Lighter weightlifters are presumably shorter and thus the power calculation will reflect that. The energy outputs from this peak power are about 0.01Wh/kg. This also demonstrates that the energy rate affects total energy available for use. Records for weight-lifting are proportional to the 2/3 power of body weight. In retrospect, this isn't too surprising since muscle force is proportional to the cross sectional area of the body and area is proportional to mass raised to the 2/3 power. [McMahon83]

The general and interesting result of this analysis is that the specific power and energy of humans is very low compared to the technologies we've developed. Perhaps this comparison in unfair to biological systems, since I am not isolating the power plant of the human. However, locomotion, computing, sensing etc. are all integral, almost inseparable, in a biological system. Perhaps this will also be true of the better integrated robotic systems of the future.

Finally, the interest in human powered vehicles, HPV's, has produced some interesting results with limited duration speed records of 100+km/hr. Practical high speed vehicles over varying terrain seems unlikely given human power and energy limits but an interesting insight into lunar HPV's is given in [Wilson78]. No air resistance and low gravity gives rise to lighter structures, lower frictional resistance, and several other factors which allow 30+km/hr across lunar soil and several hundred km/hr on a rail system! In the right environments even low energy, low-power systems can perform extraordinarily well.

9. Tethers

A tether is often mentioned as an alternative to onboard power systems for small mobile systems. A tether is a physical cable connecting the device to an offboard power source and can also be used to provide communications to the mobile system. A tether provides continuous power over a wire or cable connected, at one end, to the mobile system and to a fixed power source at the other. However, tether management and deployment can present significant additional design challenges. Tethers are not generally used for support or tensioning, although they have been used in this manner for a climbing robot. [Bares94]

If only short excursions are required and human access is possible then the tether can be simply payed out and moved as the mobile system moves. This scenario is probably the simplest because it has fixed connections at each end and tether management is handled on an as-needed basis. However, caution is recommended; assume that the system *will* run over it's own tether and design for that scenario. The worst case when this happens is that the system has run over the tether and caused a disconnect. The system is now without power and sitting on the broken tether. A shutdown circuit that is triggered by high tether tension is recommended for such a system. The system can then be manually overridden and tether rerouted.

A tether can be unreeled from either end to provide feed and extension. From the fixed station a reel system can deploy tether to the moving system. In the second case, the winch system can be on the moving mechanism and payed out as the system moves. Typically, tethers are a mix of power and communication lines with advanced tethers integrating fiber optics or coaxial cables for high bandwidth signals such as video and local area networks.

Attention to attenuation and loss of signal is critical where tethers are stressed during operation.

Power over fiber

An interesting option for a tether is to provide an onboard reel and tension of a small fiber-optic line, but use the fiber to transmit *power* in addition to information. This is possible because the transmitted light can be tuned to appropriate wavelengths for efficient conversion by photovoltaic cell technologies. Efficiencies of such a type of transmission can exceed 50%. [Henderson90]. However, power levels of tens of watts require powerful lasers which are also likely to be large. For low wattage applications, 1-2 Watts can now be supplied through semiconductor lasers and are supplied by commercial vendors.

Wireless power transmission

There have been a number of experiments in providing power via wireless transmission using microwaves and lasers. A powerful laser beam could supply continuous power and be received and the power converted to forms such as electrical or thermal through photovoltaic arrays or collectors. [Williams 95] Experiments in powering flying vehicles date back to the 1964 when Raytheon powered a small helicopter from a microwave beam. [Houston 96] More recently, in 1992, David Sarnoff Research Center developed a mobile vehicle that used an onboard rectifier antenna array and tracking system to keep the array aligned to the power source. Conversion efficiencies of 80% were reported. Still, for this technology to be practical a number of engineering issues need to still be addressed but the area still holds promise in applications where line-of-sight is guaranteed or short term drop-outs are acceptable.

Tether benefits

Direct benefits of a tether include unlimited operation time with follow-on benefits to weight and volume. Tethering also eases offboard communications and allows off-board computing resources thus further reducing on-board packaging, power and mass requirements.

Tether drawbacks

Tether management is a significant issue. Tether winding and spooling can be done on-board but this negates much of the weight and volume benefits. If spooling is off-board, i.e. at the fixed end, then it is likely that the system will not only drag the tether but the tether will significantly impede the progress of the system with only a few environment contacts. Runover or entanglement can be fatal to the system and operation can often require monitoring by human operators and additional hardware and software. Levelwind systems, the mechanisms that provide careful wrapping and unwrapping of the tether, although well understood can add undue complexity and additional mass and volume to the system.

Tethers, while providing high rates of power for indefinite periods of time can result in significant mass and external forces on the system. These external forces may result in indeterminate motions of the system, complicate path planning and motions or, in the worst case, prevent extrication of the system.

Unless enough space can be provided for a counterwind system then slip rings are also needed. Slip rings are a well-understood mechanism for transmitting power and information across a rotating interface but, again, can add to the volume, mass and complexity of the tether system.

In general, untethered operation provides compelling benefits for self-containment and mobility of the system.

10. Application Examples

Two examples will show a straightforward process in the evaluation of power technologies. The first, PIRAIA, is a small mobile device to investigate a novel form of locomotion and the second, Lunar Trek, is a more traditional larger wheeled machine used to investigate remote exploration and self-reliance.

10.1 PIRAIA

For the PIRAIA project at SICS, a small mobile machine is being designed to move without the aid of wheels, tracks or legs. The system is akin to a snake and has specific power and other requirements to move the joints and actuators. For each joint these requirements include:

- **Power**: 25W continuous for 30min, 50-100% duty cycle in periods of 30min, with constant load. Total of 8 hours of operation is desirable. It is unlikely that long standby periods will be required.
- **Voltage**: At least 6volts for the motors and the control electronics will utilize dc-dc conversion to appropriate levels.
- **Size**: 69mm diameter maximum. Link lengths is not yet fixed, but target length is between 30 and 50cm total length - leaving a severe packaging problem for any power technology.
- **Mass**: Link mass is between 2 and 4kg per link; we’ll use 3kg.

$$\text{energy} = 22W \times 8h = 176Wh \qquad \textbf{Eq. 2}$$

$$\text{energy density} = \frac{176Wh}{3kg} = \frac{59Wh}{kg} \qquad \textbf{Eq. 3}$$

The power density is then 22W/3kg = 7.3W/kg.

As we can seen in Figure 14, the PIRAIA requirements converge to a point that is achievable with current battery technology. Since the instantaneous power requirements are low it appears that NiMh would be an ideal selection due to their good energy density. Since standby periods are not an issue, the relatively high self-discharge rate of the NiMh technology should not pose a problem.

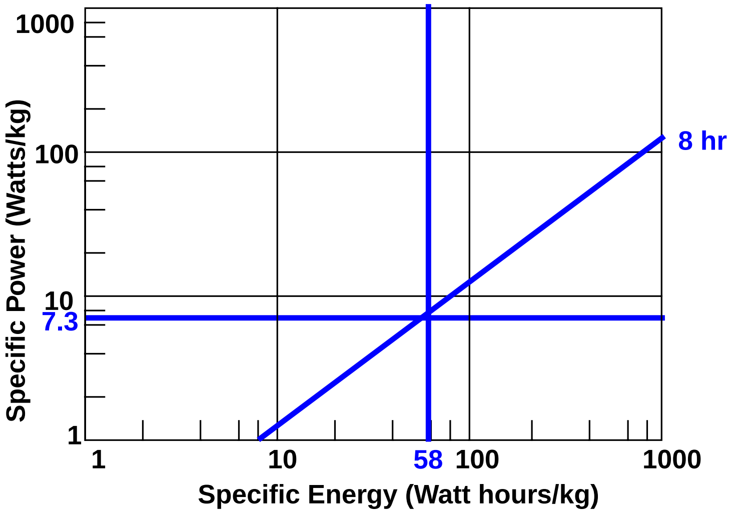

Figure 14 Plotting PIRAIA system requirements.

10.2 Desert Trek

The Desert Trek is a project undertaken by the Field Robotics Center at Carnegie Mellon to design and deploy a semi-autonomous robot system that will cross the Atacama desert in northern Chile. Power system specifications for onboard sensing, computing, communications and locomotion are:

- **Power** 1500W steady state draw
- **Peak Power** 2500 W peak during high locomotion needs. Unknown duty cycle.
- **Mass** 40-50kg for the power system.
- **Operating Time** 10 hrs
- **Volume** 0.1-0.2 m^3

Assuming the peak can be satisfied in the power system:

$$\text{energy} = 1500W \times 10h = 15kWh \qquad \textbf{Eq. 4}$$

$$\text{energy density} = \frac{15kWh}{50kg} = \frac{300Wh}{kg} \qquad \textbf{Eq. 5}$$

Power density is then 30W/kg. These values are plotted in Figure 15. Given these constraints it is pretty clear that batteries and fuel cells will not solve the problem. However, the power and energy needs are close and it may be worth iterating on the design or re-examining system specifications to incorporate one of these technologies. The alternative is a gasoline powered generator which will meet the system goals but be untenable for lunar or planetary analogue systems. It may also be possible to construct a hybrid of a small engine and battery system to provide peak power needs and long term energy needs.

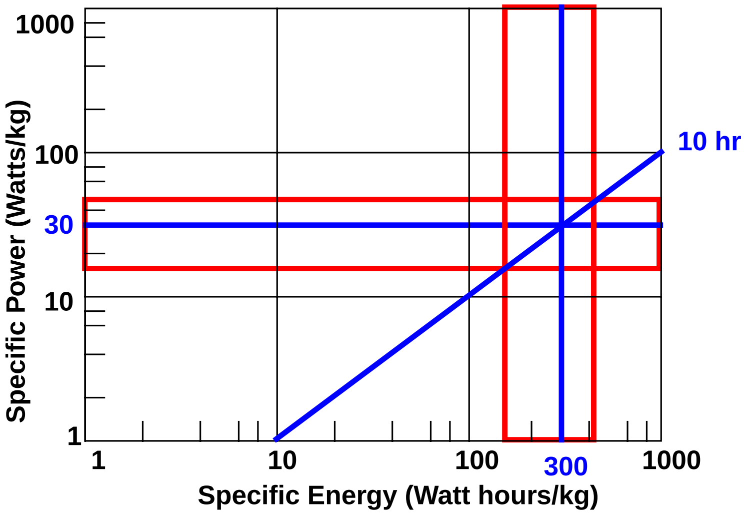

Figure 15 Plotting the Desert Trek system requirements.

11. Conclusion

In the near future, it appears that several battery technologies will continue to improve but can currently provide the necessary requirements for many applications. A tether is untenable for most operations and, as shown, several alternative technologies are either still nascent or need significant engineering as power systems to be viable for small systems.

Of the battery technologies, Nickel Metal Hydride offers high capacity, relatively good charging times, environmentally safe materials and good packaging.

For charging the batteries, a hybrid system utilizing fuel-cells appears to be a near-term possibility. In the near future, the semi-fuel cells and new developments in fuel cells are worth watching. These technologies have significantly improved in the past several years and smaller size, lower power units are entering the marketplace.

Although not viable for this application, the small generator option may be worth examining for small outdoor machines and applications where effects of noise and exhaust are not issues.

The technology development for some of the less mature technologies does not mean that they will immediately be used or useful for many applications. Integration of power sources into full systems will require a great deal of analysis and work beyond simply treating the technologies as a black box.

An additional need for a small mobile machine will be the efficient conversion of supplied power to regulated voltages suitable for other subsystems such as electronics and sensors. dc-dc converters provide this functionality by using high-speed switching technology to provide appropriate voltages at high efficiencies. Typical efficiencies are about 85% for recent high-speed switching style dc-dc converters.

Finally, it will be tempting to use the Ragone diagram to select a technology to find the crosspoint of power and energy needs. However, as we have seen there are many other issues in power source selection. These include:

- Stand-by capability - self discharge rates
- Cost
- Logistics of recharging/refueling
- Lifetime
- Hybrids and complexity
- Supply voltage and conversions
- Energy and Power per Volume

Thus it would be premature and naive to not investigate these and other issues for any particular application. Power system evaluation is a series of steps involving many facets of system design. The tools and technologies presented here only provide an overview and illustrate some of the issues in selection. A straightforward methodology to selection includes itemizing as many constraints and specifications as possible including those shown in the examples and those listed above. From that eliminate those technologies that are untenable and focus on the remaining ones. It's likely you many iterate by revisiting the system design and changing parameters to adjust to the technology. Thus, the design becomes two-way and not a simple shopping trip. This is typical of power systems design.

As stated in the introduction, power system design is best done early because of it affect on many other system issues. Configuration of any robotic power source is critical to performance.

12. Acknowledgments

Thanks to Martin Nilsson and the Swedish Institute of Computer Science (SICS) for sponsoring this work and inviting me to SICS for what was a wonderful visit to Stockholm in the summer of 1996. Martin provided guidance and feedback on much of this report. SICS's PIRAIA project is sponsored by the Real World Computing Partnership of MITI in Japan. Thanks also to NASA's Jet Propulsion Labs for providing a fellowsip during the academic year in which I completed the writing of this report.

Thanks to Ben Brown at Carnegie Mellon for many interesting discussions and ideas related to scale effects and other issues of metrics in relation to energy storage. Thanks also to David Ragone at MIT for providing both useful information, encouraging feedback and his seminal paper on evaluating energy sources. Bob Spies also provided a useful discussion of mini-generator issues and Hans Moravec at CMU was always available as a sounding board as well.

13. References

[Bares94] Bares, John, “Lessons from Dante II,” *Robotics Institute Annual Research Review*, Carnegie Mellon University, 1994.

[Binnard95] Binnard, M.B., *The Design of a Small Pneumatic Walking Robot*, Masters Thesis, MIT, Jan. 1995, Department of Mechanical Engineering.

[Calstart96] http://www.calstart.org/about/programs/p-ultrac.html at Calstart and http://www-mpl.sri.com/h[projects]pyu6496.html at SRI. PI: Subhash C. Narang. 1996.

[Collela95] Colella, Nick, Lawrence Livermore National Labs, personal conversation.

[Dorsey90] Dorsey, Gary, *The Fullness of Wings,* 1990 Viking, ISBN 0-670-82444-5, pp. 109-116.

[Henderson90] Henderson, Bruce, “Varian Develops Technology to Send Power Via Fiber Optics,” *Aviation Week and Space Technology,* Aug 13, 1990. pp74-75.

[Hively96] Hively, Will, “Reinventing the Wheel,” *Discover,* August 1996.

[Houston 96] Houston, S., Ruse, E., Riedman J., Hawkins J., Brown, W.C., “*The Saber Microwave Helicopter Project*,” Space Studies Institute Update, Vol XXII, Issue 2, 1996 pp1-3.

[Kalhammer95] Kalhammer, F.R., Kozawa, A., Moyer, C.B, Owens, B.B, “Performance and Availability of Batteries for Electric Vehicles: A Report of the Battery Technical Advisory Panel,” Prepared for California Air Resources Board, Dec, 11, 1995

[Killgoar80] Killgoar, P.C., Pett, R.A., Tabar, R.J., Foote, L.R., “An Elastomeric Energy Storage Device for Automotive Engine Restart,” Rubber Chemistry and Technology, Vol. 53, No.2, 1980, pp335-345.

[Kline58] Kline, L.V., Marco, S.M., Starkey W.L., “Work Capacities of Energy Storage Systems on Basis of Unit Weight and Unit Volume,” *Transactions of the ASME,* May 1958, pp. 909-91.

[Kyosho96] Kyosho Corporation, *1996 Catalog and Handbook,* Tokyo, Japan

[McMahon83] McMahon, T.A, Bonner, J.T., *On Size and Life*, Scientific American Library, W.H. Freeman, New York, 1983, ISBN O-7167-5000-7.

[Nadel88] Nadel, E.R, Bussolari, S.R., “The Daedalus Project: Physiological Problems and Solutions,” *American Scientist,* July-August 1988, pp.350-360.

[OS96] O.S. Engines Manufacturing Co., Ltd., *1996-1997 Full Line-Up,* Osaka, Japan

[Ragone68] Ragone, David, “Review of Battery Systems for Electrically Powered Vehicles,” Society of Automotive Engineers, Mid-Year Meeting, Detroit MI, May 20-24, 1968 SAE #680453.

[Saito96] Saito Engines, *1996 Catalog,* Distributed by United Model Products. Wheeling, IL.

[Sandvik 94] Sandvik Steel Company, *Sandvik Power Springs Designer’s Guide,* Spring Products Division, Scranton, PA. 1994

[Sullivan96] Sullivan Products, *Genesys In-Flight Power System,* Baltimore, MD. 1996.

[Tiger96] Thunder Tiger Model Company, *1996-1997 Catalog*, Taichung, Taiwan.

[Whitehead95] Whitehead, John, Scientist at Lawrence Livermore National Laboratory, personal conversation.

[Williams 95] Williams, M.D., Walker, G.H., Humes, D.H., “*Diode Laser Satellite Systems for Beamed Power Transmission*,” NASA Tech Briefs, August 1995, p42ff

[Wilson78] Wilson, D. G., Human-Powered Space Transportation, *Galileo* 11,12, November, 1978, pp 20-26.

[Zubrin96] Zubrin, Robert, “Reaching for the Stars,” *Ad Astra*, Sept/Oct 1996, pp32-34.

A. Companies

This list does not do justice to the many companies and laboratories pursuing research in power sources. Electric vehicles and portable electronics are driving much of the work today and myriad organizations are involved in this work.

Batteries

Energizer Power Systems
Gainesville FL
tel: 904.462.3911
England: +44 1 782-566622
Stockholm: +44 8 7921370

Energizer manufactures secondary batteries including NiMH, Ni-cad and soon Li+.

Yardney Technical Products, Inc. and AluPower
Pawcatuck, CT 06379 USA
tel: 860.599.1100
fax: 860.599.3903
contact: Alex Karpinski

Manufacture of AgZn and AgCd batteries and Al-air semi fuel cells.

Fuel Cells

H-Power Corp.
60 Montgomery Street, Belleville, NJ 07109
tel: 201.450.4400
contact: Jeff Fisher, X479
net: moreinfo@hpower.com
url: http://home.earthlink.net/~hpower

A variety of fuel cell products.

Analytic Power
Boston, MA
tel: 617.542.6352
contact: Dave Bloomfield, President. x27

Specializing in 50-500W range units. Working on chemical hydride storage, currently using 3000psi (20MPa) H_2. Have 150W units. 6 delivered to Fort Bennington, GA. 3.6kg stack and 2.2kg of H_2. This is equivalent to 750Whr (125Whr/kg). The system was actually used on a robot carrier. Have 50W units for Fort Belvoir. 2.5 x 5cm cell size.

Miniature Generators

Electromech/Welco A Division Of Western Sky Industries Inc.
Wichita, KS 67217 USA
tel: 316.942.3271
fax: 316.942.4823

Contract manufacturer Of High Precision D.C. Motors, Generators, Centrifugal & Vane Axial Blowers, Actuators, Fiberoptic Low Liquid Level Sensors & Electronic Speed Control, Sensing, Switching & Control Apparatus & Motors Operated Valves

Servo-Tek Products Company

Hawthorne, NJ 07506 USA
tel: 201.427.3100
fax: 201-427-4249

DC Tachometer Generators, Permanent Magnet Servomotors, Motor-Generators, Velocity & Positioning Servos, Speed Indicating Systems, Miniature DC Motors. Output Ratings From 1 To 45 V/1000 RPM; Linearity Better Than 0.1%

Vernitron Corp.
San Diego, CA 92173 USA
tel: 800.777.3393
fax: 619.428.5040

Precise Motion Controls For Industrial Automation, Office Equipment, Disks Drives, Scanners, Guidance Systems, Instrumentation

Spectrum Research
165 Jordan Road
Troy, NY 12180
tel: 518.283.7909
fax: 518.283.7813
net: spectrum@generators.com
url: http://generators.com/hfa.html
contact: Mike Ampela (ampelm@rpi.edu)

Small permanent magnet high frequency alternators - 0.5 to 50kW.

Thermoelectric Generators

Global Thermoelectric
P.O Box 3306
Humble, Texas 77347
tel: 713.359.8484 or 800.848.4113
fax: 713.359.8485
url: http://www.globalte.com/

B. Energy Lift Calculations

Energy density can be used to provide a more intuitive insight by equating it with a lift height in a uniform 1g field. As an example, taking a typical energy density for a lead acid battery of 50Wh/kg and calculating the energy in 1kg:

$$50Wh = \frac{50J}{s} \cdot \frac{3600s}{h} = 1.836 \times 10^{5}J \qquad \textbf{Eq. 6}$$

then dividing by the weight (1kg = 9.8N)

$$\frac{1.8 \times 10^{5}J}{9.8N} = 1.84 \times 10^{4}m \qquad \textbf{Eq. 7}$$

This is equivalent to the height that much energy can lift itself in a 1g field and is per unit weight and thus independent of the weight of the actual system.