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Development of a Photovoltaic Power Supply for Wireless Sensor Networks

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Abstract

This report examines the design process of a photovoltaic (solar) based power supply for wireless sensor networks. Such a system stores the energy produced by an array of photovoltaic cells in a secondary (rechargeable) battery that in turn provides power to the individual node of the sensor network. The goal of such a power supply is to enable a wireless sensor network to have an autonomous operation on the order of years. Ideally, such a system is as small as possible physically while transferring the maximum amount of available solar energy to the load (the node).

Within this report, there is first an overview of current solar and battery technologies, including characteristics of different technologies and their impact on overall system design. Second is a general discussion of modeling, predicting, and analyzing the extended operation of a small photovoltaic power supply and setting design parameters. This is followed by results and conclusions from the testing of a few basic systems. Lastly, some advanced concepts that may be considered in order to optimize future systems will be discussed.

Acknowledgements

Thank you to Dr. David L. King and Dr. David Ingersoll of Sandia National Labs for sharing their respective expertise in the fields of photovoltaic cells and battery technologies. Thank you to Jerry Turner of Amonix, Inc. for his donation of top-quality monocrystalline silicon solar cells.

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Introduction

For a variety of applications in which the ability to rapidly and discretely obtain information about changing environmental conditions is essential, applications such as border or perimeter security, disaster management, or general intelligence, Wireless Sensor Networks (WSN) provide a potentially ideal solution. Powering these systems via primary (non-rechargeable) batteries however, becomes a dominating constraint as the desired lifetime of the system increases and the desired size of the sensors decreases. The volume of batteries required to operate the system becomes unwieldy at runtimes greater than a few weeks. A power supply in which secondary (non-rechargeable) batteries are charged by a photovoltaic (solar) array can increase the lifetime of the system to a number of years while requiring only a small volume of batteries. This report includes a brief overview of currently available photovoltaic and secondary battery technologies, a discussion of the design and analysis of such systems, results and analysis from the testing of a few basic systems, and suggestions for optimizing future systems.

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Photovoltaic Overview

The first step in designing a small photovoltaic (PV) power supply is gaining an understanding of the operation, availability, and viability of current photovoltaic technologies. A photovoltaic cell is any device that generates electric energy from light energy, while a solar cell is a photovoltaic cell optimized to the light produced by the sun. There are many quirks, oddities, and intricacies of solar cell operation that make solar-based designs uniquely challenging. A basic understanding of these is essential for correctly designing and troubleshooting solar cell based systems.

Photovoltaic Operation

PV cells convert energy in the form of light into electrical energy through a process known as the photovoltaic effect. In a nutshell, the photovoltaic effect refers to photons striking the valence electrons within a material and freeing them from their molecular bonds. A photon is a packet or "particle" of energy. Although light travels as an electromagnetic wave, it may only be absorbed or created in discrete amounts of energy, thus allowing them to generally be considered as particles of zero mass. The frequency or wavelength of a photon determines its energy level. For any given material, there exists a certain minimum amount of energy that is required for a valence electron to escape from its bound state into a free state where it can participate in conduction. This energy level is known as the band-gap of the material. A photon of energy greater than or equal to the band-gap of the material will excite an electron from the valence band to the conduction band. However, any energy in excess of the band gap will be released as thermal energy as the electron and hole created by this energy fall back into their respective valence and conduction band energy levels, a process known as recombination [1]. Thus, only light of a certain energy range, an energy level above but near the band-gap of the material is useful for creating electric energy using a given material.

This explains how light creates charge carriers, but merely having mobile charge carriers is not enough to create a power source; an electric field is needed to give motion to the charge carriers. This is created using two different materials, typically a p-type semiconductor and an n-type semiconductor. The two materials are doped by adding secondary elements such that some bonds in the p-type material are missing an electron, creating a positive charge carrier known as a "hole," and the n-type material has extra electrons. Joining these two materials creates what is known as a p-n junction, with a p-type region on one side of the junction and an n-type junction on the other. Since the n-type region has a high electron concentration and the p-type region has a high hole concentration, electrons diffuse from the n-type side to the p-type side. Similarly, holes flow by diffusion from the p-type side to the n-type side. This process of majority carrier exchange continues until equilibrium is reached. Equilibrium occurs when enough minority charge carriers are present in each region to prevent any further movement of charge. At this point, an electric field is present due to the presence of opposing charges.

Any new charge carriers (such as those created via the photovoltaic effect) are swept through the region by the electric field [2].

Thus, the basic operation of a PV cell may be thought of as charge carriers created by absorbed light energy being driven through an external load by an internal electric field. A simple circuit model may represent this behavior. As shown below in Fig. 1, a PV cell may be thought of as a light-dependent current source in anti-parallel with a diode (it is after all, a p-n junction) [2]. The output of the current source is primarily dependent on the intensity of the light incident to the surface of the solar cell. Another important factor is the spectral content of that incident light and how well it is matched to the band-gap of the material used to construct the cell. The area of the cell is also an important factor, as more cell area corresponds to more valence electrons that may be converted into charge carriers. The incident angle at which the light hits the cell is also a major factor as any angle less than 90 degrees effectively shrinks the cell area. Shunt and series resistances may be included to account for losses in output due to recombination, contact resistance, and other factors.

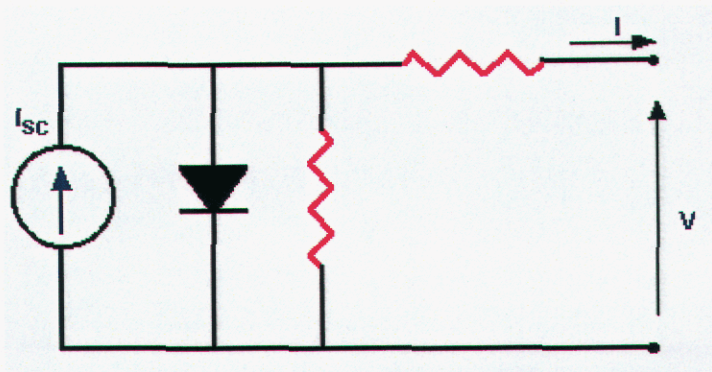

Figure 1. PV Cell Circuit Model

This circuit model explains the shape of the PV cell I-V curve, included below as Fig. 2. Although the current out of the current source is almost completely dependent on light conditions, the voltage of the cell is mainly determined by the external load through which the output current flows. Open-circuited, the output voltage is determined by the strength of the electric field at the p-n junction. Short-circuited, the voltage is zero and a maximum amount of current can flow. As the cell voltage is increased, the PV cell (diode) begins to become forward biased. The current caused by this is in the opposite direction of the current caused by the light. Thus, if the voltage across the cell is increased too much, the current it causes serves to cancel out the light-induced current and significantly reduce the total current output of the cell. Thus, there exists a max-power point at which the current out of the cell is still near its short-circuit value and the voltage of the cell is just low enough to not forward bias the cell. Any solar cell based system should aim to keep the PV cells operating at this point. This can most easily be achieved by setting the operating voltages within the system such that the PV cells operate at their maximum power voltage.

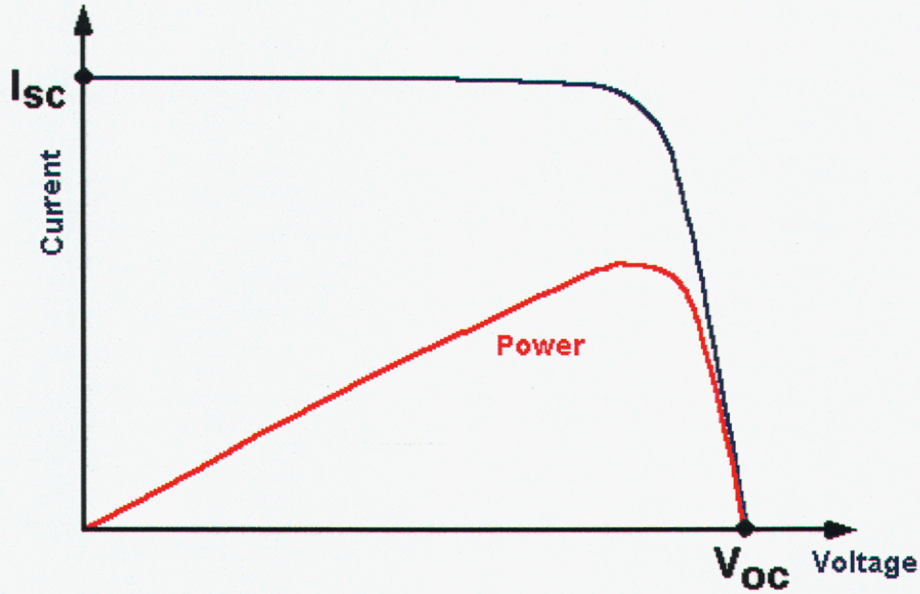

Figure 2. Solar Cell I-V Curve, With Power Curve

Photovoltaic Technologies

PV cells are currently made from many different semiconductor materials, with more materials possible. Important properties that affect the viability of a material as a PV material include its band-gap energy, density of potential charge carriers available for conduction, and its recombination characteristics. Materials used to fabricate PV cells may be classified into two groups: silicon or compound, with compound cells made from combinations of Group II-VI, Group III-V, or other elements. Despite the number of available materials, silicon remains the best option in terms of cost vs. performance for most WSN applications. More exotic materials such as gallium arsenide and indium phosphide may offer higher efficiencies, but they are roughly 7 times more expensive, less understood, and less readily available [3]. As the size of individual WSN nodes decreases, the feasibility of these more exotic materials increases as their higher efficiency becomes necessary to meet system requirements.

Silicon is mainly classified in terms of the regularity and uniformity of its crystal structure. Monocrystalline silicon is grown from a single crystal. Polycrystalline silicon is formed by joining multiple smaller crystals. Amorphous silicon has no crystalline structure. Amorphous silicon may be turned into thin-film polycrystalline silicon by heating it, causing crystallization. Of all of these, monocrystalline silicon represents the best option for WSN. It is only slightly more expensive than polycrystalline silicon, but significantly more efficient. This difference in efficiency is due to energy losses incurred at every crystal junction within a polycrystalline silicon cell.

Nevertheless, efficient is a relative term for even the best of solar cells. The best commercial monocrystalline cells are slightly over 20% efficient, while common, off-the-shelf cells have efficiencies of 13% or less. The maximum theoretical efficiency any cell made from a single material can achieve is roughly 30% [1]. This figure may be improved by stacking materials of different band-gaps energies (materials that will respond to different wavelengths of light) in multi-junction cells, but more research in this area is needed.

Secondary Battery Overview

Solar cells are an unpredictable power source as their output is very dependent on ambient conditions. In order to achieve a reliable source of power, an energy storage device such as a battery is needed to supply power during poor ambient conditions. Choosing the appropriate type of secondary battery is one of the most important initial decisions when designing a small solar power supply. The battery choice has a significant and far reaching effect on subsequent design decisions and the final design performance. Together, the PV cell and secondary battery may be thought of as a large tank designed to catch and store rainwater for later use. In such a system, it is desirable to have as large of a tank as possible. This is because, although somewhat counterintuitive, having a completely full tank is a bad thing. If the tank is full, then it can't catch any more rain, and any rain that may fall is completely wasted, unable to be used at a later date. In this analogy, tank volume is equivalent to battery capacity. Given a fixed design volume, a secondary battery with the highest possible energy density, and therefore greatest capacity, is desired. Ideally, the battery is never completely charged and is always ready to accept and store whatever random energy the solar cell may produce. The importance of energy density increases as the system size decreases, as a battery with a higher energy density will allow a higher level of performance with less battery volume. This is especially important for Microsystems scale designs.

Battery charge/discharge efficiency is equally as important as energy density when choosing a secondary battery. This figure represents the efficiency of the electrochemical reactions by which a given battery chemistry charges and discharges. For example, if 100 mWh of energy are put into a 75% efficient battery, only 75 mWh will be able to be withdrawn at a usable voltage. This characteristic is important because it cannot be circumvented through design. It represents a complete loss of energy within the system that may not be recovered, and may make necessary the use of a larger than desired PV array. Another important battery characteristic is its ability to be non-ideally charged without suffering damage. Some batteries require very specific forms of charge and may be damaged by slight deviations from ideal conditions. However, the importance of this characteristic may be offset by the availability of highly efficient protection circuits for a particular chemistry.

Other considerations include cost and availability of suitable batteries. For example, most large-scale photovoltaic power supplies (such as those intended to substitute for utility power in remote, off-grid locations) utilize lead-acid batteries similar to those found in automobiles for energy storage. However, lead-acid batteries are not readily available in a size small enough to make them practical for powering the nodes of a WSN. For WSN applications, the three most viable battery technologies are nickel cadmium, nickel metal hydride, and lithium-ion.

Nickel Cadmium (Ni-Cad)

Nickel Cadmium is one of the older secondary battery technologies, and as such, is one that quickly comes to mind when considering secondary batteries. They are readily available in standard sizes with pre-made battery packs, are well characterized, and are economically priced. Additionally, Nickel Cadmium batteries are rugged and reliable. The only irreversible failures with any realistic probability of occurrence are internal short-circuiting and loss of electrolyte within the cell, and it is unlikely that either of these would occur early enough in the battery's life to pose a major concern with regards to a WSN application. Nickel Cadmium batteries also possess excellent overchargeability. That is, it is possible to continue forcing current through the battery after it has achieved a full state of charge without dramatically reducing the battery's performance or inflicting permanent damage to the cell. However, as was stated earlier, this is only a slight advantage as low power protection circuits are readily available for some more sensitive secondary battery technologies (Li-Ion).

Another positive characteristic of Ni-Cads is their ability to handle rapid, pulse discharge, which is desirable for WSN since the output power of the battery will need to periodically pulse to a considerably higher level than average value due to RF transmissions and high power sensors. Also, due to the very low internal resistance of the cells, Nickel Cadmium batteries have an extremely flat discharge profile, meaning that almost all of the energy they do put out is of a usable voltage.

Despite the above advantages, Nickel Cadmium is a poor choice for most WSN applications where battery volume is critical. Its energy density of 100 Wh/L and its charge/discharge efficiency of 60% are both much too low to make a Nickel Cadmium solution for small volume WSN feasible [4]. Another reason for this is the decrease in deliverable capacity that is experienced after repeated cycles of shallow discharge and recharge, commonly referred to as the memory effect. It is called this because the battery behaves as if it "remembers" how much capacity it discharged before being charged and "forgets" that it is capable of discharging a greater capacity. The memory effect occurs because during a partial discharge, only some of the active materials within the cell are discharged, and the remaining uncharged material may undergo a physical change, specifically an increase in resistance. This leads to a less flat discharge profile. This is a significant drawback when powering WSN as the type of shallow discharge-recharge cycles responsible for the memory effect will certainly occur. Thus, despite its advantages, Nickel Cadmium would be a poor choice for most WSN applications. It would simply require too much battery volume and too much PV cell area.

Nickel Metal Hydride (Ni-MH)

For most WSN systems, Nickel-Metal Hydride is a better choice than Nickel Cadmium. It is a newer secondary battery technology that behaves very similarly to Nickel Cadmium, but with a few distinct advantages. The most compelling advantage of

Nickel-Metal Hydride batteries over Nickel Cadmium is its vastly superior energy density of about 240 Wh/L [4]. This is critical for WSN application, as it will allow the system to take better advantage of the available solar resource and operate for a longer period of time off of a single full battery charge with a smaller battery volume. Also, although Ni-MH batteries still exhibit a memory effect, they do so to a substantially lesser degree than Ni-Cad.

Although not quite as flat as the discharge profile of Nickel Cadmium batteries, the internal resistance of Nickel-Metal Hydride batteries is still low enough to allow for a very flat discharge profile. Ni-MH batteries can also withstand full and rapid discharge, both good traits for WSN applications.

The main disadvantage of Ni-MH as compared to Ni-Cad is that Ni-MH batteries are slightly more sensitive to damage due to overcharge. However, although more sensitive, research indicates that Ni-MH batteries are rugged enough to charge with a circuit just as simple as that which could be used to charge Ni-Cad batteries (i.e. simple diodes) without sustaining too much damage. Also, in a small PV power supply, it is unlikely that the amount of power produced by the small PV array would be enough to induce severe overcharge conditions with any frequency.

The advantages of Ni-MH make it a very feasible battery choice for basic WSN systems where perhaps a larger PV array is acceptable. However, like Ni-Cads, Nickel-Metal Hydride batteries are unsuitable for advanced WSN applications. The main reason for this is their charge/discharge efficiency, which at 60% is identical to that of Nickel Cadmium [4]. In advanced systems requiring a PV array with as small of an area as possible, this loss of energy is too crippling to allow Nickel Metal Hydride to act as an energy storage device.

Lithium Ion (Li-Ion)

Lithium Ion batteries are a more recently commercialized secondary battery technology with many striking advantages over other, older battery technologies. The most striking advantage of Li-Ion batteries is their exceptionally high energy density. At roughly 400 Wh/L, the energy density of a Li-Ion cell is four times that of a Ni-Cad cell and slightly less than twice that of a Ni-MH cell [4]. As far as WSN applications are concerned, this superior energy density will allow the system to take much better advantage of whatever energy the PV array may produce and allow operation for dramatically longer periods of time between charges given the same battery volume. Another advantage of Li-Ion batteries is that they don't exhibit a memory effect like Nickel Cadmium and Nickel Metal Hydride. Additionally, the charge/discharge efficiency under ideal charge conditions can be as high as 95% [4]. While the ideal charge conditions for Li-Ion are difficult to replicate in a photovoltaic system, Li-Ion cells were shown to exhibit a charge/discharge efficiency of over 87% under highly non-ideal charge conditions. This is a significant improvement over Nickel Cadmium or Nickel Metal Hydride.

One aspect of Lithium Ion that is normally a considerable advantage over other battery technologies is the significantly higher per-cell voltage of a Li-Ion cell. On average, the per-cell voltage of a Li-Ion cell is three times that of a Ni-Cad of Ni-MH cell (3.7V to 1.2V). However, this can be a problem for WSN applications. A battery may only be charged with energy that is of a higher voltage than its own. In order to obtain this voltage from a PV array of the same area as one designed for a Ni-MH system, more individual cells must be arranged in series and the individual cells must be smaller. Since this cuts down on the per cell area, less current will be able to be drawn from the array. This tradeoff of current for voltage can't be avoided, but Li-Ion's advantages outweigh this slight disadvantage.

Another disadvantage of Li-Ion is its lack of tolerance of imperfect charge conditions. If a Li-Ion battery is either overcharged above a certain voltage or discharged below a certain voltage, it is completely ruined. However, protections circuits designed specifically for Li-Ion batteries are readily available. Although of these consume a fair amount of power, they often provide a much greater degree protection than absolutely required. If efficiency is of particular importance, protection circuits may be found that do nothing but keep the battery between the prescribed voltage limits and provide short-circuit protection. While this will cause slight battery degradation over time, it is unlikely to be to an intolerable degree, as Lithium Ion cells are available with energy capacities high enough to compensate for the induced capacity losses.

Although it does have some disadvantages and may be the most difficult to design with, Lithium Ion is the superior battery technology for advanced WSN photovoltaic power supply designs. Its superior energy density and charge/discharge efficiency allow a higher level of performance to be achieved with a smaller battery volume and PV array area than can be achieved with any other battery technology.

Design and Analysis of Solar Systems

The analysis and prediction of solar system behavior contains many unique challenges. For one thing, precise, instantaneous quantities are of very little value. This is due in large part to the fact that conditions are constantly changing over the course of a day due to meteorological factors. This constant variation is evident in Fig. 3, which shows the power output by a standard PV array through a simple resistive load over a 24-hour period with measurements taken in 3-second intervals. It can be seen that, although the PV output voltage and current follow a distinct pattern throughout the day, rising somewhat quickly in the morning, remaining fairly constant from 11:00 am until 3:00 pm, and then dropping somewhat slowly in the evening, both may vary quit drastically in a matter of seconds. The randomizing effects of cloud cover may also be seen in the morning.

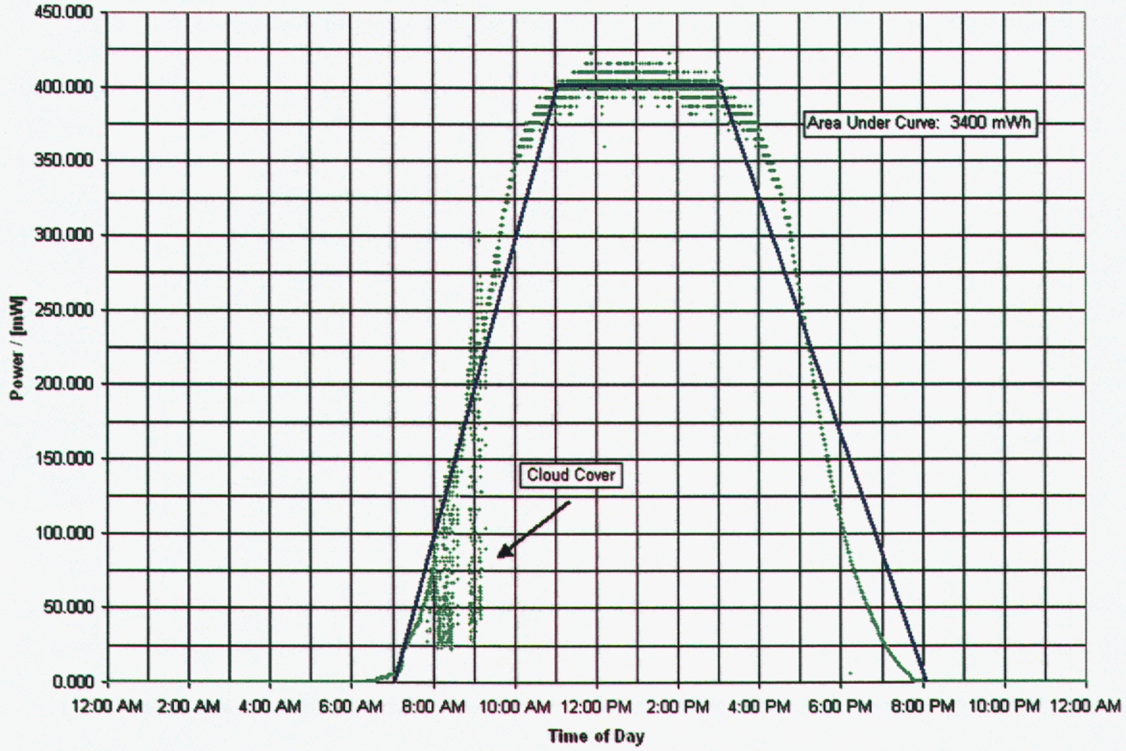

Figure 3. Output of PV Array Over 24-Hours (June 29, Livermore CA)

One simple and effective way to get around the handicap of constantly oscillating instantaneous quantities is to examine systems in terms of energy, or instantaneous power integrated over time [5]. Ultimately, it is the respective cumulative amounts of energy provided by the PV array, stored in the battery, used to power the load, and dissipated by the various components of the system that really determine how well a system is performing. In fact, when comparing different systems, perhaps the best single quantity for determining the superiority or inferiority of one system relative to another is the net gain in usable energy that the battery receives over the course of one solar day. This is useful because it takes into account the ever-important factor of battery charge/discharge efficiency. This figure really represents the amount of "dark" operation (time spent powering the WSN without sunlight being present) that is gained for every amount of "light" operation (time spent powering the WSN and charging the battery while sunlight is present). Treating the system as having two distinct modes of operation, light and dark (with and without sunlight) is another useful technique for simplifying the task of accurately modeling solar systems.

In solar system design, there is a quantity known as solar insolation. Technically, this is a measure of the rate of delivery of direct solar radiation per unit of horizontal surface and is measured in units of $kWh/m^2/day$, commonly referred to as sun hours. In more understandable terms, the sun delivers energy to the surface of the earth and delivers it over a certain area. At noon on a cloudless day, the sun will instantaneously deliver about 1000 Watts of power to a square meter of ground. If this condition continues for one hour, then the ground will have received about 1000 Wh of energy per square meter, or one sun hour of solar insolation. Solar insolation data is readily available from a variety of sources that gives the average number of sun hours per day for a given month or season for most locations. If the worst-case amount of solar insolation is used in the design process, the system should be reliable all year long [5]. The 24 hours of the day may then be divided in two periods: a period of full sun ($1000\ kW/m^2$) for the given number of sun hours and then a period of zero sun for the rest of the day. This technique obviously ignores that fact that for a day in which solar insolation is 5 hours, there may actually be only three hours of full sun in conjunction with any number of hours of partial sun, but this is still a valid approximation so long as calculations are done in terms of cumulative energy. Energy is power integrated over time, and how much power is or isn't being supplied or consumed at any given moment is not as important as the total amount of energy gained or lost by components of the system. Once a system is modeled, decisions can be made about the level of desired performance, particularly how many "light" days will be required to provide how many "dark" days of operation, etc, and the components of the system sized accordingly.

Thus, simple and accurate analysis of the energy gains and losses within a solar system may be performed by assuming the system to be operating either at full sun or in complete darkness, performing a complete power flow analysis for each condition, and then integrating the power quantities over the total duration that they are expected to occur. This technique was used to predict the long-term operation of three basic, small photovoltaic power supplies, particularly the all-important figure of daily net usable battery energy gain. The three systems modeled were the Nickel Metal Hydride Direct design, the Lithium Ion Direct design, and the Lithium Ion Boost design. The Ni-MH Direct system consists of a PV array whose voltage is matched to the appropriate charging voltage for 2 Ni-MH batteries in series and charges the batteries through a simple diode. The Li-Ion Direct system is an equivalent system with a single Li-Ion battery in place of the two Ni-MH batteries. The Li-Ion Boost system incorporates a boost converter in between the PV array and Li-Ion battery in an effort to maximize energy gains within the system.

All three designs were also built and tested. A detailed description of each, particularly the Li-Ion Boost system, including the results of those tests and a discussion of advanced concepts for optimizing the design of a photovoltaic power supply for wireless sensor networks follows. The results of these tests verified the accuracy of the discussed analysis techniques, particularly for the two direct systems. Test Results for the Li-Ion boost system are not entirely conclusive, as much optimization is required for optimal system performance. Thoughts on these optimizations are included in the discussion of advanced concepts.

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Test Results

In an effort to verify the analytical techniques used to model and predict small photovoltaic power supplies, as well as the theory upon which these techniques were based, and to gain insight into the extended operation of a photovoltaic power supply, numerous tests were conducted. The most informative of these were the tests intended to empirically investigate the extended operation of an entire system over the course of a few days. Such tests were performed for three systems: the Nickel Metal Hydride Direct system, the Lithium-Ion Direct system, and the Lithium-Ion Boost system.

Nickel Metal Hydride Direct

The Nickel Metal Hydride Direct system is a simple system, but examining its long-term operation can yield valuable insights into the general dynamics between a small PV array, a secondary battery, and a load. The system consists of a PV array charging two Ni-MH batteries directly through a series diode. The diode dissipates power, but is needed to prevent the battery from draining through the PV array (a p-n junction) when the sun isn't out. A Schottky diode was used in order to minimize the voltage drop between the PV array and the batteries. A load resistance was placed in parallel with the batteries and sized in order to mimic the power demands of a 50 mW load, typical of WSN designs.

The PV array consisted of seven RS 276-124 solar cells from Radio Shack wired in series. Although monocrystalline silicon, these off-the-shelf cells are only about 13% efficient, not nearly as good as high-grade commercial cells whose efficiencies are roughly 20%. This means that, although the test array took up an area of 56 cm^2 (8.68 in^2), identical performance could have been achieved with just 36.4 cm^2 (5.64 in^2) of better PV material. The two Ni-MH batteries used were also from Radio Shack. Both were AA batteries with ratings of 1.2V for 2000 mAh, near the top of the line for Ni-MH. Thus, with the two arranged in series, the battery pack had a rating of 2.4 V for 2000mAh, or 4800 mWh. Measurements were taken in regular intervals at points throughout the system using two small data loggers manufactured by Onset Computer Corporation. One measured the voltage across the series diode and the other measured the voltage across part of the resistive voltage divider that formed the load resistance. The diode used was extensively tested in order to obtain a formulaic representation of the relationship between the voltage across it and the current through it. This relationship was used to calculate the diode current from the measured voltage across it. All other voltages, currents, and power consumed/supplied within the system were calculated from these three values using basic circuit analysis with Ohm's and Kirchhoff's laws. Positive battery current was defined as flowing into the positive terminal of the battery, thus positive battery power represents charging while negative battery power represents discharging. Extensive analysis was performed of the day-to-day energy gains and losses within the system by integrating plots of power vs. time. All integrations were performed in a piecewise fashion from linear approximations of sections of the curves. A plot of the key components of system performance throughout the test is included below as Fig. 4.

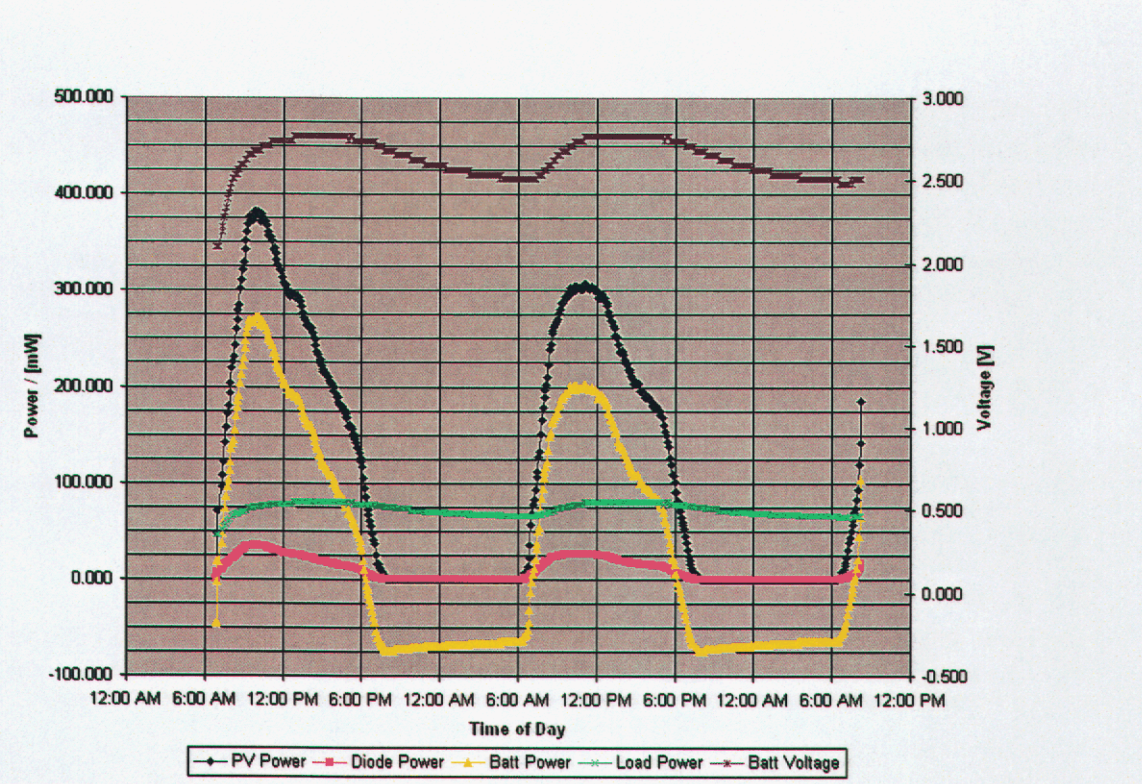

Figure 4. Extended Operation of Ni-MH Direct System

A detailed examination of the plots contained in Fig. 4 clearly reveals two ways in which the system is operating in a less than optimal manner. One immediately noticeable fact is that on both test days, the peak output of the PV array occurs roughly between the hours of 9:00 am and 11:00 am. This doesn't make much sense when it is considered that, as shown in the plot of Fig. 3, the peak sun hours occur between 11:00 am and 3:00 pm. This is when the PV array should be putting out its maximum amount of power. This discrepancy means that the system is not drawing as much power from the PV array as the array is capable of putting out. On the first day, the PV array put out roughly 2920 mWh of energy, as compared to 3400 mWh when loaded with a simple resistance. This is a major concern because, as system size is decreased, the importance of getting maximum performance from all components increases, particularly for the PV array, whose output is really the limiting factor at these sizes. The reason for this lack of PV performance is that the battery voltage increases very rapidly at the beginning of its charge cycle. As the voltage of the battery pack increases, then the voltage of the PV array must also increase in order to keep the diode forward biased. This increase in voltage pushes the array past the max power point on its I-V curve, and its ability to produce current decreases. One solution to this problem would be to increase the voltage of the PV array. However, for a given array area, any increase in voltage necessitates a decrease in current capability. Such a tradeoff would leave the array able to produce less current at all times, regardless of the battery voltage. Also, there is an upper limit to the voltage at which the batteries can be charged. Ultimately, the problem is a result of directly tying the PV array to the battery. The only way to truly allow the PV array to produce its maximum possible output is to decouple the two elements so that the PV array is able to operate at its maximum power point regardless of the voltages throughout the rest of the system.

The second readily seen inefficiency within the system is the sizeable decrease in system performance on the second day of testing as compared to the first, despite the fact that weather conditions were nearly identical on the two days. On the first day, the PV array produced 2920 mWh of energy and the battery received 1750 mWh of energy. On the second day however, the PV array only produced 2260 mWh of energy and the battery only received 1470 mWh. The reason for this decrease in performance is that the batteries are near capacity. On the first day of testing, the batteries were completely drained. They received 1750 mWh of energy over the course of the day. Taking into account the charge/discharge efficiency of 60% for Ni-MH, this represents 1050 mWh of usable energy [4]. Throughout the first night, the battery only lost 815 mWh powering the load. This means that the battery began the second day of operation with a higher state-of-charge, and a higher voltage. This goes back to the earlier analogy of a full tank not being able to catch any more rainwater. The two Ni-MH batteries are too small of a tank, and on the second day of operation, they aren't able to take in all of the energy that the PV array is capable of putting out. Using a battery pack with higher energy capacity could solve this problem, but would require more volume.

The testing also confirmed that a Ni-MH system is doomed to failure by the low charge/discharge efficiency of the batteries. For example, instead of the battery experiencing a usable energy gain of 935 mWh (1750 mWh – 815 mWh) on the first day, only a 235 mWh (1050 mWh – 815 mWh) gain was achieved, followed by a gain of only 31 mWh of usable energy on the second day.

Lithium Ion Direct

The Lithium Ion Direct system is another simple system, essentially the Ni-MH Direct system modified to allow a singe Li-Ion battery to be used instead of two Ni-MH batteries. Instead of seven RS 276-124 solar cells from Radio Shack connected in series, the Lithium Ion Direct system uses an array of nine cells. Since off the shelf components were being used, these extra cells were needed in order to achieve the higher voltage necessary to charge a Li-Ion battery. The 9-cell array had an area of 72 cm^2 (11.16 in^2). As explained earlier, identical performance could have been achieved with 46.8 cm^2 (7.25 in^2) of high quality cells. A custom array could be manufactured to output the necessary voltage using any amount of area, with less area for each individual cell and therefore less current capability. In order to compare systems with PV arrays of different areas, the load represents such a small fraction of overall power consumption, that simple fractional scaling is valid. For example, in order to accurately compare the performance of the tested Li-Ion Direct system with that of the tested Ni-MH Direct system, the Li-Ion results may simply be multiplied by a factor of 7/9 or 0.78.

The Lithium Ion battery used was the UBP103450 manufactured by Ultralife Battery, Inc. It is a prismatic cell with a nominal voltage of 3.7V and a current rating of 1800 mAh, giving it an energy capacity of 6660 mWh, almost 150% that of the two Ni-MH batteries. The single Li-Ion battery also has a slightly smaller volume than the two Ni-MH AA batteries. In order to protect the more sensitive Li-Ion battery, an electronic protection circuit (EPC) is required. For convenience, the one that comes with the battery was used. It has a quiescent current of less than 100 μA, which constitutes a negligible power loss [6]. If even greater efficiency is required, EPC's with quiescent currents of less than 10 μA are available [7]. Although more efficient, an EPC with lower current consumption may provide slightly less protection and lead to slightly greater battery damage, creating a tradeoff situation. As with the Ni-MH Direct system, measurements were taken in regular intervals at points throughout the system using two small data loggers manufactured by Onset Computer Corporation. The measurements were taken at identical points within the system with other quantities calculated in the same manner as they were for the Ni-MH system. Positive battery current was again defined as flowing into the positive terminal of the battery, thus positive battery power again represents charging while negative battery power represents discharging. Extensive analysis was again performed of the day-to-day energy gains and losses within the system by integrating plots of power vs. time. All integrations were performed in a piecewise fashion from linear approximations of sections of the curves. A plot of the key components of system performance throughout the test is included on the next page as Fig. 5.

The plots contained in Fig. 5 demonstrate that the Li-Ion Direct system operates in a manner very similar to the Ni-MH Direct system, except for one key improvement. Unlike the Ni-MH Direct system, the performance of the Li-Ion Direct system does not diminish from one day to the next. The decrease in performance experienced by the Ni-MH direct system was assumed to be due to a lack of sufficient battery energy capacity to support efficient operation with partially charged batteries. Since the only real difference between the two systems is that the Li-Ion system has significantly more battery capacity, and this behavior is no longer observed, that assumption appears to have been validated. The Li-Ion Direct system does, however, still suffer from the other major drawback of the Ni-MH Direct system. The peak period of PV array output and battery charging still occurred between 9:00 am and 11:00 am rather than during the peak sun hours of 11:00 am to 3:00 pm, indicating the array is still not being fully utilized. This is to be expected since the array is still not decoupled from the rest of the system.

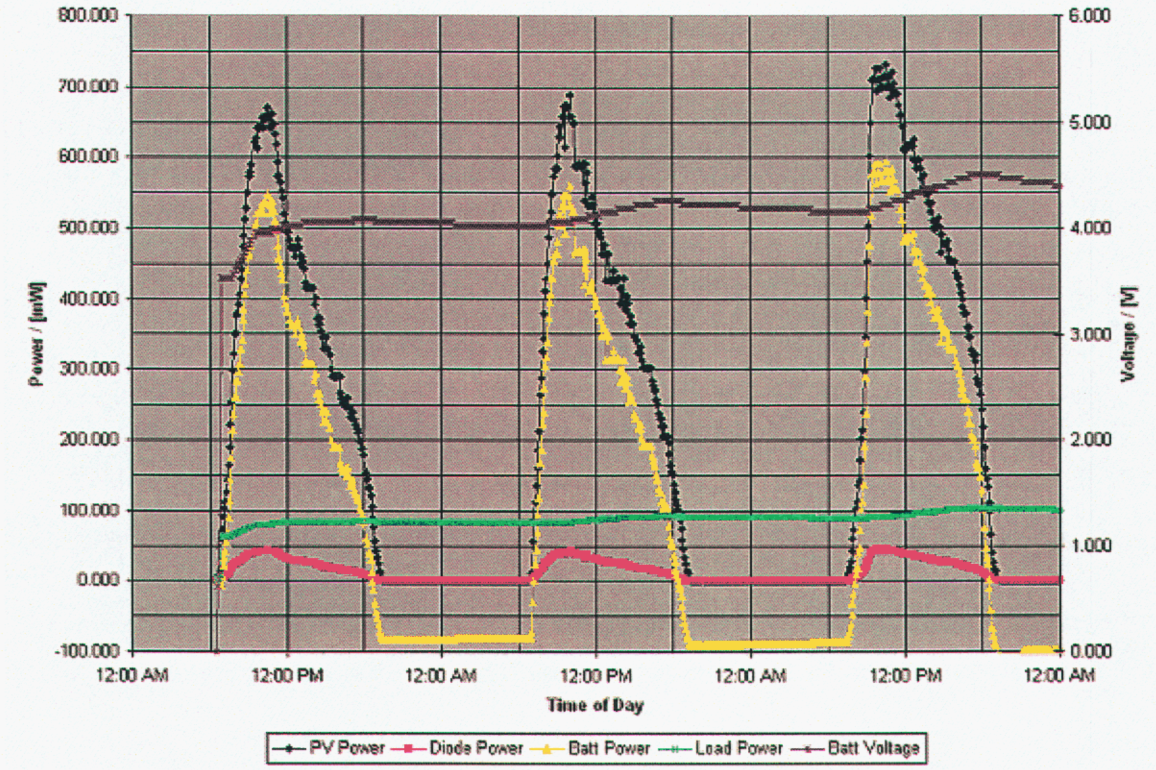

Figure 5. Extended Operation of Li-Ion Direct System

One decisive advantage of the Li-Ion Direct System as compared to the Ni-MH Direct system that is not revealed by the plots of Fig. 5 is the much improved charge/discharge efficiency of the battery. Under ideal charge conditions, the efficiency of Li-Ion batteries may be as high as 95% [4]. However, under the constant voltage charge conditions most likely to be encountered in a WSN application, this figure is closer to 88%. This is still a drastic improvement over the 60% efficiency of Ni-MH [4]. This higher battery efficiency corresponds to much greater daily gains in usable energy for the battery of the system. Over the first three days of the system, the battery experienced an average gain of 1940 mWh of usable energy, using 88% as the charge/discharge efficiency. Scaling the PV array output by a factor of 7/9 for comparison to the Ni-MH Direct system, yields an increase of 1260 mWh. Even on the fist day, when the insufficient battery capacity had not yet begun to drastically affect system performance, the Ni-MH batteries only achieved a 235 mWh gain in usable energy, despite having a difference of over 900 mWh between the energy put into the battery during the day and drawn out overnight. The difference in this value between the two systems is incredibly significant. At its best, the Ni-MH Direct system would require over 5 "light" days to gain the duration of "dark" operation gained by the Li-Ion Direct system in one "light" day.

Lithium Ion Boost

Of the three systems that were built and tested, the Lithium Ion Boost is by far the most complicated. The main feature of this system, and the source of its name, is a step-up, or boost, DC-DC converter placed between the PV array and the battery. A boost converter is a switch mode converter that works in two stages. With the switch closed, current is forced through an inductor, storing energy in its magnetic field. When the switch is opened, this energy, along with the energy from the source connected to the converter's input, is transferred to the output of the converter. This process of storing and releasing energy allows the converter to accept a DC input of a certain voltage and current and produce a DC output of higher voltage and lesser current, with the output power ideally being equal to the input power. Placing a boost converter between the PV array and the battery serves two main purposes. First, it allows the high voltage necessary to charge a Li-Ion battery to be achieved from a PV array of lower voltage and greater current capability. More importantly, it decouples the PV array from the rest of the system. Regardless of what is occurring throughout the rest of the system (the battery state-of-charge, battery voltage, instantaneous power demands of the load, etc.), the boost converter allows the PV array to continue operating at the max power point on its I-V curve. This allows the PV array to constantly put out the maximum amount of power possible for the given light conditions, with the converter altering this power into a form that may be used to charge the battery. However, as will be discussed below and even further in the section on advanced concepts, achieving this optimal performance requires much more than simply sticking a boost converter between the PV array and battery.

The first thing that must be considered is that the boost converter contains an inductor at its input. Thus, if the PV array output is connected directly to the converter input, an inductor will be connected directly between the solar cells and ground, a very inefficient arrangement. During low light conditions, the PV array is incapable of producing enough current to operate the boost converter. Placing a reservoir capacitor between the PV array and boost converter provides temporary storage for what energy the array is able to produce. A comparator circuit is also included whose output is connected to the enable pin of the boost converter. The comparator monitors the capacitor/array voltage, and when the capacitor is charged by the PV array such that its voltage reaches a certain level and is able to support full cycles of converter operation, the boost converter is enabled. Hysteresis is added to the comparator so that the converter continues to operate as energy is withdrawn from the capacitor. The capacitor voltage at which the comparator enables the converter may be optimized such that the PV array operates at its maximum power point, although this value varies with light conditions. Thus, under low light conditions, the system operates in bursts with the converter being enabled when enough energy is accumulated by the capacitor.

There are other complications at the output of the boost converter at the battery interface. A fundamental principle of reliable power electronics design is transitioning between sources of constant current and voltage. If an output of constant voltage is desired, than an input of constant current is optimal, and vice versa if an output of constant current is desired. This arrangement may be seen throughout the Li-Ion Boost system. The PV array acts as a current source. Its output is then fed into a reservoir capacitor, which serves as a voltage source. Connected to the capacitor is the inductor at the input of the boost converter, which acts as a current source. This is then fed into a capacitor placed at the boost converter output, making the output of the converter a voltage source. As would be expected, problems are encountered if the output of the boost converter is connected directly to the terminals of the Li-Ion battery, since this is essentially connecting two voltage sources in parallel. The battery voltage varies over a sizeable range as a function of its state of charge. If this voltage is significantly different from the boost converter's designed output, the boost converter is unable to function properly. It is pulled into a very inefficient mode of operation in which it constantly switches on and off as the two voltage sources battle one another.

One simple solution to this problem is to insert circuit elements to act as a "voltage buffer" between the converter output and the battery. This buffer serves to absorb the voltage difference between the two, allowing the converter to continuously operate at its designed output voltage regardless of the battery voltage, drastically improving system performance. However, this solution is far from optimal. Although the converter now puts out much more power, a portion of it is dissipated in the voltage buffer. Also, the optimal amount of resistance to be included in the buffer depends on the current light conditions and battery voltage. More optimal solutions to this problem are discussed in the section on advanced concepts. Due to time constraints, these solutions were unable to be examined in depth. Nevertheless, a Li-Ion Boost system with a less-than-optimal voltage buffer was built and tested.

The tested system used an array of seven RS 276-124 solar cells from Radio Shack wired in series. The output of this array was fed into a reservoir capacitance of over 9 mF. The voltage of this capacitance was monitored using a comparator, the LTC1440 from Linear Technologies with a maximum amount of hysteresis. The MAX1763 from Maxim was used as the controller for the boost converter. The output of the boost converter was connected to the same Lithium Ion battery used in the Li-Ion Direct system and the same EPC was also used. A resistive load was again placed in parallel with the battery to mimic the typical power demands of a WSN. At the beginning of the day, the battery was completely discharged and had a voltage of 3.7 V (the EPC used allows the battery voltage to drop to 2.3V before disconnecting the load, at which point the battery self-recovers to 3.7V) and the output of the boost converter was set at 4.1V. A Li-Ion battery will typically charge to a voltage of about 4.2V. In order to absorb the voltage difference between the converter and battery, a buffer of a Schottky diode and a resistor was used, with the diode providing a fairly constant voltage drop and the resistor providing a variable voltage drop. At the beginning of the day, a 1.8Ω resistor was used to allow the requisite voltage drop to be created without exceeding the current producing capabilities of the PV array. Later in the day (between 2:30 pm and 4:30 pm), when light conditions had improved and the battery voltage had increased, this was replaced with a 1.0Ω resistor. The goal of this switch was to examine, in general, the extent to which system performance could be improved by optimizing the converter-battery connection.

For this system, three small data loggers manufactured by Onset Computer Corporation were used to take voltage measurements at 5 different points within the system. From these measured values, other quantities within the system were calculated using basic circuit analysis with Ohm's and Kirchhoff's laws. Positive battery current was again defined as flowing into the positive terminal of the battery, thus positive battery power again represents charging while negative battery power represents discharging. Extensive analysis was again performed of the daily energy gains and losses within the system by integrating plots of power vs. time. All integrations were performed in a piecewise fashion from linear approximations of sections of the curves. Figure 6 is a plot of the performance of this system over the course of one day.

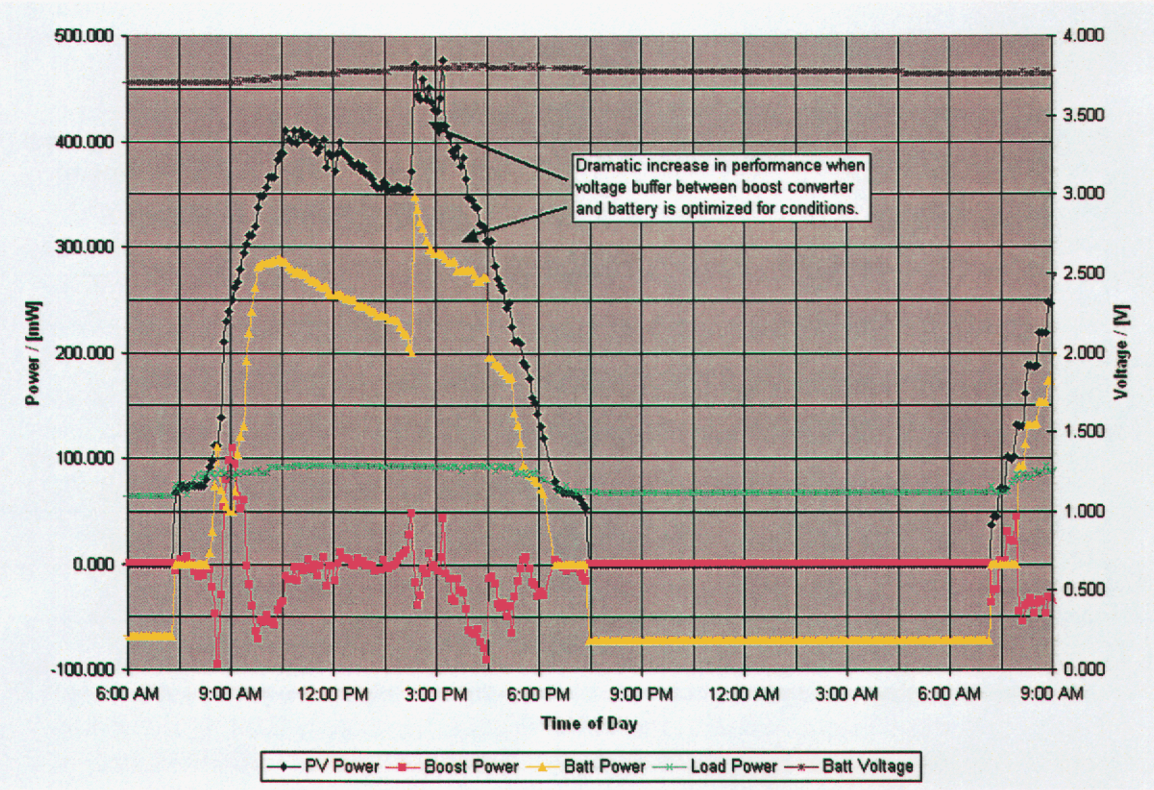

Figure 6. Extended Operation of Li-Ion Boost System

The plots in Fig. 6 contain two main pieces of information regarding the performance of the Li-Ion Boost system. The first of these is that, rather than occurring between 9:00 am and 11:00 am, the hours of peak performance by the PV array are more in agreement with the peak sun-hours. This better utilization of the PV array was to be expected since the array is decoupled from the rest of the system by the boost converter. The other important fact demonstrated by these results is the increase in performance achieved by adjusting the voltage buffer for given light and battery conditions. The real peak of system performance occurs between 2:30 pm and 4:30 pm, precisely during the time that the voltage buffer had been adjusted for current conditions. The fact that peak performance was obtained not during peak sun hours, but while the voltage buffer was adjusted, indicates that overall system performance would be hugely improved were the converter-battery connection constantly optimized for current conditions. Had the adjustment not been made, the PV array would have produced approximately 3240 mWh of energy (still 300 mWh more that were produced by the same array in the Ni-MH Direct system, further indicating the benefits of decoupling the array from the rest of the system). With the adjustment, the array was able to produce 3430 mWh of energy, meaning that slightly improvement the converter-battery connection for two hours provided 190 mWh of added energy production. This increase corresponds to a gain of 165 mWh of usable energy from the battery. The results of this test strongly confirm that decoupling the PV array from the system and optimizing the battery connection may greatly improve the performance of a small photovoltaic power supply.

Verification of Analytical Techniques

In addition to gaining insights into the general dynamics of a small photovoltaic power supply, another goal of these tests was to empirically verify the validity of the analytical techniques outlined earlier for PV based systems. The techniques consisted mainly of dividing the day into two distinct periods, one of full sun and one of no sun, conducting a complete analysis of instantaneous power flows within the system, and integrating in order to obtain energy quantities. For each of the three systems that were built and tested, these analytical techniques were used to create models in an attempt to predict system behavior. Of particular interest was verifying the predicted figure of daily net usable battery energy gain. Overall, the test results indicated that the discussed analytical techniques accurately predict the general magnitude of the energy gains and losses within a solar cell based system, although improvements are needed in order to predict these figures more precisely.

When the parameters of the various components of the tested Ni-MH Direct system were input to the corresponding analytical model (number and efficiency of solar cells, amount of solar insolation, diode characteristics, etc.), a daily net usable battery energy gain of 380 mWh was predicted. However, the measured value for the first day of operation was calculated to only be 235 mWh. On the second day, this value was measured to only be 31 mWh, with the battery gaining 882 mWh of usable energy during the day and losing 851 mWh overnight. The main reasons for the large discrepancies are the two inefficiencies within the system outlined above, both of which were not accounted for in the model. The model used simply did not take into full account the shortcomings of the Ni-MH Direct system. Nevertheless, at least for the first day of operation when the system operated more efficiently, the model did accurately provide a rough, general idea of the magnitude of usable energy gain experienced by the battery.

The analytical techniques did a much better job of predicting the performance of the Li-Ion Direct system, a system that suffered from only one of the two unaccounted for flaws that hampered the Ni-MH Direct system. For an array of 9 solar cells of 13% efficiency, the model predicted a daily net usable battery energy gain of 1800 mWh. The tested system yielded an average daily gain of 1940 mWh. For an array of 7 of these cells, the model predicts a daily net usable battery energy gain of 900 mWh, as opposed to the 1260 mWh obtained by scaling the measured results by 7/9. Although not in complete agreement, the figures again indicate that the analytical techniques correctly predict the general level of system performance.

For the Li-Ion Boost system, the created model predicted a daily net usable battery energy gain of 1400 mWh. This is much more than was predicted for any other system with an array of 7 solar cells of 13% efficiency. When the system was built and tested, a figure of 1080, mWh was measured. This discrepancy is largely due to the fact that the models did not take into account the inefficiencies that were encountered due to the converter-battery connection.

Ultimately, the test results confirm the validity of the analytical techniques that were used to predict system behavior, as well as the theories upon which they are based. The models created using these techniques accurately predicted the general magnitude of the energy gains and losses within the system. The accuracy with which they did so could be greatly improved by making modifications to take certain system shortcomings more into account, particularly the changes in battery voltage and state-of-charge.

Advanced Concepts

Throughout the course of the research and testing of photovoltaic power supplies for WSN previously discussed in this report, many ideas for the further optimization of such systems were generated. Due to multiple factors, many of these ideas were unable to be investigated fully. The following section of this report is a discussion of these advanced concepts for the benefit of future research.

Optimization of the Li-Ion Boost System

As outlined earlier in this report, it may be concluded from the research and testing that was conducted that a form of the Lithium Ion Boost system is likely to be the optimal solution to creating a photovoltaic power supply for WSN. Compared to other secondary battery technologies, lithium ion possesses an energy density and charge/discharge efficiency making it by far the best battery solution for such applications. Placing a boost converter between the PV array and battery not only converts the energy output by the array into a form of high enough voltage to charge the Li-Ion battery, but also serves to decouple the array from the rest of the system. Decoupling the array from the rest of the system allows for the maximum possible amount of energy to be withdrawn from the array by permitting the array to operate at the maximum power point on its I-V curve, regardless of what is occurring throughout the rest of the system. The following are ideas for optimizing this type of system.

As previously discussed, problems were encountered when the output of the boost converter was connected directly to the battery terminals. These problems stemmed from the fact that two voltages sources were being connected in parallel. For the sake of testing, a resistive "voltage buffer" provided an inefficient solution to this problem, but testing revealed that optimizing the converter-battery connection is capable of dramatically improving system performance. As explained earlier, it is desirable in power electronics to place a stage of constant current between two stages of constant voltage. Thus, placing an inductor to act as a current source between the two components and serve as a buffer would likely yield much better performance than was observed with the resistive buffer.

While inductance between the converter and battery may improve performance, it is unlikely to be an optimal solution as it fails to address the root of the problem, which is the fact that the battery voltage varies depending on its state-of-charge. Some form of real time control, either analog or digital, is needed to truly optimize the converter-battery connection within the Li-Ion Boost system. For the sake of discussion, it will be assumed that a low-power microcontroller will be used implement this control. The real goal of the system is to put the most energy into the battery as possible. The current into the battery could be sensed and adjustments throughout the system made in order to maximize it. These adjustments could include changing the resistance of a digital potentiometer included as part of the voltage buffer. The goal of this would be to keep the buffer resistance as low as possible while allowing the converter to maintain normal operation given the present current producing ability of the PV array as set by light conditions. The output voltage of the boost converter could also be adjusted, not so much higher than the battery voltage that it can't maintain normal operation, but as high as possible to maximize current into the battery. This could again be done using a digital potentiometer, as a resistive divider external to the control IC sets the duty cycle, and therefore the output voltage, of the converter.

A microcontroller could also be used to install a peak power tracker (PPT) into the system. A PPT monitors the PV array and ensures that it is operating at the maximum power point on its I-V curve. The output voltage and current that define this point vary nonlinearly with light and temperature conditions. However, regardless of conditions, the array maximum power voltage varies directly with the array open circuit voltage [8]. Thus, a PPT could be instituted by replacing the comparator of the tested Li-Ion Boost system with a microcontroller, monitoring the array open circuit voltage, and setting the boost-enable trip voltage such that the array is constantly operating at the maximum power point of its I-V curve. In this way, the PV array will produce the absolute maximum amount of energy that it is capable of producing for any given set of conditions. It must be noted that a PPT could be installed in some way to improve the performance of any system, provided that the PV array is decoupled from the rest of the system.

Other Advanced Concepts

In addition to those listed above, many other ideas were generated for optimizing any small photovoltaic power supply. One of these is the creation of a vertically stacked PV array. As discussed earlier in this report, different photovoltaic materials respond to different frequencies of light as determined by the band-gap energy of the material. For a given single material photovoltaic cell, light of energy greater than the band-gap is absorbed, with only light close to the band-gap contributing to electrical generation, while light of energy less than the band-gap passes right through [1]. Thus, by stacking materials of different band-gaps, light of a wider range of frequencies may be used to generate electric energy and the overall array efficiency greatly improved. This concept could be especially useful in indoor photovoltaic applications, where fluorescent lights put out a strictly defined set of light frequencies. If the band-gaps of a multiple material array were matched to these frequencies, photovoltaics could become a much more viable power source for indoor applications. Many problems have been encountered by researchers attempting to form single cells of multiple materials, but perhaps an array could be made of separate cells, each with the reflective backing (intended to reflect any missed light of the right energy level) removed, stacked on top of one another could provide some improvement.

Other optimizations that could be made involve the physical size of a particular system. For the sizes of system focused on in this report (PV arrays of a few square inches), system size and performance is really limited by the size of the PV array.

Secondary batteries are available in energy densities great enough to easily provide sufficient energy storage in a small enough volume. However, as system size is decreased, perhaps resorting to more exotic and expensive PV arrays in order to increase array efficiency, the battery will at some point become the limiting factor. As volume is decreased, battery packaging and connections take up a greater portion of total battery volume and overall energy density is decreased. This point at which the neither the PV array area nor the battery volume are the single most limiting factor may represent the optimal size for a small photovoltaic power supply.

Other possible optimizations include a primary battery as a backup. If a system is to be deployed in an area where it may experience long droughts of sunlight, a primary battery could be deployed to serve as a backup when the PV array/secondary battery system is incapable of running the system. A geographical model could also be created for the various locations of deployment so a single system could self-optimize for its location by sensing light, temperature, and other climactic conditions.

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Conclusion

Over the course of this project, currently available PV and battery technologies were investigated and evaluated in terms of their suitability for a small, photovoltaic WSN power supply. Also, analytical techniques based upon dividing the operation of such a system into two distinct modes were developed. Operational tests of three basic small, PV power supplies were conducted and their performance analyzed. The research and experiments conducted as part of this project support the validity of the developed analytical techniques. They also indicate that using monocrystalline solar cells to charge a Li-Ion battery through a boost converter represents the most promising solution for the problem of achieving long term, autonomous WSN operation.

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