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A Step-by-Step Approach for Selecting Electric Power Systems for Kit and ARF RC Model Aircraft via Watts per Pound Guidelines

By David Dust

Introduction: If you have hung-out at the flying field for any length of time, you may have seen some “not-so-good” maiden flights where an electric powered model aircraft was either horribly under-powered or the aircraft suddenly lost power, probably due to the failure of some component of the power system. The techniques I describe in this article are intended to allow you to select the components of a model aircraft’s electric power system (i.e., propeller, brushless-motor, electronic speed control (ESC), and LiPo battery) that will allow the plane to perform as expected and take some of the worry out of maiden flights.

At this point I would like to make two confessions. Even though I am a retired “engi-nerd” with a doctorate, I have tried my best to write this article so that it does NOT read like a technical journal, while still trying to provide clear and concise information. However, I will apologize now for all of the equations. Second, the procedure I describe does require that you have access to a watt meter, that can be inserted in between the battery and ESC, to be truly helpful (as shown in Figure 1).

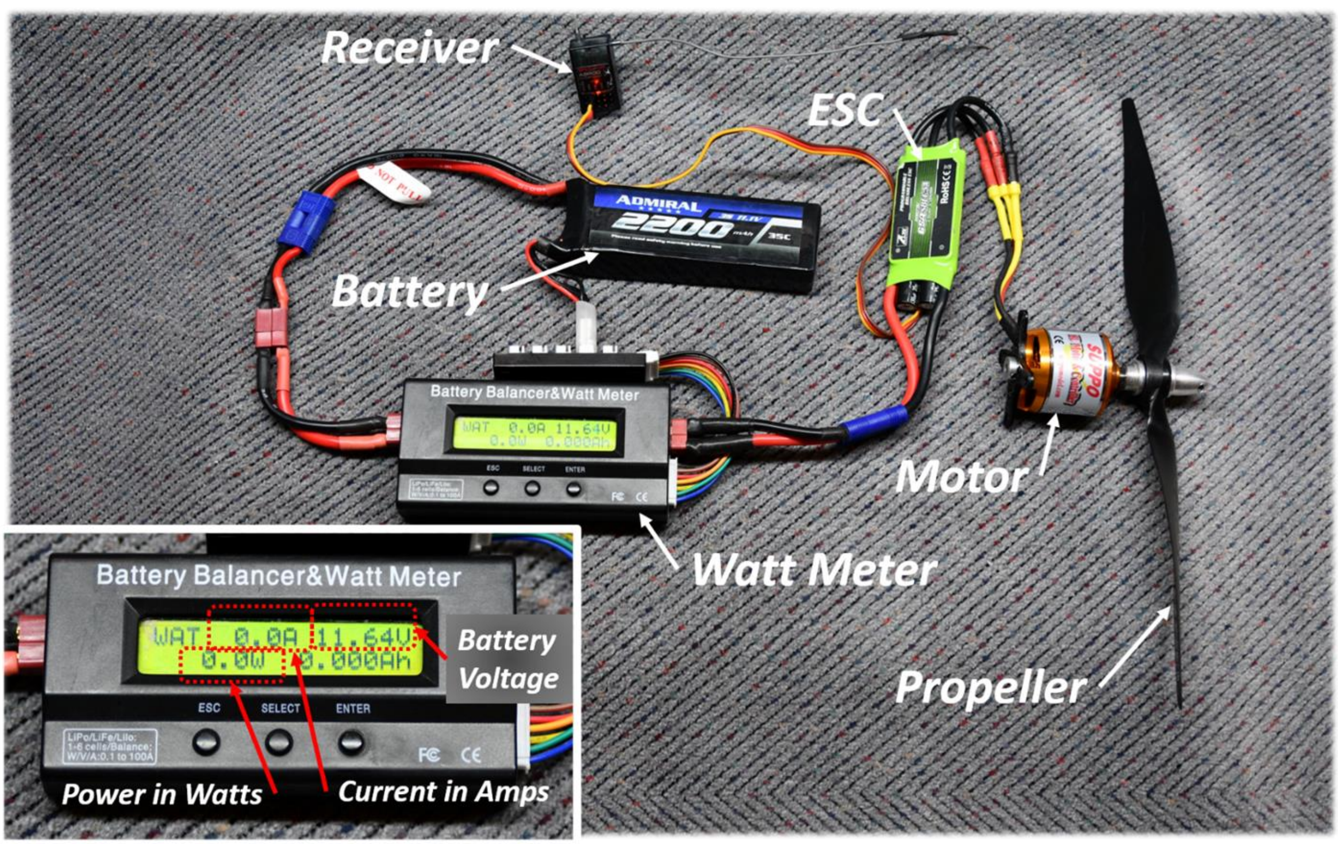

Figure 1: Example electric power system (minus the aircraft or test stand) with a watt meter inserted in between the battery and ESC

When I first got involved in flying radio-controlled model aircraft over 10 years ago, I purchased *Bind-and-Fly* and/or *Plug-and-Play* type electric aircraft, where someone else did the work in selecting a power system that provided at least good performance. However, I quickly got intrigued by the wide selection of *Almost Ready to Fly* (ARF) and kit aircraft available. Many ARF and kit manufacturers provide recommendations for power systems; however, it isn't uncommon that the recommendations are for fuel powered engines, obsolete brushed motors, and/or specific motor/battery combinations that are difficult to find and/or very expensive. So, I compiled a procedure for evaluating electric power systems based on test-stand experiments, the monitoring of the performance of my own aircraft, and compiling manufacturer specifications and recommendations. I have used this procedure to evaluate a range of power systems for both perspective model aircraft prior to purchase and to breathe new life into some of my older aircraft.

Today, a quick search on the internet and in *Model Aviation* reveals that there are a number of manufactures of electric motors, ESC's and batteries aimed specifically at model aviation. Hence, the procedure I present herein for selecting a power system is intended to allow the modeler to take advantage of the wide range of products available, as opposed to just following the retailer's or manufacture's recommendations. For example: I found an interesting ARF model of a Tucano on a website, where the manufacturer recommended a 46-size motor powered by a 6-cell battery. Using the 6-step procedure I describe below, I checked to see if the model aircraft could be safely flown using a 46-size motor and the 4-cell 4000 mAh batteries that I already owned, instead of the much more costly and heavy 6-cell batteries that were recommended. I estimated the *Watts per Pound* range to be about 85 to 100 W/lb on 4-cell batteries, which I considered appropriate for the model (per Table 1). Over the 180+ flights that I have since flown with the model on 4-cell batteries, I have found the flight performance to be spirited and quite appropriate for the model; however, I like flying the plane fast and performing a lot of vertical maneuvers, so the trade-off for using the smaller and lighter battery has been relatively short flight times of about 3 minutes.

Step-by Step Procedure: The six-step procedure that I use for evaluating alternative power systems for model aircraft is summarized below, while the rest of this article describes each of these 6 steps in detail; including equations, tables, and tips for selecting the various components of the electric power system:

1. **Estimate the Flying Weight:** After selecting an ARF or kit aircraft, identify and/or estimate the "flying weight" of the model (i.e., the total weight of the aircraft when in flight).
2. **Identify an Appropriate *Watts per Pound* Range and Initial Motor Rating:** Given the type of model aircraft selected and considering how you plan to fly it, identify an appropriate *Watts per Pound* range (via Table 1) and estimate an initial motor rating (via Eq. 1).
3. **Alternative Motor Evaluations:** Select a motor and battery combination, then compute the Watts per Pound (W/lb) that can be delivered over a flight based on the motor's *maximum current* specification and the voltage of the battery (via Eq.s 2 and 3). Comparison of this range of computed *Watts per Pound* values with the values you identified in Step 2 (via Table 1) provides a means to evaluate the adequacy of various power systems for a specific type of aircraft and your preferred flying style.
4. **ESC Rating Selection:** Select an ESC capacity and battery connector type based on the motor's *maximum-constant* current rating using a safety factor of 1.2 (via Eq. 4).

5. **Alternative Battery Evaluation:** Batteries should be selected such that their *safe* maximum discharge current (Eq. 5) is greater than the motor's maximum-constant current rating and have sufficient storage capacity for useful flight times (Eq. 6).
6. **Propeller Selection:** Test a number of propellers and select the most appropriate propeller for an aircraft's power system using a watt meter to ensure that the motor is operating near its *maximum-constant* current rating, while using the specific batteries that will be used to fly the aircraft.

Step 1 – Estimate the *Flying Weight*: Today, most retailers and manufactures provide an estimate of the flying weight for an ARF model aircraft on their websites and/or in the assembly instructions/manual, which can typically be accurate enough for evaluating power system options. In the situation where the manufacturer only provides the kit weight, it will be necessary to add on the weight of the covering, propeller, motor, ESC, battery, servos, and receiver. Upon completing the assembly of an ARF or kit, it is typically a very good idea to verify the flying weight (W_{fw}) of your aircraft with a postal scale, either in whole or in parts, and re-assess its *Watts per Pound* range. I personally have found that the actual *flying weight* for a completed ARF or kit can routinely be 5 to 10% different than that provided by the manufacturer.

Step 2 – Identify an Appropriate *Watts per Pound* Range: A Watt is the unit of measure for the rate of energy transfer through an electric motor, which is defined by the conservation of energy as the current (in amperes or amps) multiplied by the battery voltage. Over the years, many RC pilots have related the capacity of a power system and the *flying weight* of an aircraft, in terms of *Watts per Pound* (W/lb), to the requirements of various model aircraft performance types. Table 1 lists the general guidelines that I have found useful; however, there are also a number of this type of guidelines that can be found on the internet. Yet, it is also very useful to compute the Watts per Pound values for your own model aircraft and relate these values to the model aircraft's actual flight performance.

Table 1: Watts per Pound Guidelines for Model Aircraft

Aircraft Performance Type	**Watts/Pound (W/lb) Guidelines**
Very light slow flyers, with very low wing loadings (< 8 oz/sf)	50 to 70 W/lb
Powered gliders, basic park flyers, trainers, and vintage "old timer" type planes, with low wing-loadings (< 15 oz/sf)	70 to 90 W/lb
Sport aerobatic aircraft (intended for general sport flying through intermediate aerobatics) and scale/warbird-type aircraft with lighter to moderate wing loadings (< 30 oz/sf).	90 to 120+ W/lb
Sport aerobatic aircraft (intended for advanced aerobatics), 3D aircraft with lighter wing-loadings (< 15 oz/sf), and aircraft with moderately high wing-loadings (30 to 40 oz/sf) including scale warbirds	120 to 150+ W/lb
High-speed aircraft, warbirds with very high wing-loadings (> 40 oz/sf), and 3D aircraft with higher wing-loadings (> 15 oz/sf)	150 to 200+ W/lb

It is important to recognize that the information provided in Table 1 does not take into account the aerodynamic characteristics of model aircraft and this can make a big difference in actual flight performance. For example, consider models of a PT-17 (a biplane, military flight trainer from the 1930's) and a Tucano (a low-wing, military flight trainer from the 1980's), as shown in Figure 2. The Tucano will fly faster and may seem far more powerful primarily because it is far more aerodynamic than the PT-17, even if their power systems deliver similar *Watts per Pound*.

Figure 2: A visual comparison of 1930's vs 1980's aerodynamics: Maxford PT-17 vs a Phoenix Models Tucano

Given an estimate of the *Watts per Pound* appropriate for an aircraft via Table 1, Equation 1 can then be used to estimate the corresponding *maximum-constant* current (in Amps) required for a suitable motor.

$A_{mt} = (T_{W/lb} \times W_{fw})/(V_b \times F_{draw})$ Eq. (1)

Where: A_{mt} = target "maximum constant" current for the motor (A)
$T_{W/lb}$ = Target *Watts per Pound* (W/lb) via Table 1
W_{fw} = flying weight of the model aircraft (lb) per Step 1
V_b = fully charged battery voltage (V) = (N_{cells} x 4.2)
N_{cells} = the number of cells in the LiPo battery pack
F_{draw} = power draw-down factor estimated as 0.85 for batteries in very good condition.

Consider the following example for demonstrating how to use the information in Table 1 and Equation 1 to estimate an initial capacity of a perspective electric power system. Let's say we have an E-flite Slick, with an estimated flying weight (W_{fw}) of 2.3 lbs, and we would like to do at least intermediate level aerobatics (say $T_{W/lb}$ = 120 W/lb) while using a 3-cell battery (N_{cells} = 3). Via Equation 1, the target "maximum constant" current for the brushless-motor for the Slick should be about 26 Amps as follows:

Target "maximum constant" current (A_{mt}) = (120 x 2.3)/(3 x 4.2 x 0.85) = 26 A

Step 3 – Alternative Motor Evaluations: The motor controls the capacity of a power system, as a function of the motor's *maximum-constant* and *maximum-surge* current ratings. Many retailers and manufactures provide the *maximum-constant* current and/or the *maximum-surge* current specifications for their motors in units of amps, on their websites (e.g., AltitudeHobbies.com). To ensure reliable performance of a power system, it is appropriate to use the *maximum-constant* current rating for estimating the starting and ending operating limits of a power system, in terms of *Watts per Pound*, during a flight.

Another important motor specification to note is the voltage range over which the motor is designed to operate, which is typically expressed in terms of the corresponding number of LiPo battery cells. For example, many 480-size electric motors are designed to be powered by only 3 or 4 cell LiPo batteries.

The manufacturer's recommended storage level for LiPo batteries is between 3.75 and 3.9 volts per cell "at rest", while the fully charged voltage is 4.2 volts per cell "at rest". I try to fly my LiPo batteries only down to the “at rest” storage voltage of about 3.8 volts per cell; thereby, minimizing the potential for damaging the battery due to over discharging.

As we all know, the voltage of a battery drops as the battery discharges during a flight; however, the voltage of a battery also draws-down under load, due to internal resistance. That is, it can be observed with a watt meter that the battery voltage immediately drops or draws-down as soon as the throttle is advanced, but the battery voltage will recover significantly when the throttle is cut. The difference between a battery’s “at rest” and “under load” voltages can vary depending upon a battery’s *C-rating* and condition.

As the battery’s voltage decreases during a flight, the electric current (measured in amps) also decreases. The draw-down in voltage under load and the corresponding decrease in current can be measured by inserting a watt meter in between the battery and the ESC (in an electric power system for a model aircraft) and noting the variation in voltage and current, as the throttle is varied up and down. Via video recorded test-stand experiments, I measured the draw-down of the voltage and the corresponding decrease in current over simulated flights and estimated what I refer to as “power draw-down” factors. Based on these experiments, I estimate the maximum power available from the power system, in terms of Watts per Pound, at the start and end of a flight as:

Start of Flight: Max Watts per Pound (W/lb) = $(V_{bmax} \times F_{start} \times A_{max})/W_{fw}$ Eq. (2)
End of Flight: Max Watts per Pound (W/lb) = $(V_{bmin} \times F_{end} \times A_{max})/W_{fw}$ Eq. (3)

where: $V_{bmax} = (N_{cells} \times 4.2)$ = “at rest” battery voltage at start of flight
$V_{bmin} = (N_{cells} \times 3.8)$ = “at rest” battery voltage at end of flight
N_{cells} = the number of cells in the LiPo battery pack
F_{start} = power draw-down factor estimated as 0.87 at the start of a flight for a battery with a *C-rating* of about 35 and in very good condition
F_{end} = power draw-down factor estimated as 0.82 at the end of a flight for a battery with a *C-rating* of 35 and in very good condition
A_{max} = *maximum-constant* current rating for the motor per the manufacturer (A)
W_{fw} = flying weight of the model aircraft (lb)

Consider the following example analysis: For an E-flite Slick 480 (W_{fw} = 2.3 lb) with a motor rated at 25 amps (A_{max}) using a 3 cell (N_{cells}) LiPo battery, the estimated maximum *Watts per Pound* available at the start and end of flight (per Eqs. 2 and 3) are:

Start of Flight: Watts per Pound (W/lb) = (3 x 4.2 x 0.87 x 25)/2.3 = 119 W/lb
End of Flight: Watts per Pound (W/lb) = (3 x 3.8 x 0.82 x 25)/2.3 = 102 W/lb

If a 4-cell battery is used instead of a 3-cell, the estimated Watts per Pound for the given example would be (estimating the increase in the flying weight associated with the 4-cell battery of 0.1 lbs and assuming that the motor is rated for both 3 and 4-cell batteries):

Start of Flight: Watts per Pound (W/lb) = (**4** x 4.2 x 0.87 x 25)/2.4 = 152 W/lb
End of Flight: Watts per Pound (W/lb) = (**4** x 3.8 x 0.82 x 25)/2.4 = 130 W/lb

Via comparison with Table 1, the example power system using a 3-cell battery should provide sufficient power for at least intermediate level aerobatics throughout a flight with a battery in good condition, given the aerodynamic characteristics (including a wing-loading of about 14 oz/sf) of the Slick. Whereas, the example power system using a 4-cell battery should provide sufficient power for advanced aerobatics and 3D flight (and possibly even too much power for all but experienced pilots); however, the propeller may need to be different than the one used for 3-cell batteries.

Motor Selection Tip – Higher versus Lower Kv-Rated Motors:
It is important to recognize that Equations 1 and 2 inherently assume that the aircraft has sufficient clearance to select a propeller that allows the motor to operate near its *maximum-constant* current (A_{max}) with a fully charged battery (as described in Step 6). Propeller clearance limitations can become an issue for most multi-motor aircraft, float-planes, and/or tri-cycle gear aircraft, which can often have significant ground and/or fuselage clearance limitations.

A possible solution for an aircraft's propeller clearance limitation is to use a motor with a higher Kv-rating. That is, a number of manufacturers offer motors of the same physical size, but with different Kv-ratings. In short, motors with higher Kv-ratings are designed to operate at higher RPMs; as a result, they will draw a higher amperage and, thereby, generate more thrust with a smaller propeller than a motor with a lower Kv-rating. The Great Planes Twinstar and Electrifly Seawind are examples of aircraft with significant propeller clearance limitations (as shown in Figure 3) and are, therefore, good applications of higher Kv-rated motors. I fly my Twinstar and Seawind on 1400 and 1500 Kv-rated motors, respectively.

Figure 3: Examples of significant ground and/or fuselage propeller clearance limitations

Step 4 - Electronic Speed Controller (ESC) Rating: Most manufacturers print the capacity of their ESCs (in Amps) directly on the ESC and generally recommend selecting an ESC with a rating about 20% greater than the *maximum-constant* current rating (A_{max}) for the motor (i.e., a safety factor of 1.2), as reflected in Eq. 4.

Approximate Minimum ESC rating or capacity (amps) = $A_{max} \times 1.2$ Eq. (4)
where: A_{max} = the motor's *maximum-constant* current rating (A)

For example: Given a motor with a *maximum-constant* current rating (A_{max}) of 25 Amps, the manufacturer recommended ESC should have a rating (per Eq. 4) of about:

Approximate Minimum ESC rating or capacity (amps) = $A_{max} \times 1.2 = 25 \times 1.2 = 30$ Amps.

There is an old engineering or construction saying which probably dates back to the Egyptians: "When in doubt, make it stout." I believe that this saying applies to selecting the rating or capacity of an ESC. I have not seen any problems with flying an aircraft with an ESC that has some excessive capacity; however, I have seen ESC's with insufficient capacity shut down during flight, which often results in the complete loss of the aircraft. Hence, I personally would rather pay the price of up-sizing an ESC's capacity a bit, rather than losing power (even if only momentarily) during a flight.

Step 5 - Alternative Battery Evaluation: Per manufacturer's guidelines, batteries should be selected such that their *safe maximum discharge* current is at least greater than the motor's *maximum-constant* current rating and have sufficient storage capacity for useful flight times. Multiplying the *C-Rating* by the storage capacity for a battery yields the *safe maximum discharge current* for the battery, per Eq. 5.

Battery's Safe Maximum Discharge (A) = $(C_R \times B_{cap})/1000$ Eq. (5)

where: C_R = the battery's *C-rating*

B_{cap} = the battery's storage capacity (mAh)

Note: both C_R and B_{cap} should both be printed on the battery's label.

Due to their relatively high C-ratings (> 25C), today's LiPo batteries have relatively high *safe maximum discharge* currents with respect to most single motor systems; however, it is possible for multi-motor and electric ducted fan (EDF) power systems, especially those with high Kv-rated motors, to approach or exceed a battery's *safe maximum discharge* current. **Furthermore, I have found that I get the best battery longevity when batteries are never operated at a rate above about 50% of their *safe maximum discharge* rate.** Therefore, it can be quite useful to consider a battery's *safe maximum discharge* current and corresponding C-rating, with respect to both battery longevity and safety.

Consider the following example, a 30C-2600 mAh battery has a *safe maximum discharge* current of 78 amps per Eq. 5. The 450-size Suppo 2810/9 motor (Kv rating of 1350) has *maximum-constant* current rating of 35 amps. Hence, a model with twin Suppo 2810/9 motors could easily approach the *safe maximum discharge* current of a 30C-2600 mAh battery (with a *safe maximum discha*rge rating of 78 amps) and, thereby, potentially damage the battery permanently and severely reduce its longevity. Therefore, a battery with a *safe maximum discharge* current of approximately 140 amps (i.e., (2 x 35)/0.5) could be a better choice to improve the potential longevity of the battery, such as a 40C-3700 mAh battery with a *safe maximum discharge* current of 148 amps.

Flight times are a function of the electric power system, aerodynamic characteristics of the aircraft, and your flying style. However, I find it useful to get a rough estimate of the possible flight time for an aircraft with different battery capacities, for at least comparison purposes. I use the following equation to estimate a conservatively low maximum flight time for a battery:

Conservative Flight Time (min) = $B_{cap} \times (60/1000) \times (1/A_m) \times (C_1/C_2)$ Eq. (6)

where: B_{cap} = the battery's storage capacity (mAh)

A_m = maximum constant current for the motor per manufacturer (A)

C_1 = fraction of the B_{cap} available above 3.8 volts per cell = 0.44 +/-

C_2 = fraction of the motor's A_{max} rating utilized over a flight = 0.80 +/-

Note: Using C_2 = 0.80 assumes that a plane will be flown at essentially full-throttle for most of the flight.

For example: For an E-flite Slick 480 with a motor rated at 25 amps (A_m) flying on a 35C-2200mAh LiPo battery, the battery's *safe maximum discharge* current per Eq. 5 and the battery's the conservative flight time estimate per Eq. 6 are as follows:

Battery's Safe Maximum Discharge (A) = (C_R x B_{cap})/1000 = (35 x 2200)/1000 = 77 A
(Note: the battery's *safe maximum discharge* current of 77 A > motor rating of 25 A)

Conservative Flight Time (min) = 2200 x (60/1000) x (1/25) x (0.44/0.80) = 2.9 min ~ 3 min

Battery/ESC Connector Selection
It is important to select a battery/ESC connector type that has sufficient capacity for the amperages anticipated for a power system. Table 3 is a compilation of the battery connector capacity (in amps) information currently available on the internet.

Table 3: Capacities of Common Battery/ESC Connectors

Battery Connector	Max. Continuous Amps (A)
JST (red)	5
Deans/T-Connector (Red)	50
EC3 (3.5 mm Bullet) (Blue)	60
XT60 (yellow)	60
XT90 (yellow)	90
EC5 (5.0 mm Bullet) (Blue)	120

Step 6 - Propeller Selection: Although selecting the propeller is the last step in this procedure, in many ways it is the most important step, because it determines the ultimate performance of the power system and aircraft. Some motor manufacturers provide propeller compatibility information for their motors and this can provide a good starting point for selecting a propeller. However, it is important to recognize that a battery's specifications and condition can also significantly influence the actual amperage drawn by an aircraft's power system for a given propeller. Therefore, it is best to test a number of propellers and select the most appropriate propeller for an aircraft's power system using a watt meter to ensure that the motor is operating within or near its maximum-constant current rating, while using the specific batteries that will be used to fly the aircraft.

Watt meters specifically for model aviation are inserted in between the ESC and the battery of an aircraft's power system, as shown in Figure 1. With the aircraft and/or power system secure and powered-up with a fully charged battery, apply full-throttle for a few seconds and record the maximum amperage measured by the watt meter. This amperage is the actual maximum current (in amps) for the specific power system. Depending upon the manufacturer's construction and testing practices, it may be possible to operate an electric motor above its maximum-constant current rating for limited amounts of time without permanently damaging it; whereas, the risk for permanently damaging a motor by operating it near or above its maximum-max current rating, is essentially certain.

Propellers are defined by two parameters: diameter and pitch (e.g., 12x6). After performing a number of bench tests with a range of power systems, I have found that more than one propeller can result in the power system operating near the motor's maximum-constant current rating. For example: In my bench tests I have found that 11x7 and 12x6 APC-style propellers on a motor can have maximum measured currents that differ by only 2 or 3 amps, with the larger diameter propeller drawing the slightly more current. It can be helpful to identify propellers of differing diameter and pitch appropriate for a power system, because propeller clearance issues may make the shorter diameter propeller preferable.

Closing Thoughts: When I first started flying RC, I didn't have a watt meter and I didn't appreciate how much permanent damage could be done to a LiPo battery by over discharging it just once. For the past ten years, I have checked my battery voltage consistently after each flight. On two occasions I found that I had discharged a battery only slightly below 3.7 volts per cell, at rest immediately following the flight. Although in both cases the battery's voltage over time recovered to at least 3.7 volts per cell (at rest), the lives of these batteries were reduced by approximately 30%, in terms of charging cycles. Since I started flying my batteries down to no lower than about 3.75 volts per cell (at rest), my batteries routinely last 200 to 300 charging cycles, depending upon the brand and specifications of the battery. Therefore, the 6-step procedure that I describe herein for evaluating alternative power systems for model aircraft is based on only discharging batteries down to a storage level of 3.8 volts per cell (at rest).

Sources:
Altitude Hobbies
(970) 412-7303
www.altitudehobbies.com

Horizon Hobbies
(800) 338-4639
www.horizonhobby.com

MotionRC
(224) 633-9090
www.motionrc.com

Tower Hobbies
(800) 338-4639
www.towerhobbies.com

J.S.T. Mfg. Co. (Japan Solderless Terminal)
www.jst-mfg.com

Dongguan Hexie Electronic Technology Co., Ltd.
https://hexiedz.en.china.cn/

Changzhou Amass Electronics Co., Ltd
https://china-amass.en.china.cn/