# Opportunities Amid Crises

**Wally E. Rippel**

**November 4, 2009**

## 1.0 Introduction

In almost every crisis, there are hidden opportunities for something good. In 1957, the Soviet Union launched the planet's first artificial satellite - Sputnik. At the time, Sputnik was seen as something bad for America. Through Sputnik, we could see Soviet influence spreading and we could see a new military threat just over the horizon. However, America responded to the challenge and we benefited greatly. Today, when a hurricane threatens, we are better able to protect life and property, thanks to orbiting satellites, which, at best, would have been delayed without the Soviet challenge. Likewise the technologies spawned from the space race of the late 50's and 60's have given us so many of the technological wonders we now take for granted – computers, the internet, and cell phones - to mention but a few.

We now face two crises, each of which is far greater than Sputnik - Oil Depletion and Global Warming. Oil is the "blood" which powers transportation and agriculture. Without it, conventional cars, trucks, tractors and airplanes would all be "dead". And without use of these machines, most people would also be dead. There would be no way to get to the store, but no matter, for there would be no food at the store for lack of transport. And even if there were a means for food transport, there would be little to ship given the absence of fuel for farm equipment and chemicals for fertilizers. While oil will not suddenly "run out", it appears that we are now at the point where scarcity factors are overpowering technological advances such that the real cost (hours of work per barrel produced) are increasing. We have likely crossed the threshold known as "peak oil". Two years ago, world oil production was at 85 million barrels a day. Now it is at 83 million barrels. In 2008, oil reached $147 a barrel with $5 gas close at hand. It is likely that this may contributed to the present world recession. It is also likely that future prosperity will be limited by the price of oil.

While peak oil may be a threat to "our way of life", global warming may be a threat to life itself. Since the mid-nineteenth century, atmospheric carbon dioxide has increased from 270 to 385 parts per million. This has in turn has caused the average temperature of the lower atmosphere to increase by nearly 1 degree C – which in turn has triggered massive ice loss around the globe. All of this is also serving to magnify weather patterns – including drought and severe storms. Unchecked, the process of global warming may lead to a run-away situation where the loss of planetary light-reflective ice leads to further global warming – in a spiraling cycle of destruction.

Humanity's response to these two crises will determine our future. We have some choices – just as we did back with Sputnik. We can pretend that the problems do not exist. We can accept the problems as real, but choose to not respond because of the difficulty. We can respond, but without the needed commitment. Or we can meet the problems head-on with the required response. Should we choose, the last option, there will of course be expense, just as there was with the space program. There will also be benefits, such as the development of new technologies and new markets. If the future is anything like the past, the benefits will far outweigh the costs.

It is interesting to see how and where we, the designers and developers of electric motors, relate to these two crises. Let's first consider oil. While approximately half of the electrical energy generated in the U.S. is delivered to electric motors, only about 1.5% of the generated energy comes from oil. Hence, it appears that electric motors have little to do with oil consumption. On the other hand, we are new beginning to see electric motors used significantly in connection with hybrid, plug-in hybrid, and electric vehicles. In all of these cases, the use of electric motors enables either a more efficient use of oil – as in the case of hybrids, or the direct replacement of oil – as in the case of plug-in hybrids or pure electrics. So, when it comes to oil, we may be part of the solution. After decades, this is now being recognized. Federal and private investment funds are now becoming increasingly available for the development of hybrid and electric vehicles. This will mean new opportunities for the development of electric motors which have reduced manufacturing costs combined with increased power densities and increased energy efficiencies.

In the case of global warming, electric motors have some "guilt by association". More than 10% of the world's CO2 generation is associated with the generation of electric power which is specifically supplied to electric motors. The key to solving this problem will be the replacement of coal-fired generation with carbon-free generation such as wind, solar and nuclear. However, to a lesser extent, the development of more energy efficient electric motors will also play a role. Accordingly, there will likely be expanded opportunities in connection with the development of high-efficiency electric motors for all sorts of applications ranging from air conditioning systems, refrigerators and washing machines to large industrial applications such as steel rolling and water pumping.

In the following, we will focus on the challenges and opportunities for electric motors in connection with the transportation sector - electric and hybrid vehicles.

## 2.0 Trade-Offs Involving Electric Propulsion Motors

For every application, the ideal electric motor would be one which costs nothing to manufacture, which weighs nothing, and which has unity (or higher) energy efficiency. Unfortunately, none of these attributes can be attained in the real world. Like it or not, we have to settle for machines which cost money to make, and once made, have mass and lose energy. The issue at hand is to quantify the trade-offs between these and other parameters.

Trade-off numbers differ widely depending on the application. In industrial applications, cost and efficiency may be crucial with mass relatively unimportant. Conversely, for aerospace applications, mass and efficiency are usually the key drivers – with cost taking a back seat. For all those involved in the design process, it is important that readily available trade-off numbers are at hand. Without this, it is possible, for example, that one designer will focus on achieving low mass but at high manufacturing cost – while a second designer might do just the opposite. When two such efforts are merged, the worst of all worlds happens and the product is both heavy and costly; the “bad” overpowers the “good”. Indeed, it is better for all designers to be working to a common set of flawed trade-off numbers than to have no trade-off numbers at all.

Of course, the best situation is to have the right trade-off numbers. Using these, rational decisions can be made concerning candidate approaches for reducing cost (at the expense of mass or efficiency), or for reducing mass (at the expense of manufacturing cost or efficiency), etc.

All of this is quite important for electric and hybrid vehicle applications. Manufacturing cost of the motor will of course have a direct impact on the cost of the vehicle – which in turn will determine how many vehicles can be sold. Mass, size and efficiency are also critical as they too relate to cost. As efficiency drops, the battery must be up-sized – which in turn means that the rest of the vehicle bust be enlarged – which further means more money up front and more money over time in the form of energy costs. The story is much the same concerning size and mass - which cost money up front and over time. Hence, step one in the design process should be the evaluation of the trade-off numbers for the specific environments associated with electric and hybrid vehicles.

## 2.1 Determining The Cost-Efficiency Trade-off for Motors in EVs and HEVs

The economic impact of efficiency is determined primarily by battery depreciation and to a lesser degree by the cost of electrical energy. With state of the art lithium ion batteries, the high volume, packaged manufacturing cost is approximately $400 per kWh - with an average life corresponding to about 500 (100% depth) cycles. It follows that the depreciation cost is therefore about $400/500 = $0.80 per kWh throughput. The cost of electricity varies from location to location and in some cases with the time of day. Given the fact that rates are on the way up, a moderately high cost is assumed - $0.15/kWh. Finally, account must be given for the energy loss in both in the battery and the battery charger. For the present state of the art, charger efficiency (averaged over a complete recharge) is approximately 87% (including energy losses associated with blowers, etc.). For the lithium ion battery, the round trip energy efficiency is typically 92%. Taken together, the combined charger-battery efficiency is about 80%. Thus, when battery depreciation, electricity cost, and energy efficiency are combined, the total cost of energy delivered at the battery terminals is approximately $1.00 per kWh.

In the case of a mid-sized, 1500 kg electric or plug-in hybrid vehicle, the electricity use averages about 0.3 kWh per mile. Thus, over an assumed vehicle life of 150,000 miles, the energy use is 45,000 kWh and, based on the above, the value of that energy (including battery depreciation) is $45,000. Approximately 5% of this energy is used for non-propulsion functions such as lights, air conditioning and power steering; the remaining energy, valued at approximately $43,000 is applied to the drive system. Accordingly, a 1% improvement in the energy efficiency of the drive system can be valued at $430. Accordingly, the motor cost-efficiency trade-off is determined as **$430 = 1%.**

The meaning of this trade is that one who specifies and purchases the motor should be willing to spend up to $430 to gain 1% efficiency, provided other factors, such as weight remain constant. When the “cost of money” and various sales issues are considered, this number will likely revise downward.

## 2.2 Determining The Cost-Mass Trade-off for Motors in EVs and HEVs

For each kg of added mass, the vehicle structure and drive system mass must increase by a total of about 0.3 kg in order to maintain range and performance; likewise, the battery mass must increase by about 0.2 kg. Thus, adding 1 kg results in a total mass gain of 1.5 kg. For each kg of added mass, the vehicle energy use (at the wall plug) increases by approximately 0.06 Wh/mile. Hence, for the addition of 1.5 kg, the energy use (at the wall plug) would increase by 0.09 Wh/mile. Since the battery output energy is 80% of the wall plug, the energy increase at the battery would be 0.072 Wh. Thus, over the 150,000 mile vehicle life, energy use (at the battery terminals) will therefore increase by 10.8 kWh. As noted earlier, the value of battery delivered energy is approximately \$1.00 per kWh – which brings the energy related costs to \$10.80. To this, we must add the cost of the added vehicle structure, added propulsion, and added battery. The added vehicle structure and propulsion costs approximately \$4/kg. Hence, for an added 0.3 kg, this cost component comes to about \$1.20.

The battery specific energy is typically 150 Wh/kg and the battery cost is \$0.40/Wh. Accordingly, the added battery cost associated with 0.20 kg of battery is approximately \$12. The three costs sum to \$24. Accordingly, the motor cost-mass trade-off is determined as **\$24 = 1 kg.**

The meaning of this trade is that one who specifies and purchases the motor should be willing to spend up to \$24 to reduce mass by 1 kg, provided other factors, such as efficiency remain constant. When the "cost of money" and various sales issues are considered, this number will also revise downward.

## 2.3 Determining The Mass-Efficiency Trade-off for Motors in EVs and HEVs

The mass-efficiency trade (where cost is held constant) is simply the quotient of the cost-efficiency trade and the cost-mass trade. Accordingly, the mass-efficiency trade is determined as (\$430/1%) / (\$24/kg) = 18 kg/1% or **18 kg = 1%.** The meaning of this is that the one who specifies and purchases the motor should be willing to accept a mass increase of 18 kg in order to gain an efficiency of 1%.

Efficiency is of course a function of both speed and torque. Accordingly, for a vehicle application, where speed and torque are continually changing, some sort of weighted average is required. The weighting should be with respect to energy and not time. The weighting factors are based on how vehicles are driven and therefore may change some from vehicle to vehicle. In the end, all that is needed is a characteristic speed and torque under which one efficiency point is measured. From experience, it appears that for most on-road applications, the speed and torque associated with 60 mph on a 2% upgrade works reasonably well.

## 2.4 Applying the Trade-offs to the AC Propulsion EV Motor

AC Propulsion builds complete drive and recharge systems based on induction motors which use copper cage structures. For their 150 kW system, the inverter-motor system has a peak rating of 150 kW (shaft) at 6000 rpm. The continuous rating is approximately 40 kW. The measured peak point efficiency of the inverter-motor combination is 92% (at 30 kW, 6000 to 8000 rpm); the motor itself achieves a peak point efficiency of 95%. The motor mass is 46 kg and the estimated high-volume production cost (rough estimate) is $1000.

Since the cost-efficiency trade is $430/1%, it follows that for the ACP motor one should be willing to increase the manufacturing cost by something approaching 43% to gain one percent average efficiency (assuming mass is constant). Likewise, with the cost-mass trade at $24/kg, it follows that one should be willing to increase the manufacturing cost by 1.1% in order to reduce the mass by 1% (assuming efficiency is constant). Finally, using the mass-efficiency trade of 18kg/1%, one should be willing to increase the ACP motor mass by 39% in order to gain 1% in efficiency (assuming the manufacturing cost is held constant).

As mentioned before, one of the main purposes in establishing these trade-off numbers is to determine which developments make sense and which do not. For example, using the cost-efficiency trade-off it can be determined whether the added cost of the copper rotor cage is justified. Likewise, using the cost-mass trade, one can determine whether a candidate light-weight power cable might be justified.

## 3.0 Making Ever Better Motors for EVs

The quest will never end for designing and building ever better motors – ones which have lower manufacturing costs, which are smaller and lighter, yet which are more energy efficient. The question is what to focus on. Which areas of development stand to yield the greatest “bang for the buck”. We start with some basic equations which deal with power conversion and heating:

$$P = K_1 * S^4 * (J * K_p) * (B * f) \tag{1}$$

$$P_d = S^3 * [K_2 * \rho * (J * K_p)^2 / K_p + K_3 * B^{\alpha} * f^{\beta}] \tag{2}$$

$$\Delta T = \theta * P_d \tag{3}$$

$$M = K_4 * S^3 \tag{4}$$

In the first equation, P is the shaft power, S is a characteristic linear dimension of the motor such as bore diameter or stack height, J is the current density, $K_p$ is the winding packing factor, B is the magnetic flux density, and f is the applied electrical frequency; $K_1$ is a constant which is based on details of the motor design.

In the second equation, $\rho$ is the resistivity of the winding averaged with the resistivity of the rotor cage; $K_2$ is a constant based on design and $K_3$ is a constant based on design and proportionate to the magnetic loss; $\alpha$ and $\beta$ are magnetic loss constants (typically $\alpha$ is around 2.2 while $\beta$ is around 1.5).

From equation (3), $\Delta T$ is the temperature difference between the "hot spot" and ambient, while $P_d$ is the motor loss. $\theta$ is a fictitious thermal impedance constant which relates these two quantities.

Finally, in the fourth equation, M is the total machine mass and $K_4$ is a constant (which changes some with machine design).

### 3.1 Achieving Increased Specific Power

From Eqn. (1) we see that if either J, $K_p$, or f are increased, then the shaft power will also increase. When we do any of these, the power dissipation, $P_d$, will also increase – as noted by Eqn. (2). This in turn will mean that the hot spot temperature will rise, unless the critical thermal impedance is lowered via improved cooling. In most cases, it will also mean that the machine efficiency drops due to either rapidly increasing $J^2$ losses or rapidly increasing magnetic losses. However, if, however, both J and f are increased in near proportion, then the rate at which losses increase may be similar to the rate at which shaft power increases – and energy efficiency is maintained while specific power increases.

If, for example, current density is doubled and frequency (and hence shaft speed) are also doubled, then the shaft power will increase by a factor of four, while the heat dissipation will increase by a factor of four (actually a little less than a factor of four since $\beta$ is usually less than 2.0). Accordingly, the efficiency remains constant (or slightly increases), while the specific power increases by some 300%. If the critical thermal impedance is then reduced by a factor of four, the hot-spot temperature rise will remain the same as for the baseline case and all will be great.

In order to carry out the above "algorithm", it is clear that several areas of design improvement must be tackled at once. Item 1 is that the thermal impedance must be improved. In the case of induction machines, this generally means that improved means of rotor cooling must be achieved. For both induction and brushless machines, it also means that improved means of stator cooling must be employed: End turn cooling must be improved; heat transfer within the winding must be improved; heat transfer through the slot liners must be improved. The list goes on. The good news is that present designs have lots of room for improvement – especially when fluid cooling means are implemented. Reducing $\theta$ by a factor of ten for many designs is in fact realistic.

Item 2 is that the machine must be capable of operating at increased mechanical speed. In many cases, this means that design modifications are required – such as the addition of end ring captures and stiffening of the rotor stack. It may also mean that modified gearing and bearing lubrication must be used.

One direct means for increasing P is where a copper rotor cage is used in place of the conventional aluminum cage. This enables J to increase without increasing $P_d$ – which means that both rated power and efficiency can be simultaneously increased. (The efficiency increase is typically around 1.5% at the rated power point). Copper cage fabrication, however, comes at a price. Per unit volume, the cost of copper has ranged between five and fifteen times that of aluminum over the last decade. (The ACP motor rotor uses 13.6 lb of copper per rotor. In 2008, copper reached a high of $4.00 per pound. At this price, the copper cost for the rotor was $54.40. If the same cage were structured from aluminum, the cage mass would be 3.63 lb. In 2008 aluminum also reached its high - $1.75 per pound. At this price, the aluminum cost would have been only $6.36.) In addition to the large difference in material costs, the casting of copper is also much more expensive than aluminum – due in part to the higher melting temperature of copper. Other copper cage fabrication techniques, such as where extruded bars are inserted into the rotor stack and then welded within the end ring structure are even more expensive. However, when the trade-offs are considered, the copper cage appears to be justified for most EV applications.

### 3.2 Achieving Increased Efficiency

From Eqns. (1) and (2), we note that if the packing, $K_p$, is increased, that shaft power, P, will increase more rapidly than losses $P_d$. Thus, one means for improving the efficiency is to find means by which the packing factor can be increased. One approach is where machines are hand wound. In most cases, the cost trade-off numbers rule this option out. Another means is where rectangular “bus conductors” are used in place of stranded conductors. This approach is typically used for large machines, but generally requires hand labor. Recently, techniques have been developed where segments of bus windings are machine inserted in slots and then welded together using automated processes – to form the completed winding. While these approaches can achieve very high packing factors combined with good heat transfer and good manufacturing economics, they have one imperfection when compared with conventional multi-strand windings - namely increased skin and proximity losses. This problem is amplified in the EV environment where relatively high excitation frequencies are involved (up to 400 Hz). Considering the combination of issues, the ultimate answer for achieving a low-cost winding which achieves a high packing factor, but does not suffer from AC losses is where a pre-formed multi strand winding is pre-formed and then applied to a two piece stator stack such that the winding can be easily inserted in fully open slots. Further development is required before these approaches are ready for manufacturing.

Improvements in the stator and rotor magnetic cores may offer even greater opportunities for improving efficiency. While global efforts will surely continue to provide lamination materials which have reduced losses and better cost effectiveness, it is unlikely that any major materials breakthroughs will suddenly occur. Despite this, there may be some “low-hanging fruit” which has yet to be picked.

One idea is where different lamination materials are used for the stator and rotor. For the stator, the ideal material is thin, low-loss silicon steel. For the rotor, the fundamental frequency component is quite low (equal to the slip frequency), and hence, with the exception of harmonics due to tooth and slot interactions (and harmonics due to the inverter), low loss characteristics are not nearly as important as with the stator laminations. Accordingly, thicker, lower-cost materials can be used where the saturation flux density is higher than for the stator. This, in turn, can allow narrower rotor teeth, which in turn means that the cage bar cross sections are increased. This, of course will lower R2 and may make cage casting a bit easier. The economics be compromised if the stator lamination centers are lost. However, in cases where the “donut” holes can be used for other products, the economic penalty could even be a plus.

Another idea, currently being investigated, is where grain oriented material are used – either exclusively, or in combination with non-oriented materials. One design approach which might benefit from the use of oriented steel is where each lamination is replaced by several equal sectors which join together to take the place of a conventional lamination. By systematically misaligning the joining points of contacting laminations, a rigid core structure can be provided while possibly achieving improved loss and permeability characteristics. While manufacturing costs per unit frame size will surely increase, it is possible that the reduced losses will be justified by the trade-offs discussed earlier.

## 4.0 How Good Can it Get?

One of the things that makes engineering exciting is the contemplation of radical technical improvement. While it is hard to see the future – without a reliable crystal ball, we can get some insights based on the laws of physics. Physics tells us that we cannot make motors which are 110% efficient. It tells us what is impossible. But, where the laws of physics do not indicate impossibility, there is always the implication of possibility. For example, with both batteries, power electronics, and electric motors, there are no laws which set ultimate limits on specific power.

Today, we have the T-Zero and the Tesla Roadster – both with demonstrated accelerations of under four seconds to 60 mph. Today, we have the ACP-150 induction motor which has a measured peak point efficiency of 95%. Surely there is room for improvement. So we ask, how good could we make batteries and motors? What are the physical limits? If we start with present materials (e.g., silicon steel and copper or aluminum), how many horse power (or kW) could one get per pound (or kg) of machine on a continuous basis? Could we beat jet engines which put out something like 6 horsepower per pound?

Using some of the principles laid out above, where state of the art heat transfer is combined with high speed, the results are quite surprising. For both induction and brushless machines (in the 20 cm diameter class), continuous specific torques of better than 4 Nm/kg should be possible in the near term. Likewise, intermittent specific torques above 10 Nm/kg should also be possible. And, for the same machines, peak efficiencies above 97% should also be possible in the near term. And where speed is pushed to the materials' limit, continuous power levels above 3500 W/kg should be possible in the near term.

Fifty years ago, it seemed that induction motors were a mature technology. Today, it seems that we are just getting started.