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The Cost of Manufacturing Electric Vehicle Drivetrains

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Report for the California Air Resources Board

by

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Introduction

Propulsion systems designed specifically for electric vehicles (EVs) are currently produced in small volumes and sold at high costs, although some components used in hybrid EVs are beginning to see production in higher volumes. At present, there are two primary choices of motor technology for use in EV drivetrains. Most vehicles in pilot-scale production today use alternating current (AC) induction systems, but some vehicles, such as the Toyota RAV4, use systems based on brushless permanent magnet (BPM) motors. Both AC induction and BPM systems offer similar advantages over conventional direct current (DC) brush motors. These include lighter motor weights, higher efficiencies, and lower service requirements (the brushes in DC brush motors wear out and require replacement). In general, AC induction motors provide high efficiencies over a wide range of operation, while BPM motors provide higher peak efficiencies. BPM motors also tend to be lighter, but they use rare earth magnets that are somewhat costly at present. Both of these motor types require complicated control systems relative to DC brush motors, in order to operate from a DC source.

We analyze both AC induction and BPM systems because both are good choices for use in EVs, and it is not clear which system will prove to be the most popular. The control systems needed for these types of motors are costly and complex, but the necessary electronics, particularly insulated-gate bipolar transistor (IGBT) power switching devices, have been improving rapidly. Continued progress in IGBT technology is expected, particularly with regard to the saturation characteristics of the devices and their switching energies, and inverters in general are expected to progress in terms of not only the cost and performance of the IGBT silicon chips, but also in packaging, controls, processors, and transducers (Hodkinson, 1997).

Recent statements by EV project managers at GM and Ford reflect the progress that has been made in reducing the cost and complexity of EV motor controllers over the past few years. Bob Purcell of GM reports that the second generation EV-1 motor controller has only three IGBTs, while the first generation had six. The new IGBTs have twice the power handling capability of the old ones, with equal precision levels. Overall, the new electric drive control system has half the mass, one-third fewer parts, and half the cost of the first generation system (Purcell, 1998). John Wallace of Ford reports similar progress in the development of its system (Wallace, 1998):

> "We have gone down in numbers and parts in the controller – it started out quite complicated. I can remember the original Ecostar controller, which was quite complex; then there was a two-board controller and now a one-board controller, and perhaps we will go down to a no-board controller basically by mounting control circuitry right on the motor. All that stuff is tearing out cost" (p. 14)

neodymium-iron boron magnet material to drive overall cost reductions in BPM motors.

The neodymium-iron boron magnet was developed by the Sumitomo Corp. and first commercialized in 1983. Estimating the cost of this material is somewhat complicated, but the Argonne estimate of $50 per pound is reasonable for high volume purchases, according to the Sumitomo Corp., which currently supplies magnet material to Unique Mobility, Inc (Numajiri, 1997). The price charged to the OEM is dependent upon the volume of the order, the term of the contract, the commodity prices of the basic materials, and the yen/$ exchange rate, among other factors. Sumitomo has licensed production of the material to other companies, some of which operate with lower labor costs in Korea than does the Sumitomo operation in Japan, but the quality of the Sumitomo product is better because they are the inventors of the product and most knowledgeable and adept at its manufacture (Numajiri, 1997). Sumitomo is currently expanding production, with capacity expected to double from 1997 to 2002-3, and this expansion is being driven to a significant extent by demand for motors in the automotive industry. This expansion in capacity and increased emphasis on producing motor magnet materials for automotive production could potentially result in a softening in the price of neodymium iron boron magnets for EV motors. Due to the confounding factors mentioned above, however, it is difficult to confidently forecast a future cost much lower than the present one, but costs of $40 per pound are considered possible with a strong dollar, and a high-volume, long-term material supply order (Numajiri, 1997).

With the materials cost breakdowns shown in Tables 8 through 10, Cuenca estimated total motor prices with the assumption that ample jigs and equipment were available for machining, winding, welding, and assembly. The assembly and testing process was estimated at 30% to 40% of the total manufacturing cost (Cuenca, 1995). To this total manufacturing cost, a gross profit margin of 20% was added to obtain a total cost to the OEM. Table 11 presents the results of Cuenca's analysis for three different motor types. Note that these prices were estimated for motors of different power ratings. As discussed above, consistent price comparisons of different types of motors are complicated by the lack of standards for rating motors, and the different performance characteristics of AC, DC, and BPM motors. See the following section for per-kW estimates of motor prices.

Finally, one other study of EV motor costs has been published in recent years. This assessment suggests that the mature production costs, per peak kW, of DC brush, BPM, AC induction, and switched-reluctance motors are $10 per kW, $10-15 per kW, $8-12 per kW, and $6-10 per kW, respectively (Rajashekara and Martin, 1995).

Cost Estimates for Controllers

ANL has also estimated near-term but high production volume costs for motor controller materials and assembly operations. For AC motor controllers with a 70 kW capacity, Cuenca estimates that materials costs come to from $1,975 to $2,575, while for similar capacity BPM motor controllers materials costs range from $1,375 to $1,675 (Cuenca, 1996). Approximately two-thirds of total materials costs for AC

These statements suggest that in addition to production scale economies, product innovation will lead to reduced EV drive system costs as the EV market matures.

Reviewed below are the current costs and weights of electric motor and controller systems, estimates of potential system costs at higher production volumes, estimates of motor and controller materials costs, and cost functions for electric motors and systems that have been proposed in other EV cost studies. Finally, based on these data, cost functions for motor and controller systems are developed, at different production volumes, with costs estimated as a function of system peak power rating. Also, motor and controller weight functions are developed as a function of system peak power rating.

Present Costs of Industrial Motors

As a starting point to investigating the costs of manufacturing EV motors in volume production, it is worth examining the present motor industry where motors for various industrial and commercial uses are a mature product. As can be seen in Figure 1, the current average cost (in $1991) of electric motors listed in Census Bureau data is very near $40 per kW for motors above about 10 kW. These data are very highly aggregated and is only broken down by motor size and not motor type or production volume. As the data provided in this report indicate, current EV motor costs are typically much higher than those indicated in the aggregate data (this is not surprising given the higher performance of these motors and their low production volume), while projected future motor costs are in some cases considerably lower. There are at least two potential explanations for this latter discrepancy:

1. There are no well-established, widely accepted standards for motor ratings. The census data do not report whether the motors are classified by peak rating or continuous rating. Given that the difference between these two ratings can be as much as 2-4x, inconsistencies in motor ratings could account for much of the difference between current motor costs by kW and projected EV motor costs by kW. For example, one estimate of the cost of a Hughes AC motor in high volume production is approximately $13/peak kW and $37/continuous kW. Thus, if we assume that the census data classifies motors by continuous rating, the projected rating for the Hughes motor is reasonably consistent with current data.

2. The data reported in the census are aggregated across motors produced in varying production volumes, from very large volumes to small runs of custom motors. The inclusion of small production run data could bring the per-kW cost up significantly. However, it is unknown what percentage of the motors included in the census data are produced in what production volumes, and it is also not specified what percentage of the motors are AC, DC, and BPM.

Current and Projected Propulsion System Costs

EV drive systems are currently being produced in small volumes, and retail prices are available from a few different manufacturers. Most of these prices are quite high, and they would be lower for large volume orders due to economies of scale. They are included primarily for purposes of comparison. We also include analysis of some smaller motors, because the specifications of these motors are useful for establishing functions for motor weights in relation to peak power ratings, and also because some EV designs may use an additional small motor to drive compressors for auxiliaries such as HVAC, power brake, and power steering systems.

Motors

Table 1 presents current prices for a variety of EV motors. Present motor prices are quite high, but these price quotes are for single unit purchases, and even at the present time volume discounts are available. Pricing for high volume orders would be negotiated based on the volume of the order and the term of the contract, among other considerations.

Systems

An EV drive system consists of the pairing of a motor with a controller/inverter. Some manufacturers, such as Solectria and Unique Mobility, make a range of different motors and controllers. In some cases, different levels of drive system peak power and torque can be obtained by pairing a motor with one of two different controllers. Other manufacturers, such as Hughes/Delco, make a single motor and controller system, with the two components matched to each other. Tables 2 and 3 present costs for complete drive systems, based on a pairing of a motor with a controller that provides it with the power rating shown. These drive systems include regenerative braking capability, as well as controls for vehicle auxiliaries. The Hughes system also includes a built-in 15-Amp charger, as well as DC power for auxiliary systems.

System Weights and Costs by Weight

The weight of the EV drivetrain is a significant variable to the overall analysis of the vehicle, because like all components the weight of the drivetrain contributes to the overall weight of the vehicle, and the vehicle weight in turn determines the size of the drivetrain that is needed to provide a given level of performance. Tables 4 and 5 and Figure 2 present data on the weights of various EV motors, controllers, and systems, as well as calculating the current retail $/lb cost for each component.

System Costs By Kilowatt Rating

Motor and controller costs are commonly assessed as a function of their peak kW rating. For motors, this is probably a better approach than it is for controllers, since controller costs do not scale as well as a linear function of their rated power. This is because only the high power electronics in the controller change as a function of the manufacturing cost is about half the cost to the OEM, with a labor component of 22.3%, a materials component of 31.8%, and overhead costs of 45.9% (source withheld by request). This motor is rated at only 8 HP, but it weighs 150 pounds and generates over 400 lb/ft of torque when starting a vehicle from a standstill.

The same manufacturer also makes basic AC motors that they supply to both GM/Hughes and Solectria, as well as to many other companies. The motors supplied are just the basic core motor units that then require significant additional parts and assembly. Different motors are supplied to the two companies. The one for Hughes is liquid cooled with a special splined drive shaft, and it produces 50-80 kW, depending on controls, and 160 lb/ft of torque at locked rotor. The motor for Solectria is the basic industrial design, rated at about 10 hp, with 100 volt, 3 phase windings. These motors are manufactured on the company's flexible flow AC motor production lines, and they therefore benefit from volume efficiencies even in relatively short production runs. The basic cost to OEM customers for these motors is about $390, not including extras such as cable assemblies, encoders, t-stats, and the liquid cooled package for the GM/Hughes motors. Of manufacturing cost, materials make up 53.5%, labor comprised 5.8%, and overhead comes to 40.7%. The additional costs for assembling extra components include $10 for labor, and $70 for overhead, plus the costs of parts and overhead on parts (40% of parts cost).

In addition to these manufacturer data, other motor cost data are available from government research programs. Argonne National Laboratory (ANL) has conducted research on EV motors, and detailed materials costs and high-volume manufacturing costs have been estimated for DC, AC induction, and BPM motors. The materials cost estimates for these motors are presented in the Tables 8 through 10. For BPM motors, note that a substantial component of total materials cost (36.9%, as estimated by ANL) is the cost of the neodymium iron boron magnet material.

One advantage of these detailed materials breakdowns is that it is possible to take account of per pound price changes in specific motor components. For example, if the cost of the magnets used in the BPM motor were to drop from $50/lb to $30/lb, the new motor price could be calculated as follows (Cuenca, 1995):

- permanent magnets constitute 36.9% of motor cost (and by extension price because assembly and profit are calculated in proportion to materials cost in Argonne's analysis)

- the reduction from $50/lb to $30/lb is a 40% drop, yielding a 0.4 * 0.369 = .148 cost reduction

- a $520 motor would then sell for a price of: $520 - 148 * $520) = $443.

Since AC motor cores are currently produced in significant volumes and with relatively inexpensive materials, the only substantial opportunity for reducing materials costs in EV motors is to reduce the cost of the rare earth magnets in BPM motors. Consequently, we investigated the potential for material cost declines in

AC Induction Motors:

All volumes: OEM price = (kW-pk / 50) * ($470 + (1.4 * $50))
or (simplified) = $540 * (kW-pk / 50)

Where:
kW-pk / 50 = peak power scaling factor
$470 = selling price of 50 kW core motor, plus labor and overhead on extra parts
1.4 * $50 = extra parts plus 40% overhead on parts

We estimate two sets of controller cost functions. The first set of functions is for near-term production, and the second set is for long-run production that accounts for efforts to reduce controller costs in the post-2002 time frame. Our near-term controller materials cost estimates are based primarily on ANL's estimates for items such as the microprocessor ($200); driver stage board ($175); DC-DC converter ($70); current sensor ($120); ripple capacitors ($60); and hardware, chassis, and cooling ($150), although we assume that these costs are 20% lower for the 200,000 per year cases than for the 2,000 per year and 20,000 per year cases. Cost reductions of at least this nature are possible because of the likelihood of including application specific integrated circuits (ASICs) at volumes of over 20,000 per year, and reducing costs in the low power electronics section as a result. The upfront costs associated with designing an ASICs based system preclude doing so at low volumes, but at higher volumes significant cost savings can result as these fixed costs are spread over more and more units.

For the near-term functions, we estimate IGBT costs based on a recent paper by Hodkinson (1997), and consultation with an electronics industry expert for an estimate of recent and likely near-term declines in IGBT costs. Hodkinson (1997) examines wire bond, lead frame, and intelligent power module type IGBTs for 70 kW (peak) AC induction and BPM drive systems, and concludes that wire bond packaging provides the lowest silicon cost for EV motor controllers. He estimates that the current silicon cost for a 70 kW AC induction inverter is $300, based on the use of three 1200 volt, 100 amp six-pack IGBT modules, and that the silicon cost for a 70 kW BPM inverter is $200, based on the use of two such modules. We normalize these cost estimates to the 70 kW system, and then scale them linearly for different inverter power ratings since silicon costs scale to current capacity (i.e. we assume constant system voltages). Our 2,000 per year and 20,000 per year estimates assume current IGBT module costs, while the 200,000 per year estimate includes a slightly lower cost estimate that reflects a projected 20% decrease in IGBT costs over the next 2-3 years, relative to current costs (Harvey, 1998).

The results of the near-term motor and controller cost analysis are provided in Tables 14 and 15. At all production volumes and system power ratings, the AC induction systems have cost advantages relative to the BPM systems, although the advantages are very small at higher production volumes. The BPM systems have slightly lower controller costs (the BPM controller uses one less six-pack IGBT power rating, while the low power electronics section does not change. It is only necessary to add a few IGBTs in parallel in order to improve the peak rating of a controller, or to use IGBT modules with a higher current rating. In contrast, the weight of a motor, and by extension, the materials that it contains, do scale reasonably well by peak kW rating. Particularly to the extent that materials costs tend to dominate total manufacturing costs at high volumes of production, estimating motor costs as a function of $/kW is likely to be a more accurate approach than it is for controllers, although it may not be as good an approach for low and intermediate volumes of production since fixed costs are more significant portions of total manufacturing cost at these volumes.

Tables 6 and 7 and Figure 3 show present motor, controller, and system costs as a function of the peak and nominal kW ratings. An important finding from the data in the following tables is that, at least at the present retail level, system costs on a per-kW basis seem to be more consistent when calculated in terms of $/kW-peak than $/kW-nominal. A few projections of high volume system costs have also been included in the system cost table, to aid in evaluating the cost functions described in the following section.

Component Cost Breakdowns and Cost Functions

In order to estimate medium and high volume costs for EV drivetrains in the context of the overall EV cost and performance model, it is useful to estimate costs for motors and controllers as a function of their power rating, rather than estimating costs for systems with specific power ratings. Since there are a number of choices that can be made with regard to the design of the vehicle that affect its total weight and power requirements (particularly choices of chassis type and battery technology), drivetrain costs will need to be recalculated when the weight of the vehicle changes. The use of cost functions enables these calculations to be made in the spreadsheet model. The following sections describe the process for generating the cost functions that are used in the model.

Cost Estimates for Motors

In order to generate cost functions for motors and controllers, it is helpful to know how costs break down in terms of materials, labor, overhead, and other costs. In the current motor industry, aggregate data show that shop costs can be broken down as follows: materials (30-40%), direct labor (15-20%), energy costs (1-2%), and overhead, rents, depreciation, taxes, and interest (38-64%) (U.S. Commerce Dept., 1988). It is unclear, however, how well these data should apply to EV motors. Motors for EVs are designed for high efficiencies and light weights, and as a result they may use more expensive materials for some subcomponents than do typical motors, and the relative costs of materials, labor, and overhead may therefore be somewhat different.

With regard to motors suitable for use in EVs, one motor manufacturer supplied data that its 8 hp (nominal) DC electric vehicle drive motor has a retail price of about $2,200, and an OEM cost of about $1,150 in quantities of 25 units. In smaller quantities, the OEM cost would range from about $1,600 to $1,200. The total controllers are for IGBTs (and uncertainty in this cost is cause for the range of values), while about one-half of the materials cost for BPM controllers is for IGBTs.

Once assembly costs and profit margins are added, Cuenca calculates costs of from $37.3 to $47.6 per kW for AC controllers, and from $26.7 to $32.1 per kW for BPM controllers. However, the study acknowledges that estimating costs on a per kW basis and using these estimates for controllers of other power ratings may not be a good approximation (Cuenca, 1996).

Given these high present costs, efforts are currently underway to reduce the costs of EV motor controllers. One such effort is SatCon Technology Corporation's Automotive Integrated Power Module program. This program seeks to reduce high volume (i.e., 10,000 to 200,000 units per year) controller manufacturing costs by selecting low cost materials, integrating subsystems to reduce parts counts, and utilizing low cost production techniques (Bonnice, 1999). Program goals are for post-2002 production of IGBT-based inverters and controller power modules, suitable for use with both AC induction and BPM motors, with selling prices of $14-19 per kW at 20,000 units per year, and $10-14 per kW at 200,000 units per year (Bonnice, 1999). These costs are applicable to devices with a 300V DC input level, and power levels in the 50-100 kW range. The ranges in costs reflect differences in costs for controllers across the 50-100 kW power range, uncertainties in future manufacturing costs, and potential differences is customer requirements (e.g., switched reluctance motor drives would be at the high end of the range, while simple three-phase drives would be in the middle to the lower end of the range, depending on system power). These controller units are expected to be 97% efficient (Bonnice, 1999).

Cost Functions

Motor and controller costs are not exact linear functions of rated power output. In the case of motors, costs may rise as a nearly linear function of nominal power rating, but assessing costs as a function of peak power rating is complicated by the fact that the same motor can achieve a different peak power rating depending on the controller with which it is paired. The issue of formulating cost functions for motors is further complicated by the fact that motors can be rated by continuous (nominal) output or peak output, and both of these ratings vary by system voltage. Also, different types of motors have different ratios of continuous to peak power. For example, one AC induction motor analyzed here has a continuous rating of 40 kW and a peak rating of 67 kW, yielding a peak to continuous ratio of 1.68. A DC motor has a continuous rating of 20 kW and a peak of 52 kW, yielding a ratio of 2.6. Finally, one BPM motor has a continuous rating of 32 kW, and this is also its peak rating for a ratio of 1.0, but a similar although slightly heavier 32 kW BPM motor has a peak rating of 53 kW, for a ratio of 1.65.

Given the above complications, various strategies can be used to approximate a per-kW price for motors. In his analysis, Cuenca divides the average OEM cost of a motor by its peak power rating to obtain what he terms a "specific cost." For the motors analyzed, he obtains the results shown in Table 12.

It is unclear, however, how readily these results can be generalized to motors of different sizes than the ones analyzed. These estimates should be relatively accurate for motors close in size to those assessed (as should be the case for most the prospect of the reduced costs that are expected for post-2002 production. Costs at different production volumes are based on the data discussed above and presented in the tables, and costs for the 20,000 units per year volume are also based on recent data on the costs of components for the Toyota Prius hybrid EV (EEA, 1998). This is the first production vehicle with an electric driveline to be produced in volumes of over 20,000 units per year.

Our cost functions differ somewhat from the other functions presented above in that we assume that motor costs are directly (AC induction) or nearly directly (BPM) functions of the peak power rating of the device, but that motor controller costs are weaker functions of their peak power rating. As discussed above, this is because only slightly higher rated (or more in parallel) IGBTs are required to supply higher power capabilities, along with perhaps slightly larger controller enclosures and cooling systems.

Our BPM motor materials cost estimates are generally based on the Cuenca (1995) estimates shown above, with the exception that at the 200,000 per year production level, we assume that neodymium-iron boron magnet material can be purchased at $40 per pound (see above discussion). For AC induction motors, which are currently in mass production, we use as a base price the $390 quote mentioned above for a 50 kW motor, and we make additions for the additional parts, labor, and overhead costs associated with adding cooling jackets, encoders, and cable housings (we assume a liquid-cooled design). Since the tooling is already in place for these motors, and they are produced on flexible-flow production lines, we do not assume that the price is sensitive to production volume in the range of 2,000 to 200,000 units per year. Our cost functions for BPM and AC induction motors are as follows:

<u>BPM Motors:</u>

2,000/yr: OEM price = 1.18 * (($10.16*kW-pk) + ($660+($15*kW-pk)))
or (simplified) = $779 + ($29.7 * kW-pk)

20,000/yr: OEM price = 1.18 * (($10.16*kW-pk) + ($75+($1.8*kW-pk)))
or (simplified) = $89 + ($14.1 * kW-pk)

200,000/yr: OEM price = 1.18 * (($9.4*kW-pk) + ($1.2*kW-pk))
or (simplified) = $12.5 * kW-pk

Where:
1.18 = manufacturing cost + 18% supplier profit
10.16 (or 9.4) * kW-pk = materials cost
Additional term = cost of adding value to materials

module), but the extra cost for the BPM motor more than eliminates the controller cost savings. At 200,000 units per year, costs for the two systems are almost identical.

Our long-run controller cost functions are based on cost target data from SatCon Technology Corporation's Automotive Integrated Power Module program. We estimate cost functions for production of 20,000 units per year and 200,000 units per year. We used the same functional form as with the near-term cost functions, but adjusted the parameters so that the overall cost estimates reflect the cost targets. These longer term cost estimates, also shown in Table 14, simplify to the following functions:

AC Induction Controllers (long-run):
20,000/yr: OEM price = \$418 + (\$10.76 * kW-pk)
200,000/yr: OEM price = \$312 + (\$7.60 * kW-pk))

BPM Controllers (long-run):
20,000/yr: OEM price = \$392 + (\$9.44 * kW-pk)
200,000/yr: OEM price = \$262 + (\$6.94 * kW-pk))

Key Uncertainties and Comparisons with Other Results

It is important to note that there are inherent uncertainties in making cost estimates of this sort. Perhaps most fundamentally, raw material and subcomponent costs are subject to change over time, but not always in predictable ways. As the above discussion of BPM motor magnet material illustrates, even factors such as the relative strength of the yen to the dollar can have an impact. Also, suppliers will face different factory costs depending on the region in which they locate, for such costs as labor, environmental compliance, and so on. Suppliers can also trade off labor for capital, at the expense of capital investments that must be amortized over several years, and this will affect the cost of adding value to materials. Even greater uncertainty, however, exists with regard to what supplier/OEM relationships might be in place at this production volume. It is possible that an OEM producing 200,000 units per year might have a "captive" supplier that provided product only to it. However, at 2,000 units per year of production, it is likely that one supplier would provide product to more than one OEM customer in an attempt to capture economies of scale. The OEM and supplier production volumes would then be different, perhaps by as much as an order of magnitude. The supplier would then have lower per unit manufacturing costs than if it were only producing for a single OEM customer, but it may or may not be willing to pass some of the cost savings on to the OEM customers (depending on the level of competition from other suppliers, and other factors involved in the negotiations between the suppliers and OEMs). Particularly given the level of uncertainty about the volume of supplier production at the 2,000 units per year level of EV production by an OEM, the above cost estimates at the 2,000 units per year level should be taken as reasonable approximations only.

For reference, Figures 4 and 5 show near-term cost estimates for AC induction and BPM drivelines from the Cuenca, EEA/OTA, Vyas, et al., and ITS-Davis studies.

Figures 6 and 7 show long-run cost estimates from the Vyas, et al. and ITS-Davis studies.

Gearbox and Accessory Drive

A complete EV drivetrain also requires a transaxle/gearbox in order to transfer power to the axle. One EV transaxle design has been developed by Funk Manufacturing, for Unique Mobility, Inc. This 44.4 kilogram, single-speed transaxle is rated for a continuous input torque of 244 Nm, and a maximum input speed 8,000 rpm. It can be configured for ratios of from 4:1 to 8:1.

Table 16 presents cost estimates for this transaxle at different production volumes, as well as a cost estimate for the small auxiliary motor used to drive compressors for steering, brake, and HVAC systems. This component could be a small DC or BPM motor, and it would be of a size that is currently produced in high volumes for various commercial uses. We assume that the controller for this motor is integrated into the main motor controller, and that the above cost estimates include controls for the accessory motor. We use Vyas, et al.'s estimates of $50 to the OEM for this component in our 20,000 per year case (their volume is a range from 10,000 per year to 50,000 per year) and $45 in the 200,000 per year case (200,000 per year in Vyas, et al.), and we further assume that this component would cost $100 per unit to the OEM at the 2,000 per year level.

EV Drivetrain Weight Functions

With regard to system weights, weight data are available from manufacturers, and EEA has developed equations that relate weight in kilograms to peak kW output. These expressions are as follows (OTA, 1995):

AC induction system weight (kg) = 14 + 1*kW(peak)

BPM system weight (kg) = 11 + 0.8*kW(peak)

Electric vehicle drive system designers are constantly trying to reduce system weight in order to improve vehicle performance and range, and as mentioned above controller weights and sizes have been reduced in recent years. In order to assess the suitability of using the EEA functions for current drive system designs, we examined recent data on the weights of EV drive systems. We then developed the following revised relationships, because the EEA function seems to overestimate the weights of AC induction systems and to underestimate the weights of BPM systems:

AC induction system weight (kg) = 5 + 1*kW(peak)

BPM system weight (kg) = 350/kW(peak) + 1*kW(peak)
(note: not reliable for systems with >100 kW peak power)

These functions are probably somewhat conservative, in the sense that it is possible to design drive systems that are better optimized for weight. For example, the drivetrain for the General Motors EV-1 is rated for a peak power of 102 kW, and it is reported to only weigh 150 pounds (68 kg). Drive system weight may be more closely associated with torque than peak power, since as mentioned above it is possible to obtain higher system peak power ratings simply by combining a motor with a controller capable of controlling the motor to higher power levels. The EEA and ITS-Davis calculations for drive system weight are compared with actual values in Table 17.

Table 2: EV Drivetrain Prices in Single Unit Purchases

Motor/Controller System	Nom. Power Rating (Peak)	Price ($)	Type	Source
Solectria BPM BRLS8 with UMOC225 controller	6 kW (11.2 kW)	7,335	Retail	Solectria, 1997
Solectria AC Induction ACgux20 with UMOC340 controller	15 kW (45 kW)	6,320	Retail	Solectria, 1997
Solectria AC Induction AC40 with UMOC440 controller	18 kW (67 kW)	7,210	Retail	Solectria, 1997
Unique Mobility BPM with CA40-300L inverter and EVPH332 microprocessor	32 kW (53 kW)	19,300	Retail	UQM, 1998
Unique Mobility BPM with CA40-400L inverter and EVPH332 microprocessor	75 kW (100 kW)	29,050	Retail	UQM, 1998
Hughes AC Induction	~18 kW (50 kW)	18,000	Retail	Sale price (to UCD)

Notes: AC = alternating current; BPM = brushless permanent magnet; DC = direct current.

Table 3: EV Drivetrain Prices in Medium and High Volume Purchases

Motor/Controller System	Nom. Power Rating (Peak)	Price ($)	Type	Source
Advanced DC Brush	16.3 kW (62 kW)	900 (mot.) 700 (ctr.) 1,600 tot.	Medium vol. (>1,000 units)	Kochek, 1995 (motor); Booz-Allen, 1995 (controller)
Solectria AC Induction	unavail. (56 kW)	2,475 2,295 2,130	OEM cost@: 5,000/yr 10,000/yr 20,000/yr	TDM, 1997
Unique Mobility BPM	32 kW (53 kW)	6,100 4,009 2,405	OEM cost@: 2,000/yr 10,000/yr 100,000/yr	Barnes, 1998
Unique Mobility BPM	75 kW (100 kW)	8,028 3,537	OEM cost@: 2,000/yr 20,000/yr	Rankin, 1998
AC Induction	unavail. (50 kW)	2,000- 3,000	High vol. target	Withheld by request
AC Induction	unavail. (50 kW)	10,000 3,400 1,300	OEM cost@: 3,000/yr 10,000/yr 20,000/yr	Withheld by request

Notes: AC = alternating current; BPM = brushless permanent magnet; DC = direct current.

Table 4: EV Motor Weights and Prices by Weight

Motor and nominal (and peak) rating	lbs.	$/lb.	Notes
Advanced DC Brush 16.3kW (62 kW)	107	13.1	Retail, rated at 120V
Advanced DC Brush 19kW (63 kW)	143	11.1	Retail, rated at 120V
Solectria BPM 6kW (11 kW)	26	94.23	Retail
Solectria BPM 8kW (15 kW)	32	93.13	Retail
Solectria BPM 12kW (22 kW)	64	54.30	Retail
Solectria AC Induction 4kW (14 kW)	51	29.02	Retail
Solectria AC Induction 7kW (21 kW)	66	23.79	Retail
Solectria AC Induction 15 kW (45 kW)	81	24.07	Retail
Solectria AC Induction 18 kW (67 kW)	131	18.24	Retail
Solectria DC Brush 4.5kW	39	24.36	Retail
Solectria DC Brush 6.5kW	54	19.81	Retail
Hughes AC Induction ~18 kW (50 kW)	132	45.45	Approx. retail
Unique Mobility BPM 32 kW (53 kW)	105	125.71	Retail
Unique Mobility BPM 75 kW (100 kW)	190	119.47	Retail

Notes: AC = alternating current; BPM = brushless permanent magnet; DC = direct current.
Sources: Same as above.

Table 5: EV Drive System Weights and Prices by Weight

System and nominal (and peak) rating	lbs.	$/lb.	Notes
Solectria BPM 12 kW (22.4 kW) with BRLS240H controller	81	90.56	Retail
Solectria AC Induction ACgux20 15 kW (45 kW) with UMOC340 controller	107	59.06	Retail
Solectria AC Induction AC40 18 kW (67 kW) with UMOC440 controller	158	45.63	Retail
Hughes AC Induction ~18 kW (50 kW)	198	90.90	Approx. retail
Unique Mobility BPM 32 kW (53 kW) with CA40-300L inverter and EVPH332 microprocessor	133.8	144.24	Retail
Unique Mobility BPM 75 kW (100 kW) with CA40-400L inverter and EVPH332 microprocessor	218.8	132.77	Retail
AC Induction (50 kW peak)	200	10-15	High volume cost target
			OEM cost@:
BPM (53 kW peak)	133	45.86	2,000/yr
		30.14	10,000/yr
		18.08	100,000/yr

Notes: AC = alternating current; BPM = brushless permanent magnet; DC = direct current.
Sources: Same as above.

Table 7: EV Drive System Prices by **Power Rating**

System and nominal (and peak) rating	$/kW (peak)	$/kW (nominal)	Notes
Advanced DC Brush 16.3kW (65 kW) with $700 DC controller	25.40	98.16	Med. volume (>1,000 units)
Solectria BPM 12kW (22.4 kW) with BRLS240H controller[a]	327.46	611.25	Retail
Solectria AC Induction ACgux20 15 kW (45 kW) with UMOC340 contr.	140.43	421.29	Retail
Solectria AC Induction AC40 18 kW (67 kW) with UMOC440 controller	107.61	400.53	Retail
Hughes AC Induction ~18kW (50 kW)	360	1,000	Approx. with $18,000 system
Unique Mobility BPM 32 kW (53 kW) with CA40-300L inverter and EVPH332 microprocessor	364.15	603.13	Retail
Unique Mobility BPM 75 kW (100 kW) with CA40-400L inverter and EVPH332 microprocessor	290.50	387.33	Retail
AC Induction (50 kW peak)	40-60	unavail.	High volume target ($2,000-3,000 system)
BPM 32 kW (53 kW peak)	115.09 75.64 45.37	190.63 125.28 75.15	OEM cost@: 2,000/yr 10,000/yr 100,000/yr

Notes: AC = alternating current; BPM = brushless permanent magnet; DC = direct current.
[a]Peak rating depends on controller choice. It would be 28 kW with the use of the 216 Volt controller, instead of the 144 Volt controller.
Sources: Same as above.

Table 8: Materials Costs for 40 kW (continuous), 67 kW (peak) AC Induction Motors

Components	Mass (lb)	% of mass	Cost ($)	$/lb	% of cost
Core laminations, stator	51	44.6	110	2.16	43.0
Core laminations, rotor	28	24.5	60	2.14	23.5
Field winding (copper)	12.3	10.8	25	2.03	9.8
Housing (magnesium)	7.3	6.4	25	3.42	9.8
Shaft	7.0	6.1	3.5	0.50	3.0
Rotor conductor (alum.)	3.7	3.2	7.5	2.03	1.0
Miscellaneous	5.0	4.4	25	5.00	9.8
Total	114.3	100	256	2.24	100

(Cuenca, 1995).

Table 13: Comparison of Drivetrain "Cost to OEM" Estimates

System Type and Peak Rating	EEA/OTA Function[a]	Cuenca Estimate	Vyas' et al. Estimate 2000/2020	Manuf. Forecast[b]
AC Induction				
50 kW peak	$1,800	$2,225-2,740	$1,375/$550	$2,130
70 kW peak	$2,400	$3,115-3,836	$1,925/$770	
90 kW peak	$3,000	$4,005-$4,932	$2,475/$990	
BPM				
50 kW peak	$1,890	$2,150-2,420	$1,450/$600	$2,405
70 kW peak	$2,520	$3,010-3,388	$2,030/$840	
90 kW peak	$3,150	$3,870-4,356	$2,610/$1,080	

Notes:

[a] For BPM, assumes that one-third of system cost is that of the motor, and that BPM motor costs are 15% higher than AC induction motor costs (reflecting statements in the OTA report).

[b] AC induction forecast is for Solectria 56 kW (peak) system at 20,000 units/yr, and BPM forecast is for 53 kW (peak) system at 100,000 units/yr (see above tables).

Table 14: Motor Controller "Cost to OEM" Estimates

System Type and Volume	Materials ($ + $/peak kW)	Labor/Overhead	Supplier Profit	Total OEM Cost (70 kW controller)
Near-Term:				
AC Induction				
2,000/yr	$775 + $4.3/kW	$1,400+80% matl's	18% * manuf. cost	$3,937
20,000/yr	$775 + $4.3/kW	$70 + 40% matl's	18% * manuf. cost	$1,860
200,000/yr	$620 + $3.4/kW	$25 + 20% matl's	18% * manuf. cost	$1,244
BPM				
2,000/yr	$775 + $2.86/kW	$1,400+80% matl's	18% * manuf. cost	$3,723
20,000/yr	$775 + $2.86/kW	$70 + 40% matl's	18% * manuf. cost	$1,694
200,000/yr	$620 + $2.29/kW	$25 + 20% matl's	18% * manuf. cost	$1,134
Long-Run:				
AC Induction				
20,000/yr	$190 + $5.7/kW	$50+60% matl's	18% * manuf. cost	$1,171
200,000/yr	$160 + $4.6/kW	$40+40% matl's	18% * manuf. cost	$843
BPM				
20,000/yr	$170 + $5.0/kW	$50 + 60% matl's	18% * manuf. cost	$1,053
200,000/yr	$130 + $4.2/kW	$40 + 40% matl's	18% * manuf. cost	$748

Notes:

Near-term costs refer to costs in the 1999-2002 timeframe. Long-run costs reflect cost targets for production post-2002.

motors used in passenger vehicle EV applications), but these relationships should probably not be presumed to extend to motors of much larger or smaller size.

In a study for the Office of Technology Assessment, a consultant (Energy and Environmental Analysis, Inc.) developed a cost function for AC induction motor/controller systems. This function includes a constant term, so the estimated cost is not purely a function of power rating, but the cost increment for increasing power is linear. This function is as follows (OTA, 1995):

Cost to the OEM = \$300 + \$30 * kW (peak)

Of this total OEM cost, EEA/OTA estimates that roughly one-third of the cost is in the motor, and two-thirds are in the controller. This function is applicable to high-volume production of the propulsion system (i.e. a production level on the order of 100,000 units per year). EEA/OTA estimates that permanent magnet motors would cost 15-20% more, with similar production volumes (implying that the total system cost would rise by about 5-7%).

Also, Vyas, et al. (1998) have estimated motor and controller costs for EVs, based on Cuenca's work and on data gathered under the auspices of the PNGV program. Under the assumption of high volume production (10,000 to 50,000 units per year initially, rising to 200,000 per year), they estimated AC induction motor costs to the OEM of \$7.50 per peak kW in 2000, falling to \$6.00 per peak kW after 20 years. BPM motors were estimated to cost \$9.00 per peak kW in 2000, and \$7.00 after 20 years. Controllers for both systems are estimated to cost the OEM \$20.00 per peak kW in 2000, falling to \$5.00 per peak kW after 20 years (Vyas, et al., 1998).

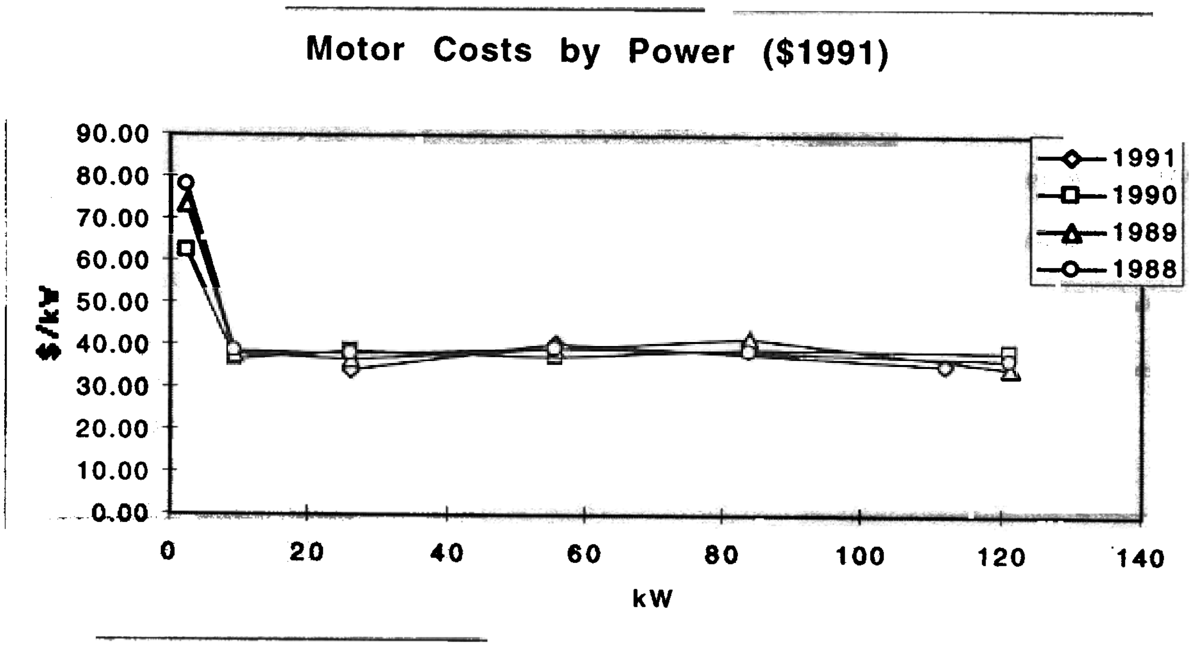
Table 13 compares cost estimates that would be predicted, using the OTA, Cuenca, and Vyas et al. methodologies, with high-volume forecasts provided by manufacturers. With regard to these estimates, it seems clear that there is reasonably good agreement between the EEA/OTA, Cuenca, and manufacturer estimates, while the Vyas et al. estimates are somewhat lower for 2000, and much lower for 2020 (only the Vyas et al. estimates project costs into the future). It is also clear that all of these drive system cost estimates are strong functions of peak power, with the Cuenca and Vyas et al. estimates being linear functions of peak power.

ITS-Davis Cost Functions

Based on our consideration of all of the above information, we develop our own cost functions for motors and controllers. The data supplied by manufacturers and from other sources, while too sparse to allow detailed statistical analysis, are complete enough in terms of covering a range of system types, sizes, and production volumes to allow both AC induction and BPM system cost functions to be developed. The motor and controller cost functions, discussed below, were developed by examining all of the available data and then developing functions to match the data as well as possible, with the use of a spreadsheet model.

We consider three production volumes (2,000, 20,000 and 200,000 units per year) and we base our estimates on materials costs and an estimate for the cost of adding value to materials, for costs of labor and overhead. For controllers, we develop two sets of cost functions (near-term and long-run) in order to account for

Figure 1



Source: (U.S. Commerce Dept., 1995)

Figure 2

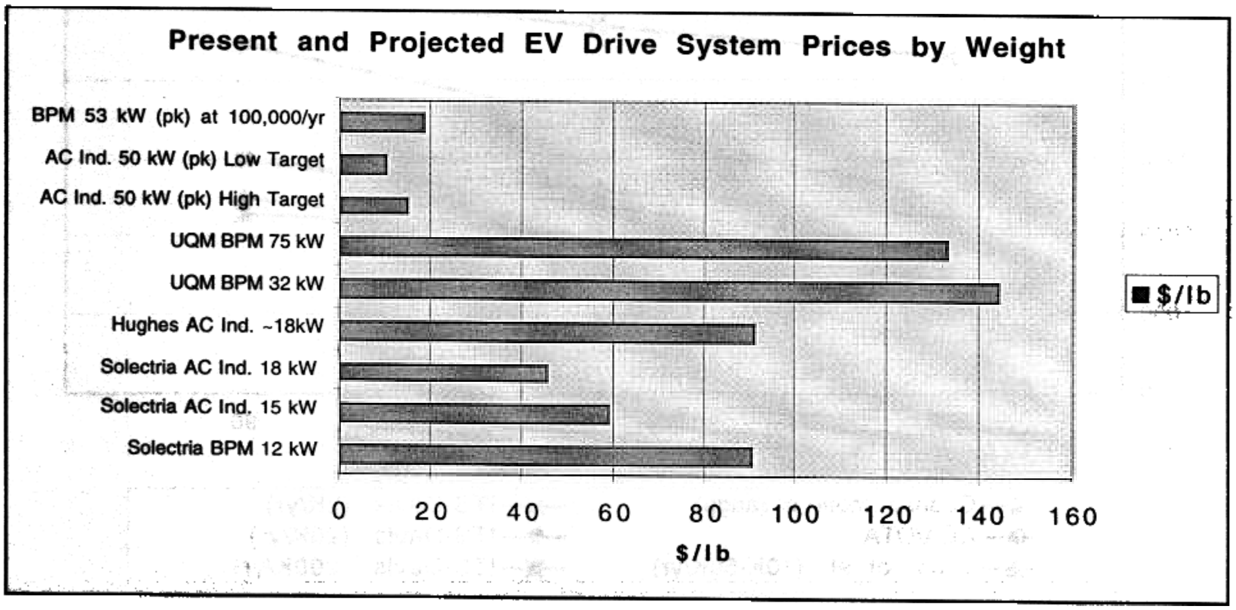


Figure 5

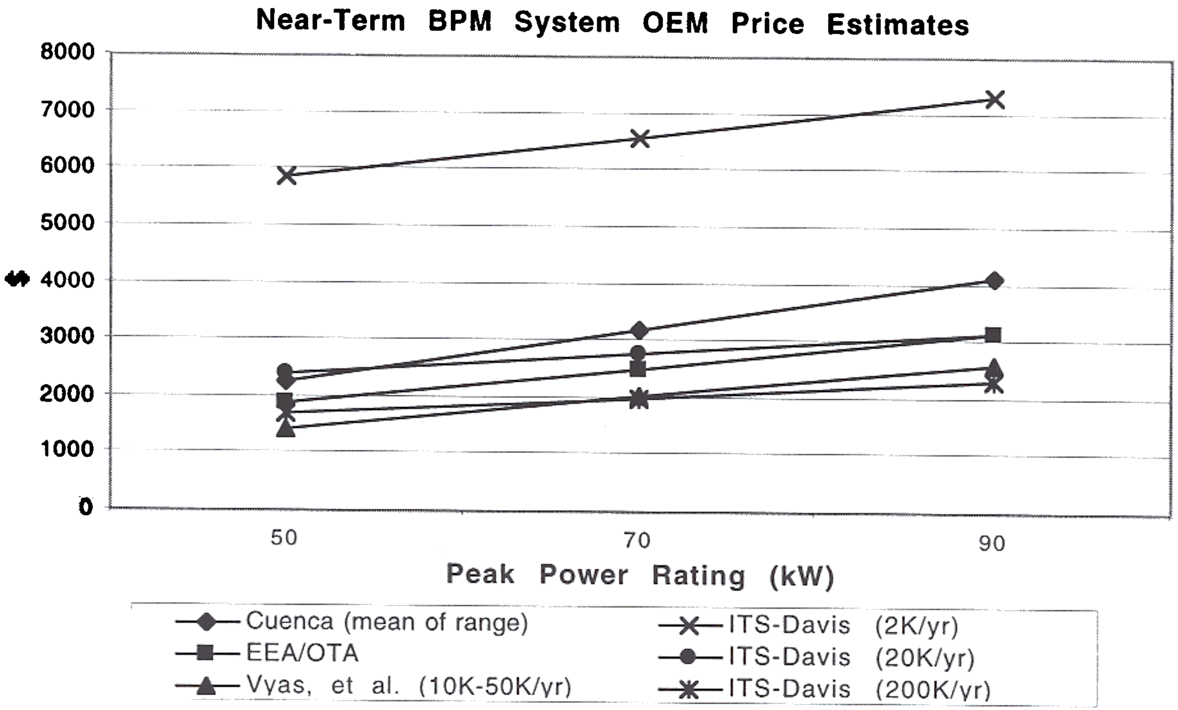


Figure 6

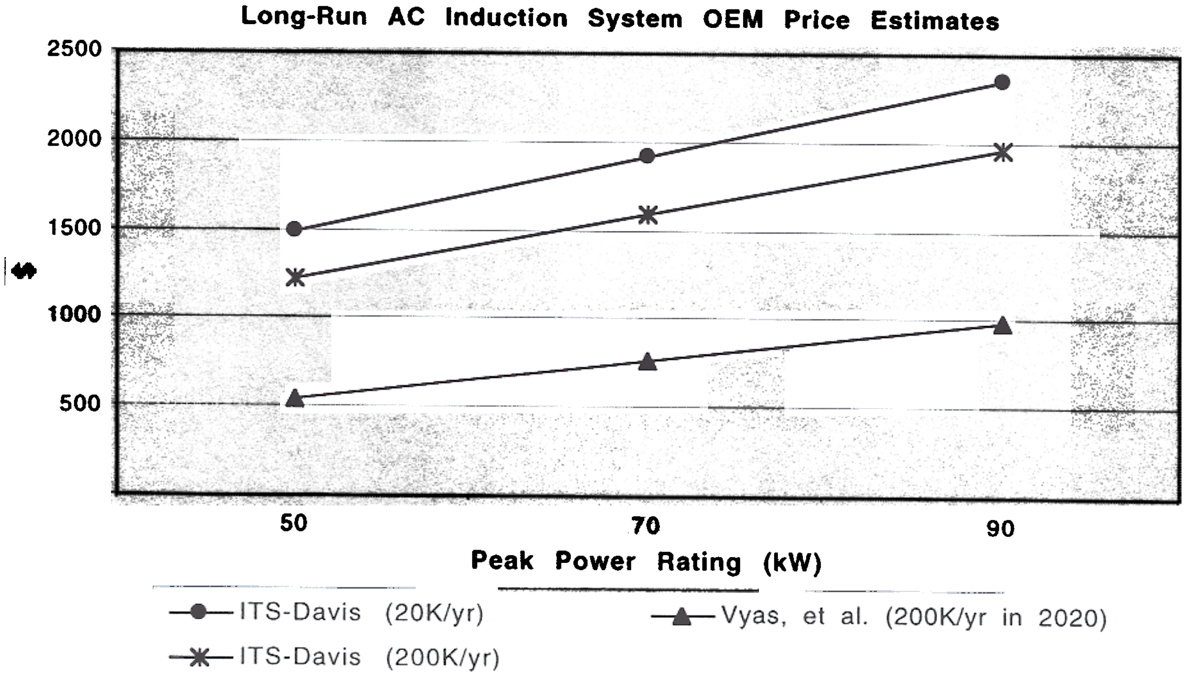


Figure 7

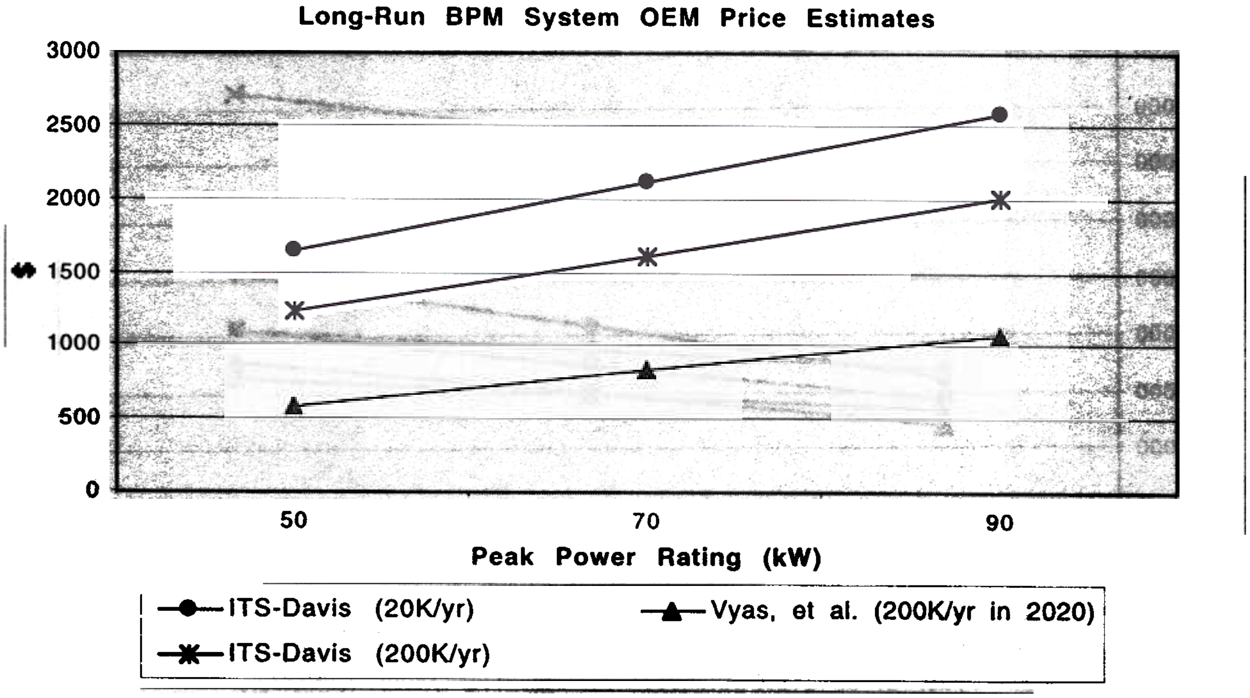

Long-Run BPM System OEM Price Estimates
$
3000
2500
2000
1500
1000
500
0
50
70
90
Peak Power Rating (kW)
ITS-Davis (20K/yr)
ITS-Davis (200K/yr)
Vyas, et al. (200K/yr in 2020)

Figure 3

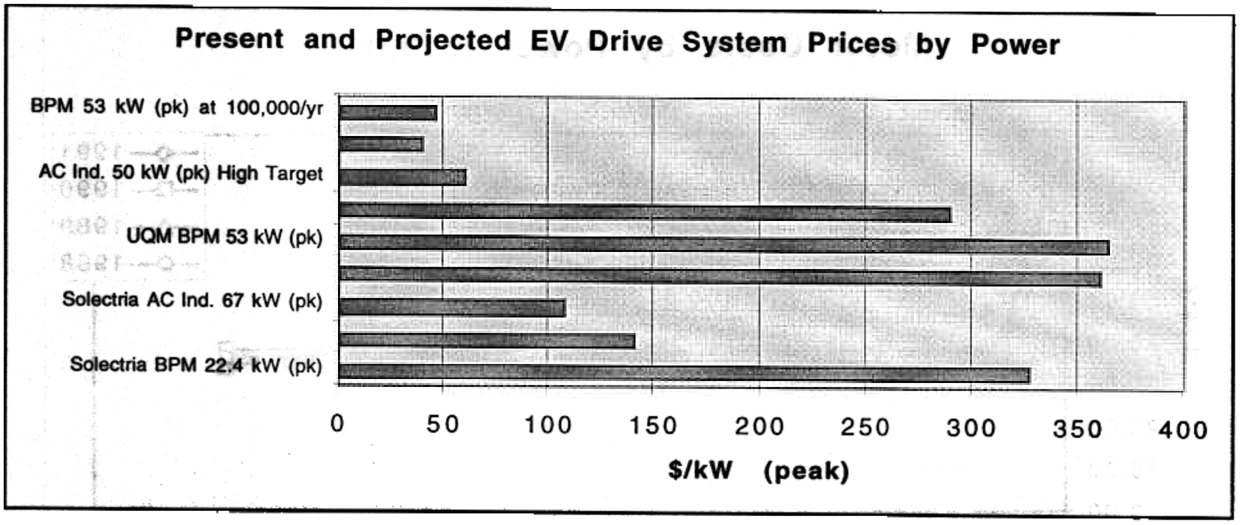


Figure 4

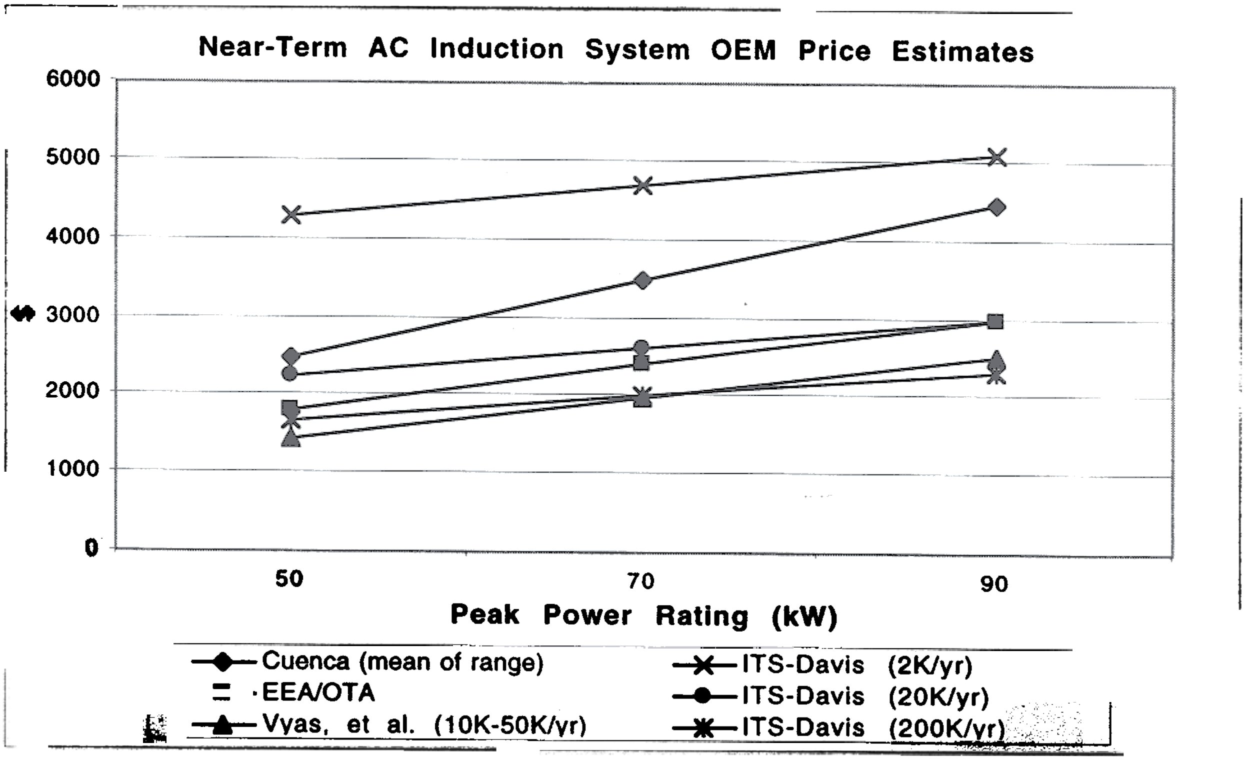


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Table 15: EV Drive System "Cost to OEM" Estimates

System Type and Rating	2,000/yr	20,000/yr	200,000/yr
Near-Term:			
AC Induction			
50 kW peak	**$4,295**	**$2,258**	**$1,688**
70 kW peak	**$4,693**	**$2,616**	**$2,000**
90 kW peak	**$5,092**	**$2,974**	**$2,313**
BPM			
50 kW peak	**$5,865**	**$2,393**	**$1,695**
70 kW peak	**$6,580**	**$2,770**	**$2,010**
90 kW peak	**$7,296**	**$3,147**	**$2,325**
Long-Run:			
AC Induction			
50 kW peak	**N/A**	**$1,496**	**$1,231**
70 kW peak		**$1,927**	**$1,599**
90 kW peak		**$2,358**	**$1,967**
BPM			
50 kW peak	**N/A**	**$1,646**	**$1,234**
70 kW peak		**$2,117**	**$1,623**
90 kW peak		**$2,588**	**$2,102**

Table 16: Gearbox and Accessory Motor OEM Prices

Production Volume	Gearbox	Accessory Motor
2,000 per year	$1,800	$100
20,000 per year	$806	$50
200,000 per year	$469	$45

Gearbox cost estimates are based on data supplied by Barnes (1998).

Table 17: EV Drive System Weight Estimates and Actual Weights

System Type	EEA Functions	ITS-Davis Functions	Actual Weight
AC Induction (37 kW peak)	51 kg	42 kg	42.0 kg
AC Induction (45 kW peak)	59 kg	50 kg	48.6 kg
AC Induction (50 kW peak)[a]	64 kg	55 kg	90.0 kg
AC Induction (67 kW peak)	81 kg	72 kg	71.8 kg
BPM (22 kW peak)	28.6 kg	38 kg	37.0 kg
BPM (53 kW peak)	53.4 kg	60 kg	60.8 kg
BPM (100 kW peak)	91 kg	103.5 kg	99.5 kg

Notes:

[a]This Hughes drive system also includes an integrated charger, and the weight data are a few years old -- it has since been made lighter.

Tables and Figures

Table 1: Current EV Motor Prices in Single Unit or Low Volume Purchases

Motor	Nominal Power Rating (Peak)	Price ($)	Type	Source
Advanced DC Brush	16.3 kW (62 kW)	1,398	Retail	Advanced DC, 1995
Advanced DC Brush	19 kW (63 kW)	1,592	Retail	Advanced DC, 1995
DC Brush (high torque 400 lb/ft)	6 kW (unavail.)	1,141	Low vol. OEM (25/order)	Withheld by request
Solectria DC Brush (BPM3)	2.2 kW (unavail.)	850	Retail	Solectria, 1997
Solectria DC Brush (BPM6)	4.5 kW (unavail.)	950	Retail	Solectria, 1997
Solectria DC Brush (BPM8)	6.3 kW (unavail.)	1,070	Retail	Solectria, 1997
Solectria BPM (BRLS8)	6 kW (11.2 kW)	2,450	Retail	Solectria, 1997
Solectria BPM (BRLS11)	8 kW (15 kW)	2,980	Retail	Solectria, 1997
Solectria BPM (BRLS16)	12 kW (22.4 kW)	3,475	Retail	Solectria, 1997
Solectria AC Induction (ACgtx20)	12 kW (37 kW)	1,800	Retail	Solectria, 1997
Solectria AC Induction (ACgux20)	15 kW (38 kW)	1,950	Retail	Solectria, 1997
Solectria AC Induction (AC30)	16 kW (37 kW)	2,390	Retail	Solectria, 1997
Solectria AC Induction (AC40)	18 kW (67 kW)	2,390	Retail	Solectria, 1997
Hughes AC Induction	~18 kW (50 kW)	6,000	Retail	Approx., based on sale to UC Davis
Unique Mobility BPM	32 kW (53 kW)	13,200	Retail	Unique Mobility, 1998
Unique Mobility BPM	75 kW (100 kW)	22,700	Retail	Unique Mobility, 1998

Notes: AC = alternating current; BPM = brushless permanent magnet; DC = direct current.

Table 6: EV Motor Prices by Power Rating

Motor and nominal (and peak) rating	$/kW (peak)	$/kW (nominal)	Notes
Advanced DC Brush 16.3kW (62 kW)	22.55	85.80	Retail, rated at 120V
Advanced DC Brush 19kW (63 kW)	25.11	83.80	Retail, rated at 120V
Advanced DC Brush 19kW (63 kW)	14.29	47.40	Med. vol. projection, rated at 120V
Solectria BPM 6kW (11 kW)	218.75	408.33	Retail
Solectria BPM 8kW (15 kW)	198.67	372.50	Retail
Solectria BPM 12kW (22 kW)	155.13	289.58	Retail
Solectria AC Induction 4kW (14 kW)	105.71	370.00	Retail
Solectria AC Induction 7kW (21 kW)[a]	74.76 56.07 (28kW)	224.28	Retail
Solectria AC Induction 15 kW (45 kW)	43.33	130.00	Retail
Solectria DC Brush 6.3kW	unavail.	169.84	Retail
Hughes AC Induction) ~18 kW (50 kW)	120.00	333.33	Approx. with $18,000 system, assumes motor is 1/3 system cost
Unique Mobility BPM 32 kW (53 kW)	249.06	412.50	Retail
Unique Mobility BPM 75 kW (100 kW)	227.00	302.67	Retail
AC Induction (50kW peak)	13.33-20.00	unavail.	High vol. target ($2,000-3,000 system), assumes motor is 1/3 system cost
BPM 32 kW (53 kW peak)	10.92	18.09	At 20,000/yr

Notes: AC = alternating current; BPM = brushless permanent magnet; DC = direct current.

[a] Peak rating depends on controller choice. It would be 28 kW with the use of the 216 Volt controller, instead of the 144 Volt controller.

Sources: Same as above.

Table 9: Materials Costs for 20 kW (continuous), 52 kW (peak) DC Motors

Components	Mass (lb)	% of mass	Cost ($)	$/lb	% of cost
Core laminations, rotor	33.3	23.4	85	2.6	29.8
Core laminations, poles	29.5	20.8	65	2.2	22.8
Frame	29.0	20.4	20	0.7	7.0
Armature windings	10.3	7.2	21	2.0	7.4
Pole windings	9.5	6.6	19	2.0	6.7
Commutator	10.5	7.4	30	2.9	10.5
Shaft	9.3	6.5	5	0.5	1.8
Housing flanges	5.0	3.5	10	2.0	3.5
Miscellaneous	6.0	4.2	30	5.0	10.5
Total	142.3	100	285	2.0	100

Source: (Cuenca, 1995).

Table 10: Materials Costs for 32 kW (continuous), 32 kW (peak) BPM Motors

Components	Mass (lb)	% of mass	Cost ($)	$/lb	% of cost
Stator core	24.0	27.8	68	2.8	20.9
Stator winding	11.0	12.7	22	2.0	6.8
Housing	21.0	24.3	50	2.4	15.4
Rotor	16.0	18.5	26	1.6	8.0
Magnets	2.4	2.8	120	50.0	36.9
Attachment band	0.5	0.6	6	12.0	1.8
Shaft	5.5	6.4	3	0.6	0.9
Miscellaneous	6.0	6.9	30	5.0	9.2
Total	86.4	100	325	3.76	100

Source: (Cuenca, 1995).

Table 11: Total Estimated Prices for AC, DC, and BPM Motors

Element	AC 40 kW ($)	DC 20 kW ($)	BPM 32 kW ($)
Material cost	256	285	325
Assembly/testing (at 30%)	115	120	80
Assembly/testing (at 40%)	175	190	140
Total manufacturing cost	370-430	400-475	405-465
Gross margin (20%)	75-85	80-95	80-93
OEM price per unit	445-515	480-570	485-558

Source: (Cuenca, 1995).

Table 12: Specific Costs of Various Motors

Parameter	AC	DC	BPM
Average cost to OEM ($)	480	525	520
Maximum power (kW)	67	52	32
Specific cost ($/kW)	7.2	10.1	16.3

Source: (Cuenca, 1995)