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The Cost of Manufacturing eletric Vehicle Batteries

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Report for the California Air Resources Board

by

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Introduction

Batteries suitable for use in electric vehicles (EVs) are in various stages of development, depending on the battery type. This report focuses on what today are generally considered the three most likely choices of battery chemistry for use in near to mid-term production EVs: lead-acid, nickel metal hydride (NiMH), and lithium-ion (Li-ion). Sealed lead-acid batteries are a relatively mature product, produced by such companies as Johnson Controls, Inc., Horizon Battery Company, and Japan Battery Storage Company. Nickel metal hydride batteries are currently in pilot-scale to low volume production by GM Ovonic (a joint venture between Ovonic Battery Company and General Motors), Panasonic EV Energy, and SAFT. Lithium-ion batteries are in pilot-scale production by Sony and SAFT. Factories to produce larger production volumes of NiMH and Li-ion batteries are currently under construction, with production expected in the next one to two years.

The general methodology employed in this study is to make use of a battery performance model developed at ITS-Davis by Dr. Andy Burke (1999) to determine battery design specifications for various battery types. Using these specifications, quantities of the various materials needed to manufacture a given battery are estimated. These materials are then costed by obtaining quotes from battery component suppliers. Finally, additional battery manufacturing and selling costs are estimated based on a variety of sources. The study considers a range of production volumes, in order estimate the reductions in manufacturing costs that occur through economies of scale in materials purchase, and in other factory costs.

The model developed by Dr. Burke currently is capable of analyzing lead-acid, NiMH, and nickel-cadmium battery types. The model has not yet been developed to analyze Li-ion batteries. As a result, only lead-acid and NiMH battery costs are analyzed in detail in this report. Li-ion battery materials cost estimates from the academic literature are discussed, however, and overall battery cost estimates and cost targets from different sources are also reported.

Lead Acid EV Batteries

Sealed, deep-cycle lead acid batteries are a mature industrial product, produced in large volumes in a range of module capacities. However, the larger cell sizes needed for EV applications are produced in somewhat smaller production volumes at the present time. Companies producing sealed lead acid batteries for EVs include Johnson Controls, Inc., Horizon Battery Company, and Japan Battery Storage Company, among others. Table 1 shows current wholesale, retail, and list prices of commercial sealed, lead-acid batteries produced by Johnson Controls, Inc. The following analysis estimates the cost of producing advanced lead-acid batteries for EVs, in the 2000-2003 timeframe. Costs and prices are reported in $1998, except where noted.

The lead acid battery analyzed is a valve-regulated, sealed type that is of a mono-block construction. Each cell contains 19 electrode plates, and the module is composed of six cells in order to obtain a nominal 12 volt design. The cell capacity is

75 Ah, and each 12-volt battery module has a nominal energy of 900 Wh. The battery plate grids are of the expanded type, and 80% of the grid is open area. Each grid measures 10 cm by 15 cm by 0.05 cm. The pasted positive and negative plates are 0.075 cm thick, and the paste density is approximately 6.3 grams per cubic centimeter. The separator, of the glass mat type, is 0.2 cm thick and it contains approximately 60% fine fiber. The electrolyte is of the sulfuric acid/absorbed glass mat (AGM) type, and it is assumed to have a specific gravity of 1300.

For this analysis, we have assumed two production scales: a small, single assembly line plant that produces 120,000 modules (about 100,000 kWh) per year, and a larger plant with four assembly lines that produces 480,000 modules (about 400,000 kWh) per year. This translates to 10,000 modules per month, or 500 modules per shift (with one shift per day and 20 shifts per month) for the small plant and 40,000 modules per month or 2,000 modules per shift for the larger plant. Unit costs associated with labor, overhead on labor, factory rental, and some capital equipment are somewhat lower for the higher production scenario, owing to more efficient use of labor, equipment, and space.

We estimate that 40,000 square feet of factory space are required for the small plant and 120,000 square feet are required for the larger plant, and that this space is rented at an annual rate of $6.00 per square foot. In order to operate the specified equipment, 32 direct production workers are needed for the small plant and 94 are needed for the larger plant. For the small plant 12 of these workers are needed for electrode construction, 10 are required for module assembly, four are needed for battery formation and final testing, and six additional direct workers are available for miscellaneous tasks including materials and product loading and unloading, inventory control, routine maintenance, etc. For the larger plant, the corresponding numbers are 40 workers, 36 workers, 12 workers, and 20 workers.

Approximately $1.76 million in capital equipment is required for the small plant (see Table 2), and we have assumed that this cost is straight-line depreciated over a 15 year period with no salvage value. For the larger plant $6.56 million in capital equipment is needed, assuming four production lines and environmental compliance costs commensurate with the larger facility size.

We have further assumed that the battery factory is located in the United States, and that factory space can be rented for $6.00 per square foot per year. Because of the critical importance of each module in an EV battery pack being of consistent construction, we have specified the use of the highest quality equipment available, with tight tolerances for grid and plate thickness. This assumption results in substantial capital costs for equipment, but relatively low labor costs due to the highly automated nature of equipment of this high level of sophistication. Based on detailed literature supplied by MAC Engineering and Equipment Company, Inc. and conversations with manufacturers, we have estimated requirements for factory space, personnel, and energy. These estimates are presented in Table 3.

Materials requirements for constructing the battery have been derived from calculations based on its physical characteristics, using the specifications described above and additional information derived from the ITS-Davis battery performance model (Burke, 1999). Materials quantity and cost estimates are presented in Table 4, along with additional details regarding the calculation of materials requirements.

This cost analysis results in estimates of battery selling prices (to the OEM or battery dealer) of about \$113/kWh in the smaller production scale and \$107/kWh in the larger scale (see Tables 5 and 6). These figures include a 20% rate of manufacturer profit, and a licensing fee. Table 1 shows how these cost estimates compare with current (and past) list, retail, and wholesale prices of similar Johnson Controls modules.

Nickel-Metal Hydride EV Batteries

Several major battery companies have developed nickel-metal hydride (NiMH) batteries for EV applications. These companies include Ovonic Battery Company, Panasonic, SAFT, Varta, and Yuasa. GM Ovonic (a joint venture between Ovonic and General Motors), Panasonic EV Energy, and SAFT have begun to manufacture NiMH EV batteries, and some of these batteries have already been incorporated into EVs now being leased in California. Product literature supplied by these companies reports that GM Ovonics is achieving a specific energy of 70 Wh/kg with modules of 85 Ah and 13.2 V (GM Ovonic, n.d.). Panasonic's batteries achieve 63 Wh/kg, with a 95 Ah, 12 V design (Panasonic EV Energy Co., n.d.).

This cost study is based on a first generation design of the NiMH batteries currently in use in California. Our estimates are based on publicly available information on NiMH batteries that use transition metal-based metal hydride alloys. The detailed materials quantity requirement estimates used in this analysis have, as in the lead acid battery cost analysis, been derived from a battery performance model developed at UC Davis (Burke, 1999). These materials have then been costed through interviews with materials suppliers. However, since this battery is not yet in high-volume production, and detailed cost estimates for capital equipment and labor requirements are therefore not readily available, a somewhat different approach has been taken to estimate the present and future costs of this battery than was used for the lead-acid battery. The approach used here is to assess in detail the materials costs of the NiMH battery, and then to estimate the costs to the battery manufacturer of adding value to those material inputs. The labor and overhead rate assumptions have been generated through conversations with manufacturers, and from similar analyses that were conducted on other EV battery types (Hasuike, 1991; Quinn, et al., 1989). Similar estimates have been made for the additional costs associated with marketing and distributing the batteries as were made for lead-acid batteries, although the "distribution and marketing" cost category has been adjusted downward (as a percentage of battery selling price) to reflect the approximately double specific energy of NiMH batteries, relative to lead-acid batteries.

A detailed analysis of the materials costs of the NiMH battery is especially warranted because some of the materials used in the NiMH battery have a higher \$/kWh cost, as assembled into an EV battery, than the materials used in lead-acid batteries. As a result, the cost of materials for this battery is much higher than the cost of the materials used in lead-acid batteries, both on a per-kWh and per-kg basis. Furthermore, some of these materials are not "raw materials" but instead are "value-added materials" that require prior processing steps. As a result, the costs of these materials may themselves drop somewhat over time, as production volumes increase and production processes improve in design and efficiency.

Typical NiMH EV battery cells have a capacity of 90-100 Ah. These 1.2 volt battery cells are designed in a prismatic configuration, with negative and positive electrode plates sandwiched with layers of separator material. Initially, we assume that the cell has a capacity of approximately 90 Ah, but we also consider future cases in which more advanced cells achieve 100 Ah. The negative electrode plates are composed of nickel or other metal grids that are pasted with a nickel hydride alloy, while the positive electrode plates are composed of a nickel foam substrate that is coated with spherical nickel hydroxide. Further details of specific battery materials are discussed below.

In the early generation, each battery module is composed of eleven of the cells described above, and the cells are connected in series. This configuration provides a nominal operating voltage of 13.2 volts for the module. In later generation, higher volume cases, each module is composed of ten cells, providing a nominal voltage of 12 volts, but the capacity of each cell is higher, so the total energy capacity of the module remains constant. These assumptions reflect the production strategy of one major battery manufacturer (Gifford, et al., 1997).

Four production levels are analyzed here in order to assess potential volume discounts in materials purchasing arrangements, and to explore the potential for economies of scale through reductions in per-unit fixed costs and labor requirements. The first production level is pilot-scale production of 350 vehicle battery packs per year (about 10,800 kWh/yr). This production level implies the manufacture of about 9,100 modules, or about 100,000 cells. The next production level is 7,700 vehicle packs per year (about 240 MWh/yr), or about two hundred thousand modules. These modules would be composed of about 2 million cells, depending on the configuration of the module. The third production level is high volume, mature production of 20,000 vehicle battery packs per year (about 624 MWh/yr). This production level implies the manufacture of about five hundred thousand modules, for a total production of over five million cells per year. Finally, a very high volume case is included, wherein 100,000 vehicle packs per year are manufactured (about 3,124 MWh/yr). These packs are composed of 2.6 million modules, and 26 million cells. All of these cases assume that 26 modules are used for each battery pack, with a resulting nominal pack voltage of 312 or 343 volts.

In addition, four different generations of NiMH battery technology are examined (hereafter Gen1-4). These generations are based partly on projections of the advance of NiMH battery technology for EV applications (Gifford, et al., 1997), and partly on additional assumptions that are discussed below. In general, future generations of NiMH EV batteries will be smaller, lighter, and cheaper due to significant improvements in energy density, along with cost reductions in key battery materials.

Table 7 summarizes the cases examined in this analysis, and a few of the key estimates underlying each case. These and other estimates and assumptions are explained in more detail in the tables that follow.

NiMH Battery Materials

Nickel

Nickel is the most abundant material used in NiMH battery construction, as the anode grids and grid tabs are almost entirely composed of nickel, and the cathode foam substrate, anode active material, and cathode active material are substantially composed of nickel. The price of nickel is rather volatile, and analysis of the 27 month history of nickel trading on the London Metal Exchange (prior to April, 1998) reveals a high price of approximately $9,000 per tonne (or $9.00 per kilogram) in September, 1995, and a low price of $5,600 per tonne (or $5.60 per kilogram) early in 1998. The recent low price of nickel has reportedly caused one large supplier, Inco, Inc., to curtail production in order to prevent further nickel price declines.

New York nickel dealer prices closely track the London Metal Exchange prices, although they tend to be approximately 4-5% higher. These nickel exchange prices provide an indicator of the overall world nickel market, but these prices for raw nickel do not necessarily translate directly into per weight costs of the nickel used in various components of NiMH batteries. First, battery-grade nickel suitable for use in the negative and positive active materials costs somewhat more than that of generic raw nickel, on the order of $7-8 per kg versus $5-6 per kg. Second, processing and delivery costs must be included for products that require processing (rather than using raw nickel directly as an input), and the resulting prices for specific nickel-based products can therefore be much higher than the general market price for unprocessed nickel.

For example, Vista Metals, Inc. of Seekonk, Massachusetts, produces nickel tabs for use in the battery industry. These 0.005 gauge tabs are manufactured in widths of from one-eighth of an inch to three-eighths of an inch, and they are composed of a 201 alloy that is approximately 99.5% nickel. Prices in small orders of 25 to 100 pounds are on the order of $20 per pound ($44/kg), while larger orders of 1,000 pounds would cost just over $10 per pound ($22/kg) (Almeida, 1998). These prices are based on the current low price of nickel of approximately $2.50 per pound ($5.60/kg), and they would be adjusted with changes in the raw nickel price. Thus, for this nickel-based battery subcomponent, the final cost is almost four times the cost of raw nickel, even with high volume purchasing.

Because of the processing costs associated with manufactured battery components, we have generally estimated their costs explicitly, by gathering data from specific subcomponent material suppliers. For the computations (below) of possible costs of different hydride alloys (Table 8), and of estimating the value-added share associated with production of spherical nickel hydroxide and nickel foam (Figures 1 and 2), we have assumed a battery-grade nickel cost of $7.50 per kilogram, based on data in Sandrock (1997) and from battery manufacturers. This compares to an early-1999 prevailing cost of generic nickel of about $5.60 per kilogram.

Nickel Hydride Alloy

Battery manufacturers use proprietary formulations for the nickel hydride materials used in the anode plates, and the exact specifications of these hydride materials are company secrets. Some manufacturers are using transition metal-based hydrides (AB_2), while most are using misch-metal based hydrides (AB_5). This analysis is for a transition metal-based hydride battery, and these hydrides are primarily composed of nickel, titanium, zirconium, vanadium, and chromium. We focus on AB_2 hydride-based batteries because AB_2 hydrides have several advantages over AB_5 hydrides that may ultimately make them better choices for EV batteries. These advantages include higher hydrogen storage capacities, better oxidation and corrosion resistance, and higher volumetric electrode capacities (Liu, et al., 1996). AB_2 hydride alloys also are reported to have higher tolerance to impurities than AB_5 hydride alloys, and to potentially have lower processing costs associated with removing impurities (Magnuson and Gibbard, 1994).

The general composition of AB_2 hydride alloys is $(Ti_{2-x}Zr_xV_{4-y}Ni_y)_{1-z}Cr_z$. These alloys are designated as AB_2 because the Ti-Zr atomic fraction and the Ni-V atomic fractions are in the ratio of 1:2. Transition metal hydrides with varying compositions have commonly been reported in the literature, and analysis of the relative advantages of different hydride compositions is an active area of research (Knosp, et al., 1998).

Deriving a $/kg cost for transition-metal hydride alloy material is complicated by variations in the chemical form of the various hydride alloys that can be used, and by the range of different costs for each metal that are observed in metals markets. Materials costs for titanium, vanadium, and zirconium are quite variable depending on the grade and form of the material required. For example, vanadium chips can be purchased in large quantities from Oremet Wah-Chang (an Allegheny-Teledyne subsidiary, formerly Teledyne Wah-Chang) for approximately $55.00 per pound (Jansen, 1998). Meanwhile, vanadium in a vanadium-nickel alloy sells for approximately $23.10 per kilogram, and in the "ferro" form, the cost can be as low as $11.39 per kilogram (Sandrock, 1997). Titanium chips in grade 2 or 3 sell for about $3.50 per pound, titanium sponge dust sells for about $4.50 per pound, and zirconium sponge sells for about $7.50 per pound, in a minus-20 mesh (Jansen, 1998).

Other metals that are sometimes used as additives in the production of the hydride alloy include chromium, manganese, cobalt, aluminum, and iron. Chromium sells for approximately $4.00 per pound at the present time, although this cost has fluctuated somewhat in recent years (Slagle, 1998). Of these other metal additives, only cobalt is expensive, with a price of nearly $60.00 per kilogram. Manganese, aluminum, and iron all have prices in the range of $0.44 to $2.30 per kilogram, in forms suitable for the formation of alloys (Sandrock, 1997).

Transition metal prices have been relatively stable for the past few years, and they are not expected to change appreciably in the near future (Jansen, 1998). A few years ago, chromium prices were somewhat lower than they are today, at nearly $3.00 per pound, but this was substantially lower than the price was a few years prior to that. Thus, the cost of chromium has rebounded somewhat from a low of a few years ago, but still is relatively low compared to what it has been in the past several years.

We examined the materials costs for various hydride formulations available in the academic literature, and also discussed the present costs of suitable hydride alloys with industry experts. Table 8 presents cost estimates for different transition metal hydrides, based on formulas that are available in the literature. For comparison, we also include an analysis of a mischmetal (AB_5) alloy. Metals cost estimates are taken from the sources discussed above, and from Sandrock (1997).

These calculations show that production of a transition metal hydride with a cost of <$10.00 per kilogram is possible, particularly given that the formulas used have not necessarily been optimized for low manufacturing cost. A high volume cost estimate of $9.00 per kilogram for a metal hydride powder seems reasonable, given that the relatively expensive metals vanadium and zirconium can, to some degree, be substituted with titanium and nickel (respectively) in order to reduce costs, and that some of these metals are available at lower costs than assumed in the above analysis. The hydride production process requires that the hydride materials be melted together before being powdered, and there are opportunities to use metal alloys with combinations of various metals, rather than the pure form assumed for most of the metals in the tables. Also, some metals are available on the scrap market, or as byproducts from other industrial processes. For example, in addition to the titanomagnetite source that is mined in South Africa, Russia, and China to produce pure vanadium and vanadium-nickel alloys, vanadium is also available from fly ash residues from petroleum production. Approximately 16% of the world's vanadium production comes from this source (Andersson and Rade, 1998). Furthermore, the costs associated with melting and powdering the alloy are relatively small at high volumes.

Thus, based on the above analysis, and our consultations with industry experts, we assume hydride powder costs of $12.00 per kilogram in pilot-scale production, and costs as low as $9.00 per kilogram at high volume production. In the higher-cost case we also consider the possibility that hydride costs do not drop below $12.00 kilogram, in case inadequate scrap or byproduct materials are available to meet demand, or in case the high production levels assumed here (up to 100,000 packs per year) result in upward pressure on nickel, titanium, vanadium, zirconium, and/or chromium prices. It is important to note that the use of magnesium based hydrides could lead to lower hydride costs than $9.00 per kilogram (and potentially better performance -- see concluding section), but since the use of magnesium hydrides is still under development, we have not assumed their use in NiMH battery generations 1-3. See Table 9, below, for further details of materials cost estimates for the different cases examined.

Spherical Nickel Hydroxide

Another key material to the construction of NiMH battery cells is spherical nickel hydroxide ($Ni(OH)_2$). This material forms the basis of the active material used in the positive electrode battery plates. Spherical nickel hydroxide is currently produced by several manufacturers in the U.S., Canada, Europe, and Japan. The Tanaka Corporation in Japan is the premier vendor, but Stark Chemical and the OMG Company in Ohio also produces this material. OMG quotes a price of $14.00-15.00 per kg in large orders, depending on the specific grade required (Montgomery, 1997). Inco also produces this product, reportedly at a somewhat lower cost than OMG. Some industry experts believe that this material could potentially be produced for about $8.00 per kg, with improvements in processing techniques and equipment. Such improvements are actively being pursued in the both the U.S. and Japan, and in Japan, Ishikawajima-Harina Heavy Industries and Fujisaki Electric reportedly make high-quality spherical nickel hydroxide using a new type of nozzle developed by Fujisaki. The system reportedly produces particles one-sixth to one-fourth the size of the currently available product, and the companies say the new product can improve battery quality, and cut the cost of battery manufacturing (CALSTART, 1998).

Figure 1 shows the percentages of the total cost of the hydroxide that is the cost of the nickel needed for its production, and the percentage of the cost that is the cost of adding value. This analysis generally supports industry projections of about $8.00 per kilogram, because even at this cost, the value added still exceeds the cost of the nickel input. Thus, based on price quotes and our analysis, we assume that nickel hydroxide costs $15.00 per kilogram in pilot-scale production, and that the cost drops steadily to as low as $8.00 per kilogram in the most optimistic, high-volume scenarios.

Cobalt Oxide

Cobalt oxide is also used in the production of the positive plates, as an additive in small quantities. This material can be purchased for about $65.00-75.00 per kg, depending on order size (Montgomery, 1997).

Nickel Foam

The positive electrodes in NiMH EV batteries typically consist of a foam or felt nickel substrate material that is pasted with nickel hydroxide active electrode material and then dried and compressed. Nickel foam is used because it allows the production of a battery with a high level of active mass utilization, resulting in a greater amp-hour capacity than is possible with the current limits of sintered electrode technology. The standard nickel foam material, produced by companies such as the Eltech Systems Corp., is a 1.6 mm foam that weighs roughly 500 gm/m^2. The Eltech product is produced with an electrolytic process, although the use of a carbonyl process is also possible. A 40 kWh battery would use roughly 75-100 m^2 of this material.

In order sizes of 1-2 million m^2/year, the price of the Eltech material is presently in the range of \$15.00-16.00/m^2 (Cahill, 1997). At higher production volumes of several million m^2, prices of \$12.00-14.00/m^2 are considered possible, but this production volume is much higher than Eltech's current capacity of about 800,000 m^2 per year, and these prices are thus somewhat speculative (Cahill, 1997). The cost of nickel becomes an increasingly important variable at these production volumes, and low prices are thus more likely if the cost of nickel stays low. Nickel foam prices as low as \$10.00/m^2 are expected in the future by some analysts (Reisner, et al., 1996), but process breakthroughs may be required to realize these lower prices.

Figure 2 shows the percentages of the total price of the nickel foam that is the cost of the nickel needed for its production, the cost of the urethane foam that is used as a substrate during production (before being eventually vaporized), and the percentage of the price that is the cost of adding value, along with supplier profit. The urethane foam cost is estimated to be \$1.63 per m^2, based on a cost estimate for SIF foam in a 110 PPI grade of \$2.25 per board foot, cut to the proper width (Glennon, 1998). The foam would then shaved to a thickness of 1.6 mm before being plated with nickel. At \$16.00 per m^2, the cost of adding value substantially exceeds the cost of the raw material input. Even at \$10.00 per m^2, the raw material input accounts for less than 50% of the total cost. This suggests that \$10.00 per m^2 is a reasonable estimate for high volume production in a competitive, mature battery industry. Based on this analysis and the supplier price quoted above, we use estimates of \$20.00 per m^2 for production volumes of 350 packs per year, \$15.00-16.00 per m^2 for production volumes of 7,700 packs per year, \$14.00-15.00 per m^2 for production volumes of 20,000 packs per year, and \$10.00-14.00 per m^2 for production volumes of 100,000 packs per year.

Metal Mesh or Grid

The construction of the anode requires the use of a grid substrate, that acts both to support the metal hydride active material and as a current collector. The specific design of the substrate is not important, and any type of wire mesh, perforated metal, or expanded metal can be used (Fetcenko, et al., 1992). At present, nickel or nickel alloy is used for this purpose, although in principle it may be possible to use other less expensive metals. We initially assume the use of expandable nickel grid that is purchased in roll form and cut to the proper size. The cost of this material is presently about \$0.30 per linear foot. We assume this cost for the Gen1 cases, but for the Gen2 and Gen3 technologies we assume that a less-expensive substrate can be used, with a cost of \$0.10-0.15 per linear foot (\$0.10-0.12 for 100,000 packs per year). This assumption is based on the fact that a variety of common metals could be manufactured in this form for this cost, since \$0.10 per foot is equivalent to a cost of nearly \$20 per kilogram,[1] and this would be sufficient to cover the metal input cost, and the costs of processing, plating, packaging and delivery, for such materials as nickel-plated stainless steel or iron.

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[1] Assuming a grid that is 0.025 cm thick, 8 cm wide, 90% open, and with a density of 8.8 mg/cm^3.

Separator

The separator material used in the NiMH EV battery is a 0.005 inch thick polypropylene material. This material is presently produced by only a few U.S., European, and Japanese companies, including the Freudenberg Company in Germany and the Hollingsworth-Vose Company in the U.S. The raw fiber used in producing the separator material is manufactured in Japan, and since the separator material demands the finest grade of fiber produced today, the cost of the basic fiber material used in the separator is greater than the cost of coarser fibers produced for other purposes. Once obtained, the fibers are then blended and then processed to produce a "wettable" surface. Finally, a washing process is used to clean and finish the material. The cost of this material is currently in the range of \$2.50-3.00/m^2, depending on order size (Bennett, 1997). These costs are expected to perhaps \$2.00-2.25/m^2 decline as the market for NiMH batteries develops and the market for the separator material becomes more competitive.

Electrolyte

NiMH batteries use a liquid potassium hydroxide (KOH) electrolyte. Electrolyte requirements of approximately 2.0 grams per Ah are reported for nickel cadmium batteries (Scott and Rusta, 1978), and manufacturers of NiMH cells confirm that this is also the electrolyte fill level used for practical NiMH batteries (although levels as high as 4.5 g/Ah have been reported in the literature). KOH is produced and sold at a variety of locations around the country, and its final delivered cost is partly a function of how far it is transported. In small, drum quantities, KOH can be purchased for approximately \$0.50 per pound. In tanker truck quantities of 45,000 pounds, the purchase price drops to \$0.20 to \$0.25 per pound, depending on transport distance (Banisch, 1998). The standard product is a 45% KOH solution, whereas NiMH battery production calls for a 30% solution. The lower volume production scenario analyzed here would require approximately 60,000 pounds of 45% KOH per year, which would then be diluted to 90,000 pounds of 30% solution. The higher volume scenario would require approximately 1.2 million pounds of 45% solution. The electrolyte needs for the lower volume scenario are assumed to be met with 55-gallon drums, since approximately 15 drums per month would be sufficient. The cost of KOH supplied in this form is assumed to be \$0.50 per pound for the 45% solution, or \$0.33 for the final 30% solution. For the higher volume scenarios, it is more reasonable to assume that the solution would be delivered by tanker truck, in 45,000 pound lots. For the 7,700 pack per year scenario, between 26 and 27 truck deliveries would be required per year, so deliveries would be taken about twice a month and the solution would be stored onsite in a storage tank between deliveries. The larger volume scenarios would require either more frequent deliveries, or multiple truck deliveries with larger storage tanks. At these volumes, the cost is assumed to be \$0.20 per pound for the 45% solution, resulting in a final cost of \$0.13 per pound for the 30% solution.

Casing

Various metal product companies and tool and die shops produce steel casings suitable for battery applications. Hudson Tool and Die, in New York, is a large metalworking operation that produces orders of metal casings in a huge range of pre-determined shapes, sizes, and tolerances. However, the casings that they produce have curved edges, while prismatic battery designs require casings with square edges. Even though they do not manufacture exactly the right type of case, they are familiar with that type of product and they were able to offer an approximate price quote on square edge designs in low and high volumes. For stainless steel cases that are approximately four inches wide, two inches deep, and six inches high, they estimate that in lower volumes of ten to fifty thousand units per year, the cost for the cases and covers could be as high as $7.00-8.00 for each case/cover assembly. At higher volumes of over 100,000 units per year, the cost of the case would drop to approximately $3.00 per unit (Hynes, 1998). Bison ProFab in New York confirms the price of at least $8.00 per case for the container and lid in quantities of a few thousand units per year, and suggests that costs could be as high as $13 per case in smaller volumes. In quantities of hundreds of thousands of units per year, it would be cost-effective to set up an automated extruding process for production of the cases. Bison estimates that this would reduce costs by approximately two-thirds, with resulting unit costs on the order of $3.00 per case (Pladson, 1998). Containers can also be produced from rolled tubes that are shaped through extrusion or die-like expansion processes and then fitted with a bottom piece, or they can be deep-drawn.

For this analysis, we use cost estimates for a rolled tube is extruded into the proper shape. A bottom piece is welded to the shaped container, and the resulting assembly is then leak-tested before delivery. These cost estimates are similar to those discussed above for the other processes. See individual tables for details.

Lid, Terminals, and Miscellaneous Hardware

The costs of the terminals and pressure vents that are incorporated into the lid of each battery cell container are quite variable depending on production volume and the manufacturing processes used. In low volumes, these pieces would be custom machined at high per-unit costs, while in larger volumes it becomes economical to mass produce them with tool and die production lines, and to use metal stamping processes for some components.

The parts that compose each battery lid are the lid itself, two terminals, a vent, and other miscellaneous parts including a vent spring and O-rings. In low volume production, these parts would cost approximately $16 per lid assembly, while in higher volume production of over 2,000 packs per year, the costs would fall to about $2.80 per assembly, with the terminals and terminal assembly accounting for approximately $1.90 of this total. These cost estimates are based on quotes to battery manufacturers, from various suppliers of these parts.

Finally, there are some minor hardware costs associated with assembling separate cells into a module. We estimate that battery terminal interconnects and module compression straps add an additional $1.50 to the cost of each module.

Estimates of Key Materials Costs

Table 9 presents the materials cost estimates used in the analysis, for each case examined. In each case, except for the pilot-scale case, two different sets of materials cost estimates were used based on our assessment of a reasonable range of costs for each key material. In one case relatively high materials cost estimates were used, and in the other case relatively low materials cost estimates were used. In this way, a range of manufacturing costs and selling prices was estimated for each case.

Other Factory Costs

Labor and overhead rates, and costs associated with administration, marketing and distributing the battery have been derived from a variety of sources, including conversations with various battery manufacturers, and published cost estimates for other battery types (Hasuike, 1991; Quinn, et al., 1989). We believe that the labor and overhead estimates are reasonable, but unlike in the lead-acid battery analysis, they are not based on our own detailed analysis of factory costs and labor requirements. Distribution and service costs are assumed to be proportional to the weight of the battery, and thus are a lower percentage of costs for NiMH batteries than for lead-acid batteries (see tables for details). Costs associated with "marketing and other corporate costs" can be highly variable depending on the structure of the company, the number of product lines that it has, it's marketing strategy and requirements for marketing expenditures, the amount spent on product R&D, licensing arrangements, and other factors. Given these uncertainties, we consider a range of costs for this category, from 2% of selling price in the lower cost cases (assuming direct sales to OEMs with no associated marketing costs, and no licensing costs), to 7% of selling price in the higher cost cases. Since the estimates for labor, overhead, marketing/corporate costs, warranty, and profit are expressed as a function of manufacturing cost or selling price, they vary for each case when the high and low materials cost estimates are used. Thus, to some degree, uncertainty in these parameters is incorporated into the analysis even when the percentages themselves do not vary.

With regard to manufacturer profit, it is reasonable to assume that the level of profit per module is more or less constant even as production volume increases. This is because automobile manufacturers tend to set the level of profit that they allow their suppliers to make. If profit margin is assumed to be constant, then the dollar profit per module is much higher in low volume production, when manufacturing costs are high. It is unlikely that automotive customers would allow profits to vary in this manner. For this analysis, we assume that the targeted level of profit is approximately $40 per module.

Cell Capacity, Specific Power, and Selling Price

It is possible to design NiMH cells in such a way as to increase cell specific power, although this tends to decrease cell specific energy. Nevertheless, in order to reduce the cost of the battery pack for a specific vehicle, it may be desirable to produce smaller, higher power cells, that can still provide enough power to meet a given power requirement, at the expense of a shorter vehicle range. In order to explore potential trade-offs in battery costs and vehicle ranges in the context of the ITS-Davis EV cost and performance model, it is necessary to characterize the costs of a range of different NiMH cell sizes.

One issue with modeling costs of different battery cell sizes is that many different designs are possible, and these designs give varying results for the effect of cell plate size on the specific power of the cell. The specific power of the cell can generally be increased by increasing the plate count and decreasing plate thicknesses. However, manufacturer data show that considerable specific power can also be gained simply by making the plates shorter, holding plate count constant. This is because current can be collected more efficiently through a smaller plate. Thus, there are two effects to consider. First, cell power can be increased through specific changes in the battery design, and second there is an "automatic" increase in cell power as plate size is decreased.

For this analysis, Dr. Burke's model was modified to account for the latter effect, by including values for the resistivity of various materials, and the model was then used to analyze battery designs for different cell sizes. Table 10, below, shows the characteristics of these different cell size designs, based on the "Gen3" technology discussed above, as calculated with the battery performance model. This table shows that cell specific power generally increases as plate area and cell capacity are decreased, with the exception of the 80 Ah case (which apparently is not well optimized for peak power).

The manufacturing costs and selling prices of these 10 Ah to 150 Ah cells have been estimated by making a few adjustments to the assumptions used for the 100 Ah reference cell. First, we assumed a different packaging scheme for the smallest cell sizes, with the 10 Ah cells packaged in 10-cell "multibloc" modules. These modules have internal cell connectors, so that only one set of terminal hardware is used for each 10-cell, 12V module. This packaging scheme reduces containment and hardware costs, and probably more accurately reflect the strategy that manufacturers would actually employ for smaller cells, relative to the simpler "1 cell, 1 container" assumption.[2] Second, costs of the battery containers were assumed to scale in proportion to their surface area. As in the analysis of the 100 Ah cells, both low and high price estimates were made in order to capture some of the uncertainty in key battery materials cost and corporate level cost parameters.

The following figures present selling price estimates for different battery cell sizes, at different production volumes. Figures 6 and 7 show prices as a function of price per kWh and price per kilogram. Figure 8 shows the results when the values at a production level of 20,000 packs per year are normalized to the value for the reference 100 Ah cell, in order to show the relative range of variation. As can be seen, prices of the smaller cells are considerably less variable as a function of cell weight than they are as function of cell energy, but they are not a constant function of either parameter.

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[2] The trade-off to this strategy is that it is much harder to replace a single failed cell in a module.

Figure 9 shows the fit of battery selling price functions to calculated battery prices per module weight. These functions were estimated by calculating the increase in the average \$/kg price[3] for battery cells smaller than 100 Ah, and using regression analysis to estimate the increase in price as a function of cell energy (Wh). These functions were estimated for cell sizes between 100 Ah (or 120 Wh) and 50 Ah (or 60 Wh), and they should not be used to calculate prices for cell sizes outside of this range.

The functions shown in Figure 9 are as follows:

7,700 packs/year: \$/kg OEM price = 26.04 + (106.98 - (22.41*ln[cell Wh])

20,000 packs/year: \$/kg OEM price = 20.79 + (80.69 - (16.89*ln[cell Wh])

100,000 packs/year: \$/kg OEM price = 18.02 + (69.43 - (14.53*ln[cell Wh])

Notes:

Cell Wh is calculated as 1.2 V/cell * cell Ah: 60 Wh for 50 Ah cells, 96 Wh for 80 Ah cells, 120 Wh for 100 Ah cells.

The first term in the equation is the \$/kg price of the 100 Ah cell (average of high and low cost cases), and the term in parentheses is the correction for smaller cells.

Results of NiMH Battery Manufacturing Cost and Selling Price Analysis

The detailed results of the manufacturing cost analysis for 90-100 Ah NiMH cells are presented in Tables 11 through 19. Table 20 presents final selling prices and effective battery prices (including salvage value -- see discussion below) for each case examined. Figure 3 presents the results of the analysis in graphical form. The data presented in the figure are mean values for the range of selling prices that are shown in the tables. Figure 4 shows the difference between the high and low estimates for one technology at each production volume. The figure shows estimated prices for Gen1 technology at 350 packs per year, Gen2 technology at 7,700 packs per year, and Gen3 technology for 20,000 and 100,000 packs per year. Figure 5 presents selling price projections that were developed independently by GM Ovonics (Adams, 1995). The two projections compare favorably, particularly at the 20,000 pack per year level for Gen3 technology, where GM Ovonics projects a price of \$240 per kWh, and we project a range of prices of \$239-279 per kWh.

As discussed above, the results of the analysis of Gen3 battery selling prices as a function of cell size are presented in Figures 6 through 9 and in Table 21. These results show that as battery cells decrease in size, battery cell prices increase as a function of price per kWh, and also but to a lesser extent as a function of price per kilogram.

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[3] i.e., the average of the higher and lower cost cases.

Potential Further Cost Reductions

It is important to note that the "effective" prices of NiMH batteries could be lower than the sale prices shown in Figures 3 and 4 for two reasons. First, the fact that NiMH batteries contain substantial quantities of nickel means that it likely would be economically attractive to recover this material at the end of the batteries' useful life. In contrast to the case of lead-acid batteries, where lead sells for only about $1.00 per kilogram and battery recycling efforts are driven largely by the desire to prevent lead from entering landfills, a NiMH battery recycling industry could presumably be driven by the opportunity to recover nickel and resell it at the prevailing price of $5.00-6.00 per kilogram. Recent research in Japan has shown that 96% of the nickel and cobalt in NiMH battery electrodes can be recovered, using sulfuric acid and oxalic acid recovery techniques (Zhang, et al., 1999). Tables 11 through 19 show the potential salvage value of NiMH batteries, assuming that 40% of the battery weight is recovered as nickel, that the recovered nickel is sold at $5.60 per kilogram, and that processing costs consume 25% of the salvage value (in reality, of course, processing costs would be dependent on the scale of the recycling operation and the nature of the processes used). These figures show that battery salvage could result in a return of about 6-9% of battery selling price at the end of battery life, thereby lowering the "effective price" of the battery.

Second, it is possible that a secondary market for EV batteries may develop. Once the performance of a battery pack drops to a level below which it is not suitable for use in an EV, it could be reconfigured for other, less-demanding uses, such as load-leveling utility power systems or providing electrical energy storage for remote photovoltaic, fuel-fired generator, or other "off the grid" systems. This market has not yet been established, so we do not quantify the potential impact on battery "effective prices," but Ovonic Battery Company believes that the value of used NiMH EV batteries could potentially be comparable to the present cost of lead-acid batteries since they may be able to provide similar performance and cycle life once their useful life as an EV battery expires (Corrigan, 1998).

Furthermore, it is important to note that the above discussion of the costs of key NiMH battery value-added materials, such as nickel foam and nickel hydroxide, stopped short of pointing out that the costs of these materials could potentially drop to levels below those assumed here. In high volume production, many common products have total manufacturing costs that are only 25-30% higher than the cost of raw materials, whereas even the lowest costs assumed here for nickel foam and nickel hydroxide include costs of adding value that are on the order of the value of the underlying materials cost. Thus, further cost reductions of 20-25% in these materials may be possible with process innovation and increases in production volume. For nickel foam, cost reductions could become even more substantial if a suitable material could be produced without the use of the urethane substrate that is currently used in the nickel foam production process.

Finally, new active materials for NiMH EV batteries are currently under development, and the future use of these materials could result in performance improvements and cost reductions that would lead to prices significantly below those shown here. For example, Ovonic Battery Company is currently being funded by NIST to develop magnesium-based metal hydride alloys that could potentially lower the weight of hydride needed by a factor of two, at a lower hydride cost than assumed here for the Ni-Ti based hydrides (Corrigan, 1998). The combination of these factors could reduce the cost of metal hydride material needed for a given level of anode performance by more than 50%. Work is also underway to increase the utilization of nickel hydroxide electrodes by up to about 50%, making use of quadrivalent nickel in the nickel electrode (Corrigan, 1998). Together, these two approaches could result in significant cost reductions in future generation NiMH batteries.

In order to account for this future potential of NiMH batteries that use next-generation active materials, we estimate additional "Gen4" cases, shown in Tables 18 and 19. These cases assume that a magnesium-based hydride material with a storage capacity of approximately 600 mAh/g can be produced in powdered form at a cost of \$5-7 per kilogram (based on analysis of the potential costs of one recently-published magnesium hydride formula (Cui and Luo, 1999), using a calculation similar to those shown in Table 8). These cases also assume somewhat higher theoretical hydroxide utilization levels (363 mAh/g versus 291 mAh/g for Gen3). More fundamentally, these cases assume that the significant hydride stability and cycle life degradation problems that magnesdum-based hydrides currently face are solved.

The 100,000 pack per year, higher cost cases also assume slightly lower costs for other battery materials than used in the Gen3 100,000 pack per year, higher cost cases (reflecting the likelihood that by the time Gen4 hydride materials become available, other materials costs may be nearer the lower end of the assumed ranges). As such, these examples represent somewhat optimistic future cases. However, the results (\$155 to \$211 per kWh, depending on the case) do not appear to be overly optimistic given the expectations of some manufacturers. Costs as low as \$100 to \$150 per kWh are expected by Ovonic Battery Company for batteries that use the next-generation, magnesium-based hydride materials (Corrigan, 1998). Based on the estimates made here, selling prices per kWh of these Gen4 modules would be about 25% lower than Gen3 cells produced in volumes of 20,000 packs per year and 100,000 packs per year (see Table 21).

Figure 10 shows that, when normalized to the 100 Ah case, the dollar per kilogram and dollar per kWh prices of these Gen4 modules are somewhat less variable over the range of sizes of from 60 Ah to 20 Ah than are the prices of the Gen3 modules.[4] As in the Gen3 cases, the flattening of the price per kilogram curves shown in Figure 10 between 60 Ah and 20 Ah is due to the assumption that the 20 Ah modules are packaged in "multibloc" containers, each holding five cells, and resulting in a reduction in hardware costs. The reduced variation in costs of the Gen3 modules with cell sizes from 60 Ah to 20 Ah is presumably due in part to the earlier introduction of the "multibloc" strategy (at 20 Ah vs. 10 Ah for Gen3). In general, the Gen4 modules have considerably lower prices than Gen3 modules

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[4] 60 Ah and 20 Ah Gen3 modules were not analyzed, but the corresponding prices can be approximated by examining trends in the prices of the 80 Ah, 50 Ah, and 10 Ah Gen3 modules.

when prices are expressed as a function of price per kWh, but prices are very similar when expressed as a function of price per kilogram. This is due to the lighter weights of the Gen4 modules, compared to Gen3 modules of the same capacity. OEM price results for all of the the Gen4 module cases are shown in Table 21, both as a function of price per kWh and price per kilogram.

Lithium-Ion EV Batteries

Lithium-ion batteries are attractive for use in EVs because of their high potential energy and power densities. However, safety and other technical issues, as well as cost considerations, have slowed the development of practical lithium-ion EV batteries. At present, only Nissan has produced an EV with a lithium-ion battery pack. This battery pack, developed by Sony, is reported to have an energy density of 90 Wh/kg, and a very high cycle life of approximately 1,200 charge-discharge cycles (Vreeke, 1998).

A critical issue with regard to developing a commercially feasible lithium-ion battery is developing suitable, low-cost cathode materials. Anodes can be constructed from inexpensive graphite material, but the material presently used in most commercially produced lithium-ion cell cathodes is $LiCoO_2$. This material has a cost of approximately \$48 per kilogram (Brandt, 1995), due primarily to the high cost of cobalt. However, nickel and magnesium based compounds, such as $LiNiO_2$ and $LiMn_2O_4$, are also suitable for use as cathode materials. These compounds have much lower costs per kilogram, but they produce cells with lower amp-hour capacities for a given cell size. One estimate suggests that $LiNiO_2$ could be produced at a cost of about \$6.10 per kilogram, and that $LiMn_2O_4$ could be produced for about \$3.00 per kilogram (Brandt, 1995).

Table 22 presents two estimates of the distribution of materials costs for lithium-ion cells, based on $LiNiO_2$ and Li-Mn spinel cathodes. These data indicate that costs of cathode materials are only one cost driver, with costs of separator material and other components also figuring heavily into the total cost of manufacturing lithium-ion cells. The relative costs for materials for these systems appear to be rather different, with costs of negative material being comparable to costs of positive material in the manganese-based system, and separator and electrolyte costs being more significant cost drivers in the nickel-based system.

In addition to cost considerations, safety issues are a concern with lithium based batteries. Overcharge can result in formation of metallic lithium at the anode, or decomposition of the organic electrolyte and gassing at the cathode, both of which can result in damage to the battery, or even catastrophic battery failure. As a result, cell-level control during charge and discharge is required for safe lithium-ion batteries. These control systems will add cost and complexity to any practical lithium-ion EV battery.

Assuming that lithium-ion EV batteries can be designed to assure safety under potential adverse conditions, and that cobalt based cathodes can be eliminated, lithium-ion batteries could become a good choice high performance EV battery packs. If the reported cycle life characteristics of the current Sony batteries can be maintained with the use of different cathode materials, a lithium-ion EV battery pack could potentially last for as much as 10 years of normal driving.

With regard to overall costs of complete lithium-ion EV battery packs, no detailed, publicly-available study has been completed, although one is underway at Argonne National Laboratory. However, both Sony and SAFT have identified a cost target of $200/kWh in high-volume production (Broussely, et al., 1996; Kalhammer, et al., 1995). Costs of at least $500/kWh are considered likely for early production (Kalhammer, et al., 1995). The USABC mid-term goal of $150/kWh is apparently not considered feasible, but Nissan believes that when life-cycle costs are factored in, lithium-ion batteries could be cost competitive with lead-acid batteries when in mature production (Vreeke, 1998).

Comparison of Results with CARB Battery Panel and ANL Delphi Study

Finally, in order to put these battery price estimates in context, we compare them to the results of two other well-known studies. These include the CARB battery panel (Kalhammer, et al., 1995), which gathered information from a variety of manufacturers and developed cost forecasts from those data, and the Argonne National Laboratory (ANL) delphi study of battery performance and cost (Vyas, et al., 1997). For purposes of comparison, we match the ANL estimates for calendar years 2000, 2010, and 2020 with the production volume estimates assumed here of 7,700 packs per year, 20,000 packs per year, and 20,000 packs per year. Also, we use ANL's modifications to the CARB battery panel data to fit the same time frame, given the change in the ZEV mandate since the findings of the battery panel were released (see Vyas, et al., 1997). These comparisons are shown in Table 23.

Tables and Figures

Table 1: Estimated and Observed Sealed Lead Acid Battery Prices ($1998)

Battery	**Voltage**	**Capacity**	**Manufacturer List**	**Retail Price**	**Wholesale (>100 mod./mo.)**
JC U1-31B	12 V	31 Ah	$100/module $269/kWh $150/module[a] $403/kWh[a]	$75/module $202/kWh $115/module[a] $309/kWh[a]	$39-55/module $105-149/kWh $70-80/module[a] $188-215/kWh[a]
JC GC1245V	12 V	45 Ah	$134/module $298/kWh	$98/module $218/kWh	$68-75/module $151-167/kWh
JC GC1265V	12 V	65 Ah	$160/module $246/kWh	$135/module $208/kWh	$90-110/module $138-169/kWh
ITS-Davis Estimate	12 V	75 Ah	N/A	N/A	$97-102/module $107-113/kWh

Notes:

[a] Battery module list, retail, and wholesale cost circa 1993, and in $1993. Manufacturer list price is the price listed by Johnson Controls, retail price is the actual small order price by Cell-Con, Inc., and wholesale price is the large order (>100 modules/month) order price from Cell-Con, Inc.

Source: Johnson Controls battery costs from Mumma (1998).

Table 2: Lead Acid Battery Manufacturing Equipment and Environmental Compliance Costs for Single Production Line Plant

Vendor	Equipment Model	Quantity	Specifications	Cost
MAC	instaMAC 250 grid feeder w/parter	1	90-170 panels/min plates 1-3.8 mm thick	$23,892
MAC	autoMAC 170 plate paster	1	90-170 panels/min	$39,460
MAC	supraMAC oven gas powered	1	20,000-800,000 BTU 80-250 panels/min	$58,890
MAC	oven conveyor (10')	1		$3,375
MAC	MAC paste return system	1		$17,325
MAC	mixMAC 1200 paste mixer	1	1200 pounds/hour	$43,975
MAC	accuMAC parter 190 w/conveyor and saw	1	250 panels/min	$36,860
MAC	MACexpander feeder	1		$11,640
MAC	MACexpander	1	grids 0.5-1.27mm thick	$53,360
MAC	MACexpander dies & tooling	1		$33,840
MAC	MACgrid shaper	1		$56,284
MAC	MACgrid shaper die	1		$16,350
MAC	MAC C.O.S. cast-on-strap machine	1	1,000 modules/shift	$149,980
MAC	C.O.S. lug pots	1		$21,376
MAC	C.O.S. addt'l moldings	1		$980
MAC	C.O.S. auto unload system	1		$75,988
MAC	industroMAC welder	1	600-800 modules/shift	$38,960
MAC	meltMAC 2000G	1	2,000 pound capacity	$7,186
MAC	pumpMAC 2	1		$1,270
MAC	MAC battery short tester	1	5 modules/min	$27,065
MAC	MACsealer	1	3-6 modules/min	$42,600
MAC	MACsealer tooling	1		$6,860
MAC	MAC battery leak tester	1	5 modules/min	$24,225
MAC	industroMAC sleever	3	240 inches sleeve/min	$69,980/ea $209,940 tot.
Bitrode	battery formers (chargers) 16 circuits per cabinet 20 Amp, 300 V	4	18 batteries/circuit Assume 48 hr formation	$38,000/ea $152,000 tot.
BESCO	stacking tables with air ventilation hook-ups	3		$1,620/ea $4,860 tot.
BESCO	air ventilation equipment including bag house, ducts, and filter system	1		$30,000
BESCO	acid handling equipment	1		$8,000
BESCO	miscellaneous material handling equipment	1		$15,000
BESCO	vacuum fill system	1		$50,000
Bolder est.	environmental controls/ reg. compliance equipment	1		$500,000
Total Equipment				**$1,761,541**

Sources:
(Bennett, 1996; Hennen, 1996; MAC Inc., 1995; Winkel, 1996)

Table 3: Lead Acid Battery Manufacturing Equipment Power and Personnel Requirements (One Production Line)

Vendor	**Equipment Model**	**Quantity**	**Power Required**[a]	**Personnel**[b]
MAC	instaMAC 250 grid feeder w/parter	1	0.75 kW	1
MAC	autoMAC 170 plate paster	1	14 kW	2
MAC	supraMAC oven gas powered	1	13 kW/ + 1,050 cu. ft. nat. gas/hr	2
MAC	MAC paste return system	1	1.1 kW	1
MAC	mixMAC 1200 paste mixer	1	6 kW	2
MAC	accuMAC parter 190 w/conveyor and saw	1	4 kW	4
MAC	MACexpander feeder	1	2 kW[c]	none
MAC	MACexpander	1	4 kW[c]	1
MAC	MACgrid shaper	1	4 kW[c]	none
MAC	MAC C.O.S. cast-on-strap machine	1	10 kW[c]	2
MAC	C.O.S. lug pots	1	190 cu. ft. nat. gas/hr	none
MAC	C.O.S. auto unload system	1	1 kW[c]	none
MAC	industroMAC welder	1	35 kW	2
MAC	meltMAC 2000G	1	232 cu. ft. nat. gas/hr	1
MAC	pumpMAC 2	1	0.5 kW	none
MAC	MAC battery short tester	1	1.5 kW	set-up only
MAC	MACsealer	1	20 kW	set-up only
MAC	MAC battery leak tester	1	1.5 kW	set-up only
MAC	industroMAC sleever	3	15 kW	3
Bitrode	battery formers (chargers) 16 circuits per cabinet 20 Amp, 300 V	4	384 kW[c]	4
BESCO	air ventilation equipment including bag house, ducts, and filter system	1	5 kW[c]	
BESCO	vacuum fill system	1	3 kW[c]	1
Total		electricity nat. gas	**525.35 kW/hr** **1,472 cu. ft./hr**	**26**

Sources:

[a] (MAC Inc., 1995)

[b] (MAC Inc., 1995)

[c] Author estimate, based on similar equipment.

Table 4: Lead Acid Battery Manufacturing Total Materials and Direct Labor Costs

Component	**Materials** (cost/qty.)	**Materials** (qty./module)	**Materials** ($/module)	**Labor**[a] ($/module)
Plate Production:				
lead grids[b]	$0.45/lb	7.94 lbs	3.57	
lead oxide paste (cathode)[c]	$0.48/lb	12.77 lbs	6.13	
spongy lead (anode)	$0.45/lb	11.9 lbs	5.36	
pasting belts[d]	$90/belt	.0002 belts	0.018	
Total Plate Production			**15.08**	**2.84**
Battery Assembly:				
sulfuric acid electrolyte[e]	$57/2700 gal.	1.02 gal.	.02	
separator material[f]	$60/1000 ft.	124 ft.	7.44	
terminals	$0.45/lb	0.156 lbs	.07	
containment[g]	$11/container	1 container	11.00	
Total Battery Assembly			**18.53**	**2.37**
Utilities:[h]				
electrical equipment	$.047/kWh	8.41 kWh	.395	n/a
natural gas equipment	$.00266/cu. ft.	23.56 cu. ft.	.0627	n/a
lighting[i]	$.047/kWh	0.16 kWh	.0075	n/a
miscellaneous equipment[j]	$.047/kWh	0.24 kWh	.0113	n/a
Total Utilities			**0.4765**	
Total			**34.09**	**5.21**

Notes:

[a] Based on a 1997 labor rate of $14.80/hr. This rate was derived from a 1992 labor rate of $12.77 per hour for SIC 3691 (storage batteries) production workers, reported in the 1992 Census of Manufacturers. The 1992 rate was inflated at 3% per year to arrive at the 1997 rate.

[b] Grid materials cost is based on a lead cost of $0.45/lb, which is based on recent lead price fluctuations between $0.40/lb and $0.52/lb.

[c] Paste cost of $0.48/lb is based on a mixture of 45% lead, at $0.45/lb, and 55% oxide, at $0.50/lb. The mixture figures were provided by Winkel, 1996.

[d] Belts are assumed to be replaced every 10 shifts.

[e] Electrolyte cost supplied by Koss, 1996. The provided figure of $79.56 per 2700 gallons of electrolyte was adjusted by the ratio of 1300/1800 to account for the fact that delivered electrolyte has a specific gravity of 1800, while battery manufacture requires an electrolyte specific gravity of approximately 1300. This adjustment results in a cost of $57 per 2700 gallons.

[f] Separator cost was supplied by Entek, 1996.

[g] Containment costs were supplied by Mason, 1996.

[h] Energy costs are average industrial energy costs for 1995, reported in EIA, 1996.

[i] Lighting load assumed to be 10 kW.

[j] Miscellaneous equipment includes safety systems, emergency lighting, employee amenities, etc. Load is assumed to be 15 kW.

Sources:

(Entek Corp., 1996; Koss, 1996; Mason, 1996; U.S. Census Bureau, 1992)

Table 5: Lead Acid Battery Total Manufacturing Costs (120,000 modules/year)

Quarter-Scale Plant	**$/module**	**120,000 modules per year**
Plate Production:		
Labor	$2.84	12 workers
Materials	$15.08	grids, paste, spongy lead
Module Assembly:		
Labor	$2.37	10 workers
Materials	$18.53	separator, casing, terminals, electrolyte
Battery Formation:		
Labor	$0.95	4 workers
Electricity	$1.00	
Misc. Direct Labor	$1.42	6 workers
Total Labor and Materials:	**$42.19**	
Other Factory Costs:		
Overhead on Materials	$3.36	10% of materials
Overhead on Labor	$11.37	150% of labor
Rent	$2.00	$6/sq. ft., 40,000 sq. ft.
Amortized Equipment Cost	$0.98	straight-line, 15 yrs., no salvage
Misc. Utilities	$0.48	From Tables 3 and 4
Total Other Factory Costs:	**$18.19**	
Other Expenses:		
Distribution and Service[a]	$7.32	$0.31 per kilogram
Marketing[b]	$2.03	2% of selling price
Warranty[b]	$4.07	4% of selling price
Disposal[b]	$4.50	$5/kWh
Total Other Expenses:	**$17.92**	
Total Manufacturing Cost:	**$78.29**	
License Fee[b]	$3.045	3% of selling price
Profit[b]	$20.34	20% of selling price
Selling Price:[c]	**$101.68 per module**	
	$112.97 per kWh **($4.31 per kg)**	0.90 kWh/module

Notes:

[a] Distribution and service costs assume the same $/kg cost estimated for sodium sulfur batteries in (Quinn, et al., 1989).

[b] Estimated through discussions with Pb-acid battery manufacturers.

[c] Wholesale selling price, to automotive OEMs and battery dealers.

Table 6: Lead Acid Battery Total Manufacturing Costs (480,000 modules/year)

Full Scale Plant	**$/module**	**480,000 modules per year**
Plate Production:		
Labor	$2.37	40 workers
Materials	$15.08	grids, paste, spongy lead
Module Assembly:		
Labor	$2.13	36 workers
Materials	$18.53	separator, casing, terminals, electrolyte
Battery Formation:		
Labor	$0.71	12 workers
Electricity	$1.00	
Misc. Direct Labor	$1.18	20 workers
Total Labor and Materials:	**$41.00**	
Other Factory Costs:		
Overhead on Materials	$3.36	10% of materials
Overhead on Labor	$9.59	150% of labor
Rent	$1.50	$6/sq. ft., 120,000 sq. ft.
Amortized Equipment Cost	$0.91	straight-line, 15 yrs., no salvage
Misc. Utilities	$0.48	From Tables 3 and 4
Total Other Factory Costs:	**$15.84**	
Other Expenses:		
Distribution and Service[a]	$7.32	$0.31 per kilogram
Marketing[b]	$1.93	2% of selling price
Warranty[b]	$3.87	4% of selling price
Disposal[b]	$4.50	$5/kWh
Total Other Expenses:	**$17.62**	
Total Manufacturing Cost:	**$74.46**	
License Fee[b]	$2.90	3% of selling price
Profit[b]	$19.34	20% of selling price
Selling Price:[c]	**$96.70 per module**	
	$107.45 per kWh **($4.10 per kg)**	0.90 kWh/module

Notes:

[a] Distribution and service costs assume the same $/kg cost estimated for sodium sulfur batteries in (Quinn, et al., 1989).

[b] Estimated through discussions with Pb-acid battery manufacturers.

[c] Wholesale selling price, to automotive OEMs and battery dealers.

Table 7: Cases Examined for NiMH EV Battery Production

Production Level/ Technology	**350 packs/yr**	**7,700 packs/yr**	**20,000 packs/yr**	**100,000 packs/yr**
Generation 1 **(~70 Wh/kg)**	90 Ah cells 11 cells/module 30% overhead 25% labor	90 Ah cells 11 cells/module 20% overhead 16% labor	Not examined	Not examined
Generation 2 **(~80 Wh/kg)**	Not examined	100 Ah cells 10 cells/module 20% overhead 16% labor shorter plates	100 Ah cells 10 cells/module 12% overhead 10% labor shorter plates	100 Ah cells 10 cells/module 8% overhead 5% labor shorter plates
Generation 3 **(~90 Wh/kg)**	Not examined	Not examined	100 Ah cells 10 cells/module 12% overhead 10% labor shorter plates better hydride	100 Ah cells 10 cells/module 8% overhead 5% labor shorter plates better hydride
Generation 4 ***(~120 Wh/kg)*** ***Future Technology***	*Not examined*	*Not examined*	*100 Ah cells* *10 cells/module* *12% overhead* *10% labor* *Mg-based hydride* *better hydroxide*	*100 Ah cells* *10 cells/module* *8% overhead* *5% labor* *Mg-based hydride* *better hydroxide*

Table 8: Cost of Nickel-Hydride Alloy Materials (with pure alloying metals)

Alloy and Materials	**Weight (kg)**	**Cost per kg**	**Cost per Weight**
$V_{22}Ti_{17}Zr_{16}Ni_{39}Cr_7$[a]			
Vanadium	1.12068	$23.10	$25.89
Titanium	0.8143	$9.92	$8.08
Zirconium	1.45952	$16.53	$24.13
Nickel	2.28969	$7.50	$17.17
Chromium	0.364	$8.82	$3.21
Total:	6.04819	**$12.97**	$78.47
$Ti_{0.5}Zr_{0.5}Mn_{0.9}Cr_{0.9}Ni_{0.4}$[b]			
Titanium	0.02395	$9.92	$0.24
Zirconium	0.04561	$16.53	$0.75
Manganese	0.049446	$2.29	$0.11
Chromium	0.0468	$8.82	$0.41
Nickel	0.023484	$7.50	$0.18
Total:	0.18929	**$8.95**	$1.69
$V_{15}Ti_{15}Zr_{16}Ni_{31}Cr_6Co_6Fe_6$[c]			
Vanadium	0.7641	$23.10	$17.65
Titanium	0.7185	$9.92	$7.13
Zirconium	1.45952	$16.53	$24.13
Nickel	1.82001	$7.50	$13.65
Chromium	0.312	$8.82	$2.75
Cobalt	0.35358	$57.87	$20.46
Iron	0.3351	$0.44	$0.15
Total:	5.76281	**$14.91**	$85.92
$V_{0.2}Ti_{0.2}Zr_{0.8}Ni_{0.8}Mn_{0.8}Co_{0.15}Al_{0.05}$[d]			
Vanadium	0.010188	$23.10	$0.24
Titanium	0.00958	$9.92	$0.10
Zirconium	0.072976	$16.53	$1.21
Nickel	0.046968	$7.50	$0.35
Manganese	0.043952	$2.29	$0.10
Cobalt	0.0088395	$57.87	$0.51
Aluminum	0.001349	$1.60	$0.00
Total:	0.1938525	**$12.91**	$2.50
$Ni_{3.5}Co_{0.8}Al_{0.3}Mn_{0.4}Mm$[e]			
Nickel	0.205485	$7.50	$1.54
Cobalt	0.047144	$57.87	$2.73
Aluminum	0.008094	$1.60	$0.01
Manganese	0.021976	$2.29	$0.05
Mischmetal	0.0575	$7.00	$0.40
Total:	0.340199	**$13.92**	$4.74

Notes:

Where necessary, costs were converted from per pound costs to per kilogram costs using 2.204 lbs/kg. Quantities of materials were calculated by multiplying the molecular weight of each metal by the coefficient given in the chemical formula. The overall $/kg estimate was computed by dividing the total cost of metals by the total weight.

[a] Hydride formula is from (Fetcenko, et al., 1992).

[b] Hydride formula is from (Liu, et al., 1996).

[c] Hydride formula is from (Knosp, et al., 1998).

[d] Hydride formula is from (Venkatesan, et al., 1994).

[e] Hydride formula is from (Sakai, et al., 1992).

Table 9: Estimated Cost Ranges for Key NiMH Battery Materials

Production Level/ Technology	**350 packs/yr**	**7,700 packs/yr**	**20,000 packs/yr**	**100,000 packs/yr**
Generation 1 (~70 Wh/kg)	AG @\$0.30/ft. CF @\$20/m^2 MH @\$12/kg NH @\$15/kg SP @\$3.00/m^2	AG @\$0.30/ft. CF @\$15-16/m^2 MH @\$10-12/kg NH @\$10-12/kg SP @\$2.50-2.75/m^2	Not examined	Not examined
Generation 2 (~80 Wh/kg)	Not examined	AG @\$0.10-0.15/ft. CF @\$15-16/m^2 MH @\$10-12/kg NH @\$10-12/kg SP @\$2.50-2.75/m^2	AG @\$0.10-0.15/ft. CF @\$14-15/m^2 MH @\$9-12/kg NH @\$9-10/kg SP @\$2.25-2.50/m^2	AG @\$0.10-0.12/ft. CF @\$10-14/m^2 MH @\$9-12/kg NH @\$8-10/kg SP @\$2.00-2.50/m^2
Generation 3 (~90 Wh/kg)	Not examined	Not examined	AG @\$0.10-0.15/ft. CF @\$14-15/m^2 MH @\$9-12/kg NH @\$9-10/kg SP @\$2.25-2.50/m^2	AG @\$0.10-0.12/ft. CF @\$10-14/m^2 MH @\$9-12/kg NH @\$8-10/kg SP @\$2.00-2.50/m^2
Generation 4 (~120 Wh/kg) Future Technology	*Not examined*	*Not examined*	*AG @\$0.10-15/ft.* *CF @\$14-15/*m^2 *MH @\$6-7/kg* *NH @\$9-10/kg* *SP @\$2.25-2.50/*m^2	*AG @\$0.10-12/ft.* *CF @\$10-12/*m^2 *MH @\$5-6/kg* *NH @\$8-9/kg* *SP @\$2.00-2.25/*m^2

Notes: AG = anode grid; CF = cathode foam; MH = metal hydride; NH = spherical nickel hydroxide; SP = separator. Gen4 case assumes that battery cycle life and performance improvements allow magnesium-based hydrides to become practical anode materials.

Table 10: NiMH Cell Characteristics Based on Gen3 Technology Assumptions

Cell Capacity	**Cell/Module Specific Energy (C/3 rate)**	**Cell/Module Specific Power (peak to .8 V)**	**Plate Area (per plate)**	**Cell/Module Weight**
10 Ah	72.1/60.8 Wh/kg	648/547 W/kg	60 cm^2	0.18/0.21 kg
50 Ah	120.7/91.3 Wh/kg	343/260 W/kg	72 cm^2	0.54/0.71 kg
80 Ah	120.7/93.7 Wh/kg	235/183 W/kg[a]	98 cm^2	0.86/1.11 kg
100 Ah	113.6/88.1 Wh/kg	304/235 W/kg	92 cm^2	1.14/1.47 kg
150 Ah	117.0/88.9 Wh/kg	254/193 W/kg	180 cm^2	1.67/2.19 kg

Note: [a]Not a misprint -- specific power decreases from 100 Ah to 80 Ah for the particular 80 Ah battery design analyzed.

Table 11: Nickel Metal Hydride Battery Manufacturing Costs in Pilot-Scale Production
(350 battery packs per year, 90 Ah cells (Gen1), 1.19 kWh/module, 31 kWh/pack)

Component	**Materials** (cost/qty.)	**Materials** (qty./mod)	**Total** ($/mod)	**Total** ($/kWh)
Plate Production:				
anode grids[a]	$0.30/ft	97.441 ft	$29.23	$24.61
cathode foam substrate[b]	$20.00/$m^2$	2.665 m^2	$53.30	$44.86
hydride alloy for anode[c]	$12.00/kg	3.13 kg	$37.23	$31.34
$Ni(OH)_2$ for cathode[d]	$15.00/kg	4.404 kg	$66.06	$55.61
cobalt oxide for cathode[e]	$70.00/kg	0.132 kg	$9.25	$7.79
grid tabs for electrodes[f]	$23.00/kg	0.259 kg	$5.96	$5.02
Mat'ls for Plate Production			**$201.04**	**$169.22**
Battery Assembly:				
KOH electrolyte[g]	$0.72/kg	1.98 kg	$1.43	$1.20
separator material[h]	$3.00/$m^2$	10.38 m^2	$31.14	$26.21
lid/terminals/pressure vent	$16.00/set	11 sets	$176.00	$148.15
containment	$7.50/cont.	11 containers	$82.50	$69.44
misc. hardware	$1.50/set	1 set	$1.50	$1.26
Mat'ls for Battery Assembly			**$292.56**	**$246.26**
Total Materials Cost:			**$493.60**	**$415.49**
Overhead (30% of manuf. cost)			$329.07	$276.99
Labor (25% of manuf. cost)			$274.22	$230.83
Total Manufacturing Cost:			**$1,096.88**	**$923.30**
Distribution and Service[i]			$5.66	$4.76
Marketing and Corporate Costs (10% of selling price)			$128.20	$107.91
Warranty (4% of selling price)			$51.28	$43.17
Profit (n/a for pilot)			$0.00	$0.00
Total Selling Price:			**$1,282.03 per module**	**$1,079.15 per kWh**
Less (Salvage Value)[j]			($30.68)	($25.82)
Total Effective Price[k]			**$1,251.35**	**$1,053.33**

Notes:
See text for sources of material cost estimates.

[a] Grids are assumed to be composed of nickel or nickel plated metal, and the quantity of material required was calculated by multiplying the height of each plate by the number of plates used.

[b] The nickel foam substrate material is assumed to be 1.6 mm thick prior to pasting and compression, and the quantity of material required was calculated by multiplying the area of each plate by the number of plates used.

[c] Quantity estimated by calculating the volume of the plates, subtracting the volume of the grids, and multiplying by the density of the hydride. The hydride density is estimated to be 5.69 g/cm^3.

[d] Quantity estimated by calculating the volume of the plates, subtracting the volume of the foam substrate, and multiplying by the density of the hydroxide. The hydroxide density is estimated to be 4.15 g/cm^3.

[e] Assuming that cobalt oxide content is 3% of the spherical nickel hydroxide content.

[f] Grid tabs are estimated to be 1.9 cm wide and 3.1 cm long. They are .005 inches or .0127 cm in thickness, and they are assumed to be composed of nickel with a density of 8.8 gm/cm^2.

[g] Assumes 2.0 g KOH electrolyte per Amp-hour (see text for source).

[h] Assuming that each electrode plate is inserted into a separator "envelope" and that the surface area of separator is thus twice the total plate surface area.

[i] Assuming same distribution and service cost per kg as in lead acid case, and in (Quinn, et al., 1989) of $0.31 per kilogram.

[j] Salvage value is based on an estimate that 40% of the battery weight can be reclaimed as nickel, that reclaimed nickel has a value of $5.60 per kilogram, that the weights of Gen1, Gen2, and Gen3 cells are 1.66 kg, 1.55 kg, and 1.38 kg, respectively, and that 25% of the salvage value is lost to processing costs.

[k] Effective price is selling price minus undiscounted salvage value.

Table 12: Nickel Metal Hydride Battery Manufacturing Costs in Medium Volume Production (7,700 battery packs per year, 90 Ah cells (Gen1), 1.19 kWh/module, 31 kWh/pack)

			Lower Materials and Corporate Costs:		Higher Materials and Corporate Costs:	
Component	**Materials** (cost/qty.)	**Materials** (qty./mod)	**Total** ($/mod)	**Total** ($/kWh)	**Total** ($/mod)	**Total** ($/kWh)
Plate Production:						
anode grids[a]	$0.30/ft	97.44 ft	$29.23	$24.61	$29.23	$24.61
cathode foam substrate[b]	\$15-16/m^2	2.665 m^2	$39.97	$33.65	$42.64	$35.89
hydride alloy for anode[c]	$10-12/kg	3.103 kg	$31.03	$26.12	$37.23	$31.34
$Ni(OH)_2$ for cathode[d]	$10-12/kg	4.404 kg	$44.04	$37.07	$52.85	$44.49
cobalt oxide for cathode[e]	$65.00/kg	0.132 kg	$8.59	$7.23	$8.59	$7.23
grid tabs for electrodes[f]	$15.00/kg	0.259 kg	$3.89	$3.27	$3.89	$3.27
Mat'ls for Plate Production			**$156.75**	**$131.95**	**$174.43**	**$146.83**
Battery Assembly:						
KOH electrolyte[g]	$0.29/kg	1.98 kg	$0.57	$0.48	$0.57	$0.48
separator material[h]	\$2.50-2.75/m^2	10.38 m^2	$25.95	$21.84	$28.54	$24.02
lid/terminals/pressure vent	$2.80/set	11 sets	$30.80	$25.93	$30.80	$25.93
containment	$2.90/cont.	11 cont.	$31.90	$26.85	$31.90	$26.85
misc. hardware	$1.50/set	1 set	$1.50	$1.26	$1.50	$1.26
Mat'ls for Battery Assembly			**$90.72**	**$76.36**	**$93.32**	**$78.55**
Total Materials Cost:			**$247.47**	**$208.31**	**$267.75**	**$225.37**
Overhead (20% of manuf. cost)			$77.33	$65.10	$83.67	$70.43
Labor (16% of manuf. cost)			$61.87	$52.08	$66.94	$56.34
Total Manufacturing Cost:			**$386.67**	**$325.48**	**$418.35**	**$352.15**
Distribution and Service[i]			$5.66	$4.76	$5.66	$4.76
Marketing and Corporate Costs (2% or 7% of selling price)			$9.17	$7.72	$36.64	$30.84
Warranty (4% of selling price)			$18.34	$15.44	$20.94	$17.62
Profit (10% of manuf. cost)			$38.67	$32.55	$41.84	$35.21
Total Selling Price:			**$458.51 per mod.**	**$385.95 per kWh**	**$523.42 per mod.**	**$440.59 per kWh**
Less (Salvage Value)[j]			($30.68)	($25.82)	($30.68)	($25.82)
Total Effective Price[k]			**$427.84**	**$360.13**	**$492.75**	**$414.77**

Notes: Same as previous table.

Table 13: Nickel Metal Hydride Battery Manufacturing Costs in Medium Volume Production (7,700 battery packs per year, 100 Ah cells (Gen2), 1.2 kWh/module, 31 kWh/pack)

			Lower Materials and Corporate Costs:		Higher Materials and Corporate Costs:	
Component	Materials (cost/qty.)	Materials (qty./mod)	Total ($/mod)	Total ($/kWh)	Total ($/mod)	Total ($/kWh)
Plate Production:						
anode grids[a]	$0.10-0.15/ft	70.89 ft	$7.09	$5.91	$10.63	$8.86
cathode foam substrate[b]	$15-16/$m^2$	1.951 m^2	$29.26	$24.38	$31.21	$26.01
hydride alloy for anode[c]	$10-12/kg	3.092 kg	$30.92	$25.77	$37.11	$30.92
$Ni(OH)_2$ for cathode[d]	$10-12/kg	4.299 kg	$42.99	$35.82	$51.59	$42.99
cobalt oxide for cathode[e]	$65.00/kg	0.129 kg	$8.38	$6.99	$8.38	$6.99
grid tabs for electrodes[f]	$15.00/kg	0.210 kg	$3.15	$2.63	$3.15	$2.63
Mat'ls for Plate Production			**$121.80**	**$101.50**	**$142.07**	**$118.39**
Battery Assembly:						
KOH electrolyte[g]	$0.29/kg	2.00 kg	$0.58	$0.48	$0.58	$0.48
separator material[h]	$2.50-2.75/$m^2$	7.57 m^2	$18.93	$15.78	$20.83	$17.36
lid/terminals/pressure vent	$2.80/set	10 sets	$28.00	$23.33	$28.00	$23.33
containment	$2.90/cont.	10 cont.	$29.00	$24.17	$29.00	$24.17
misc. hardware	$1.50/set	1 set	$1.50	$1.25	$1.50	$1.25
Mat'ls for Battery Assembly			**$78.01**	**$65.01**	**$79.91**	**$66.59**
Total Materials Cost:			**$199.81**	**$166.51**	**$221.98**	**$184.98**
Overhead (20% of manuf. cost)			$62.44	$52.03	$69.37	$57.81
Labor (16% of manuf. cost)			$49.95	$41.63	$55.49	$46.25
Total Manufacturing Cost:			**$312.20**	**$260.17**	**$346.84**	**$289.04**
Distribution and Service[i]			$4.81	$4.00	$4.81	$4.00
Marketing and Corporate Costs (2% or 7% of selling price)			$7.54	$6.28	$30.93	$25.78
Warranty (4% of selling price)			$15.08	$12.57	$17.68	$14.73
Profit (12% of manuf. cost)			$37.46	$31.22	$41.62	$34.68
Total Selling Price:			**$377.10 per mod.**	**$314.25 per kWh**	**$441.88 per mod.**	**$368.23 per kWh**
Less (Salvage Value)[j]			($26.04)	($21.70)	($26.04)	($21.70)
Total Effective Price[k]			**$351.06**	**$292.55**	**$415.84**	**$346.53**

Notes: Same as previous table.

Table 14: Nickel Metal Hydride Battery Manufacturing Costs in High Volume Production (20,000 battery packs per year, 100 Ah cells (Gen2), 1.2 kWh/module, 31 kWh/pack)

			Lower Materials and Corporate Costs:		Higher Materials and Corporate Costs:	
Component	Materials (cost/qty.)	Materials (qty./mod)	Total ($/mod)	Total ($/kWh)	Total ($/mod)	Total ($/kWh)
Plate Production:						
anode grids[a]	$0.10-0.15/ft	70.89 ft	$7.09	$5.91	$10.63	$8.86
cathode foam substrate[b]	$14-15/$\mathrm{m}^2$	1.951 m^2	$27.31	$22.76	$29.26	$24.38
hydride alloy for anode[c]	$9-12/kg	3.092 kg	$27.83	$23.19	$37.11	$30.92
$Ni(OH)_2$ for cathode[d]	$9-10/kg	4.299 kg	$38.69	$32.24	$42.99	$35.82
cobalt oxide for cathode[e]	$65.00/kg	0.129 kg	$8.38	$6.99	$8.38	$6.99
grid tabs for electrodes[f]	$15.00/kg	0.210 kg	$3.15	$2.63	$3.15	$2.63
Mat'ls for Plate Production			**$112.45**	**$93.71**	**$131.52**	**$109.60**
Battery Assembly:						
KOH electrolyte[g]	$0.29/kg	2.00 kg	$0.58	$0.48	$0.58	$0.48
separator material[h]	$2.25-2.50/$\mathrm{m}^2$	7.57 m^2	$17.04	$14.20	$18.93	$15.78
lid/terminals/pressure vent	$2.80/set	10 sets	$28.00	$23.33	$28.00	$23.33
containment	$2.61/cont.	10 cont.	$26.10	$21.75	$26.10	$21.75
misc. hardware	$1.50/set	1 set	$1.50	$1.25	$1.50	$1.25
Mat'ls for Battery Assembly			**$73.22**	**$61.02**	**$75.11**	**$62.59**
Total Materials Cost:			**$185.67**	**$154.73**	**$206.64**	**$172.20**
Overhead (12% of manuf. cost)			$28.57	$23.80	$31.79	$26.49
Labor (10% of manuf. cost)			$23.80	$19.84	$26.49	$22.08
Total Manufacturing Cost:			**$238.04**	**$198.37**	**$264.92**	**$220.77**
Distribution and Service[i]			$4.81	$4.00	$4.81	$4.00
Marketing and Corporate Costs (2% or 7% of selling price)			$5.98	$4.98	$24.55	$20.46
Warranty (4% of selling price)			$11.95	$9.96	$14.03	$11.69
Profit (16% of manuf. cost)			$38.09	$31.74	$42.39	$35.32
Total Selling Price:			**$298.87 per mod.**	**$249.06 per kWh**	**$350.69 per mod.**	**$292.24 per kWh**
Less (Salvage Value)[j]			($26.04)	($21.70)	($26.04)	($21.70)
Total Effective Price[k]			**$272.83**	**$227.36**	**$324.65**	**$270.54**

Notes: Same as previous table.

Table 15: Nickel Metal Hydride Battery Manufacturing Costs in High Volume Production (100,000 battery packs per year, 100 Ah cells (Gen2), 1.2 kWh/module, 31 kWh/pack)

			Lower Materials and Corporate Costs:		Higher Materials and Corporate Costs:	
Component	**Materials** (cost/qty.)	**Materials** (qty./mod)	**Total** ($/mod)	**Total** ($/kWh)	**Total** ($/mod)	**Total** ($/kWh)
Plate Production:						
anode grids[a]	\$0.10-0.12/ft	70.89 ft	\$7.09	\$5.91	\$8.50	\$7.09
cathode foam substrate[b]	\$10-14/m^2	1.951 m^2	\$19.51	\$16.26	\$27.31	\$22.76
hydride alloy for anode[c]	\$9-12/kg	3.092 kg	\$27.83	\$23.19	\$37.11	\$30.92
$Ni(OH)_2$ for cathode[d]	\$8-10/kg	4.299 kg	\$34.39	\$28.66	\$42.99	\$35.82
cobalt oxide for cathode[e]	\$65.00/kg	0.129 kg	\$8.38	\$6.99	\$8.38	\$6.99
grid tabs for electrodes[f]	\$15.00/kg	0.210 kg	\$3.15	\$2.63	\$3.15	\$2.63
Mat'ls for Plate Production			**\$100.35**	**\$83.63**	**\$127.45**	**\$106.21**
Battery Assembly:						
KOH electrolyte[g]	\$0.29/kg	2.00 kg	\$0.58	\$0.48	\$0.58	\$0.48
separator material[h]	\$2.00-2.50/m^2	7.57 m^2	\$15.15	\$12.62	\$18.93	\$15.78
lid/terminals/pressure vent	\$2.80/set	10 sets	\$28.00	\$23.33	\$28.00	\$23.33
containment	\$2.50/cont.	10 cont.	\$25.00	\$20.83	\$25.00	\$20.83
misc. hardware	\$1.50/set	1 set	\$1.50	\$1.25	\$1.50	\$1.25
Mat'ls for Battery Assembly			**\$70.23**	**\$58.52**	**\$74.01**	**\$61.68**
Total Materials Cost:			**170.58**	**\$142.15**	**\$201.46**	**\$167.88**
Overhead (8% of manuf. cost)			\$15.69	\$13.07	\$18.53	\$15.44
Labor (5% of manuf. cost)			\$9.80	\$8.17	\$11.58	\$9.65
Total Manufacturing Cost:			**\$196.07**	**\$163.39**	**\$231.56**	**\$192.97**
Distribution and Service[i]			\$4.81	\$4.00	\$4.81	\$4.00
Marketing and Corporate Costs (2% or 7% of selling price)			\$5.02	\$4.19	\$21.87	\$18.22
Warranty (4% of selling price)			\$10.05	\$8.37	\$12.50	\$10.41
Profit (18% of manuf. cost)			\$35.29	\$29.41	\$41.68	\$34.73
Total Selling Price:			**\$251.24** per mod.	**\$209.37** per kWh	**\$312.42** per mod.	**\$260.35** per kWh
Less (Salvage Value)[j]			(\$26.04)	(\$21.70)	(\$26.04)	(\$21.70)
Total Effective Price[k]			**\$225.20**	**\$187.67**	**\$286.38**	**\$238.65**

Notes: Same as previous table.

Table 16: Nickel Metal Hydride Battery Manufacturing Costs in High Volume Production (20,000 battery packs per year, 100 Ah cells (Gen3), 1.2 kWh/module, 31 kWh/pack)

			Lower Materials and Corporate Costs:		Higher Materials and Corporate Costs:	
Component	**Materials** (cost/qty.)	**Materials** (qty./mod)	**Total** ($/mod)	**Total** ($/kWh)	**Total** ($/mod)	**Total** ($/kWh)
Plate Production:						
anode grids[a]	$0.10-0.15/ft	71.69 ft	$7.17	$5.97	$10.75	$8.96
cathode foam substrate[b]	$14-15/$m^2$	1.840 m^2	$25.76	$21.47	$27.60	$23.00
hydride alloy for anode[c]	$9-12/kg	2.433 kg	$21.90	$18.25	$29.20	$24.33
$Ni(OH)_2$ for cathode[d]	$9-10/kg	4.055 kg	$36.49	$30.41	$40.55	$33.79
cobalt oxide for cathode[e]	$65.00/kg	0.122 kg	$7.91	$6.59	$7.91	$6.59
grid tabs for electrodes[f]	$15.00/kg	0.248 kg	$3.73	$3.11	$3.73	$3.11
Mat'ls for Plate Production			**$102.96**	**$85.80**	**$119.73**	**$99.78**
Battery Assembly:						
KOH electrolyte[g]	$0.29/kg	2.00 kg	$0.58	$0.48	$0.58	$0.48
separator material[h]	$2.25-2.50/$m^2$	7.18 m^2	$16.15	$13.46	$17.94	$14.95
lid/terminals/pressure vent	$2.80/set	10 sets	$28.00	$23.33	$28.00	$23.33
containment	$2.61/cont.	10 cont.	$26.10	$21.75	$26.10	$21.75
misc. hardware	$1.50/set	1 set	$1.50	$1.25	$1.50	$1.25
Mat'ls for Battery Assembly			**$72.33**	**$60.27**	**$74.12**	**$61.77**
Total Materials Cost:			**$175.28**	**$146.07**	**$193.85**	**$161.55**
Overhead (12% of manuf. cost)			$26.97	$22.47	$29.82	$24.85
Labor (10% of manuf. cost)			$22.47	$18.73	$24.85	$20.71
Total Manufacturing Cost:			**$224.72**	**$187.27**	**$248.53**	**$207.11**
Distribution and Service[i]			$4.56	$3.80	$4.56	$3.80
Marketing and Corporate Costs (2% or 7% of selling price)			$5.74	$4.78	$23.42	$19.52
Warranty (4% of selling price)			$11.48	$9.56	$13.39	$11.15
Profit (18% of manuf. cost)			$40.45	$33.71	$44.74	$37.28
Total Selling Price:			**$286.94 per mod.**	**$239.12 per kWh**	**$334.63 per mod.**	**$278.86 per kWh**
Less (Salvage Value)[j]			($24.70)	($20.58)	($24.70)	($20.58)
Total Effective Price[k]			**$262.25**	**$218.54**	**$309.94**	**$258.28**

Notes: Same as previous table.

Table 17: Nickel Metal Hydride Battery Manufacturing Costs in High Volume Production (100,000 battery packs per year, 100 Ah cells (Gen3), 1.2 kWh/module, 31 kWh/pack)

			Lower Materials and Corporate Costs:		Higher Materials and Corporate Costs:	
Component	**Materials** (cost/qty.)	**Materials** (qty./mod)	**Total** (\$/mod)	**Total** (\$/kWh)	**Total** (\$/mod)	**Total** (\$/kWh)
Plate Production:						
anode grids[a]	\$0.10-0.12/ft	71.69 ft	\$7.17	\$5.97	\$8.60	\$7.17
cathode foam substrate[b]	\$10-14/m^2	1.840 m^2	\$18.40	\$15.33	\$25.76	\$21.47
hydride alloy for anode[c]	\$9-12/kg	2.433 kg	\$21.90	\$18.25	\$29.20	\$24.33
$Ni(OH)_2$ for cathode[d]	\$8-10/kg	4.055 kg	\$32.44	\$27.03	\$40.55	\$33.79
cobalt oxide for cathode[e]	\$65.00/kg	0.122 kg	\$7.91	\$6.59	\$7.91	\$6.59
grid tabs for electrodes[f]	\$15.00/kg	0.248 kg	\$3.73	\$3.11	\$3.73	\$3.11
Mat'ls for Plate Production			**\$91.54**	**\$76.28**	**\$115.74**	**\$96.45**
Battery Assembly:						
KOH electrolyte[g]	\$0.29/kg	2.00 kg	\$0.58	\$0.48	\$0.58	\$0.48
separator material[h]	\$2.00-2.50/m^2	7.18 m^2	\$14.35	\$11.96	\$17.94	\$14.95
lid/terminals/pressure vent	\$2.80/set	10 sets	\$28.00	\$23.33	\$28.00	\$23.33
containment	\$2.50/cont.	10 cont.	\$25.00	\$20.83	\$25.00	\$20.83
misc. hardware	\$1.50/set	1 set	\$1.50	\$1.25	\$1.50	\$1.25
Mat'ls for Battery Assembly			**\$69.43**	**\$57.86**	**\$73.02**	**\$60.85**
Total Materials Cost:			**\$160.97**	**\$134.14**	**\$188.76**	**\$157.30**
Overhead (8% of manuf. cost)			\$14.80	\$12.34	\$17.36	\$14.46
Labor (5% of manuf. cost)			\$9.25	\$7.71	\$10.85	\$9.04
Total Manufacturing Cost:			**\$185.03**	**\$154.19**	**\$216.97**	**\$180.81**
Distribution and Service[i]			\$4.56	\$3.80	\$4.56	\$3.80
Marketing and Corporate Costs (2% or 7% of selling price)			\$4.82	\$4.02	\$20.84	\$17.36
Warranty (4% of selling price)			\$9.64	\$8.04	\$11.91	\$9.92
Profit (20% of manuf. cost)			\$37.01	\$30.84	\$43.39	\$36.16
Total Selling Price:			**\$241.05 per mod.**	**\$200.88 per kWh**	**\$297.66 per mod.**	**\$248.05 per kWh**
Less (Salvage Value)[j]			(\$24.70)	(\$20.58)	(\$24.70)	(\$20.58)
Total Effective Price[k]			**\$216.35**	**\$180.30**	**\$272.97**	**\$227.47**

Notes: Same as previous table.

Table 18: Nickel Metal Hydride Battery Manufacturing Costs in High Volume Production (20,000 battery packs per year, 100 Ah cells (Gen4), 1.2 kWh/module, 31 kWh/pack)

			Lower Materials and Corporate Costs:		Higher Materials and Corporate Costs:	
Component	**Materials** (cost/qty.)	**Materials** (qty./mod)	**Total** ($/mod)	**Total** ($/kWh)	**Total** ($/mod)	**Total** ($/kWh)
Plate Production:						
anode grids[a]	\$0.10-0.15/ft	49.21 ft	\$4.92	\$4.10	\$7.38	\$6.15
cathode foam substrate[b]	\$14-15/m^2	1.360 m^2	\$19.04	\$15.87	\$20.40	\$17.00
hydride alloy for anode[c]	\$6-7/kg	1.607 kg	\$9.64	\$8.03	\$11.25	\$9.37
$Ni(OH)_2$ for cathode[d]	\$9-10/kg	3.497 kg	\$31.47	\$26.22	\$34.97	\$29.14
cobalt oxide for cathode[e]	\$65.00/kg	0.105 kg	\$6.82	\$5.68	\$6.82	\$5.68
grid tabs for electrodes[f]	\$15.00/kg	0.197 kg	\$2.96	\$2.47	\$2.96	\$2.47
Mat'ls for Plate Production			**\$74.85**	**\$62.38**	**\$83.77**	**\$69.81**
Battery Assembly:						
KOH electrolyte[g]	\$0.29/kg	2.00 kg	\$0.58	\$0.48	\$0.58	\$0.48
separator material[h]	\$2.25-2.50/m^2	5.27 m^2	\$11.86	\$9.88	\$13.18	\$10.98
lid/terminals/pressure vent	\$2.80/set	10 sets	\$28.00	\$23.33	\$28.00	\$23.33
containment	\$1.97/cont.	10 cont.	\$19.70	\$16.42	\$19.70	\$16.42
misc. hardware	\$1.50/set	1 set	\$1.50	\$1.25	\$1.50	\$1.25
Mat'ls for Battery Assembly			**\$61.64**	**\$51.36**	**\$62.96**	**\$52.46**
Total Materials Cost:			**\$136.49**	**\$113.74**	**\$146.73**	**\$122.27**
Overhead (12% of man. cost)			\$21.00	\$17.50	\$22.57	\$18.81
Labor (10% of man. cost)			\$17.50	\$14.58	\$18.81	\$15.68
Total Manufacturing Cost:			**\$174.98**	**\$145.82**	**\$188.11**	**\$156.76**
Distribution and Service[i]			\$3.48	\$2.90	\$3.48	\$2.90
Marketing and Corporate Costs (2% or 7% of selling price)			\$4.47	\$3.72	\$17.73	\$14.78
Warranty (4% of selling price)			\$8.93	\$7.45	\$10.13	\$8.44
Profit (18% of manuf. cost)			\$31.50	\$26.25	\$33.86	\$28.22
Total Selling Price:			**\$223.36 per mod.**	**\$186.14 per kWh**	**\$253.32 per mod.**	**\$211.10 per kWh**
Less (Salvage Value)[j]			(\$18.87)	(\$15.72)	(\$18.87	(\$15.72)
Total Effective Price[k]			**\$204.50**	**\$170.42**	**\$234.45**	**\$195.38**

Notes: Same as previous table.

Table 19: Nickel Metal Hydride Battery Manufacturing Costs in High Volume Production (100,000 battery packs per year, 100 Ah cells (Gen4), 1.2 kWh/module, 31 kWh/pack)

			Lower Materials and Corporate Costs:		Higher Materials and Corporate Costs:	
Component	Materials (cost/qty.)	Materials (qty./mod)	Total ($/mod)	Total ($/kWh)	Total ($/mod)	Total ($/kWh)
Plate Production:						
anode grids[a]	$0.10-0.12/ft	49.21 ft	$4.92	$4.10	$5.91	$4.92
cathode foam substrate[b]	$10-12/$m^2$	1.360 m^2	$13.60	$11.33	$16.32	$13.60
hydride alloy for anode[c]	$5-6/kg	1.607 kg	$8.03	$6.69	$9.64	$8.03
$Ni(OH)_2$ for cathode[d]	$8-9/kg	3.497 kg	$27.97	$23.31	$31.47	$26.22
cobalt oxide for cathode[e]	$65.00/kg	0.105 kg	$6.82	$5.68	$6.82	$5.68
grid tabs for electrodes[f]	$15.00/kg	0.197 kg	$2.96	$2.47	$2.96	$2.47
Mat'ls for Plate Production			**$64.31**	**$53.59**	**$73.11**	**$60.93**
Battery Assembly:						
KOH electrolyte[g]	$0.29/kg	2.00 kg	$0.58	$0.48	$0.58	$0.48
separator material[h]	$2.00-2.25/$m^2$	5.27 m^2	$10.54	$8.78	$11.86	$9.88
lid/terminals/pressure vent	$2.80/set	10 sets	$28.00	$23.33	$28.00	$23.33
containment	$1.90/cont.	10 cont.	$19.00	$15.83	$19.00	$15.83
misc. hardware	$1.50/set	1 set	$1.50	$1.25	$1.50	$1.25
Mat'ls for Battery Assembly			**$59.62**	**$49.68**	**$60.94**	**$50.78**
Total Materials Cost:			**$123.93**	**$103.27**	**$134.05**	**$111.71**
Overhead (8% of manuf. cost)			$11.40	$9.50	$12.33	$10.27
Labor (5% of manuf. cost)			$7.12	$5.94	$7.70	$6.42
Total Manufacturing Cost:			**$142.44**	**$118.70**	**$154.08**	**$128.40**
Distribution and Service[i]			$3.48	$2.90	$3.48	$2.90
Marketing and Corporate Costs (2% or 7% of selling price)			$3.71	$3.09	$14.82	$12.35
Warranty (4% of selling price)			$7.42	$6.18	$8.47	$7.06
Profit (20% of manuf. cost)			$28.49	$23.74	$30.82	$25.68
Total Selling Price:			**$185.55 per mod.**	**$154.62 per kWh**	**$211.66 per mod.**	**$176.39 per kWh**
Less (Salvage Value)[j]			($18.87)	($15.72)	($18.87)	($15.72)
Total Effective Price[k]			**$166.68**	**$138.90**	**$192.80**	**$160.66**

Notes: Same as previous table.

Table 20: Selling and (Effective) Price Estimates for 90-100 Ah NiMH EV Batteries

Production Level/ Technology	**350 packs/yr**	**7,700 packs/yr**	**20,000 packs/yr**	**100,000 packs/yr**
Generation 1 **90 Ah/cell** **(~70 Wh/kg)**	$1,079/kWh ($1,053/kWh)	$386-441/kWh ($360-415/kWh)	Not examined	Not examined
Generation 2 **100 Ah/cell** **(~80 Wh/kg)**	Not examined	$314-368/kWh ($293-347/kWh)	$249-292/kWh ($227-271/kWh)	$209-260/kWh ($188-239/kWh)
Generation 3 **100 Ah/cell** **(~90 Wh/kg)**	Not examined	Not examined	$239-279/kWh ($219-258/kWh)	$201-248/kWh ($180-227/kWh)
Generation 4 *100 Ah/cell* *(~120 Wh/kg)*			*$186-211/kWh* *($170-195/kWh)*	*$155-176/kWh* *($139-161/kWh)*

Notes:

Generation 4 is a speculative case, based on specifications of active materials that are in the research and development phase.

Effective prices, shown in parentheses, are selling prices less salvage value.

Table 21: Selling Price Estimates for Gen3 and Gen4 NiMH EV Batteries

Generation and Cell Size	Low Cost Case	High Cost Case	Average
Generation 3 @ 20,000/yr:			
10 Ah	$694.53/kWh ($36.24/kg)	$829.61/kWh ($43.28/kg)	$762.07/kWh ($39.76/kg)
50 Ah	$359.95/kWh ($30.85/kg)	$409.24/kWh ($35.08/kg)	$384.60/kWh ($32.97/kg)
80 Ah	$263.08/kWh ($22.75/kg)	$305.45/kWh ($26.42/kg)	$284.27/kWh ($24.59/kg)
100 Ah	$239.12/kWh ($19.52/kg)	$278.86/kWh ($22.76/kg)	$258.99/kWh ($21.14/kg)
150 Ah	$203.70/kWh ($16.74/kg)	$237.59/kWh ($19.53/kg)	$220.65/kWh ($18.14/kg)
Generation 3 @ 100,000/yr:			
10 Ah	$580.89/kWh ($30.31/kg)	$740.22/kWh ($38.62/kg)	$660.56/kWh ($34.47/kg)
50 Ah	$306.84/kWh ($26.30/kg)	$358.18/kWh ($30.70/kg)	$332.51/kWh ($28.50/kg)
80 Ah	$220.51/kWh ($19.07/kg)	$271.45/kWh ($23.48/kg)	$245.98/kWh ($21.28/kg)
100 Ah	$200.88/kWh ($16.40/kg)	$248.05/kWh ($20.25/kg)	$224.47/kWh ($18.33/kg)
150 Ah	$171.36/kWh ($14.08/kg)	$206.83/kWh ($17.00/kg)	$189.10/kWh ($15.54/kg)
Generation 4 @ 20,000/yr:			
20 Ah	$251.76/kWh ($25.18/kg)	$287.93/kWh ($28.79/kg)	$269.85/kWh ($26.99/kg)
60 Ah	$238.69/kWh ($24.91/kg)	$269.02/kWh ($28.07/kg)	$253.86/kWh ($26.49/kg)
100 Ah	$186.14/kWh ($19.89/kg)	$211.10/kWh ($22.56/kg)	$198.62/kWh ($21.23/kg)
150 Ah	$162.36/kWh ($18.38/kg)	$185.00/kWh ($20.94/kg)	$173.68/kWh ($19.66/kg)
Generation 4 @ 100,000/yr:			
20 Ah	$211.29/kWh ($21.13/kg)	$240.23/kWh ($24.02/kg)	$225.76/kWh ($22.58/kg)
60 Ah	$199.23/kWh ($20.79/kg)	$225.66/kWh ($23.55/kg)	$212.45/kWh ($22.17/kg)
100 Ah	$154.62/kWh ($16.52/kg)	$176.39/kWh ($18.85/kg)	$165.51/kWh ($17.69/kg)
150 Ah	$133.94/kWh ($15.16/kg)	$153.63/kWh ($17.39/kg)	$143.79/kWh ($16.28/kg)

Table 22: Bottom cost distribution of lithium-ion cell materials

Material	**Cost percentage[a]** **Li-Mn Positive**	**Cost percentage[b]** **Li-Ni Positive**
Positive material	20%	21%
Negative material	20%	4%
Separator	9%	33%
Electrolyte	13%	29%
Collectors		6%
Other	38%	7%

Sources:

[a](Brohm, et al., 1998)

[b](Broussely, et al., 1996)

Table 23: Comparison of ITS-Davis, CARB Panel, and ANL Delphi Study Results

Battery Type	**ITS-Davis** Price by packs/yr	**CARB Panel** Price by year	**ANL Delphi** Price by year
Lead-Acid:			
2000 (or 5,000 packs/year)	\$113/kWh	\$150/kWh	\$185/kWh
2010 (or 20,000 packs/year)	\$107/kWh	\$120/kWh	\$179/kWh
2020 (or 20,000 packs/year)	\$107/kWh	\$120/kWh	\$184/kWh
Nickel-metal hydride			
2000 (or 7,700 packs/year)	\$314-368/kWh (G2)	\$550/kWh	\$569/kWh
2010 (or 20,000 packs/year)	\$239-279/kWh (G3)	\$350/kWh	\$426/kWh
2020 (or 20,000 packs/year	\$239-279/kWh (G3)	\$250/kWh	\$382/kWh
100,000 packs/year	\$201-248/kWh (G3)		
100,000 packs/year)	*\$155-176/kWh (G4)*		
Li-ion			
2000	Not estimated	\$1,000/kWh	Not estimated
2010		\$300/kWh	
2020		\$180/kWh	

Sources: Modified CARB data and ANL delphi study data are from (Vyas, et al., 1997).

Figure 1

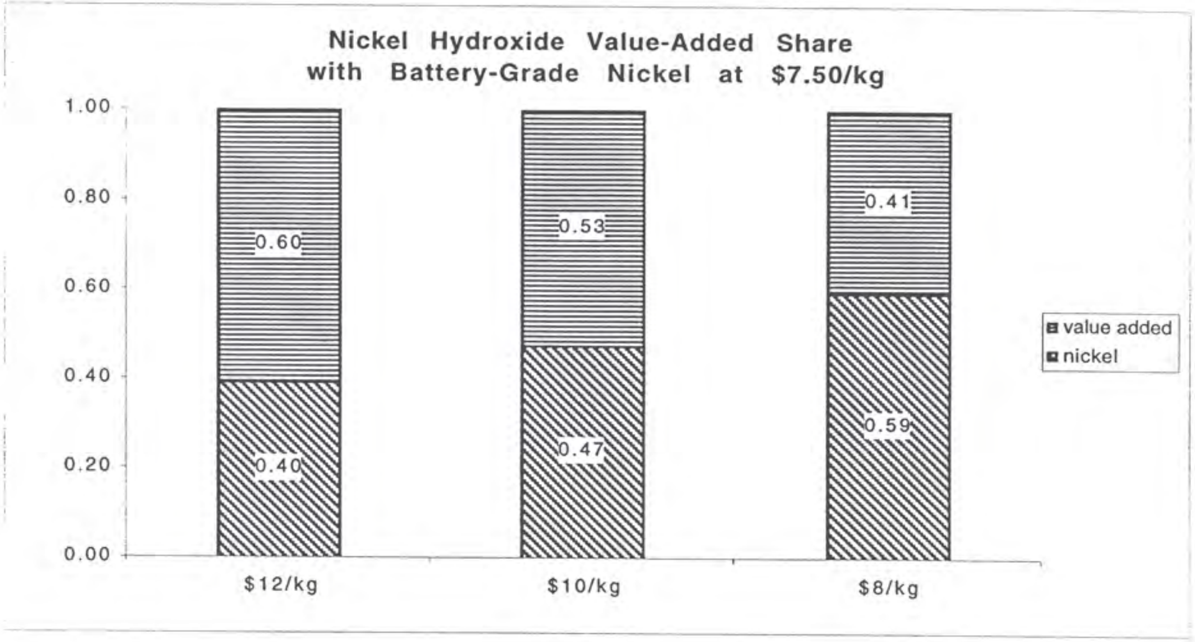
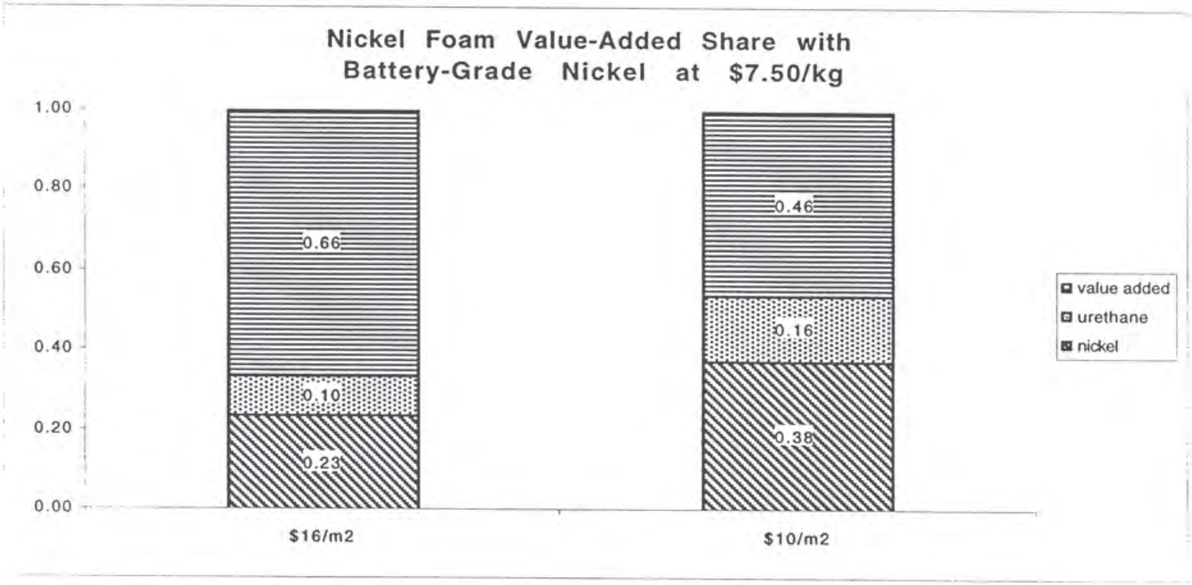


Figure 2



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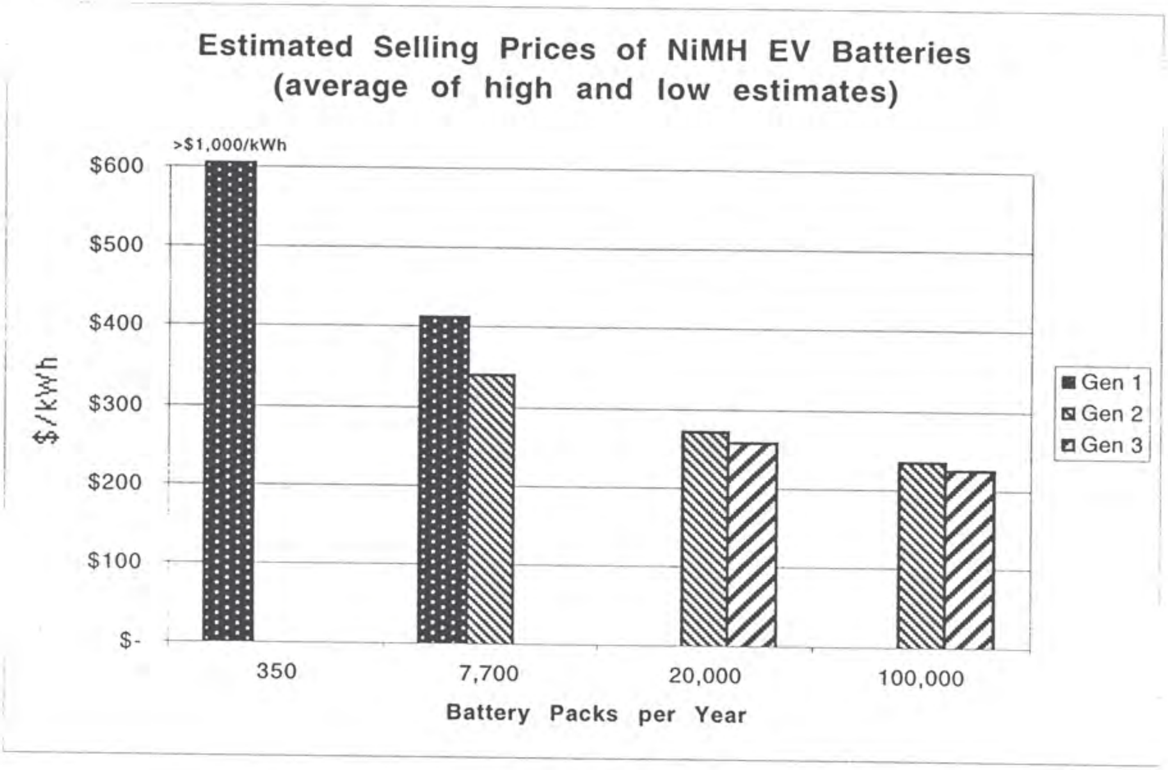

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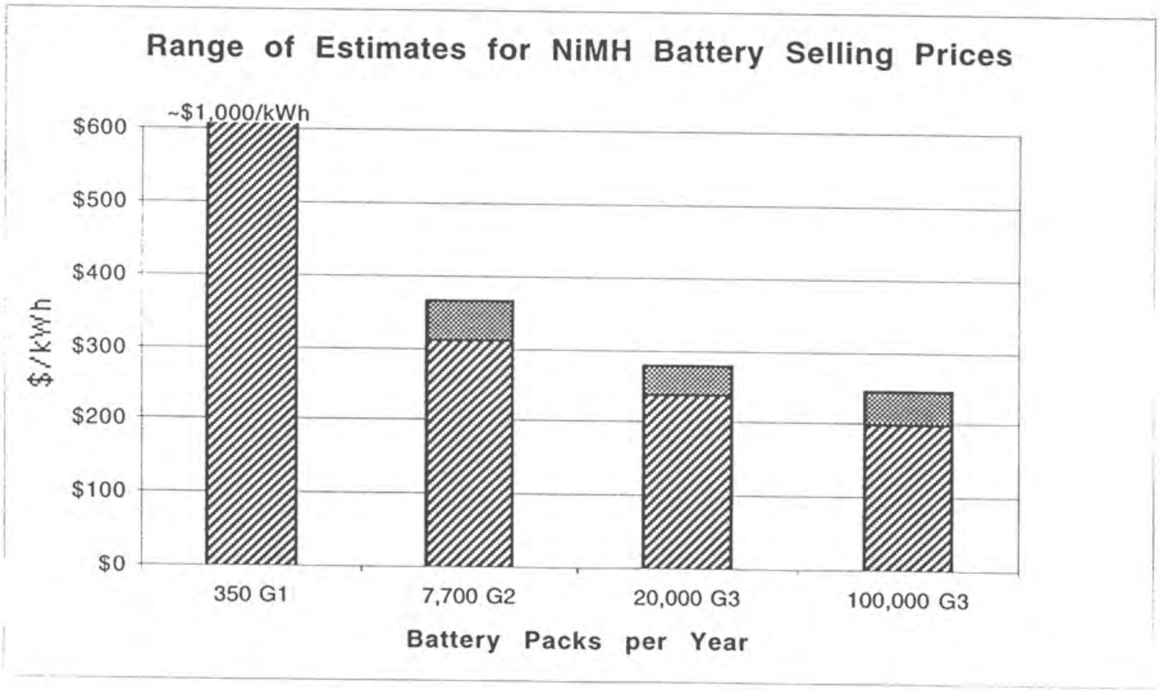

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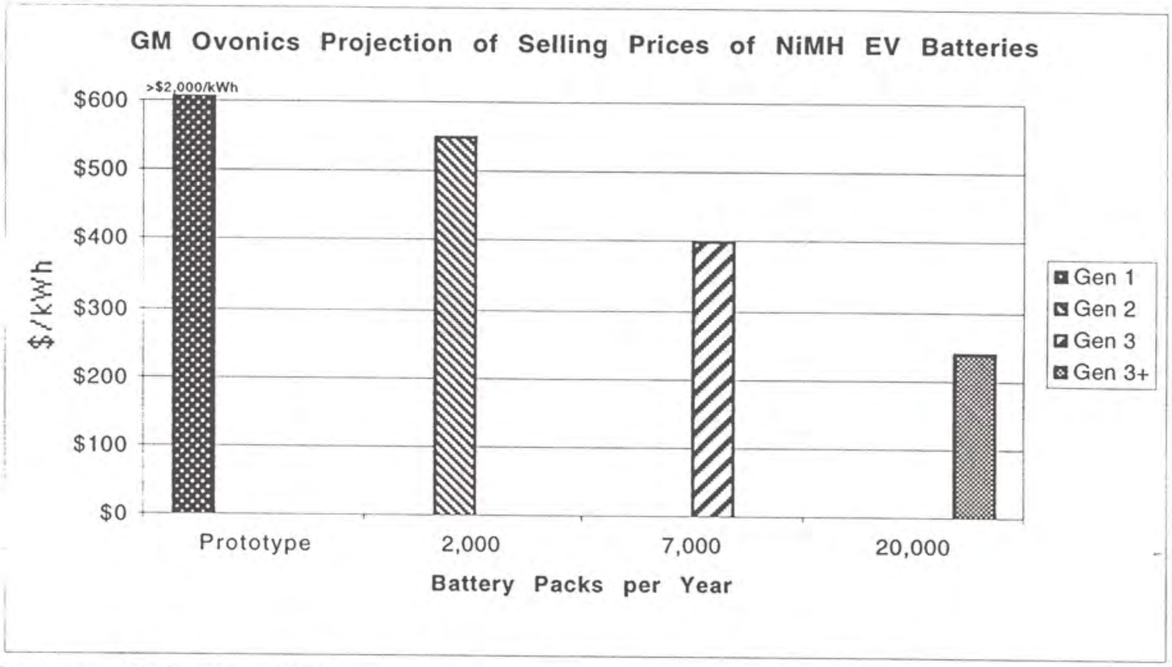
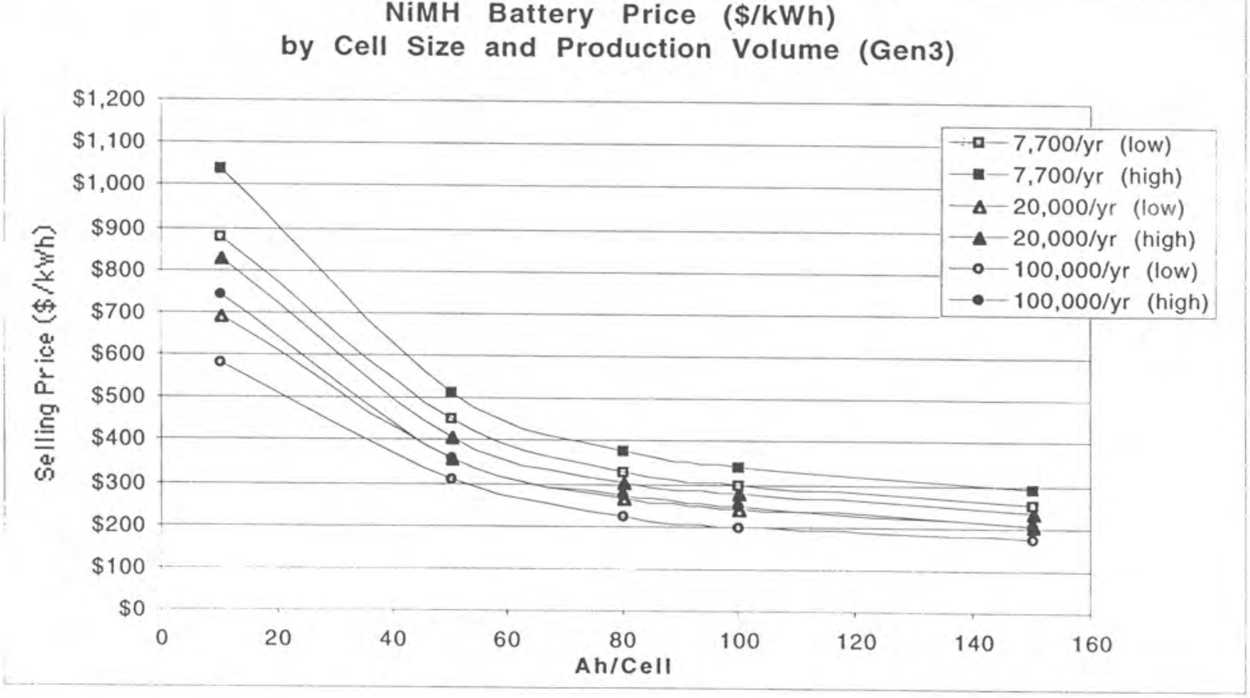


Source: (Adams, 1995)

Figure 6



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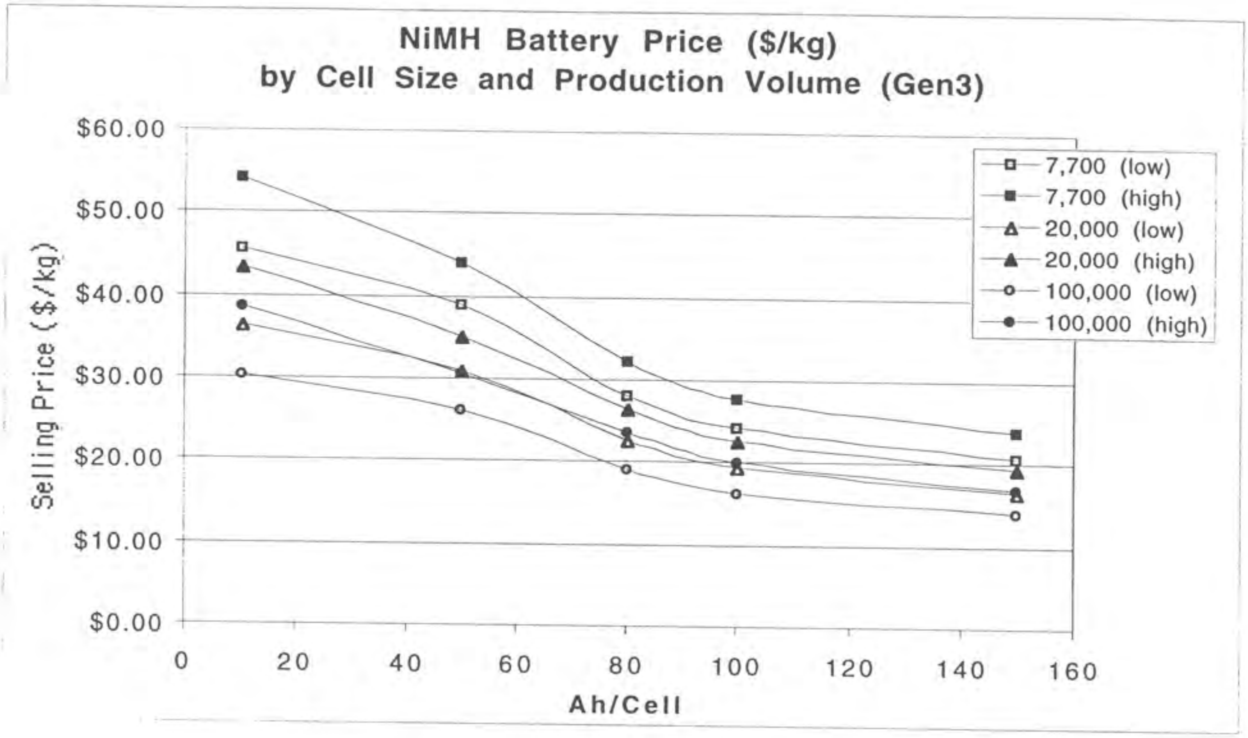

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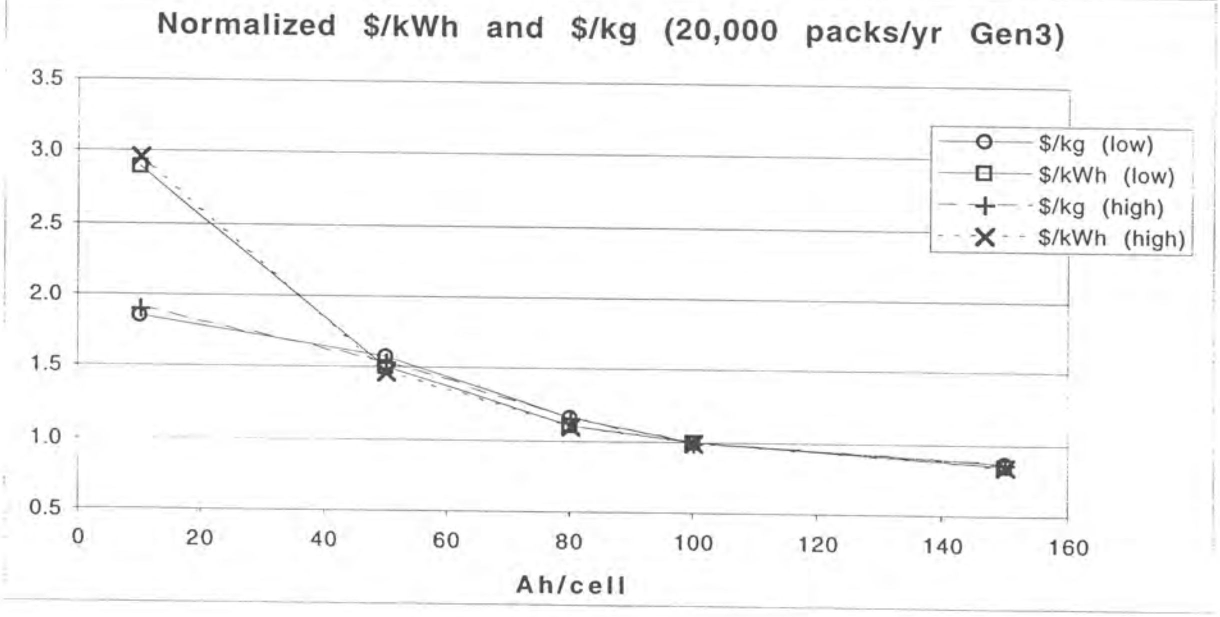

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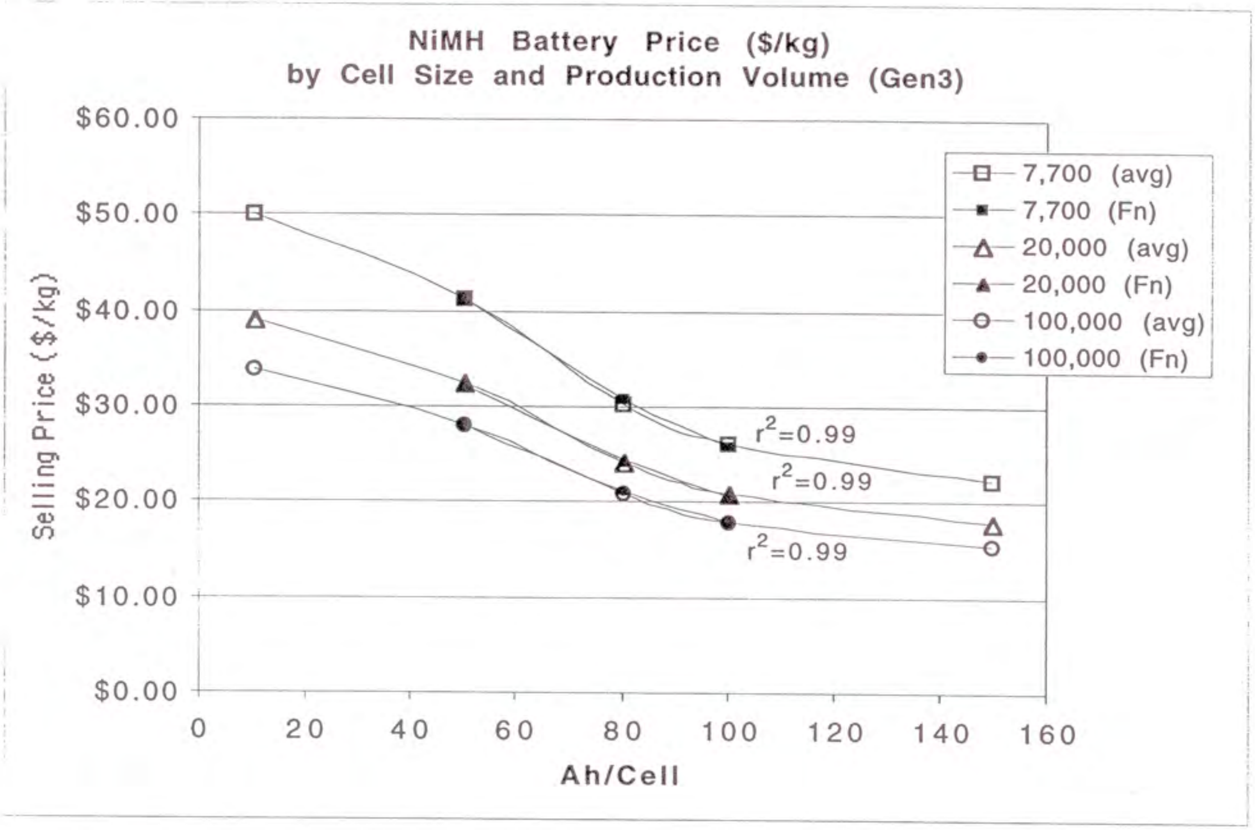
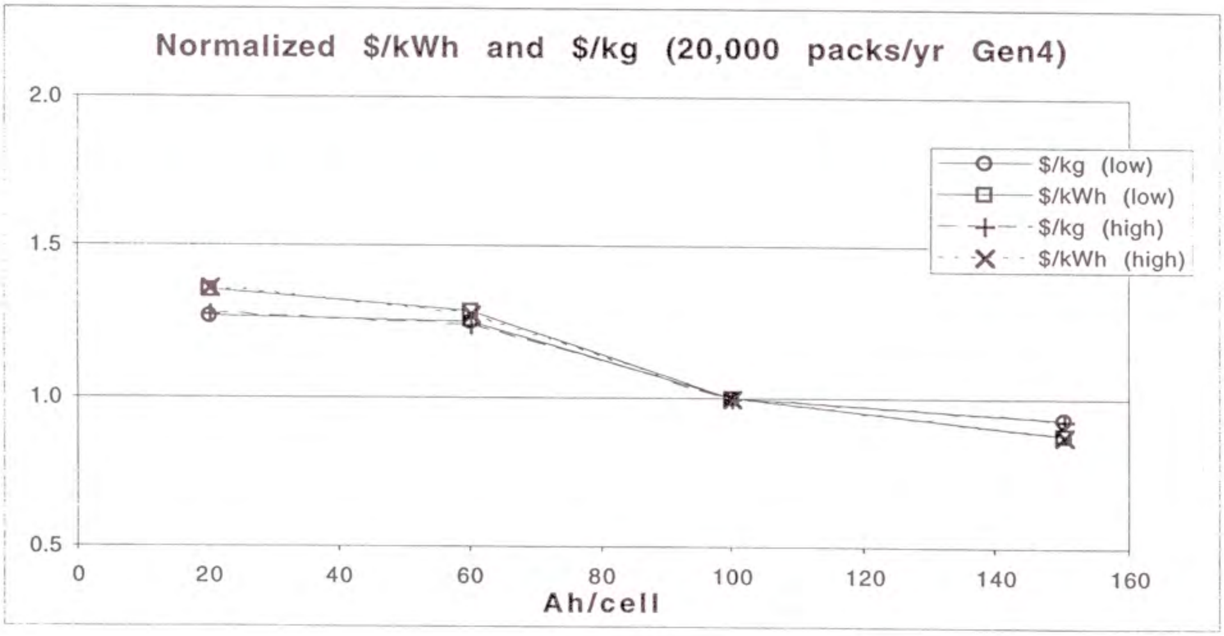


Figure 10



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