

CHAPTER SIX

Look Before You Leap: *Exploring the Implications of Advanced Vehicles for Import Dependence and Passenger Safety*

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The sleek lines of the black Tesla Roadster glistened as it slid gracefully into a high-speed curve along California's picturesque Pacific Highway one evening in the summer of 2009. The whoosh of its tires was the only sound above a whisper, as its battery-powered electric motor and racing suspension propelled it rapidly along the precipice above the ocean's edge. In the oncoming lane, the muscular outlines of a prototype Chevy Volt suggested that the thrills of the pony-car days might be returning to America's roads.

The emergence of this new generation of vehicles—powered by electric drivetrains with energy from electric storage batteries—tantalizes the car-loving American consumer. These vehicles—including advanced gas-electric hybrids (HEVs), plug-in hybrids (PHEVs), and all-electric vehicles (AEVs)—promise to deliver a smooth driving experience with abundant acceleration, little vibration, and many creature comforts, while lowering oil consumption in transportation and reducing emissions of carbon dioxide as well as other air pollutants.

But a rapid transition to HEVs, PHEVs, and AEVs is not without risks. All current designs for these vehicles incorporate significant amounts of heavy metals and rare earth elements into critical drivetrain components. In many cases, today's world markets for these materials are quite tight.¹ Acquiring additional supplies may require relying on national governments

that are unstable or overtly hostile to U.S. interests. In addition, some of the exotic materials used in these vehicles carry significant risks in the event of accidents or major malfunctions.² None of the risks, however, need be a “show-stopper” that keeps these promising new vehicles from entering the market. Nevertheless, avoiding the most dangerous risks will require careful attention to the available alternatives and may argue for development of an option that is neither cheapest in the short term nor closest to commercial readiness today. This chapter highlights some of the potential risks and identifies less risky alternatives.

Materials Requirements for Electric Drivetrains

What makes HEVs, PHEVs, and AEVs distinctive are their electric drivetrains (including electric motors, regenerative braking systems, and electric storage batteries). These components create unique design and manufacturing challenges for automakers and battery manufacturers.

Electric Motors and Related Subsystems

Electric motors generate torque to accelerate advanced vehicles; motors of several different designs can be used. The 2009 Tesla Roadster AEV, for example, incorporates a brushless, three-phase, four-pole induction motor that accelerates the vehicle from zero to 60 miles per hour (100 kilometers per hour) in about four seconds. The Toyota Prius and Honda Civic sedans, which dominate today’s HEV market, use permanent magnet motors.³ The motors in the Toyota and Honda hybrids generate far less torque than the Tesla, but they are powerful enough to reach highway speeds easily and safely.

Most current designs for HEVs, PHEVs, and AEVs use electric motors incorporating “hard magnets” that are fabricated from neodymium-iron-boron (Nd-Fe-B) alloys. They use similar hard magnets in their electric generators, power-assisted steering, and regenerative braking subsystems. This type of magnet was developed simultaneously in 1984 by General Motors (United States) and by Sumitomo Special Metals (Japan).⁴ Raskin and Shah⁵ and Chavasse⁶ estimate that each current Toyota Prius employs, on average, 1 to 2 kilograms of neodymium (Nd) in these components, as well as nearly 0.075 kilograms of cobalt (Co) in its electric motors, brakes, and steering subsystems.

Electric Storage Batteries

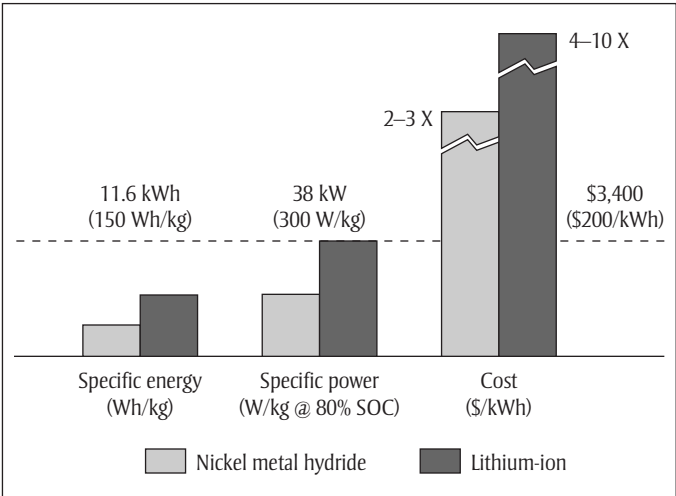
Batteries based on nickel-metal-hydride (NiMH) chemistry meet the power, energy, and weight requirements of today's hybrids. They are employed in more than 95 percent of today's HEVs, including the 2008 models of the Toyota, Honda, Ford, and Lexus brands. NiMH batteries typically contain 4 to 6 percent cobalt by weight. In today's Toyota Prius, for example, the batteries weigh about 28 kilograms, including approximately 1.4 kilograms of cobalt.⁷ Current hybrids also contain small amounts of samarium and lanthanum, additional rare earth elements.

Most analysts believe that tomorrow's HEVs, PHEVs and AEVs will require a new generation of stronger batteries. Batteries for these advanced vehicles must provide higher levels of *energy density* and *power density*, and they must sustain a larger number of charging and discharging cycles than the NiMH batteries in today's hybrids.⁸ Several alternative battery chemistries are being developed to address these requirements, but none meets all of the U.S. Department of Energy's long-term goals for PHEV performance and cost effectiveness. The alternatives closest to achieving those long-term goals employ variations of conventional lithium-ion (Li-ion) chemistries. Material requirements, performance capabilities, and cost characteristics differ significantly among the possible alternatives.⁹

Figure 6-1 below compares the current status of NiMH batteries with that of some Li-ion batteries currently under development. The green dotted line illustrates the Department of Energy (DOE) long-term PHEV goals for energy density (labeled *specific energy* in the figure), power density (labeled *specific power* in the figure), and cost (measured in dollars per kilowatt hour stored in the battery). The figure indicates that Li-ion batteries already have up to twice the energy density of NiMH batteries of similar size but still fall short of DOE's long-term goal for energy density. The power density achieved by the best Li-ion batteries, which can be as much as 2.5 times the power density of NiMH devices, could meet the long-term power density goal.¹⁰ Neither conventional NiMH batteries nor current Li-ion batteries are anywhere close to achieving DOE's long-term goal for cost effectiveness.

First-Generation Li-ion Batteries. The Li-ion batteries that are closest to commercial readiness are "traditional" Li-ion batteries, which employ a cobalt-oxide cathode. This type of battery (called an LCO cell) was first

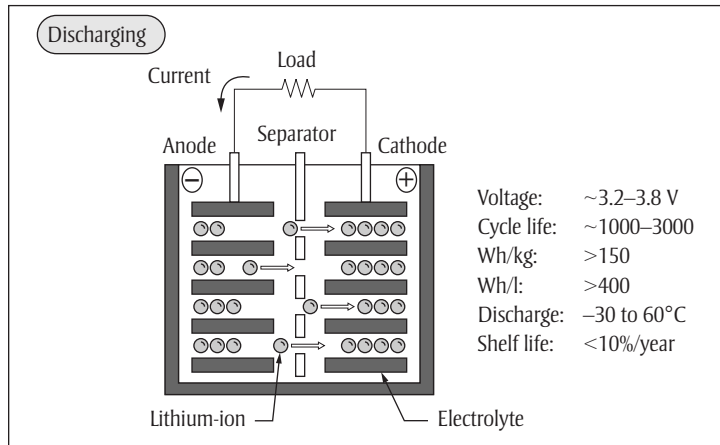
FIGURE 6-1. PHEV Battery Capabilities and Long-Term Capability Goals



Source: Don Hillebrand, testimony before the U.S. House of Representatives Subcommittee on Energy and Water Development, *Overview Hearing on Gas Prices and Vehicle Technology*, 110 Cong., 2nd. sess., February 14, 2008.

introduced by Sony Corporation of Japan in 1991.¹¹ LCO cells account for about 70 percent of today’s \$7 billion market for small, rechargeable batteries,¹² and more than 1.3 billion LCO cells were manufactured globally in 2007.¹³ Most current laptop computers and cell phones use this type of battery. Figure 6-2 presents a schematic illustration of an LCO cell. Some believe that this traditional LCO cell will be the first type employed in PHEVs and AEVs. Recent announcements support that belief: the all-electric Tesla Roadster as well as several low-cost PHEVs announced by Chinese auto companies are expected to use batteries containing LCO cells.¹⁴ Part of the attraction of LCO cells for manufacturers is that they are inexpensive and widely available as a commodity in the international market.

Advanced Li-ion Batteries. In efforts to address safety concerns and other issues with LCO cells, a number of U.S. and international companies are working aggressively to develop advanced batteries using alternative chemistries.¹⁵ Figure 6-3, which illustrates the evolution of battery tech-

Figure 6-2. Lithium-Ion Battery with Cobalt-Oxide Cathode

Source: Ahmad Pesaran, "Battery Choices and Potential Requirements for Plug-in Hybrids," National Renewable Energy Laboratory, February 13, 2007 (www.nrel.gov/vehiclesandfuels/energystorage/pdfs/41328.pdf [December 31, 2008]).

nology, displays the range of new Li-ion chemistries currently under development. Some advanced Li-ion chemistries employ new composites and nano-materials. They require much smaller quantities of cobalt than do LCO cells and show significant potential for meeting the DOE's long-term goals for PHEVs and AEVs. The most promising chemistries include

- lithium with nickel-cobalt-manganese and graphite electrodes (called NCM cells)

- lithium with nickel-cobalt-aluminum and graphite electrodes (called NCA cells)

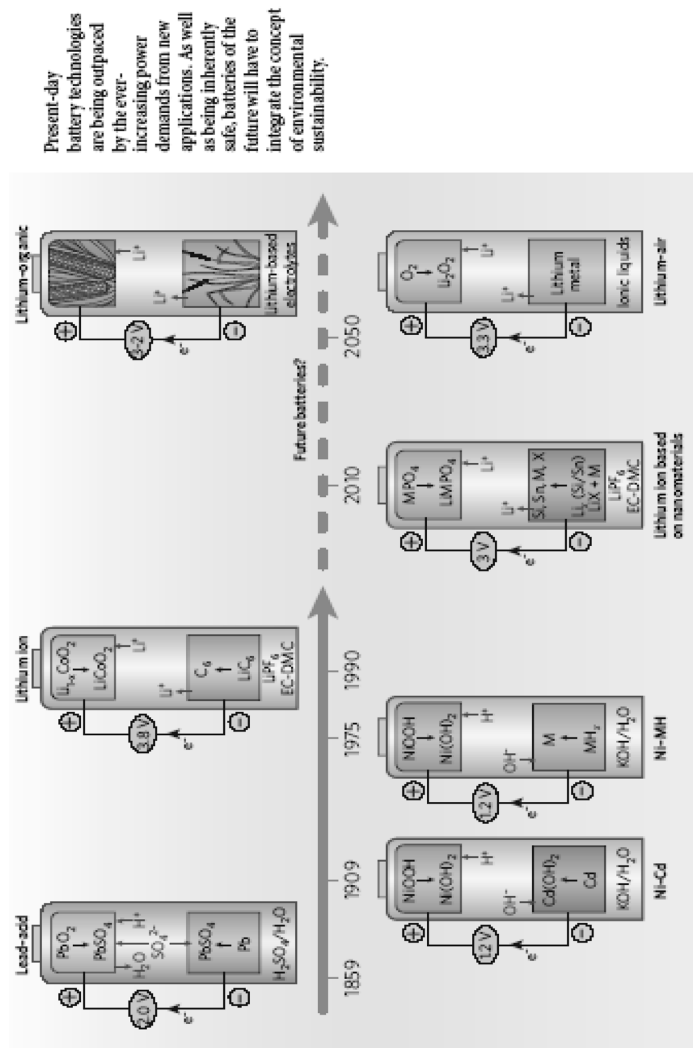
- lithium-manganese-spinel with lithium-titanate (called LMS cells)

- lithium-manganese-oxide with lithium-titanate (called LTO cells)

- lithium-iron-phosphate with graphite electrodes (called LFP cells).¹⁶

Advanced HEVs, PHEVs, and AEVs using these new battery materials would likely contain from zero to 5 kilograms of cobalt, along with 0.1 to 0.5 kilograms of cobalt in other vehicle subsystems (today's Prius has about 1.5 kilograms of cobalt).¹⁷ Table 6-1 compares batteries based on the new Li-ion chemistries with LCO cells.

FIGURE 6-3. Battery Chemistries over the Years



Source: Michel Armand and J-M Tarascon, "Building Better Batteries," *Nature* 451 (February 7, 2008), p. 653. Reprinted by permission.

TABLE 6-1. Characteristics of Leading Advanced Li-ion Chemistries

Chemistry	Electrodes		Strengths	Limitations	State of development
	Positive	Negative			
Lithium cobalt oxide (LCO)	LiCo ₂ (Graphite)		Good power; good energy density	Safety and cost issues	In widespread use in consumer rechargeable goods; planned for use in Tesla Roadster
Lithium nickel cobalt manganese (NCM)	Li(Ni _{1/3} Co _{1/3} Mn _{1/3})O ₂ (Graphite)		Potentially high energy density	Performance lower than that of NCA and LFP	In testing stage with several companies
Lithium nickel cobalt aluminum (NCA)	Li(Ni _{0.85} Co _{0.1} Al _{0.05})O ₂ (Graphite)		Good power density, energy density, and lifetime	Safety and cost issues	In testing stage with several companies
Lithium manganese spinel (LMS)	LiMnO ₂ or LiMn ₂ O ₄ (Li ₄ Ti ₅ O ₁₂)		Potentially excellent safety and lifetime and moderate cost	Moderate power and poor energy density	In intermediate development stage with several companies
Lithium titanium	LiMnO ₂ (LiTiO ₂)		Potentially good safety and lifetime	Poor to moderate power, poor energy, and high cost	In development stage with several companies
Lithium iron phosphate (LFP)	LiFePO ₄ (Graphite)		Good power, moderate energy, moderate safety, and potentially good cost	Possibly significant limits on energy density	In advanced testing stage with several companies

Source: Alan Madian and others, U.S. Plug-in Hybrid and U.S. Light-Duty Vehicle Data Book (LECG Inc.: Washington, 2008).

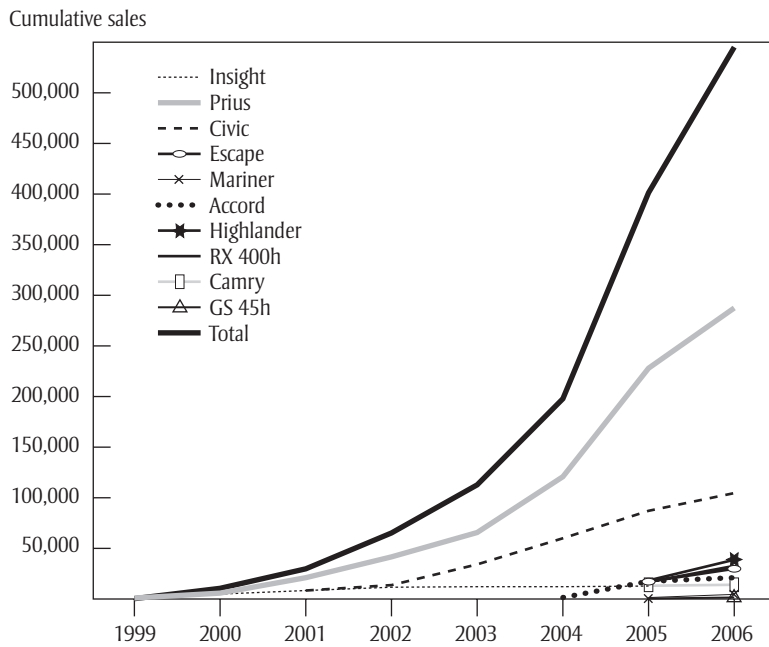
The Market for HEVs, PHEVs, and AEVs

More than 620 million light-duty vehicles are on the road today,¹⁸ of which about 235 million are registered in the United States.¹⁹ In 2007, approximately 70 million new light-duty vehicles were sold worldwide,²⁰ about 16 million of them in the United States.²¹ Estimates of the future size of the global light-duty vehicle fleet vary, depending on assumptions about global economic conditions, future oil prices, new car sales, and the future retirement rate for used vehicles. The International Energy Agency estimated that the global fleet of cars and light trucks would reach 1.3 billion in 2030.²² In 2007, Exxon estimated that the world's light-duty vehicle fleet would reach about 1.1 billion units in 2030.²³ *The Economist* estimated that the global light-duty vehicle fleet could reach 1.25 billion by 2025, growing to more than 2 billion vehicles by 2050.²⁴

In 1997, Toyota sold the first hybrid Prius in Japan. Worldwide sales of hybrid cars exceeded 500,000 units in 2007, with more than half sold in the United States. By the end of 2007, the U.S. hybrid fleet exceeded 600,000 units (see figure 6-4).²⁵ In May 2008, Toyota's cumulative hybrid sales topped 1.5 million units worldwide.²⁶ Analysts Raskin and Shah and Hillebrand argue that hybrid sales will continue to grow in the United States and in other developed countries because hybrids offer purchasers a host of desirable attributes.²⁷ In 2008, Hillebrand projected U.S. hybrid sales to grow at an average annual rate of 30 percent through 2012, suggesting sales of more than 1,200,000 vehicles.²⁸ Chavasse projects that global sales of advanced vehicles will reach 4 to 6 million units in 2015.²⁹

Projections of the aggregate size of the global hybrid vehicle fleet have increased in recent years. The International Energy Agency (IEA) estimated that by 2030, advanced vehicles (including hybrids and fuel cell vehicles) would represent about 0.7 percent of light-duty vehicles worldwide and 15 percent of light-duty vehicles in North America.³⁰ The DOE Energy Information Administration estimated that hybrids would grow from 0.5 percent of the U.S. light-duty vehicle fleet in 2004 to about 30 percent in 2030.³¹ Raskin and Shah projected that hybrids would represent 30 percent of the global light-duty fleet by 2020 (approximately 300 million vehicles) and reach 72 percent in 2030 (more than 900 million vehicles).³²

Figure 6-4. Cumulative U.S. Sales of Hybrid Gas-Electric Vehicles



Source: Don Hillebrand, testimony before the U.S. House of Representatives Subcommittee on Energy and Water Development, *Overview Hearing on Gas Prices and Vehicle Technology*, 110 Cong., 2nd. sess., February 14, 2008.

Implications for U.S. Import Dependence

Growing concern about continued U.S. dependence on imported oil has created a sense of urgency about accelerating the commercialization of HEVs, PHEVs, and AEVs.³³ Shifting the U.S. light-duty vehicle fleet away from conventional gasoline vehicles toward advanced vehicles offers an important opportunity for reducing oil import dependence and simultaneously reducing U.S. greenhouse gas emissions from the transportation sector.

Although shifting to HEVs, PHEVs, and AEVs will reduce U.S. demand for gasoline (and thus oil imports), it will *not* necessarily reduce U.S. import dependence. The strategic materials and rare earth elements critical to current designs for advanced vehicles are neither mined nor refined in the United States today; they too will have to be imported, in increasing

TABLE 6-2. Estimated 2030 Requirements for Cobalt and Neodymium in Successful Commercialization Scenarios for HEVs, PHEVs, and AEVs^a

<i>Estimated sales (2030)</i>	<i>Global vehicle fleet (per year)</i>	<i>U.S. vehicle fleet (per year)</i>
Total light-duty vehicles	72 million vehicles	15 million vehicles
HEVs, PHEVs, and AEVs	24 million vehicles	5 million vehicles
High-demand scenario (2030)		
Cobalt (5 kilograms per vehicle)	120,000 MT	25,000 MT
Neodymium (2 kilograms per vehicle)	48,000 MT	10,000 MT
Low-demand scenario (2030)		
Cobalt (0.5 kilogram per vehicle)	12,000 MT	2,500 MT
Neodymium (1 kilogram per vehicle)	24,000 MT	5,000 MT

a. Figures shown in this table are based on author's estimates that annual global sales of light-duty vehicles will increase from 70 million vehicles per year during the period April 2007–March 2008 to 72 million vehicles per year in 2030. Estimate for 2007–08 is based on data from Johnson Matthey (www.johnson-matthey.com/AR08/etd.html). Annual U.S. sales of light-duty vehicles are conservatively estimated by the author to decline and then level off at around 15 million light-duty vehicles per year in 2030. This is well below the DOE 2030 reference case projection of 20 million new domestic sales of light-duty vehicles presented in Department of Energy, Energy Information Administration, Annual Energy Outlook 2007 with Projections to 2030 ([http://tonto.eia.doe.gov/ftproot/forecasting/0383\(2007\).pdf](http://tonto.eia.doe.gov/ftproot/forecasting/0383(2007).pdf) [December 31, 2008]). The author assumes that advanced vehicles will capture one-third of all new light-duty vehicle sales, both global and U.S., by 2030.

MT = metric tons.

volumes. Depending on which battery chemistries and power train configurations achieve substantial market penetration, this new import dependence may be quite extreme. In the case of certain materials—for example, cobalt and neodymium—rapid penetration of the U.S. light-duty vehicle market by HEVs, PHEVs, and AEVs could lead to extensive reliance on supplier countries whose governments are fragile and unstable or overtly hostile to the United States.

To investigate this issue, let us examine the materials requirements in two possible scenarios for successful commercialization of advanced vehicles. In both scenarios, the U.S. and world economies avoid major economic dislocations during the next two decades, despite continued high oil prices. Under those conditions, annual worldwide light-duty vehicle sales are conservatively estimated to reach 72 million vehicles in 2030, with U.S. sales of 15 million. Advanced vehicles are assumed to capture one-third of all new light-duty vehicle sales worldwide in 2030. Table 6-2 outlines a high-demand scenario and a low-demand scenario, illustrating in each scenario the author's estimates of U.S. and global requirements for cobalt and neodymium for advanced vehicle applications. In both of the

scenarios, future demand for cobalt and neodymium depends strongly on the technologies chosen for batteries, electric motors, and other subsystems used in the vehicles. These two scenarios are used in the following sections to explore the implications of advanced vehicle deployment for future U.S. import dependence.

Sources and Availability of Cobalt

Cobalt is a strategic mineral and a heavy metal. It occurs naturally in low concentrations in the Earth's crust and is produced commercially as a by-product of extraction of other minerals, primarily nickel, copper, and arsenic. Global production of *raw* cobalt is dominated by copper mining operations in the Democratic Republic of Congo (DRC) and Zambia. Other large sources include nickel mining operations in Russia, China, Canada, Cuba, and Australia.³⁴ In 2007, worldwide production of raw cobalt was approximately 62,000 metric tons,³⁵ reflecting a decline of about 900 metric tons (MT) from 2005 to 2006 and a further decline of 5,000 MT from 2006 to 2007.³⁶ Part of the reason for the recent decline in world production was the deterioration of mining infrastructure in the DRC due to a violent civil war in the Shaba region, a conflict that has been under way since 1997. New deposits and potentially large sources of cobalt production have been identified in the Cameroons, Australia, and Canada, but it may take many years for new mines to reach full-scale production in those locations.

The United States did not mine or refine cobalt in 2007.³⁷ Approximately 80 percent of U.S. cobalt consumption was derived from imports of *refined* cobalt, with the remainder coming from recycled scrap and sales from the government's strategic stockpiles. China is the world's largest refiner of cobalt ores. U.S. imports of refined cobalt and cobalt-containing products from China have increased steadily since 2003.³⁸ In 2007, the principal sources of refined cobalt imports to the United States were Norway (21 percent), Russia (19 percent), Finland (10 percent), and China (9 percent).³⁹ Table 6-3 shows where cobalt is mined or refined today and whether refinery capacities are increasing, decreasing, or likely to remain unchanged.

As market conditions evolved, the average world spot price for refined cobalt increased from nearly \$11 per pound in 2003 to slightly more than \$30 per pound in early 2007.⁴⁰ By December 2007, the spot price for refined cobalt had increased to about \$40 per pound.⁴¹ Recently, the world

TABLE 6-3. Countries Where Cobalt is Mined or Refined or Both and 2007 Estimated Production

<i>Country</i>	<i>Mined</i>	<i>Refined</i>	<i>Approximate quantity (refined metric tons)^a</i>
Australia	✓	✓	3,400 ↑
Belgium		✓	2,850 ↓
Botswana	✓		
Brazil	✓	✓	900 ↓
Canada	✓	✓	5,000 ↑
China	✓	✓	12,700 →
Cuba	✓		
Finland		✓	8,600 ↑
France		✓	250 →
India		✓	1,200 →
Japan		✓	900 ↑
Morocco	✓	✓	1,400 ↓
New Caledonia	✓		
Norway		✓	5,000 →
Russia	✓	✓	4,700 →
Democratic Republic of Congo	✓	✓	600 ↓
Republic of South Africa	✓	✓	250 →
Uganda		✓	700 ↑
Zambia	✓	✓	5,000 ↓
Estimated total			53,450

Source: Cobalt Development Institute, "Cobalt Supply and Demand 2007," in Cobalt Facts (Washington: Cobalt Development Institute, 2007).

a. Direction of arrows indicates whether production is estimated to increase (up), decrease (down), or remain the same (right).

market for cobalt has been as tight as the world oil market, despite rising metal prices. Although demand increased, availability of refined cobalt was slightly lower in 2007 (~53,500 MT) than in 2006 (~53,900 MT).⁴²

How, then, might all this play out? In the high-demand scenario illustrated in table 6-2, successful commercialization of advanced vehicles leads to their capturing one-third of new light-duty vehicle sales. This scenario assumes that each advanced vehicle incorporates technology requiring 5 kilograms of cobalt; thus, incremental global demand for refined cobalt in HEVs, PHEVs, and AEVs reaches approximately 120,000 MT a year by 2030. This scenario suggests incremental U.S. demand for refined cobalt for advanced vehicles of approximately 25,000 MT in 2030. By contrast, the low-demand scenario assumes each advanced vehicle requires only 0.5 kilogram of cobalt. Thus, in the low-

demand scenario, the implied global cobalt demand in 2030 for advanced vehicles is approximately 12,000 MT and the incremental U.S. demand for cobalt for these vehicles is 2,500 MT.

Global production of refined cobalt was approximately 53,000 MT in 2007. If we assume that all other cobalt demands remain unchanged, global cobalt production would have to more than triple by 2030 to meet incremental worldwide demand for cobalt for advanced vehicles in the high-demand scenario. Meeting just incremental U.S. cobalt demand in that scenario would require a nearly 50 percent increase above 2007 global cobalt production. The low-demand scenario—if all other demands for cobalt remain unchanged—would require expanding annual global cobalt production by about 23 percent of the 2007 level to meet worldwide demand for cobalt for advanced vehicles in 2030. In this scenario, meeting the needs for U.S. advanced vehicles alone would require less than a 5 percent increase above 2007 global cobalt production.

The cheapest Li-ion batteries and those closest to use in vehicle applications today incorporate LCO cells. Using LCO cells would lead to cobalt requirements similar to those illustrated in the high-demand scenario. However, some advanced lithium-ion chemistries currently under development for advanced vehicle applications would lead to much lower requirements.⁴³ Many of these alternative chemistries look extraordinarily promising and could reduce future U.S. cobalt imports.⁴⁴ Nonetheless, these alternative battery chemistries still face a number of engineering challenges related to battery lifetime, energy density, and ability to increase manufacturing output without raising production costs or reducing performance and reliability.⁴⁵

The rate of growth in worldwide demand for refined cobalt has accelerated during the last few years and not only because of growing requirements for cobalt in rechargeable batteries. Other fast-growing applications include catalysts, anti-corrosion coatings, paint-drying additives, and super-alloys for turbine blades. The aggregate growth in cobalt demand is one explanation for the recent run-up in refined cobalt spot prices. If the future aggregate rate of growth in cobalt demand can be limited, then the projected price impacts and the possible implications for U.S. cobalt import dependence may be moderated.

Worldwide cobalt production can and will be increased. Nonetheless, it would be very difficult to meet the cobalt requirements of the high-demand scenario illustrated above. To meet global requirements in that

scenario, much of the growth in cobalt mining and refining facilities would likely occur in countries where production could be expanded relatively quickly—China, Russia, Democratic Republic of Congo, Cuba, and Zambia. Needless to say, not all of these regimes are robust and thriving democracies, dedicated to the economic and environmental success of the United States. By contrast, in the low-demand scenario, expanded cobalt production from Canada, Australia, and the Cameroons might be sufficient to meet incremental demand from advanced vehicles.

Sources and Availability of Neodymium

Current market conditions with respect to neodymium and other rare earth elements are similar to but perhaps more extreme than conditions in the cobalt market. The high-demand scenario illustrated in table 6-2 assumes that each advanced vehicle requires 2 kilograms of neodymium. In that scenario, incremental global demand for neodymium in HEVs, PHEVs, and AEVs reaches approximately 48,000 MT a year by 2030. In the same scenario, incremental U.S. neodymium demand for advanced vehicles reaches approximately 10,000 MT. By contrast, the low-demand scenario assumes that each vehicle requires 1 kilogram of neodymium. Thus, in the low-demand scenario, incremental global demand for neodymium in 2030 for HEVs, PHEVs, and AEVs is approximately 24,000 MT. Incremental U.S. neodymium demand reaches 5,000 MT.

Global neodymium production was approximately 7,300 MT in 2006.⁴⁶ If we assume that all other demands for neodymium remain unchanged, global production would have to increase more than five-fold in the high-demand scenario to meet incremental worldwide demand from advanced vehicles by 2030. Meeting just incremental U.S. neodymium demand in the high-demand scenario would require a 150 percent increase in annual global production. In the low-demand scenario—if all other demands remain unchanged—annual global neodymium production would have to more than triple the 2006 level by 2030 to meet worldwide demand from advanced vehicles. In the low-demand scenario, meeting the needs of U.S. advanced light-duty vehicles alone would require additional production equivalent to more than two-thirds of global output of neodymium in 2006.

Although such increases in world production are technically feasible, several factors suggest that they would be difficult to achieve in the near- to mid-term. Most global production of neodymium and other rare earth ele-

ments results from extraction of rare earth oxides (REOs). Extraction of REOs, unlike that of cobalt, is very concentrated geographically. Until the 1950s, most of the world's REO production occurred in India and Brazil.⁴⁷ Following the discovery of REO-rich monazite in South Africa, production shifted to that country.⁴⁸ In the 1970s and 1980s, global production was dominated by REO output from the large open-pit mine at Mountain Pass, California, which closed in 1998 for environmental and economic reasons.⁴⁹ Molycorp Minerals LLC purchased the Mountain Pass mine in September 2008 and plans to resume production of didymium at the site as soon as possible, but that will not increase neodymium supplies in the near term.⁵⁰ Currently, more than 95 percent of global REO production takes place in one country, the People's Republic of China.⁵¹ Most Chinese REOs are extracted from the bastnaesite ores of Inner Mongolia, which are especially rich in neodymium.⁵²

Significant deposits of REO-containing minerals have been found in a number of other countries, including Canada and the United States. But to increase production of rare earth elements at the rate implied by the high-demand scenario for neodymium would seem to depend strongly on the willingness of the Chinese government to increase current levels of output and to expand exports significantly. Recent events suggest that that may be unlikely. In 2008, Beijing stopped issuing permits to export any rare earth elements after domestic Chinese demand equaled current output levels. The export ban was imposed despite a recent run-up in the world price for neodymium and other rare earth metals.⁵³

Global demand for neodymium will be affected by factors other than the commercial production of advanced automobiles. For example, Nd-Fe-B magnets are attractive and cost effective in a variety of other applications due to their outstanding magnetic properties, ease of manufacture, and relatively low cost. Nd-Fe-B magnets have found widespread use in non-automotive applications, including "stepper" motors for computer hard disk drives, speaker "cones" for in-ear headphones used with Ipods and other MP3 players, and even electric bicycles. One may reasonably expect that future demand for hard magnets will be driven not only by the growth in demand for advanced vehicles but also by their increasing use in non-automotive applications. Global competition for neodymium supplies is likely to be complicated by the growing demand for neodymium in applications ranging from colored phosphors used in LCD screens, colorants used in enamel coatings, and the optical amplifiers required for lasers.

Alternative materials exist for all hard magnet applications (including vehicles), although the alternatives generally have somewhat higher cost and lower performance.⁵⁴ Magnets based on samarium-cobalt alloys probably are the most attractive alternatives for use in advanced vehicles. (Samarium also is a rare earth element.) However, substitution of samarium-cobalt magnets in these applications would probably increase the cost for electric motors, regenerative braking systems, and steering-assist devices in the vehicles. In addition, it would increase global cobalt demand.

Mineral deposits containing mixtures of REOs exist in Canada, Australia, and the United States. Several could be developed over the next five to ten years. At today's high prices, promising locations include California's old Mountain Pass mine; a remote site in Saskatchewan, Canada, where a large deposit has been found alongside Hoidas Lake; and at several sites in Australia.⁵⁵ It would be difficult at best to bring new production from these sites online fast enough to meet the growing demand for neodymium or samarium in either the high- or the low-demand scenarios described above. A recent U.S. Geological Survey analysis concludes that China will dominate global production of rare earth elements in the near- to mid-term due to the favorable number, size, and elemental composition of Chinese REO deposits; much lower Chinese labor and regulatory costs; China's access to the continually expanding Asian electronics and manufacturing sectors; and the ongoing environmental and regulatory problems at Mountain Pass.⁵⁶

In a world of tight supplies and rising prices for cobalt, neodymium and other rare earth elements, the technologies developed for electric storage batteries, electric motors, regenerative braking systems, and other critical components of advanced vehicles could have big impacts on strategic competition among the United States, China, Japan, Russia, Korea, India, and the European Union. Making smart choices among the technology options available today or just over the horizon may help to reduce tomorrow's risk of dangerous geopolitical competition for scarce resources.

Hidden Dangers: Health and Safety Issues

Traditional LCO batteries are likely to be the first to market in advanced HEVs, PHEVs, and AEVs.⁵⁷ The structure of LCO batteries makes them very vulnerable to internal electrical short circuits, which can occur when

a cell's separator membrane is squeezed or the battery case is punctured. Ignition or explosion also can occur, under some conditions, in the event of too-rapid discharge or overcharging during battery recharge.

Fire. One of the principal concerns about LCO batteries in vehicles is their potential to ignite or explode in a collision.⁵⁸ If battery cells experience a short circuit following a collision, a highly exothermic chemical reaction can be initiated within the cells, causing cell temperature to increase rapidly. If the process is not interrupted quickly, the cell can undergo what is called "thermal runaway," ultimately bursting into flames and often exploding. This type of failure sequence destroyed many laptop computer batteries and caused Sony Corporation to recall 3.5 million batteries in 2007.⁵⁹

Injury. Fires resulting from thermal runaway in LCO cells are especially dangerous if they occur in a closed vehicle carrying fuel and passengers. Because combustion is fed with oxygen generated from the chemical reaction within the cell, the flames can be difficult to extinguish. In addition, once the failure sequence has started, inadvertent heating of adjacent cells in the battery pack can reinitiate thermal runaway, even after the fire in the first failed cell has been put out.

Exposure. The unusual characteristics of LCO battery fires may create special hazards and therefore require special training for first responders, who would be called upon to extinguish fires resulting from collisions involving advanced vehicles containing LCO batteries. The same characteristics will drive development of new standards for special fire-extinguishing compounds to be carried on fire engines or other rescue vehicles. They should lead to new protocols on when to use self-contained breathing apparatus during a vehicle rescue operation so as to avoid first responders' exposure to aerosols of fine metal particles emitted from burning batteries.

Risk Reduction

Several manufacturers have recently claimed that their proprietary Li-ion battery technology has addressed the problem of thermal runaway and eliminated the risk of fires from hybrid-vehicle batteries. Tesla Motors, which probably will be the first to bring a new AEV to market,⁶⁰ employs an active, highly redundant, battery management system coupled to the 6000+ LCO cells employed in the Tesla Roadster. Tesla claims that its system makes a fire

due to battery failure extremely unlikely. The Massachusetts-based company A123, which will provide batteries for the Chevrolet Volt PHEV, argues that its nanophosphate LFP battery is inherently safe with respect to thermal runaway. A123 claims that LFP chemistry eliminates any buildup of excess lithium at the cell's graphite cathode, making it unlikely that lithium plating will occur during any overcharging episode and thus reducing the probability of an internal short circuit that could lead to thermal runaway. Other manufacturers, including 3M and Johnson Controls-SAFT, make similar claims for their NMC and NCA battery chemistries.

The Federal Role in Development of HEVs, PHEVs, and AEVs

The choice of battery and electric motor technologies for advanced HEVs, PHEVs, and AEVs can strongly affect the cost and resulting market penetration rates for these vehicles. Furthermore, technology choices have important implications for U.S. import dependence and will affect the character of the health and safety risks associated with advanced vehicles.

The federal government should work with vehicle manufacturers and battery producers to achieve the best long-term solution for U.S. environmental interests and national security. Its role is especially important if federal policies provide subsidies or other incentives to accelerate market uptake. The federal government must balance the desire to accelerate commercialization of HEVs, PHEVs, and AEVs with the necessity to encourage automakers and battery manufacturers to make smart choices among technology alternatives—choices that will advance U.S. environmental and security interests. Subsidizing development of the cheapest options—or the first alternatives to reach the commercial market—is not necessarily the best long-term solution for the nation.

The Environmental Protection Agency, Department of Energy, Department of Transportation, Federal Highway Safety Administration, and Federal Transportation Safety Board should develop consistent testing procedures and coordinate their efforts to set standards for battery safety and performance as well as standards for electric motors, regenerative braking systems, and steering-assist units. To the extent practical, government policies should discourage increased dependence on exotic or strategic materials for which the United States must rely excessively or

exclusively on imports. The associated standards should encourage recapture, reuse, and recycling of all exotic materials in order to maximize their value to the U.S. economy.

Many governments—including those of Japan, Korea, and China—have designated production of advanced batteries as a strategic industry. They seek to establish global dominance in the advanced battery industry and are willing to subsidize its domestic development; they therefore will go to great lengths to ensure access to critical inputs for their companies. Understanding the global trajectory of industry development will require increased federal attention to smuggling and to global trade in illegal materials. In addition, particular attention should be paid to efforts by the Chinese government and Chinese industrial groups to corner the market in strategic minerals in Africa.

Lisa Margonelli has suggested that federal policy could encourage U.S. automakers or electric utilities to become the permanent owners of the batteries used in advanced vehicles. She argues that federal policy should require the companies to recycle or reuse the batteries when they are no longer fit for use in vehicles. Doing so, she observes, could completely change the economics of the battery business, making it worthwhile for U.S. battery manufacturers to develop a cradle-to-cradle design philosophy, investing in more expensive—but easily recyclable—designs that pose lower risks to the economy and the environment. Such an approach could improve U.S. battery manufacturers' competitive position with respect to their Japanese, Korean, and Chinese counterparts, even though their foreign competitors are directly subsidized by their governments and may treat vehicle batteries as “throwaway” commodities.⁶¹

Conclusions: Look before You Leap

This preliminary assessment regarding advanced vehicles leads to several principal conclusions:

—HEVs, PHEVs, and AEVs can play a significant role in addressing U.S. oil import dependence, but some vehicle development paths may lead to important vehicle safety issues and create new forms of import dependence.

—It would be extraordinarily prudent now, during the earliest stages of commercial development of advanced vehicles, to examine those risks systematically and from a systemic perspective. Such an analysis could

stimulate the design of thoughtful and flexible policies that have the lowest likelihood of creating dangerous future safety and import-dependence problems.

—To the extent possible, concurrent initiatives to provide subsidies or other incentives for accelerating commercialization of advanced vehicles should avoid promoting technologies that would exacerbate potential future problems.

—Efforts made now to establish adequate federal standards for performance and recycling of HEV, PHEV, and AEV batteries as well as other power train components could reduce future risk of import dependence and avoid negative environmental impacts from the widespread deployment of advanced vehicles.

If efforts to “look before you leap” are not undertaken now, the United States could replace its dangerous current dependence on foreign oil with a new dependence on unstable or hostile foreign governments to supply strategic materials and rare earth elements to the U.S. transportation sector. Furthermore, dependence on first-generation lithium-ion batteries could increase the probability of a few spectacular and fatal collisions that might significantly dampen consumer acceptance of the broader family of advanced vehicle technologies that might be developed down the road. To best facilitate commercialization of advanced HEVs, PHEVs, and AEVs, the federal government must set strong standards to ensure the safety of advanced vehicles and to encourage the development of vehicle technologies that will advance the energy and security interests of the United States.

None of these potential safety and import dependence risks need be a “show stopper” for advanced vehicle development. Federal agencies can work together to fashion adequate policies and standards, thereby avoiding the worst outcomes. But if we fail to address those risks now, giving them the careful attention that they require, then we collectively “roll the dice,” having done nothing more than hope that everything works out for the best.

Notes

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