Project Report

Environmentally Sound Management of End-of-Life Batteries from Electric-Drive Vehicles in North America

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About the author(s):

Kelleher Environmental is a consulting company based in Toronto, Ontario, specializing in environmental research, policy development, and program and policy analysis in waste management, energy and climate change.

Gracestone, Inc. is a US-based firm consulting in the management of hard-to-recycle complex engineered materials (such as batteries, electronics, tires, etc.), providing policy, technical, operational, compliance, and programmatic analysis services.

SAMI Environmental is an environmental consulting firm based in Timmins, Ontario, providing environmental research services on a wide range of topics to public and private sector clients.

José Castro Díaz is an environmental consultant based in Mexico City, Mexico, providing environmental research services focusing on hazardous wastes and toxic substances.

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For more information:

Commission for Environmental Cooperation
393, rue St-Jacques Ouest, bureau 200, Montreal (Quebec) H2Y 1N9 Canada
t 514.350.4300 f 514.350.4314
info@cec.org / www.cec.org

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AEO	Annual Energy Outlook
AFV	alternative-fuel vehicle
AMDA	*Asociación Mexicana de Distribuidores de Autos* (Mexican Association of Car Dealers)
ARA	Automotive Recyclers of America
ARC	Automotive Recyclers of Canada
C2R	Call 2 Recycle
CEC	Commission for Environmental Cooperation
CSU	Colorado State University
DoE	US Department of Energy
DoT	US Department of Transportation
EDTA	Electric Drive Transportation Association
EDV	electric-drive vehicle
EIA	Energy Information Administration (US)
ELV	end-of-life vehicle
EOL	end of life
EPRI	Electric Power Research Institute
ESM	environmentally sound management
EV	(all-)electric vehicle
EVSE	electric vehicle supply equipment
G/X	Glencore/Xstrata
HEV	hybrid electric vehicle
ICE	internal combustion engine
INEGI	*Instituto Nacional de Estadística y Geografía* (National Institute for Statistics and Geography)
JMC	Japan Metals & Chemicals
Li-ion	lithium-ion
kWh	kilowatt-hour
MIT	Massachusetts Institute of Technology
MTU	Michigan Technological University
NAAEC	North American Agreement on Environmental Cooperation
NAATBatt	National Alliance for Advanced Technology Batteries, and Rechargeable Battery Association
NAFTA	North American Free Trade Agreement
NBNL	Lawrence Berkeley National Laboratory
NiMH	nickel metal hydride
NREL	National Renewable Energy Laboratory
PHEV	plug-in hybrid electric vehicle
PRBA	Rechargeable Battery Association
RCRA	Resource Conservation and Recovery Act (US)
RPS	Renewable Portfolio Standard

SE	*Secretaría de Economía* (Ministry of Economy)
Semarnat	*Secretaría de Medio Ambiente y Recursos Naturales* (Ministry of the Environment and Natural Resources)
SWCNT	single-walled carbon nanotube
SMM	Sumitomo Metal Mining
SNAM	*Société Nouvelle d'Affinage des Métaux*
TMC	Toyota Motor Corporation
UL	Underwriters Lab
USABC	US Advanced Battery Consortium
US EPA	US Environmental Protection Agency
VOC	volatile organic compound

Abstract

The market for electric-drive vehicles (EDVs), including hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs), and electric, pure battery-powered vehicles (EVs), is expected to experience significant and rapid growth over the coming decades. In the year 2013 all EDVs together represent about 1.44 percent of annual vehicle sales in Canada, about 0.09 percent in Mexico and about 3.81 percent in the US, and numbers are expected to grow rapidly in the coming years. As the market for EDVs expands, there will be a vital opportunity to recapture and recycle the materials used in EDV batteries (nickel, cobalt, steel and other valuable components) once they reach end of life (EOL). This report characterizes the types, quantities, and composition of batteries used in EDVs in North America, and outlines best practices and technologies to support their environmentally sound management (ESM) at end of life. It is projected that about 276,000 EDV batteries will reach EOL in North America in 2015. Most of these batteries are likely to be nickel metal hydride (NiMH), which is the predominant battery chemistry used in HEVs. By 2030, almost 1.5 million EDV batteries will reach EOL. By that time, close to half the EOL EDV batteries will be lithium-based, with the remainder being NiMH batteries.

The current domestic infrastructure to handle EOL EDV batteries is limited; however, it is expected to expand over time. A promising second-life use as energy storage units is currently being explored for EOL EDV batteries.

Executive Summary

In the last ten years, the market in North America for hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs) and electric vehicles (EVs), which are collectively referred to as electric-drive vehicles (EDVs), has surged. Annual sales of HEVs reached almost 520,000 units in North America in 2013. Most of the sales were in the US, more than 495,000 units, or about 3.2 percent of all vehicle sales. HEV unit sales were about 23,000 in Canada in 2013, representing 1.32 percent of all vehicles sales. Available information indicates that about 1,000 units were sold in Mexico in 2013, representing about 0.09 percent of annual vehicle sales. Several factors have contributed to this rising market penetration of EDVs, including greater consumer preference for fuel-efficient cars; increasing gasoline prices; advances in battery technology; low-carbon fuel standards; and government support in the form of tax incentives and rebate programs.

As the number of EDVs on the road increases and the battery packs they contain reach the end of their lives, there will be a vital opportunity to recapture and recycle the materials used in the batteries. It is essential that environmentally sound management (ESM) practices are adopted in the recycling of batteries from EDVs to ensure that they are recycled in a manner that is protective of human health and the environment.

The Commission for Environmental Cooperation (CEC) approved the project Environmentally Sound Management (ESM) of Selected End-of-life (EOL) Vehicle Batteries in North America, which includes hybrid vehicle and electric vehicle batteries, as part of the Operational Plan for 2013–2014. The purpose of this project is to characterize the types, content, quantities, use, and management of EDV batteries used in North America, and to describe current and prospective best practices and technologies that support ESM.

EDVs today use either nickel metal hydride (NiMH) or lithium-ion (Li-ion) batteries. In 2013, about 80 percent of HEVs used NiMH batteries. The remaining 20 percent of HEVs and all PHEVs and EVs use Li-ion batteries, though the exact chemistry often varies. Research and development on new and emerging battery technologies, to reduce the cost and extend their useful lifecycle, is ongoing.

The table below shows that there will be a substantial increase in EDV batteries reaching EOL between now and 2030 in all three North American countries, with most of the EDV EOL batteries generated in the US, where the numbers of EDVs on the road are increasing rapidly. It is projected that about 276,000 EDV batteries will reach EOL in North America in 2015. Most of these batteries are likely to be NiMH, which is the predominant battery chemistry used in HEVs. By 2020, the total number of EDV batteries reaching EOL will increase to 358,000—again, most having NiMH battery chemistry. By 2025, some of the PHEVs and EVs introduced into the market in 2011 and later will have reached the end of their useful lives, and the numbers of EDV EOL batteries will increase substantially to a projected 849,000 units. By 2030, almost 1.5 million EDV batteries will reach EOL. By that time, close to half the EOL EDV batteries will be lithium-based, with the remainder NiMH-based.

Estimated EDV Batteries at End of Life, in North America, by 2030 (in thousands of units)

Year	EDV Batteries at EOL in Canada		EDV Batteries at EOL in Mexico		EDV Batteries at EOL in the US		EDV Batteries at EOL in North America		Total EDV Batteries at EOL in North America
	NiMH	Li-ion	NiMH	Li-ion	NiMH	Li-ion	NiMH	Li-ion	
2015	8	2	0	0	217	49	225	51	276
2020	13	4	0	0	255	86	268	90	358
2025	37	23	6	8	528	247	571	278	849
2030	64	60	25	36	693	580	782	676	1,458

There is an existing infrastructure in place in Canada, Mexico and the United States to collect, transport, and recycle EOL EDV batteries, including the steps involved in ESM. There are currently only a handful of companies that have the technology and capacity to process these batteries: Retriev, Raw Materials Company, and Glencore/Xstrata in Canada; Sitrasa and TES-AMM in Mexico; and Inmetco, Retriev, Umicore, and MCT in the US. These companies are particularly interested in recovering valuable metals such as nickel (from NiMH batteries) and cobalt from Li-ion batteries. Industry players expressed a concern that new battery chemistries under development at this time may contain less-valuable components in the future, thereby reducing the incentive for effective recycling.

At EOL, retired EDV batteries still retain about 80 percent of their capacity. While they are no longer suitable for vehicular use, these EOL EDV batteries may still have reasonable energy storage and standby power capabilities that could be used for residential and commercial electric-power management, power-grid stabilization, and renewable energy system firming. Considerable research is underway in the US and elsewhere to fully explore this potential.

Directing used EDV batteries to second-use applications could benefit the environment by delaying the recycling of batteries and fully utilizing their capabilities prior to recycling. Over the long term, recycling and refurbishing of EDV batteries will play an important role in reducing the costs of EDVs.

The estimates in this report should be updated on a periodic basis as the EDV market matures in North America.

Introduction

The Commission for Environmental Cooperation (CEC) is an intergovernmental organization created by Canada, Mexico and the United States under the North American Agreement on Environmental Cooperation (NAAEC). The CEC was established to address regional environmental concerns, help prevent potential trade and environmental conflicts, and promote effective enforcement and environmental law. The Agreement complements the environmental provisions of the North American Free Trade Agreement (NAFTA).

The CEC's Council—its governing body—approved the project Environmentally Sound Management (ESM) of Selected End-of-life (EOL) Vehicle Batteries in North America as part of the Operational Plan for 2013–2014.

With the growth in the market for electric-drive vehicles (EDV), which include hybrid, plug-in hybrid and electric vehicles, the CEC commissioned a study in early 2014 to describe the use and management of spent batteries used in hybrid and electric vehicles, including an examination of current and prospective best practices and technologies which support environmentally sound management (ESM). The purpose of the ESM EOL vehicle battery project is to characterize the types, content, quantities, use and management of end-of-life automotive and industrial batteries used in EDVs, for each North American country.

ESM can be defined as *taking all practicable steps to ensure that used and/or end-of-life products and wastes are managed in a manner that will protect human health and the environment*.[1] There are a number of recognized benefits that come from adopting and implementing ESM practices:

- There can be critical impacts to worker health, the community, and to the environment that come from the processing of end-of-life batteries. ESM at such facilities can result in improved worker health and safety, as well as in protection of the local community and the environment.
- ESM requires compliance with health and safety regulations and environmental protection regulations, which results in improved environmental performance.
- ESM can increase business opportunities for companies. Clients now frequently demand that processors of end-of-life components associated with their products use ESM practices. Thus ESM can be a marketing advantage for all companies throughout the supply chain.
- ESM can increase the recovery of materials that are of high economic value—for example, precious metals such as nickel, cobalt, steel, and sometimes rare-earth elements can be recovered from the batteries that are addressed in this study.
- Implementing ESM improves operational efficiency through new systems and procedures that focus on reducing waste, reusing, and recycling.

[1] Commission for Environmental Cooperation. N.d. CEC training manuals on environmentally sound management. <www.cec.org/Page.asp?PageID=1226&SiteNodeID=1282>. (Accessed on 26 March 2015.)

Background

Electric-drive vehicles (EDVs) come in three designs:[2]

- Hybrid electric vehicles (HEVs) make use of two power sources: a gasoline combustion engine and a battery. The combustion engine is used to recharge the battery.
- Plug-in hybrid electric vehicles (PHEVs) have two power sources but can also charge their battery by plugging in to a grid-provided electricity system. PHEVs are typically categorized according to their all-electric range (AER), which is the maximum distance over which the vehicle can travel without using the internal combustion engine.
- Electric vehicles (EVs) are powered entirely by batteries and electric drive-trains. These vehicles are recharged by plugging them into a grid-provided electricity system.

The different types of EDVs require different battery performance characteristics.[3] Two of the most important characteristics to consider are energy density and power density.[4] While batteries with a higher energy density provide a higher vehicle range per charge, those with a higher power density sacrifice range to provide a faster acceleration rate. EVs require batteries with higher energy density, in order to get the most range possible between charging stations, while HEVs can take advantage of batteries with higher power density,[5] since they are recharged by the gasoline combustion engine. This is why most HEVs (about 80 percent in 2013) use nickel metal hydride (NiMH) batteries whereas PHEVs and EVs use lithium-based (Li-ion) batteries.

For the remainder of the study, the three types of vehicles will be described collectively as electric-drive vehicles (EDVs), unless the text is referring to one specific type of vehicle within the EDV group.

Rationale for Assignment

Environmentally sound management (ESM) of EDV batteries at end of life needs to be addressed prior to the expected increase in numbers of end-of-life (EOL) EDV batteries in the future. With the growth in the use of all types of EDVs, the CEC seeks to know how the batteries used in EDVs are currently handled at EOL in North America, and to determine whether there is sufficient infrastructure in place to manage EOL EDV batteries in an environmentally sound manner.

Objectives and Scope of Project

The objectives of this research assignment are to produce a report characterizing the types, content, quantities, use and management of end-of-life batteries used in hybrid (HEV), plug-in hybrid (PHEV) and electric vehicles (EV) in each North American country. This includes examination of current and prospective best practices and technologies that support environmentally sound management (ESM). Specific tasks in the study are as follows:

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[2] US EPA. 2012. *Lithium-ion batteries and nanotechnology for electric vehicles: A life cycle assessment* (DRAFT). Office of Pollution Prevention and Toxics, and National Risk Management Research Laboratory Office of Research and Development. <http://nepis.epa.gov>. (Accessed on 21 April 2015.)

[3] Ibid.

[4] Ibid.

[5] Ibid.

- Identify types of batteries used in hybrid and electric vehicles in North America, and the substances contained in the batteries, as well as any risks in not handling these materials properly and any inherent economic value in them.
- Identify the current and projected quantities of EDV batteries that will enter the North American market and will reach end of life during the years 2010 to 2030.
- Identify the existing infrastructure and its capacity to manage each of the battery types used in EDVs.
- Identify best technical, regulatory and policy practices for managing EDV batteries in other jurisdictions (Europe and Asia) compared to current North American practices.
- Comment on the extent to which ESM is currently practiced for processing of EOL EDV batteries in North America.

Report Structure

The findings of the project research are presented in the following manner:

- Section 1 presents a description of the types of batteries used in EDVs, as well as estimates of current and future sales of EDV vehicles and batteries, in the three North American countries.
- Section 2 presents projections of EDV batteries reaching end of life between 2010 and 2030 in Canada, Mexico and the US, and the assumptions on which these projections are based.
- Section 3 presents a description of the current infrastructure for collection and processing of EOL EDV batteries in Canada, Mexico and the US.
- Section 4 presents information on best practices for management of EOL EDV batteries, and issues of concern regarding the environmental fate of battery constituents.
- Section 5 presents conclusions and recommendations rising from the study research.

1 Electric-drive Vehicle (EDV) Battery Composition, Sales and Projections

This section presents information on the composition of batteries used at present in electric-drive vehicles (EDVs), and current and projected sales of EDV batteries in Canada, Mexico and the US.

1.1 History and Development of EDV Market in North America

Hybrid-electric vehicle (HEV) technology was developed to help reduce the dependence on petroleum as a vehicle fuel.[6] The Honda Insight was the first mainstream HEV on the North American market in 2000. A number of other HEVs entered the market over time. As discussed later in this section, sales of HEVs were modest but grew steadily each year. Sales of plug-in electric vehicles (PHEVs) and electric vehicles (EVs) are also growing steadily since their introduction to the North American market in December 2010. Over 618,000 EDVs were sold in North America in 2013. This equates to 3.4 percent of the total sales volume of 18.3 million vehicles (see later tables in this section for details).

Factors which have contributed to the growth of the EDV market include:

- consumer preference for vehicles which are "green" and "environmentally friendly;"
- the increasing price of gasoline, which encourages consumers to explore vehicles that are more fuel-efficient;
- reduction in the cost, and increased autonomy of electric batteries;[7]
- a higher comfort level with the technology as EDVs are in the market longer and are purchased by more consumers, etc.
- parking fee reductions, permission to use high-occupancy lanes, and other incentives provided in some cities;[8]
- mandatory GHG reduction targets and requirements to meet low emissions for vehicles, through purchasing specifications;
- efforts by governments at all levels to establish green fleets in order to reduce CO_2 emissions;
- low-carbon fuel standards and emission limitations in some locations, which encourage the purchase of low-emission and zero-emission vehicles; and
- government support in the form of federal income tax incentives,[9] rebate programs, or grants.

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[6] Early US research was developed through collaborative research between the US Department of Energy (DOE), the National Renewable Energy Laboratory (NREL), and the auto industry.

[7] Perdiguero, J., and J. Jimenez. 2012. *Policy options for the promotion of electric vehicles: A review.* Research Institute of Applied Economics (*Institut de Recerca en Economia Aplicada Regional i Publica*—IREA). <www.ub.edu/irea/working_papers/2012/201208.pdf>. (Accessed on 30 September 2014.)

[8] Ibid.

[9] Beresteanu, A., and S. Li. 2008. *Gasoline prices, government support, and the demand for hybrid vehicles in the U.S.* <http://public.econ.duke.edu/Papers//PDF/hybrid.pdf>. (Accessed on 30 September 2014.)

1.2 Batteries Used in EDVs

EDV batteries need to provide a combination of:

- power density, which affects the amount of energy that can be delivered in a given period of time and therefore how fast a vehicle accelerates; and
- energy density, which is the capacity to store energy and thus affects the range an EDV can travel between charges.

EDVs currently use one of two types of batteries:

- nickel metal hydride (NiMH) batteries (mostly used in hybrids because of power needs and because they can be charged from the engine); or
- lithium-based (Li-ion) batteries (needed in electric and plug-in hybrid electric vehicles, which are charged from the electrical grid). [10]

1.2.1 Batteries Used in Hybrid Vehicles (HEVs)

Table 1 presents information on the type and weight of batteries used in HEVs. It shows that Toyota (the dominant player in the HEV market at this time) uses a NiMH battery for its HEVs, although, as do other manufacturers, it uses a lithium-based battery for PHEVs and EVs. Ford uses a lithium-based battery for its HEVs (Ford Fusion and Ford C-Max). Hyundai also uses a lithium-based battery for its Sonata HEV. Each manufacturer bases the decision on a number of factors. Toyota tested lithium-based batteries in their HEVs but decided to continue to use NiMH batteries. Based on the US market share of each auto manufacturer (the US is by far the largest market for HEVs in North America, as discussed later in this section), about 19 percent of HEVs use Li-ion batteries and about 81 percent of HEVs use NiMH batteries. This value excludes PHEVs, which all use Li-ion batteries.

[10] US Department of Energy. N.d. Batteries for hybrid and plug-in electric vehicles. <www.afdc.energy.gov/vehicles/electric_batteries.html>. (Accessed on 30 September 2014.)

Table 1. Type and Weight of Battery Used in Hybrid Vehicles (HEVs)

Model	Battery Type	Battery Weight	Percentage of US HEV Market[a]
Toyota Prius Liftback Hybrid	1.3 kWh nickel metal hydride battery pack	42 kg (92 lbs)[b]	29.3%
Toyota Camry Hybrid	1.6 kWh nickel metal hydride battery pack	56 kg (124 lbs)[c]	9.0%
Toyota Prius c Hybrid	0.9 kWh nickel metal hydride battery pack	31 kg (68 lbs)[d]	8.5%
Ford Fusion Hybrid	1.4 kWh lithium-ion battery pack[e]	48 kg (106 lbs)[f]	7.5%
Toyota Prius v	1.3 kWh nickel metal hydride battery pack	41 kg (90 lbs)[g]	7.1%
Ford C-Max Hybrid	1.4 kWh lithium-ion battery pack[h]	No data	5.7%
Hyundai Sonata Hybrid	1.4 kWh lithium-polymer battery pack	44 kg (96 lbs)[i]	4.4%
Lexus ES Hybrid/300h	1.6 kWh nickel metal hydride battery pack	46 kg (103 lbs)[j]	3.3%
Toyota Avalon Hybrid	1.6 kWh nickel metal hydride battery pack	68 kg (150 lbs)[k]	3.3%
Lexus CT200h Hybrid	1.3 kWh nickel metal hydride battery pack	41 kg (90 lbs)[l]	3.0%

Note: kWh = kilowatt-hour; kg = kilogram(s); lbs = pound(s).

Sources:

a. See later text in this section for details.
b. SAE International. 2012. NAIAS 2012: Toyota shows smaller, lighter Prius and plug-in concept targeted for 2015. <http://articles.sae.org/10558/>. (Accessed on 23 April 2014.)
c. Grayson Hyundai. N.d. Hyundai Sonata Hybrid. <www.graysonhyundai.com/sonata-hybrid.htm>. (Accessed 23 April 2014.)
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g. Toyota Motor Corporation. 2011. Toyota Prius V gasoline-electric hybrid synergy drive: Hybrid vehicle dismantling manual. <https://techinfo.toyota.com/techInfoPortal/staticcontent/en/techinfo/html/prelogin/docs/priusvdisman.pdf> (Accessed on 23 April 2014.)
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i. Austin, M. 2010. 2011 Hyundai Sonata Hybrid. *Car and Driver.* <www.caranddriver.com/reviews/2011-hyundai-sonata-hybrid-prototype-drive-review>. (Accessed on 23 April 2014.)
j. Toyota Motor Corporation. 2012. Lexus ES300h Hybrid 2013 Model: Emergency response guide. <http://afvsafetytraining.com/erg/Lexus-ES300-2013.pdf>. (Accessed on 23 April 2014.)
k. Raia, J. 2012. 2013 Toyota Avalon Hybrid: Redesign adds further appeal to surprising sedan. *The Weekly Driver*. <http://theweeklydriver.com/2013-toyota-avalon-hybrid-redesign-adds-further-appeal-surprising-sedan/>. (Accessed on 23 April 2014.)
l. Toyota Motor Corporation. 2010. Lexus CT200h Hybrid 2011 Model: Emergency response guide. <http://afvsafetytraining.com/erg/Lexus-CT200h-2011.pdf>. (Accessed on 23 April 2014.)

1.2.2 Batteries Used in Plug-in Hybrid (PHEV) and Electric (EV) Vehicles

Table 2 presents available information on the type and weight of batteries used in PHEVs and EVs. Both of these vehicle types need lithium-based batteries because of power and energy requirements. Batteries for PHEVs and EVs are considerably heavier than those for HEVs, weighing anywhere from 150 kilogram s (kg) to 450 kg per unit.

Information on unit sales of each type of PHEV and EV was not available; therefore, the market share of each vehicle model could not be identified.

Table 2. Type and Weight of Battery Used in Plug-in Hybrid (PHEV) and Electric Vehicles (EV)

Model	Vehicle Type	Battery Type	Battery Weight
Toyota Prius PHEV	Plug-in hybrid	4.4 kWh lithium-ion battery	150 kg (330 lbs)
Fisker Karma	Plug-in hybrid	20 kWh lithium-ion battery pack with nanophosphate technology	273 kg (600 lbs)
Ford Fusion Energi	Plug-in hybrid	7.6 kWh lithium-ion battery	No data
Chevrolet Volt	Electric	16 kWh lithium-ion battery pack comprising more than 200 lithium-ion cells	182kg (400 lbs)
Nissan Leaf	Electric	24 kWh lithium-ion battery comprising 48 lithium-ion modules	294 kg (647 lbs)
Mitsubishi i-MiEV	Electric	16 kWh lithium-ion battery comprising 88 cells	150 kg (329 lbs)
Tesla Model S	Electric	3 battery options; 40 kWh, 60 kWh, or 85 kWh lithium-ion battery	85 kWh battery weighs 600 kg (1,323 lbs)
Ford Focus Electric	Electric	23 kWh liquid-cooled, lithium-ion battery	No data
Smart electric drive	Electric	17.6 kWh lithium-ion battery	182 kg (400 lbs)
Tesla Roadster	Electric	56 kWh lithium-ion battery pack comprising 6,831 lithium-ion cells	450 kg (990 lbs)
Toyota RAV4 EV	Electric	41.8 kWh lithium-ion battery comprising 4,500 cells	423 kg (845 lbs)

Note: kWh = kilowatt-hour; kg = kilogram(s); lbs = pound(s).

1.3 Design and Composition of EDV Batteries

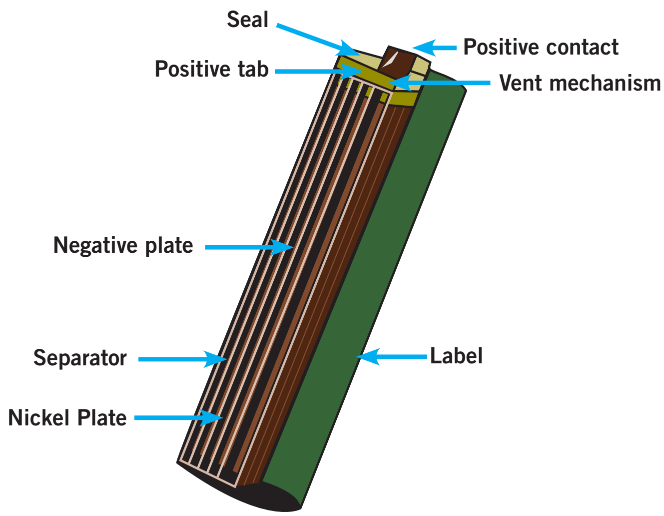
The recycling of EDV batteries (discussed in Section 4) is driven by the composition of EDV batteries, discussed in this section.

1.3.1 Design and Composition of Nickel Metal Hydride Batteries

NiMH batteries are made up of a positive electrode, a negative electrode, an electrolyte and a separator. In a NiMH battery, the positive electrode is typically composed of nickel hydroxide, hence the name. The negative electrode is typically made of a metal hydride material, or hydrogen-absorbing alloys, but the metals used vary (for instance, alloys of palladium, zirconium, vanadium or titanium are often used). The electrolyte is an aqueous chemical solution, often potassium hydroxide, which allows for ion transfer between the positive and negative electrodes. The separator is made of fine nylon fibers and is used to physically separate the positive and negative electrodes while allowing ion transfers.

Figure 1 presents a schematic of the different components of a consumer-type NiMH battery, as a schematic for a NiMH battery in an EDV could not be found.

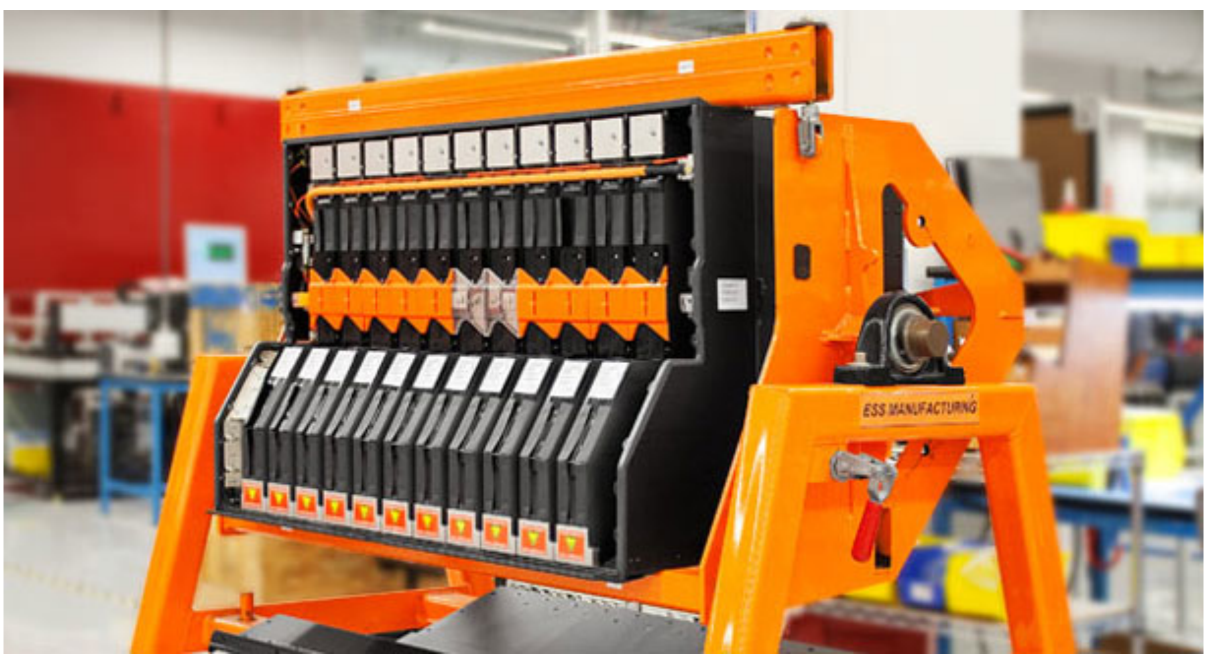
Figure 1. Components of a NiMH Battery



Source: Energizer. 2010. Nickel Metal Hydride (NiMH) *Handbook and Application Manual*. <http://data.energizer.com/PDFs/nickelmetalhydride_appman.pdf >. (Accessed 30 September 2014.)

Figure 2 shows a typical NiMH battery from a HEV.

Figure 2. Nickel Metal Hydride (NiMH) Battery from a Hybrid Electric Vehicle (HEV)



Source: Berman, B. 2010. Toyota: Nickel batteries for hybrids, lithium for electric cars. *Hybrid Cars* <www.hybridcars.com/toyota-nickel-batteries-hybrids-lithium-electric-cars-29073/>. (Accessed on 30 September 2014.)

Toyota (the dominant hybrid vehicle manufacturer today) uses NiMH batteries in its HEVs. This type of battery is also found in the Ford Escape Hybrid, Honda Insight, and Saturn VUE.[11] Toyota tested lithium-based batteries in HEVs but elected to continue to use NiMH batteries.

Table 3 presents the typical composition of a NiMH battery cell using two different types of alloys (AB2 and AB5 in the table refer to the most common alloys used).[12] In all cases, vehicle batteries are made up of a number of separate cells.

Compositions can vary widely, depending on the application:

- NiMH-AB2 batteries are those whose NiMH anodes are made up of the following group of metals: titanium (Ti), zirconium (Zr), Ni, and vanadium (V).
- NiMH-AB5 are those whose anodes are made up of "misch-metals" (metals from the lanthanide series—or rare-earth metals—from lanthanum to lutetium).

Table 3. Typical Composition of a NiMH Battery Cell

Material	NiMH Composition (using AB2 alloy)	NiMH Battery Composition (using AB5 alloy)
Ni	12%	15%
Nickel(II) hydroxide [$Ni(OH)_2$]	12%	15%
Metals: Nickel [Ni], Titanium [Ti], Vanadium [V], Zirconium [Zr]	13%	
Metals: Lanthanum [La], Neodymium [Nd], Praseodymium [Pr], Cerium [Ce]		8%
KOH (Potassium hydroxide)	3%	3%
Polypropylene (plastic)	5%	5%
Steel	44%	44%
Other	11%	10%

Source: Ekermo, V. 2009. *Recycling opportunities for Li-ion batteries from hybrid electric vehicles.* Master of Science thesis in chemical engineering. Department of Chemical and Biological Engineering, Chalmers University of Technology. <www.yumpu.com/en/document/view/3270204/recycling-opportunities-for-li-ion-batteries-from-hybrid-electric-vehicles>. (Accessed on 30 September 2014.)

The nickel in NiMH batteries provides the most value for recyclers. Companies like Umicore (Belgium) have sophisticated systems that also recover the rare-earth metals.

1.3.2 Lithium-ion and Other Lithium-based Batteries in EDVs

The term lithium-ion (Li-ion) battery is used to describe a family of the following battery chemistries:[13]

- lithium cobalt oxide (also lithium cobalt or lithium-ion-cobalt)
- lithium manganese oxide (also lithium manganate or lithium-ion manganese)
- lithium iron phosphate
- lithium nickel manganese cobalt oxide (also lithium-manganese-cobalt-oxide)

[11] Berman, B. 2008. The hybrid car battery: A definitive guide. *Hybrid Cars.* <www.hybridcars.com/hybrid-car-battery/>. (Accessed on 21April 2014.)

[12] Mathur, A. 2012. Insight—How NiMH cell works. *Engineers Garage*. <www.engineersgarage.com/insight/how-nimh-cell-works>. (Accessed on 30 September 2014.)

[13] Battery University. N.d. BU-205: Types of lithium-ion. *Battery University*. http://batteryuniversity.com/learn/article/types_of_lithium_ion. (Accessed on 30 September 2014.)

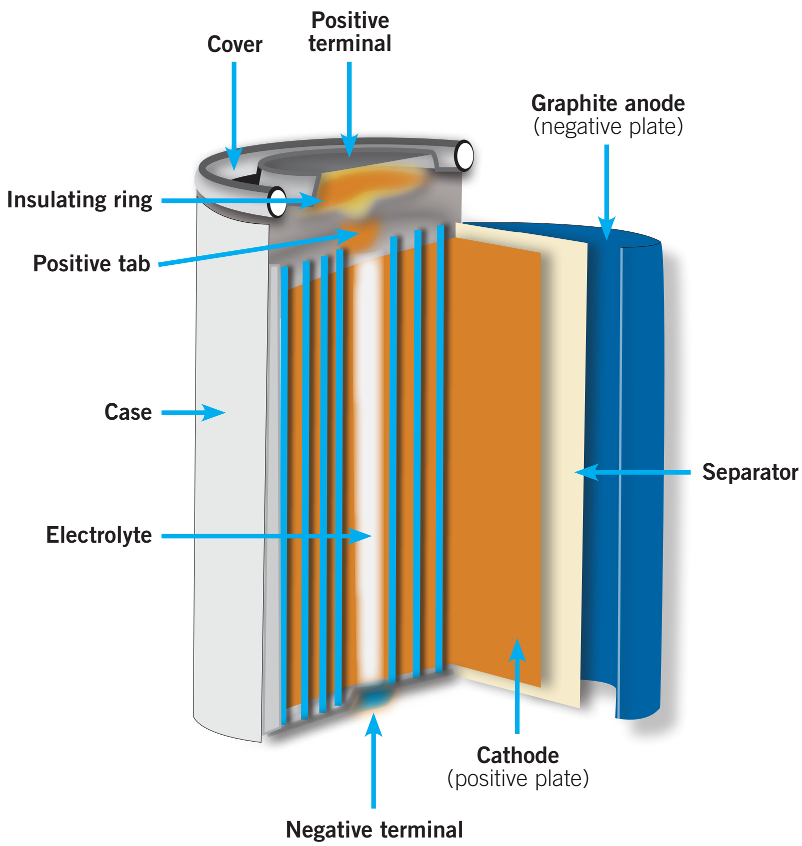
- lithium nickel cobalt aluminum oxide
- lithium titanate

The three primary functional components of a Li-ion battery are:

- the positive electrode;
- the negative electrode; and
- electrolyte.

Figure 3 presents a schematic showing the different components of the Li-ion battery.

Figure 3. Schematic of Lithium-ion Battery Components



Source: Chris Hillseth Enterprises. 2014. Lithium battery. <http://chrishillsethenterprises.com/battery/wp-content/uploads/2014/01/lithiumbattery.jpg>. (Accessed on 30 September 2014).

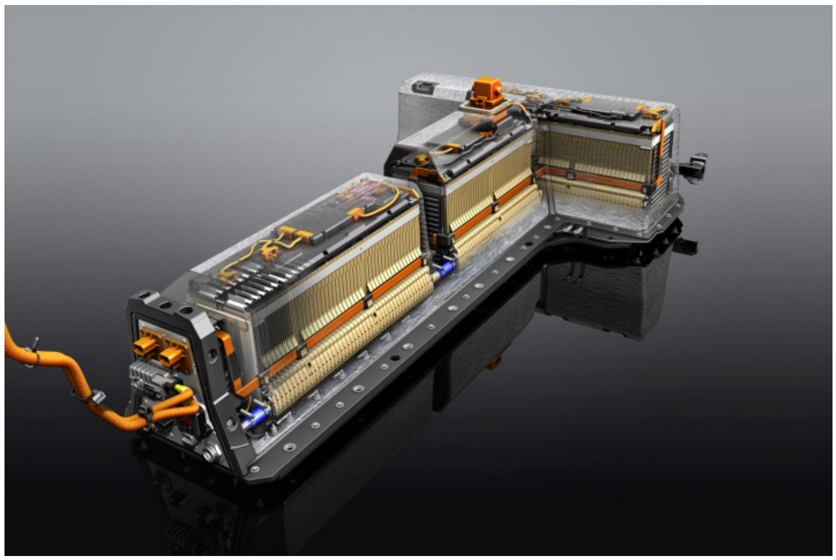
The most commercially popular negative electrode is graphite (a form of carbon). The positive electrode is a metal oxide, generally one of three materials: a layered oxide (such as lithium cobalt oxide); a polyanion (such as lithium iron phosphate); or a spinel (such as lithium manganese oxide). The electrolyte is a lithium salt in an organic solvent.

Pure lithium is highly reactive. It reacts vigorously with water to form lithium hydroxide and hydrogen gas. Thus, a non-aqueous electrolyte is typically used, and a sealed container rigidly excludes moisture from the battery pack.

The electrolyte is typically a mixture of organic carbonates such as ethylene carbonate or diethyl carbonate containing complexes of lithium ions. These non-aqueous electrolytes generally use non-coordinating anion salts such as lithium hexafluorophosphate ($LiPF_6$), lithium hexafluoroarsenate monohydrate ($LiAsF_6$), lithium perchlorate ($LiClO_4$), lithium tetrafluoroborate ($LiBF_4$) and lithium triflate ($LiCF_3SO_3$).

Figure 4 presents a Li-ion battery from a Chevrolet Volt EV.

Figure 4. Lithium-ion Battery from Chevrolet Volt Electric Vehicle (EV)



Source: O'Dell, J. 2014. What happens to EV and hybrid batteries? Going green with battery recycling. *Edmunds*. <www.edmunds.com/fuel-economy/what-happens-to-ev-and-hybrid-batteries.html>. (Accessed on 30 September 2014.)

Figure 5 shows a Li-ion battery from a Nissan Leaf. The casing holds a number of packs which each contain a number of cells. For recycling, the battery packs are generally taken out of the larger casing.

Figure 5. Lithium-ion Battery from Nissan Leaf

Source: O'Dell, J. 2014. What happens to EV and hybrid batteries? Going green with battery recycling. *Edmunds*. <www.edmunds.com/fuel-economy/what-happens-to-ev-and-hybrid-batteries.html>. (Accessed on 30 September 2014.)

Table 4 presents the relative weights of different components of typical lithium-based batteries.

Table 4. Average Composition of Lithium-ion Battery Components (%)

Lithium-ion Battery Component	Composition (% by weight)
Cathode + anode + electrolyte	39.1% ± 1.1%
Plastic case	22.9% ± 0.7%
Steel case	10.5% ± 1.1%
Copper foil	8.9% ± 0.3%
Aluminum foil	6.1% ± 0.6%
Polymer foil (cathode-anode separator) + electrolyte	5.2% ± 0.4%
Non-aqueous solvent	4.7% ± 0.2%
Electrical contacts	2.0% ± 0.5%

Source: ASEAN Environment. N.d. <www.aseanenvironment.info/Abstract/41016797.pdf>. (Accessed on 30 September 2014.)

Table 5 presents more detail on the specific materials in the cathode, anode, electrolyte, separator and case.

Table 5. Average Composition of Different Components of Lithium-ion Batteries, by Material

Lithium-ion Battery Component	Materials	Percentage (%) Composition
Cathodes	Li_2CO_3 (lithium carbonate) $LiCoO_2$ (lithium cobalt oxide) $LiMn_2O_4$ (lithium manganese oxide) $LiNiO_2$ (lithium nitrogen oxide) $LiFePO_4$ (lithium iron phosphate) $LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$ $LiNi_{0.8}Co_{0.15}A_{l0.05}O_2$	15–27
Anodes	LiC_6 (graphite) $Li_4Ti_5O_{12}$	10–18
Electrolyte	Ethylene carbonate Diethyl carbonate $LiPF_6$ (lithium hexafluorophosphate) $LiBF_4$ (lithium tetrafluoroborate) $LiClO_4$ (lithium perchlorate)	10–16
Separator	Polypropylene	3–5
Case	Steel	40

Source: Sullivan, L., and L. Gaines. 2010. *A review of battery life-cycle analysis: State of knowledge and critical needs*. Argonne National Laboratory, Energy Systems Division. <https://greet.es.anl.gov/files/batteries_lca>. (Accessed on 30 September 2014.)

Table 5 shows that some lithium-based batteries are made up of 40 percent steel and smaller amounts of other materials. The material of most interest to recyclers is the cobalt (Co), which is very valuable. However, because of the high cost of cobalt, battery designers are beginning to move to other lithium-battery chemistries which do not use cobalt. This market development is not good for incentivizing recycling of lithium batteries, as the value of the battery to the recycler is based on cobalt content.

1.3.3 New and Emerging Battery Chemistries

Research and development to reduce the cost and extend the useful life cycle of batteries is ongoing. Numerous partnerships are working on this issue, including USEPA's Design for Environment, and Office of Research and Development on Batteries and Nanotechnology for Electric Vehicles partnership; the US Department of Energy (DOE); Arizona State University; Electrovaya Inc., Energel Inc., Umicore Group, Kinsbursky Brothers Inc. (Toxco); RSR Technologies Inc., Novolyte Technologies Inc., Rochester Institute of Technology; NextEnergy; the Rechargeable Battery Association (PRBA); and the National Alliance for Advanced Technology Batteries (NAATBatt); among others.

Many different lithium-ion (Li-ion) chemistries are currently available and are being tested to improve the design and performance and lower the costs of these batteries. Li-ion battery manufacturing facilities are being established in the US with financial support from a US$2.4 billion grant program established by the Obama administration to promote electrical vehicles.

Significant research is underway to make batteries which are safer but lighter, and with extended range and lower costs. Some of these emerging battery technologies include the following:

- Carbon Nanotube Electrode Lithium—Massachusetts Institute of Technology (MIT):[14] Scientists at MIT are developing a cathode (the electrode through which electrons flow out of a battery) that can store and release many more positive ions than a conventional lithium battery, using layers of carbon nanotubes—strong microscopic hollow threads with relatively large area. The nanotubes used in a 2010 MIT demonstration are commercially available, but because of testing and development time, potentially marketable battery/capacitor electrodes are at least five years away. Combined with a typical new vehicle development timetable of five years, it could be a decade before these hybrid battery/capacitors are incorporated into a production EV.

- Copper Nanowire Cathode Lithium—Colorado State University (CSU): The copper nanowire cathode lithium battery in development at CSU would replace the porous and conductive graphite electrode with microscopically thin copper wires. This battery has delivered such an increase of energy storage capacity over current ones that it has spawned a commercial company funded in part by new US Department of Energy support of electric-vehicle research.

- Lithium-air Carbon—IBM: IBM's goal is to increase the range of a battery-powered vehicle before recharging to 500 miles (800 km). To do this, the company is developing a lithium-air battery with the potential for far more energy density than current lithium-ion batteries. IBM reports that its battery can last much longer after a charge because it uses carbon electrodes in which the ions react with oxygen, yet that oxygen does not deplete the electrolyte medium. The battery technology is not expected to be commercially available to electric vehicle makers until 2020.

- Lithium Silicon—Northwestern University: Faculty at the McCormick School of Engineering and Applied Science at Northwestern University are researching use of silicon electrodes rather than carbon electrodes, hoping to build a battery with more storage capacity and thus more range.

- Carbon Foam Capacitor Hybrid—Michigan Technological University (MTU): Scientists at MTU have been working on a power-storage device to combine the electrical-storage density of a chemical battery with the power-delivery efficiency of a solid-state capacitor. Using a carbon anode, the hybrid battery/capacitor not only weighs less than a conventional lithium battery but also delivers more of its charge than a typical capacitor. The unit can be recharged thousands of times without showing signs of degraded performance.

- Lithium Silicon Polymer—Lawrence Berkeley National Laboratory (LBNL; US Department of Energy): Scientists at LBNL in California are developing a lithium silicon polymer battery, which uses silicon electrodes and has a specially constructed polymer that maintains the structure of electrodes while they expand and contract. This allows the battery to store more energy than today's battery.

- Lithium Sulfur Carbon Nanofiber—Stanford University:[15] Scientists at Stanford University are working on increasing power density with silicon nanofibres with sulfur coating.

- Lithium Manganese Composite/Silicon Carbon Nanocomposite—Envia Systems: Envia's primary development is a proprietary cathode material based on manganese, an abundant

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[14] Berg, P. N.d. 8 potential EV and hybrid battery breakthroughs: Why wild new battery technology could soon mean EVs with a 500-mile range. *Popular Mechanics*. <www.popularmechanics.com/cars/g785/8-potential-ev-and-hybrid-battery-breakthroughs/>. (Accessed on 30 September 2014.)

[15] Pacific Northwest National Laboratory. 2014. Battery development may extend range of electric cars. *Science Daily*. <www.sciencedaily.com/releases/2014/01/140109175504.htm>. (Accessed on 30 September 2014.)

metal that is stable when used in the battery. Manganese is also less expensive than the more common cobalt-based cathode material, according to Envia. The firm has received grants from US auto companies and US and California energy agencies to continue developing the battery for commercial use; it says the battery could give a range of 300 miles (480 km) in an EV.

- Improving NiMH battery design—BASF:[16] NiMH batteries currently have an energy density of 1 kilowatt-hour (kWh). In order to be a viable replacement for lithium-ion batteries, they need an energy density of 30 to 50 kWh. BASF is looking to develop metal hydride alloys using low-cost metals to replace rare-earth metals for use in the NiMH battery, improving the NiMH-battery chemistry and making the new batteries cheaper and more efficient. But for a pure-EV battery, lithium still has the advantage over NiMH because it is considerably lighter.

Discussions with members of the battery recycling and metals industries indicate that industry players do not expect any significant designs to emerge for a number of years, and that for the short to medium term, NiMH and various lithium batteries will continue to be used.

1.4 EDV Sales in Canada, 2000 to 2013

HEV Sales in Canada

While the study research identified a number of sources of data on EDV sales in the US, very little information was available on HEV annual sales in Canada until the last 3–4 years. From 2010 on (when PHEV and EV were introduced to the Canadian market), statistics were found in various EDV-focused websites.

The total number of EDVs sold in Canada as of July 2009 was reported as approximately 60,000 out of 21.6 million registered vehicles.[17] Information on HEV sales in Canada from 2004 to 2009 was found in a document prepared by Sustainable Waterloo[18] (a not-for-profit in Waterloo Region that guides organizations towards a more environmentally sustainable future), which obtained the data from research compiled by Polk Canada (a leading automotive consulting firm) through a review of Canadian hybrid vehicle registrations. Estimates for HEV sales from 2010 to 2013 have been based on pro-rating US HEV sales data (which are well documented) to Canada, taking different market penetration rates (as a percentage of total vehicle sales) in the two countries into account.

Table 6 presents the available estimates of annual HEV sales in Canada from 2000 (when only 400 were sold—0.03 percent of total vehicle sales) to 2013 (when annual sales were estimated at over 23,000 units—1.32 percent of total vehicle sales).

PHEV and EV Sales in Canada

Information on sales of PHEV and EV sales in Canada from December 2010 (when they were

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[16] Hiler, K. 2013. What's next in electric-car-battery tech. *Popular Mechanics.* <www.popularmechanics.com/cars/alternative-fuel/electric/whats-next-in-electric-car-battery-tech-16280750>. (Accessed on 30 September 2014.)

[17] International Energy Agency (IEA). N.d. Canada: On the road and deployments. Hybrid and Electric Vehicle Implementing Agreement (IA-HEV). <www.ieahev.org/by-country/canada-on-the-road-and-deployments/>. (Accessed on 4 May 2014.)

[18] Sustainable Waterloo. 2010. *Calculating GHG emissions from personal vehicle travel.* <www.sustainablewaterlooregion.ca/files/downloads/RCIM/CalculatingGHGEmissionsfromPersonalVehicleTravel.pdf>. (Accessed on 26 June 2014.)

introduced to the Canadian market) to the end of 2013 were found on the Electric Drive Transportation Association website, which publishes monthly vehicle sales data.[19] Table 6 shows that sales were only 468 units in 2011 (the first full year that PHEVs and EVs were available on the Canadian market), increasing to 2,183 units by 2013.

Total EDV Sales in Canada

Estimated annual sales of all EDVs in Canada, and the proportion of total annual vehicle sales which EDVs represent, are presented in Table 6.

Table 6. Annual Sales and Estimated Sales of EDVs in Canada, 2000–2013

EDV Type, Percent	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
HEV	400[a]	876	1,510	2,144	2,303[b]	5,124	8,924	14,832	19,693	17,638	15,255[c]	11,671	20,894	23,033
PHEV/EV	0	0	0	0	0	0	0	0	0	0	0	468	1,974	2,183
Total EDV	400	876	1,510	2,144	2,303	5,124	8,924	14,832	19,693	17,638	15,255	12,139	22,868	25,216
Total Vehicle Sales	1,545,378	1,570,633	1,703,511	1,593,469	1,534,500	1,583,599	1,615,056	1,653,771	1,640,020	1,461,639	1,558,487	1,587,429	1,677,990	1,745,188
% Hybrids	0.03%	0.06%	0.09%	0.13%	0.15%	0.32%	0.55%	0.90%	1.20%	1.21%	0.98%	0.74%	1.25%	1.32%
% PHEV/ EV								0.00%	0.00%	0.00%	0.00%	0.03%	0.12%	0.13%
% EDV								0.90%	1.20%	1.21%	0.98%	0.76%	1.36%	1.44%

Notes: PHEV and EV sales: Electric Drive Transportation Association. <http://electricdrive.org/>. (Accessed on September 2014.)

Sources
a. Assumed to be twice the reported Prius sales, which were accessible through Toyota sources. Assumed that Prius sales make up the majority of the total hybrid vehicle sales in the early years of the market development. This leads to a conservatively low estimate of total hybrid vehicle sales.
b. Hybrid sales for 2004 to 2009 from: Sustainable Waterloo. Calculating GHG emissions from personal vehicle travel. Appendix 4, page 18. [ed: no longer available.]
c. Sales 2010 to 2013 pro-rated to US reported sales (<www.hybridcar.com> and other sources), pro-rated to lower penetration levels in Canadian market.
d. Good Car Bad Car. 2012. Overall Canada auto industry sales figures—Monthly and yearly. <www.goodcarbadcar.net/2012/10/canada-overall-auto-industry-sales-figures.html?m=1>. (Accessed on 4 May 2015.)

1.5 EDV Sales in Mexico, 2000 to 2013

Information provided to the study team by the Mexican Automobile Dealers Association (*Asociación Mexicana de Distribuidores de Autos*—AMDA)[20] on annual unit sales of EDVs in Mexico since 2006, total vehicle unit sales, and HEV unit sales in Mexico as a percentage of total unit sales are presented in Table 7.

[19] Electric Drive Transportation Association. <http://electricdrive.org/>. (Accessed on 30 September 2014.)
[20] Camarena Ramos, Miguel Ángel. Personal communication with the author, 21 March 2014.

Table 7. Annual Sales of EDVs (units) in Mexico, 2006–2013

	2006	2007	2008	2009	2010	2011	2012	2013
Honda Civic Ima	484	465	445	272	246	263	95	166
Honda CR-Z	-	-	-	-	-	-	-	498
Honda Prius	-	-	-	-	168	247	93	213
Infiniti QX	-	-	-	-	-	27	102	120
Total Hybrid Vehicles		**465**	**445**	**272**	**414**	**537**	**290**	**997**
Total Vehicle Sales		1,099,866	1,025,520	754,918	820,406	905,886	987,747	1,063,363
Hybrids, as a % of Total Vehicle Sales		0.04%	0.04%	0.04%	0.05%	0.06%	0.04%	0.09%
Electric Nissan Leaf		-	-	-	-	3	88	12

Source: Ramos, C., and M. Ángel. *Asociación Mexicana de Distribuidores de Autos* (AMDA). Personal communication with the authors, 21 March 2014.

HEV Unit Sales in Mexico

HEVs were introduced to the Mexican market in 2006, and PHEVs and EVs were introduced in 2011. The table shows that the Honda Civic IMA was the only HEV offered on the market in Mexico from 2006 to 2010. The peak year for Honda Civic IMA sales was 2006, with 484 units sold, while in 2012, sales went down to 95 units. Honda sold 2,436 units of this model between 2006 and 2013. The Honda CR-Z model entered the Mexican market in 2013, with sales of 498 units in 2013. Compared to other North American countries where Toyota has the predominant market position for HEVs, to date Honda has had a predominant place in the Mexican HEV market, with almost 3,000 HEVs sold between 2010 and 2013.

Compared to all vehicle sales in Mexico (about 1 million vehicles per year, presented in Table 7), sales of HEVs made up a very modest percentage of the total for 2006 to 2012. However, HEV sales increased in 2013, so that HEVs accounted for 0.09 percent of Mexican national vehicle sales in 2013.

A number of companies are exploring the introduction (through export and local production) of EDVs into the Mexican market in the short and medium terms. Some initiatives include:

- GM[21] started a pilot project in 2013, with 50 imported Volts, which were distributed to GM and General Electric staff members.
- Via Motors[22] announced in March 2013 the future production of large HEV models such as the Suburban, vans, and pick-ups like the Cheyenne and Silverado. The new plant in San Luis Potosí will convert these conventional GM vehicles produced in Silao, Mexico, into HEVs. An estimated 7,000 units will be produced in 2014 and 10,000 units in 2015.
- Ford announced in 2009[23] the introduction of a hybrid version of the 2010 Fusion model produced in its plant at Hermosillo, Sonora, Mexico. However no data related to sold and produced units was found during the study research.

[21] Salado, D. 2013. Autos eléctricos: ¿son sustentables? *El Economista.* <http://eleconomista.com.mx/industrias/2013/09/02/autos-electricos-son-sustentables>. (Accessed on 30 September 2014.)

[22] Autos México. 2013. Via Motors inaugura planta de autos hibridos en Mexico. *Autos México*. <http://autosmexico.mx/mundo-verde/via-motors-inaugura-planta-de-autos-hibridos-en-mexico>. (Accessed on 21 April 2015.)

[23] Mayer, E.H. 2009. Fusión híbrido rompe récord. *El Universal.* <www.eluniversal.com.mx/articulos/53870.html>. (Accessed on 21 April 2015.)

- Infinity (Nissan) announced on its Mexican website[24] the availability in 2014 of its new and second hybrid model, the Q50. Nissan introduced its first HEV model, the Infiniti QX, into the Mexican market in 2011(see Table 2). To date, information related to units of the Q50 model is not available.

Information related to other HEVs such as the Porsche Cayenne, Porsche Panamera and Nissan Pathfinder, which could possibly be available on the Mexican market, was not found during the study research.

PHEVs and EVs in Mexico
In October 2009, Nissan reportedly reached an agreement with the local government of Mexico City, through which 500 units of the Leaf would be delivered by 2011 for use of government and corporate fleets. In exchange, recharging infrastructure was to be deployed by the city government, and an exemption from the ownership tax was being pursued. The city government of Mexico DF also reached an agreement with Nissan in November 2010 for the first 100 Leafs in the country to join the capital's taxi fleet. The first Leafs destined for the taxi fleet were delivered by late September 2011, allowing the country to become the first Latin American market where the Leaf is available.

By February 2013, there were about 70 Leafs deployed as taxis—50 in Aguascalientes[25] and 20 in Mexico City. The Aguascalientes program began in May 2012, and its implementation included the deployment of a garage with 58 charging points, the largest of its kind in the world. Carrot Mexico, a car-sharing company operating in Mexico City, acquired 3 Leafs, which are available to its 1,600 customers.

Two other companies have been exploring the introduction of HEVs, PHEVs and EVs into the Mexican market in the short and medium terms:

- BMW Mini E,[26] which uses a Li-ion battery, initiated a pilot project with 12 units in 2013.
- MIA Electric México[27] (a French company) is planning to build a plant in Mexico to produce four models with a lithium ferrous phosphate battery.

The market in Mexico for electric vehicles is likely to grow more slowly than the HEV market, because EVs generally have a price premium of about US$10,000.

1.6 EDV Sales in the US, 2000 to 2013

A significant amount of information was available on unit sales of HEVs, PHEVs and EVs for the US for the years 2000 to 2013. These data are presented separately in this section for the three categories of EDV.

HEV Sales in the US
Annual HEV sales data for the US from 2000 to 2013 were compiled from two sources:

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[24] Infinity. N.d. Infinity Q50. <www.infiniti.mx/Q50/modelos>. (Accessed on 21 April 2015.)

[25] Nissan Newsroom. 2013. Growing the grid: EV taxis drive infrastructure transformation in Mexico, Latin America. 2 May 2013. Video clip. You Tube. <http://nissannews.com/en-US/nissan/usa/releases/video-report-growing-the-grid-ev-taxis-drive-infrastructure-transformation-in-mexico-latin-america>. (Accessed on 21 April 2015.)

[26] Smilovitz, E. 2012. México venderá su primer coche 100% eléctrico en 2013. *Altonivel.* <www.altonivel.com.mx/22410-mexico-vendera-su-primer-coche-electrico-en-2013.html>. (Accessed on 21 April 2015.)

[27] MIA Electric México. 2015. <www.mia-electric.mx/>. (Accessed on 21 April 2015.)

- Sales data for 2011, 2012 and 2013 were compiled, by vehicle model, from HybridCars.com and were consolidated into total values.
- All other vehicle sales values were obtained from the Alternative Fuels and Advanced Vehicle Data Center (US Department of Energy).

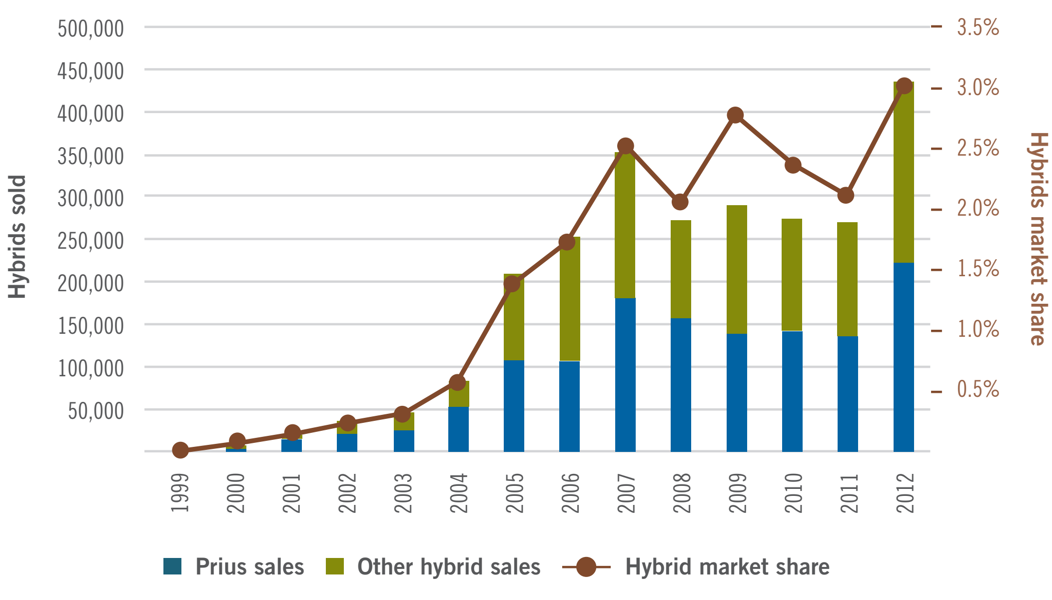
The information is presented in Table 8, along with unit sales data for PHEVs and EVs from 2010 to 2013.

It is estimated that a total of 3.1 million HEVs (including over 1.5 million Toyota Prius models) have been purchased in the US since 1999, out of 212 million vehicles sold in the US during that period. HEVs could therefore account for potentially 1.45 percent of all vehicle stock in the US.

The data presented in Table 8 show that almost 500,000 HEVs were purchased in the US in 2013, representing 3.2 percent of the 15.3 million vehicles purchased that year. This proportion has increased significantly from a value of 1.4 percent of US vehicle sales in 2005.

Figure 6 shows annual HEV sales in the US from 1999 to 2012, and the percentage of the total vehicle sales which HEVs represented, as well as the proportion of HEV sales which were Toyota Prius models each year. The figure shows the rapid increase in HEV sales from 2005 on. Despite the effects of the 2008 recession in the US, during which absolute numbers of hybrid and traditional vehicle sales fell dramatically, HVs more than held market share, increasing from 1.5 percent of US annual vehicle sales in 2005, to 2013, when HEVs represented over 3 percent of US vehicle sales.

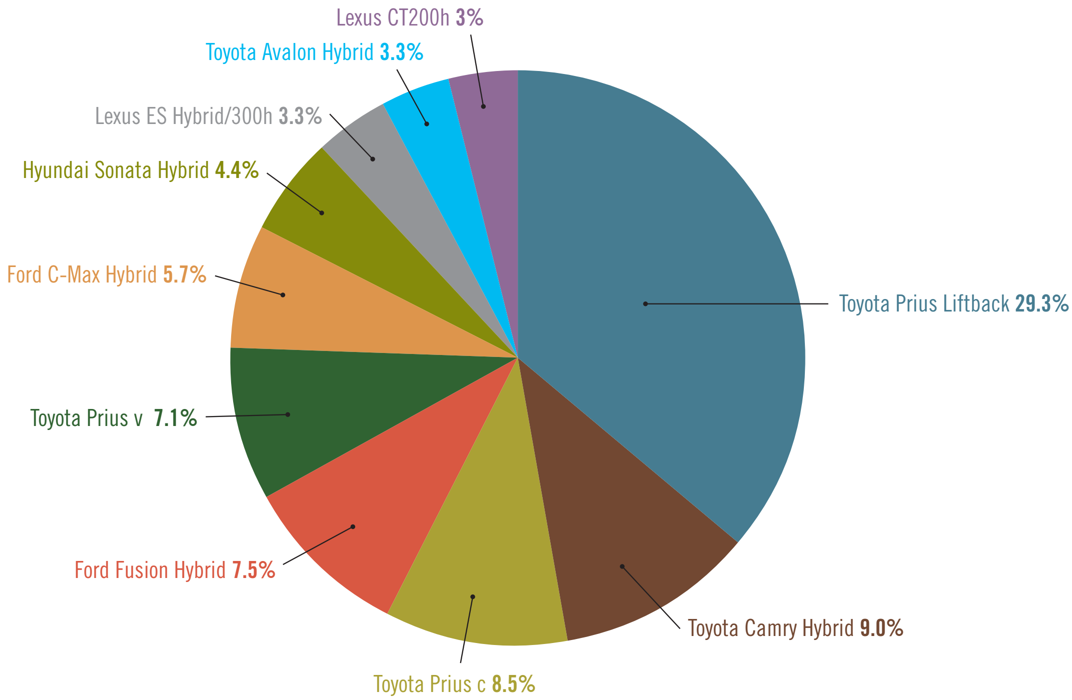
Figure 6. US Hybrid Vehicle Sales, Prius Sales, and Hybrid Market Share, 1999–2012



Source: Hybrid Cars. DOE Alternative Fuels Data Center. *Hybrid cars*. <www.hybridcars.com>. (Accessed on 21 April 2014.)

Figure 7 shows the market share of different HEV brands in the US in 2013. The figure shows that Toyota has a dominant market share, at over 60 percent of the HEV market in the US with a number of different vehicles (the Prius is the most popular, followed by HEV versions of the Toyota Camry and Avalon, and two Lexus HEVs). Ford models account for over 13 percent of HEVs sold in the US in 2013.

Figure 7. Market Share of Ten Top-selling HEV Brands in the US, 2013



Source: Duran Ortiz, M.R. 2013. U.S. top selling HEVs by market share. <http://en.wikipedia.org/wiki/Hybrid_electric_vehicles_in_the_United_States#mediaviewer/File:U.S_top_selling_HEVs_by_market_share.png>. (Accessed on 30 September 2014.)

Sales of PHEVs and EVs in the US

Table 8 presents sales data for PHEVs and EVs in the US from 2010 to 2013. Sales of these vehicles have increased dramatically since they were first introduced to the US market in December 2010. There has been rapid adoption of plug-in electric technology, with almost 100,000 units sold in 2013. PHEVs and EVs use Li-ion batteries because of the requirement for different charging and power characteristics. Figure 8 shows the cumulative sales of all PHEVs and EVs in the US from December 2010 to October 2013.[28]

Total EDV Sales in the US

Table 8 and Figures 5 and 7 show that the number of EDVs currently in the US market is very modest, but that the numbers are growing at a rapid pace. In 2013, HEVs accounted for 3.2 percent of all US vehicle unit sales, and PHEVs and EVs together accounted for 0.6 percent of US vehicle unit sales, for a total of 3.8 percent of the US market for all EDVs.

[28] Electric Drive Transportation Association. N.d. Electric drive sales dashboard. <http://electricdrive.org/index.php?ht=d%2Fsp%2Fi%2F20952%2Fpid%2F20952>. (Accessed on 21 April 2015.)

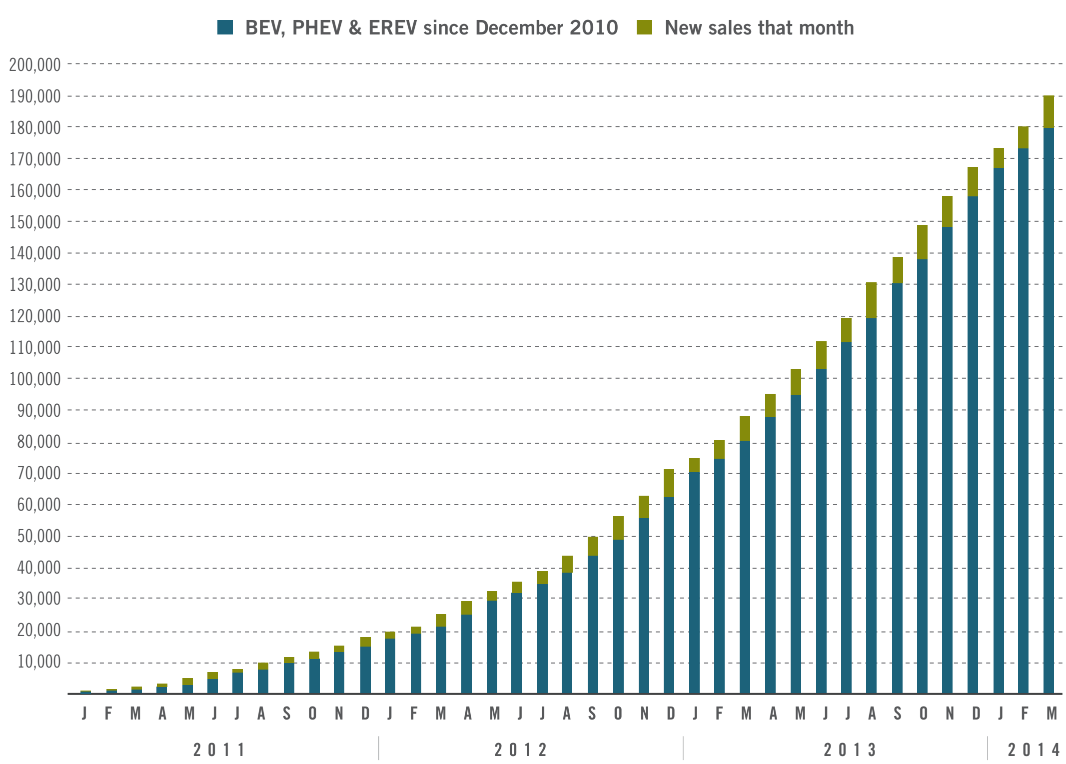
Table 8. EDV Sales in the US, 2000–2013

Vehicles	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
HEVs	9,350	20,282	36,035	47,600	84,199	209,711	252,636	352,274	313,673	290,292	274,210	226,329	434,645	495,530
PHEVs & EVs								0	0	0	345	17,735	52,835	96,902
Total EDVs								352,274	313,673	290,292	274,555	244,064	487,480	592,432
Total Vehicle Sales (TVS)								11,777,314	13,260,747	10,429,014	11,588,783	12,734,356	14,439,684	15,531,609
% HEVs of TVS								3.0%	2.4%	2.8%	2.4%	1.8%	3.0%	3.2%
% PHEVs & EV of TVS								0.00%	0.00%	0.00%	0.00%	0.14%	0.37%	0.62%
% EDVs of TVS								2.99%	2.37%	2.78%	2.37%	1.92%	3.38%	3.81%

Note: HEV = hybrid electric vehicle; PHEV = plug-in electric vehicle; EV = (all-)electric vehicle.

Source: Electric Drive Transportation Association. N.d. Electric drive sales dashboard. <http://electricdrive.org/index.php?ht=d%2Fsp%2Fi%2F20952%2Fpid%2F20952>. (Accessed on 21 April 2015.)

Figure 8. Total Monthly EDV Sales in the US, 2011–2013, and Projections for 2014



Note: BEV = battery-electric vehicle; PHEV = plug-in hybrid electric vehicle; EREV = extended-range electric vehicle. (BEVs use only rechargeable batteries to power their electric motors, e.g., Nissan Leaf or Tesla S; EREVs have a built-in range extender unit, e.g., Chevrolet Volt.)

Source: Electric Drive Transportation Association. N.d. Electric drive sales dashboard. <http://electricdrive.org/index.php?ht=d%2Fsp%2Fi%2F20952%2Fpid%2F20952>. (Accessed on 21 April 2015.)

1.7 Projections of Future EDV Battery Sales in North America

Projections of EDV battery unit sales are based on sales of EDVs, which include a new battery when sold, and sales of replacement batteries when the original EDV battery is at EOL. These projections are described in this section.

A number of factors will affect the growth of EDVs in North America. These include the following, in no particular order:

- **Demographic trends:** Overall vehicle miles traveled are expected to decline in the US due to the aging of the driving population from 2018 to 2040 (and decreasing rates of licensing and travel among younger age groups) combined with employment and income factors. This is the reason for an expected increase of only 30 percent in vehicle miles traveled, from 2012 to 2040, according to the US Energy Information Administration's *Annual Energy Outlook 2014*, as compared with an expectation of a growth of 41 percent in the 2013 projections.[29]
- **Natural gas prices:** These will affect electricity costs, which in turn will have impact on the cost of operating a plug-in EDV.
- **Oil prices:** These will affect the cost of operating a gasoline-powered light-duty vehicle.
- **CO_2 policy:** This will determine costs of CO_2 emissions, if it addresses the transportation sector.
- **Renewable Portfolio Standards (RPSs):** If RPSs are adopted at regional or national levels, they will affect the cost of electricity, and may mandate "green purchasing" of EDVs.
- **Battery cost and technological development:** The pace and scale of battery innovation will help determine the cost-effectiveness of EDVs relative to other light-duty vehicle options, as technological innovations are likely to improve EDV battery weight, energy intensity, and overall efficiency.[30] The costs of batteries have come down significantly since the early days of HEV development, when the cost increment to purchase a HEV was up to US$10,000. This increment has now come down to a reported range of US$1,500 to US$3,000.[31]

While EDVs are already readily available in Canada and the US, the options are limited in Mexico as of 2013.

Two sources of projections for the growth of the EDV market share (US Energy Information Administration [EIA] and researchers at the University of Minnesota and at North Carolina State University) were reviewed to develop projections presented later in this section.

- The United States' Energy Information Administration's Annual Energy Outlook (AEO) 2014 Early Release Overview results available as of 15 April 2014 assume that total US vehicle stock will grow from 129 million vehicles in 2011 to 159 million vehicles by 2040.[32] HEVs are included in the ICE (internal combustion engine) projections. PHEVs and EVCs are not projected to gain a significant share of the light-duty vehicle market over the period

[29] US Energy Information Administration. 2014. *Annual energy outlook 2014 with projections to 2040.* <www.eia.gov/forecasts/AEO/pdf/0383%282014%29.pdf>. (Accessed on 14 April 2015.)
[30] Babaee, S., A.S. Nagpure, and J.D. DeCarolis. 2014. How much do electric drive vehicles matter to future US emissions? *Environmental Science and Technology* 48(3):1382–1390. <www4.ncsu.edu/~jfdecaro/papers/Babaee_etal_2014.pdf>. (Accessed on 23 April 2014.)
[31] Brooks, David. 2014. Personal communication with the author, April 2014.
[32] US Energy Information Administration. 2013. *Annual energy outlook 2014: Early release reference case*. <http://energypolicy.columbia.edu/sites/default/files/energy/AEO2014%20Early%20Release%20Presentation__CGEP(12-18-13).pdf>. (Accessed on 17 April 2014.)

from 2012 to 2040, but alternative fuel vehicles in general are expected to grow from a current base of 4 million to 9 million units by 2040.

- HEVs are expected to increase to five percent of new vehicle sales by 2040, up from three percent in 2012.
- PHEVs and EVs are expected to each account for one percent of all new light-duty vehicle sales in 2040, up from “negligible amounts” in 2012—for a total 2040 market share of seven percent.[33]
- The EIA bases these projections on sophisticated models, starting with current sales data, and on modeling expected sales, using expected fuel prices, updated manufacturer product offerings, changing technological attributes, and consumer perception data. However, recent sales data obtained during the research for this study already show rapid sales growth for PHEVs and EVs since their introduction to the US market in December 2010. For this reason, some of the EIA data but not [certain] other components [of their research] were used for our projections. We used the projected 30 million unit increase in the US auto stock to assume that sales would grow by about 1 million units per year from 2014 to 2040, and pro-rated these values to Canada and Mexico for the projections presented later in this section.
- Academic research from the University of Minnesota and North Carolina State University looked at a total of 108 different scenarios driven by five key variables (natural gas prices, oil prices, CO_2 policy, RPS adoption, and battery costs) that would influence the quantity of EDVs sold as a percent of the light-duty vehicle market. The study concludes that by 2050, the total EDV market share could be between 0 and 42 percent of all light-duty vehicles (LDVs), with an average value of 24 percent of all LDVs.[34] This value (for 2050) was chosen to carry out projections for this study, as it provides a conservatively higher value for the likely number of EDV batteries at EOL each year. With current market penetration rates of about 3 percent in the US in 2013, and a projected rate of 24 percent by 2050, an approximate annual increase of 1.5 percent in the penetration rate for EDVs was assumed for the US.

The wide disparity between long-term market penetration estimates developed by the EIA’s AEO projections and the academic research are an indication of a market that is still very much in flux. The number of variables affecting the growth of the EDV market—and subsequent generation of EOL EDV batteries—is very high, indicating a great deal of uncertainty at this time. For this reason, it is recommended that these projections be updated periodically to take account of newer studies and more certainty regarding how the markets for all EDVs are developing in all three North American countries.

Table 9 presents estimates of EDV batteries entering the North American market each year from 2010 to 2030. The table has been developed based on the following assumptions:

- Vehicle sales projections were based on a starting base for 2014 of the average annual sales in each country from 2007 to 2013. This average took account of the economic recession in 2009/2010, which resulted in dramatically lower vehicle sales than in years before or after these years.

[33] US Energy Information Administration. 2014. *Annual energy outlook 2014 early release overview*. <www.eia.gov/forecasts/aeo/er/pdf/0383er(2014).pdf>. (Accessed on 17 April 2014.)

[34] Babaee, S., A.S. Nagpure, and J.D. DeCarolis. 2014. How much do electric drive vehicles matter to future US emissions? *Environmental Science and Technology* 48(3):1382–1390. <www4.ncsu.edu/~jfdecaro/papers/Babaee_etal_2014.pdf>. (Accessed on 23 April 2014.)

- Projections for 2015 to 2030 for each North American country were based on an average annual growth rate of two percent.
- About 80 percent of HEVs would continue to use NiMH batteries (the current value is slightly over 80 percent).
- About 20 percent of HEVs and all PHEVs and EVs would use lithium-based batteries.
- All EDVs together would represent 12 percent of all vehicles sold in each of the three North American countries (halfway to the 24 percent goal for 2050 used in one US scenario developed by University of Minnesota and North Carolina State University, discussed earlier) by 2030. This value was chosen to carry out projections for this study as it provides a conservatively higher value for the likely number of EDV batteries at EOL each year.
- Increases in EDV unit sales to reach these goals in each country were assumed to be linear (but adjusted in the early years to be realistic).
- The numbers of HEVs and PHEV/EVs in the market would be equal by 2030 in each of the three North American countries, assuming that the infrastructure for EVs will grow.
- Twenty percent of EDVs would replace a battery 8, 9 or 10 years after the original battery purchased with the new vehicle had been through sufficient cycles to deplete it for use as a vehicle battery.

Table and Figure 9 show the substantial increase in the number of NiMH and Li-ion batteries projected to be sold for use in EDVs between 2010 and 2030 in all three North American countries, with most of the sales being in the US for the foreseeable future. The table shows that over 630,000 EDV batteries were sold in North America in 2013. Of these, about 430,000 units were NiMH batteries and over 200,000 units were Li-ion batteries.

Table 9. Past and Projected Sales of Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion) Batteries for Use in Electric-drive Vehicles (EDVs) in Canada, Mexico and the US, 2000–2030

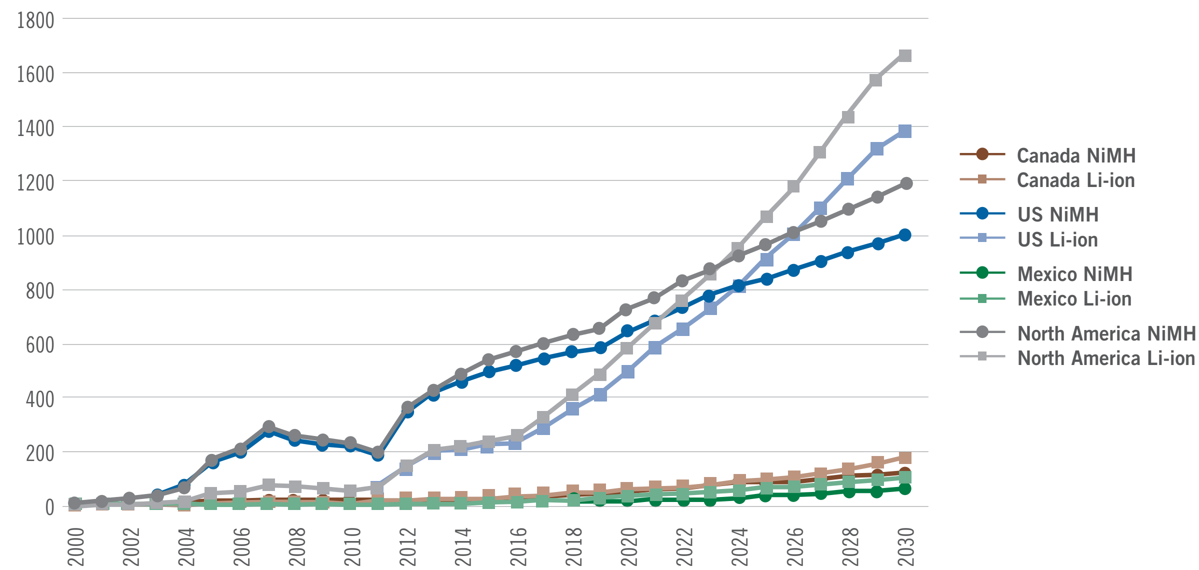
Year	EDV Batteries Sold Canada (thousands of units)		EDV Batteries Sold Mexico (thousands of units)		EDV Batteries Sold in the US (thousands of units)		Total EDV Batteries Sold in North America (thousands of units)	
	NiMH	Lithium	NiMH	Lithium	NiMH	Lithium	NiMH	Lithium
2000	0	0	0	0	7	2	8	2
2001	1	0	0	0	16	4	17	4
2002	1	0	0	0	29	7	30	8
2003	2	0	0	0	38	10	40	10
2004	2	0	0	0	67	17	69	17
2005	4	1	0	0	168	42	172	43
2006	7	2	0	0	202	51	209	52
2007	12	3	0	0	282	70	294	73
2008	16	4	0	0	251	63	267	67
2009	14	4	0	0	234	58	248	62
2010	12	3	0	0	223	55	235	58
2011	10	3	0	0	187	63	197	66
2012	17	6	0	0	355	140	373	146
2013	19	7	1	0	410	196	430	203
2014	25	11	2	1	465	212	492	225
2015	31	17	3	4	507	222	542	242
2016	37	23	6	7	527	232	570	262
2017	42	29	9	12	550	288	601	329
2018	47	36	13	18	573	358	634	412
2019	52	43	17	24	592	421	661	488
2020	58	51	21	30	652	502	731	583
2021	64	59	25	36	688	582	776	677
2022	70	69	29	43	741	657	840	768
2023	76	79	33	49	774	734	883	862
2024	82	89	37	56	807	815	926	960
2025	89	101	42	63	839	909	970	1,073
2026	95	113	46	71	872	1,007	1,014	1,191
2027	101	125	51	79	905	1,110	1,057	1,314
2028	107	139	56	88	938	1,217	1,101	1,443
2029	113	156	60	95	971	1,329	1,144	1,580
2030	120	173	68	101	1,004	1,390	1,192	1,665

Source: Projections from analysis in sections 1.7 and 1.8.

These numbers will almost double by 2020, when it is projected that over 730,000 NiMH batteries and 580,000 Li-ion batteries for EDVs will be sold in North America.

These projections need to be updated periodically to account for the significant and rapid changes occurring in the EDV market, as the product options increase rapidly and North American consumers buy these vehicles in increasing numbers.

Figure 9. Past and Projected Sales of Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion) Batteries for Use in Electric-drive Vehicles (EDVs) in Canada, Mexico, and the United States, 2010–2030 (in thousands of units)



Source: Projections from analysis in sections 1.7 and 1.8.

1.8 Limitations of Analysis

An exhaustive search of Internet-based sources and available literature was carried out to identify reliable sources of sales data for EDVs in each of the three North American countries.

It was very challenging to find sources of data on total national sales of HEVs in Canada, as statistics are not yet consistently tracked in a readily accessible centralized location. It was also challenging to identify sales of HEVs in Mexico, but the numbers are reported by automobile industry associations to be minimal at this time.

Significant data were available on HEV sales for the US. Unit sales data for PHEV and EVs for Canada and the US were available through the Electric Drive Transportation Association (EDTA).[35] Unit sales data for Mexico were obtained through the automotive industry association (*Asociación Mexicana de Distribuidores de Autos*—AMDA).[36]

Projections of future EDV sales developed by different groups were reviewed, but were based on very different assumptions, depending on which organization carried out the projections. The projections in this report were developed using data from the various sources identified.

Projections are approximate and are built on a number of assumptions documented in the report. The projections should be updated periodically, when the market for EDVs has developed further.

[35] Electric Drive Transportation Association. N.d. <www.electricdrive.org>. (Accessed on 21 April 2015.)

[36] Camarena Ramos, Miguel Ángel. Personal communication with the author, 21 March 2014.

2 Projections of EDV Batteries at End of Life, in North America, to 2030

This section presents projections of the quantities of EDV batteries at end of life (EOL) in each North American country, along with the assumptions used for the estimates.

2.1 Lifespan Model Method to Develop EOL Estimates

The estimates of NiMH and lithium-based batteries from EDVs reaching end of life (EOL) from 2010 to 2030 in the three North American countries were developed using a lifespan model which takes a number of factors into account, including:

- unit sales, by year, for NiMH and Li-ion batteries in EDVs (including batteries in new vehicles and replacement batteries);
- lifespan of the NiMH and Li-ion batteries (discussed in Section 3.2 below);
- the extent to which NiMH and Li-ion batteries are re-used after their first life; and
- the length of time NiMH and Li-ion batteries are stored at end of first life before they are discarded and are thus at end of life.

The lifespan model has been used to develop EOL estimates for a range of products, including electronics, consumer batteries, lead-acid batteries, large household appliances, and fluorescent lamps. It is described in more detail in Appendix A.

2.2 Lifespan of EDV Batteries

Manufacturers of EDV vehicles provide a warranty of 8 years, as well as a warranty that varies from 100,000 to 125,000 miles. It is anticipated that battery life for future battery designs expected to be on the market by 2030 will be 9 to 15 years. A value of 10 years was used in a recent life-cycle assessment of lithium ion batteries.[37] For lifespan modeling in this study, a value of eight to ten years was used. Considerable research is currently underway on the possibility of using EOL EDV batteries as energy storage devices (for applications such as renewable energy, like wind and solar). Given the uncertainty around its adoption, this approach was not considered in the lifespan modeling for this study.

2.3 Replacement Batteries for EDVs, Refurbishing of EDV Batteries, and Second Life for EDV Batteries

Interviews carried out for this project, and the literature reviewed indicated that replacement batteries are not often purchased for EDVs unless the vehicle is kept for a long time by the original owner. The NiMH battery in all Toyota Prius hybrids (the most popular model) comes with a guarantee of 100,000 miles or 8 years. Owners have reported that the batteries actually last longer, in some cases for up to 150,000 miles before they need replacement. In general, about one to three percent of batteries need to be replaced before this time because of accidents and product failures, although the latter are reported to be very rare.

[37] Abt Associates. 2013. *Application of life cycle assessment for nanoscale technology: Lithium ion batteries for electrical vehicles*. <http://seeds4green.net/sites/default/files/LCA%20for%20Lithium-Ion%20Batteries%20for%20Electric%20Vehicles.pdf>. (Accessed on 23 April 2014.)

An assumption was made in sales projections that batteries in 20 percent of EDVs would be replaced after the first life of eight to ten years, and that in the case of the remaining 80 percent the owners would purchase a new vehicle with a new battery. The retired vehicle might be scrapped (in which case the battery would be recycled or reused). If the retired vehicle was purchased by another owner as a second-hand vehicle, a new battery would likely be required.

Refurbishing NiMH batteries is practical, as cells or packs can be examined to identify spent and useable packs, and a new battery can be made from good components of an old battery. Refurbishing of lithium-ion batteries is not considered practical as they are too dangerous to work with because of the flammable and explosive nature of lithium (particularly when it comes in contact with water).[38] For these reasons, no assumption was made regarding re-use of EDV batteries after their first life. Should these estimates be updated periodically as recommended in this report, this assumption should be revisited when the refurbishment market is more mature.

Considerable research is underway in the US by the US Department of Energy (DoE) on the possible use of EDV batteries as energy storage devices. No conclusions have been drawn on this potential application of a second life for EDV batteries, but if successful it would considerably extend the lifespan of these batteries and it would result in a delay in the requirement to recycle large numbers of these large-format batteries. While there is a significant need for energy storage (to store wind and solar energy in particular), industry experts interviewed for this project commented that electrical utilities are exploring storage options but are not “wedded to any battery in particular.” Given the uncertainty regarding this potential use of EOL EDV batteries (discussed in more detail in Section 5), it was not taken into consideration in EOL projections.

2.4 Projections of EDV Batteries at End of Life, to 2030

The lifespan model projections in this study used the following assumptions:

- Annual unit sales presented in Section 2 were used as the baseline on which projections of EOL batteries were developed.
- HEVs would continue to use both NiMH and Li-ion batteries (80 percent NiMH and 20 percent Li-ion).
- PHEVs and EVs would use Li-ion batteries.
- All EDV batteries have a lifespan of eight to ten years (equally distributed, in the lifespan model).
- Replacement batteries would be purchased for 20 percent of EDVs after the initial lifespan of eight to ten years was complete.
- Potential use of spent EDV batteries as energy storage devices (discussed in Section 5) was not considered in the estimates.

Quantities of EOL batteries calculated by the lifespan model are presented in Table 10. The numbers shown are for EDV batteries at end of first life. Given the number of variables still at play in the EDV and energy storage market, it is prudent to simply look at the batteries at EOL for preliminary ESM discussions, and not consider the potential longer lifespan that energy storage would provide, until this option is clearer. It can be considered in future projections, recommended on a periodic basis.

[38] Battery recycling industry representative. Personal communication (confidential), April 2014.

Table and Figure 10 show that most EOL EDV batteries will be produced in the US for the foreseeable future, with smaller numbers in Canada and minimal numbers in Mexico. This is because HEV batteries have a lifespan of at least eight years; EDVs were only introduced to the Mexican market in 2006, and there are still only a minimal number being sold there. Numbers are also relatively low in the Canadian market, as HEV sales have been very modest to date.

Table 10. Estimated Number of Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion) Batteries from Electric-drive Vehicles (EDVs) at End of First Life, in Original Vehicle, in Canada, Mexico and the US, 2010–2030

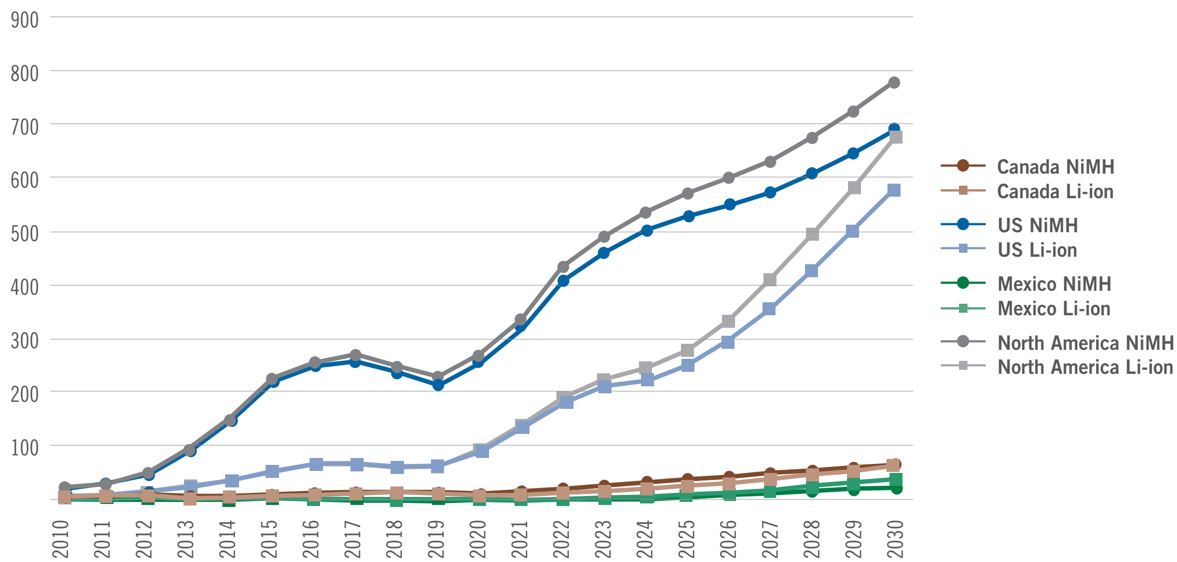
Year	EDV Batteries at EOL in Canada (thousands of units)		EDV Batteries at EOL in Mexico (thousands of units)		EDV Batteries at EOL in the US (thousands of units)		Total EDV Batteries at EOL in North America (thousands of units)	
	NiMH	Li-ion	NiMH	Li-ion	NiMH	Li-ion	NiMH	Li-ion
2010	1	0	0	0	18	2	18	2
2011	1	0	0	0	28	6	29	7
2012	2	0	0	0	45	10	46	10
2013	3	1	0	0	91	20	94	21
2014	4	1	0	0	146	33	150	34
2015	8	2	0	0	217	49	225	51
2016	12	3	0	0	245	61	257	64
2017	14	3	0	0	255	64	270	67
2018	14	4	0	0	236	59	250	62
2019	12	3	0	0	214	59	227	62
2020	13	4	0	0	255	86	268	90
2021	15	5	0	0	317	133	333	138
2022	21	8	1	1	410	183	431	191
2023	25	12	2	2	461	210	488	223
2024	31	17	4	4	500	222	535	243
2025	37	23	6	8	528	247	571	278
2026	42	29	9	13	550	293	602	334
2027	47	36	13	18	572	356	632	410
2028	52	43	17	24	606	427	675	494
2029	58	51	21	30	644	502	723	583
2030	64	60	25	36	693	580	782	676

Source: Projections from the analysis of sections 2.4 and 2.5.

PHEVs and EVs were only introduced to the North American market in December 2010, and sales only began to reach higher values in 2013, therefore it will be at least 2020 before very many of these batteries reach the end of their service lives.

NiMH batteries from early HEVs will begin to reach EOL in significant numbers by 2015, when the lifespan model predicts that 10,000 will reach EOL in Canada, a minimal number in Mexico, and 266,000 in the US. By 2020, an estimated 268,000 NiMH batteries are predicted to reach EOL in North America (about 13,000 in Canada, 600 in Mexico and 255,000 in the US). It is projected that in 2020, 90,000 Li-ion batteries from EDVs will reach EOL (4,000 in Canada, minimal numbers in the Mexico and 86,000 in the US). Therefore, for the foreseeable future, management of NiMH and Li-ion batteries from EDVs is predominantly a US issue, as the US has significant numbers of HEVs (estimated to be 2 million on the road in 2013), and growing numbers of PHEVs and EVs.

Figure 10. Estimated Number of Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion) Batteries from Electric-drive Vehicles (EDVs) at End of First Life, in Original Vehicle, in Canada, Mexico, and the United States, 2010–2030 (in thousands of units)



Source: Projections from the analysis of sections 2.4 and 2.5.

2.5 Limitations of the Analysis

The analysis of EOL EDV batteries at end of first life is built on a number of assumptions which will change as each year passes and new vehicle sales projections and technology changes arrive on the North American market.

The analysis assumes that EDVs will make up 12 percent of vehicle sales in all three North American countries by 2030. This value was chosen to be halfway to the 24 percent value projected for 2050 in the analysis completed by University of Minnesota and North Carolina State University, and provides a projection for PHEVs and EVs that is consistent with the most recent US Department of Energy (DoE) projections. It also assumes that the market for PHEVs and EVs will grow substantially and be equal to the market share of HEVs by 2030. This assumption would require development of charging infrastructure for electric vehicles in each of the three North American countries.

The analysis should therefore be updated by the Parties on a periodic basis.

3 Current EDV Battery Collection, Management, Processing Infrastructure and Legislation

Battery recycling generally involves a number of players:

- companies which collect batteries;
- companies which pre-process batteries and send them to larger, specialized processing facilities;
- specialized battery processing operations; and
- large refining and smelting operations which use batteries as one of a number of feed-stocks in their operations.

Many players are assessing the market for recycling EDV batteries and are planning for the time when the numbers of these batteries increase. A handful of companies are currently involved in EDV battery recycling. The economics and viability of the recycling businesses are based on the value of commodities found in EDV batteries. This is also discussed in this section.

3.1 Value of Materials in EDV Batteries, and Economics of EDV Battery Recycling

The market for recycling EDV batteries, like other commodities, is influenced by the value of the materials contained in the batteries (discussed in Section 2).

Values for the commodities found in EDV batteries fluctuate over time due to normal economic conditions in the commodity market. Table 11 presents a snapshot of recent pricing history for constituents from EDV batteries.

Table 11. Value of Commodities in EDV Batteries

Recovered Commodity	Current Average Price (US$/tonne)	EDV Batteries which Contain Commodities
Nickel	$19,401[a]	NiMH (80% of HEV)
Cobalt	$30,400[b]	Li-ion (but concentrations are decreasing rapidly)
Lithium carbonate	$6,000[c]	Li-ion (all PHEV and EV, 20% of HEV)
Ferrous metal scrap	$390[d]	Steel casings around EDV batteries

Sources:

a. London Metals Exchange value, 31 May 2014.
b. London Metals Exchange value, 17 June 2014.
c. Fox Davies Resource Specialists. *The Lithium Market*, September 2013.
d. Metals Exchange. Average price for 2013. <www.metalsexchange.com>. (Accessed on 27 May 2014.)

Market prices for nickel and cobalt in Mexico are available from the Mexican Geologic Service (SGM).[39] These prices are based on London Metal Exchange (LME) spot prices or non-LME prices.

[39] Servicio Geológico Mexicano (SGM). <http://portalweb.sgm.gob.mx/economia/es/precio-metales/niquel.html>. (Accessed on 30 April 2014.)

On 30 May 2014, the value of nickel, based on non-LME prices, was US$19,240/tonne,[40] while the value of cobalt was US$30,100/tonne.[41]

It is important to note that these prices correspond to those of primary or secondary refined metals, which need to be processed in specialized facilities not available in Mexico. For this reason, prices of secondary metals such as nickel scrap range from P$80 (80 pesos) to P$120 per kilogram[42] (US$6.40 /kg to US$9.60/kg, or US$6,400/tonne to US$9,600/tonne), which are lower than the values in Table 11.

Prices for ferrous metal scrap in Mexico range from P$3.40 to P$3.70 per kilogram[43] (US$0.27/kg to US$0.30/kg, or US$270/tonne to US$300/tonne), which are similar to those in Table 11.

EDV battery makers are under continuous pressure to reduce their material costs, and the costs of battery constituents such as cobalt and rare-earth metals are increasing. Use of cobalt, for example, is declining over time.

A senior EDV battery recycling executive interviewed for this study said that "the ultimate goal of EDV battery recycling will be to recover materials and return them to the manufacture of new batteries." This type of "closed-loop" recycling is the best way to retain the most amount of value embedded in an EDV battery. For example, ferrous phosphate ($FePO_4$) can be recovered from EDV battery recycling, but this material's value is in its energy characteristics when used in EDV batteries. A recycler can recover iron and phosphate separately but there is little to no value in selling those constituents by themselves. Many battery recyclers interviewed for this project expressed serious concern regarding the move to this type of EDV battery, as it has virtually no value to them. Hence, work done by interested parties on the developing and enhancing the EDV battery recovery and recycling infrastructure should emphasize closed-loop recycling recovery technologies.

3.2 EDV Battery Collection and Management Infrastructure

EDVs are relatively new to the North American auto market, and EDV batteries have long lives, so a relatively small number of them have reached the end of their useful lives to date. As a result, few EOL batteries from EDVs have yet reached the recycling market, thus limiting the extent of the current battery recycling infrastructure. As EDVs become increasingly common, the battery recycling market will likely expand. The current infrastructure consists predominantly of consolidation of EOL NiMH and Li-ion EDV batteries at dealerships with service departments which service the EDVs (which requires specialized technical skills) and the batteries. When a sufficient number of EDV batteries are consolidated at the service center, they are periodically shipped to a battery recycler. One waste management company interviewed as part of the project reported that a client had asked the waste management company to store Li-ion batteries from EDVs at the waste management company site rather than at the auto dealership site. The waste management company was reluctant to do this as they suffered a fire in a shipment of post-consumer Li-ion batteries a few years ago that was difficult to get under control, and they have since been wary of handling Li-ion batteries as a result.

[40] Servicio Geológico Mexicano (SGM). Metal Prices. <www.metalprices.com/metal/cobalt/lme-cobalt-cash-official>. (Accessed on 30 April 2014.)

[41] Servicio Geológico Mexicano (SGM). Kitco Metals. <www.kitcometals.com/charts/nickel.html>. (Accessed on 30 April 2014.)

[42] Representative prices of secondary metals can be found at: Chatarrera Metales Z.1. <http://metaleszi.com.mx/sistema/pdf/precios_compra.php>. (Accessed on 30 April 2014.)

[43] Ibid. In both cases, the US dollar was estimated equivalent to 12.50 pesos.

A few key companies in North America have the processing technology and capacity to process NiMH and Li-ion batteries from EDV vehicles. These include:

- Retriev, which has been formed by Kinsbursky Brothers and Toxco;
- Inmetco (for nickel-based batteries);
- Glencore/Xstrata (for cobalt based batteries);
- Umicore (for both lithium and nickel based batteries); and
- RMC (for nickel based batteries).

Retriev currently has the predominant market share. Umicore (based in Belgium) has established consolidation centers in the US and carries out some pre-processing of EDV batteries before shipping them to Hoboken, Belgium, for processing (see description in Section 5). Retriev reports that less than one percent of its current battery processing across two US facilities is of batteries from EDVs.[44]

The recycling of EOL NiMH and Li-ion batteries from EDVs is in its infancy, with many players currently vying for positions in the market. It is anticipated that other market entrants will appear in the next two to five years, but at the moment, industry contacts report that there are but a few market players (which all do business with each other) that have commercial arrangements to ship batteries of particular chemistries to the facility with the expertise to recycle the particular battery chemistry.

The supply chain for EOL EDV batteries is controlled by auto dismantlers and auto manufacturers, with auto repair shops and auto mechanics feeding in small amounts of product. Toyota (the dominant player in the HEV market) uses a NiMH battery in its HEVs and is working on securing the reverse supply chain on recycled batteries, to recover and re-use the metals (nickel, etc.) in the production of new EDV batteries. A full-cycle recycling program is already in place in Japan (see Section 5) and Toyota Tsusoho America is working with Retriev to establish a similar approach in North America.

EDV battery makers are in dialogue with EDV manufacturers to develop a more formal system for collecting EDV batteries—much like the take-back system established in Canada and the US for collection of mercury switches. These market players would prefer to establish a voluntary system without regulatory drivers (beyond current hazardous waste management regulations).

Generally, the battery makers are leaving management of the EDV battery collection infrastructure to the vehicle manufacturers in North America.[45] Complex issues emerge during the collection phase of spent EDV batteries regarding which party holds the liability and how risks are allocated for improper management or accidents that may occur during this phase. These issues have not yet been resolved.

Company representatives interviewed for this study have seen very few EOL EDV batteries so far, but expect the numbers to increase over time. Some of the current challenges noted regarding Li-ion batteries include:

- difficulty in identifying the battery chemistry (see Section 5, on labeling);
- uncertainty regarding how to safely dismantle them;
- lack of knowledge of how electronics work in the battery cells; and
- uncertainty regarding aftermarket values for the metals recovered, particularly as battery chemistries change (significant concerns were expressed regarding the lower cobalt concentrations in Li-ion batteries).

[44] Coy, Todd. Personal communication with the author, 11 March 2014.
[45] Confidential EDV battery manufacturer. Personal communication with author, 12 March 2014.

3.3 Auto Recyclers and Auto Dismantlers

Most EDV batteries at EOL will come through the auto dismantling or auto recycling supply chain in the three North American countries. Some come through auto mechanics, but most of these likely come through official Toyota, GM, Ford and other dealers, given the early stage of the EDV technology and the need for trained mechanics to service EDVs.

Auto recyclers and dismantlers are represented by the following associations:

- Automotive Recyclers Association (ARA), in the US, which represents 5,000 companies (2,000 direct members and 3,000 affiliated members). The total industry in the US includes 8,400 auto recycling businesses, generating about US$23 billion worth of business each year.
- Automotive Recyclers of Canada, which represents seven provincial associations and 490 companies (about 50 percent of the total market).

Generation of end-of-life vehicles (ELVs) in Mexico was estimated at approximately 837,000 units by 2012.[46]

Most ELVs are delivered to:

- small dismantling facilities, which recover valuable used parts for sale to individuals, and
- vehicle repair workshops.

In both cases dismantled parts are re-used (glass, radios, tire, batteries, etc.). According to the Mexican National Institute for Statistics and Geography (INEGI), an estimated 7,346 small and regular-size businesses[47] are involved in salvaging and selling used automobile parts.

The remaining scrap is collected by scrap dealers, which classify and shred metals and sell them to steel mills for metal recycling. In Mexico there are eight big metal recycling companies and ten authorized companies involved in crushing and compacting the ELV scrap.[48]

Two important initiatives in Mexico focus on the management of ELVs:

- The Vehicle Renovation Program is an initiative of the *Secretaría de Economía* (Secretariat of the Economy—SE), which authorized 14 certificated companies with 25 Authorized Reception Centers for ELVs. Most of these centers are focused on recycling of automobiles and large trucks;
- The Secretariat of Environment and Natural Resources (*Secretaría del Medio Ambiente y Recursos Naturales*—Semarnat) has designed and published a complete Management Plan for ELVs; however, to date no companies (dismantlers, shredders and other entities involved in the ELV activities) have committed to this plan.

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[46] Semarnat. 2012. *Plan de manejo de vehículos al final de su vida útil*. México. <www.semarnat.gob.mx/archivosanteriores/temas/residuos/vehiculos/Documents/plan-manejo-vehiculos.pdf>. (Accessed 21 April 2015.)

[47] National Institute for Statistics and Geography (Instituto Nacional de Estadistica y Geografia—INEGI). N.d. Directorio estadístico de Unidades Económicas. Comercio al por menor de partes y refacciones usadas para automóviles, camionetas y camiones. <www3.inegi.org.mx/sistemas/mapa/denue/default.aspx>. (Accessed 15 April 2014.)

[48] Semarnat. 2009. *Estudio de análisis, evaluación y definición de estrategias de solución de la corriente de residuos generada por los vehículos usados al final de su vida útil*. México. <http://web2.semarnat.gob.mx/temas/residuos/vehiculos/Documents/estudio-elv-2009.pdf>. (Accessed on 30 April 2014.)

A list of 25 selected auto recyclers identified in Mexico was compiled for the study. All of these companies were contacted as part of the project research. Of the fourteen companies interviewed, none reported receiving any EOL EDVs and batteries. This is not surprising, given how new EDVs are to the Mexican market (see Section 2).

3.4 Refurbishing of EDV Batteries

There does not appear to be a formal refurbishment or re-use business in place for EDV batteries at this time, although do-it-yourselfers and small businesses are quite likely exploring various applications. Barriers to refurbishment of EDV batteries at end of their first life, for second use include:

- sensitivity to uncertain degradation rates in second use;
- high cost of battery refurbishment and integration;
- low cost of alternative energy storage solutions;
- lack of market mechanisms and presence of regulation; and
- perception of used batteries.[49]

The possibility of using EOL EDV batteries for energy storage has been researched by many stakeholders. This potential development is discussed in more detail in Section 5.

Auto dismantlers which come across an EOL EDV battery generally try to sell the battery to auto dealers or auto repair shops.

Refurbishing EDV batteries can be dangerous, as the battery can discharge 200 volts, which is sufficient to seriously injure or kill a worker who is not trained on proper procedures. For this reason, Automotive Recyclers of America (ARA) and Automotive Recyclers of Canada (ARC) have put considerable focus on developing resources such as the *Hybrid Vehicle Dismantling Guide*[50] in an effort to protect worker safety. Underwriters Lab (UL) has published *Safety Issues for Lithium-Ion Batteries*.[51]

Significant work is underway on EOL management of EDV batteries, with a focus on worker health and safety, by groups which include the Auto Recyclers of America (ARA), US National Renewable Energy Laboratory (NREL), EPRI, the US Advanced Battery Consortium (USABC), the Fire Protection Research Foundation, the Society for Automotive Engineers, and others. While some of these groups focus on best practices and safe handling of batteries, others focus on re-purposing EDV batteries at end of first life to other energy-related uses.

Interviews carried out for this project indicated that some small operators assess spent batteries and create a new battery from the 30 percent of cells that are still good. These refurbished batteries are typically sold on eBay and other websites. EDV battery cells can have electrolytes replaced and be used in stationary applications (for energy storage).

[49] Neubauer, J., and A. Pesaran. 2010. *PHEV/EV li-ion battery second-use project* (NREL/PR-540-48018). National Renewable Energy Laboratory. <www.nrel.gov/docs/fy10osti/48018.pdf>. (Accessed on 18 March 2014.)

[50] MacDonald, E. March 2013. Hybrid vehicle dismantling—Recycling the future. Presentation to International Automobile Recycling Congress, Green Recycled Parts.

[51] Underwriters Lab. 2012. *Safety issues for lithium-ion batteries.* <www.ul.com/global/documents/newscience/whitepapers/firesafety/FS_Safety%20Issues%20for%20Lithium-Ion%20Batteries_10-12.pdf>. (Accessed on 18 March 2014.)

Below is a list of MSRP battery cost details to replace a spent battery with a new battery, for the three generations of Prius model, as well as for the Camry Hybrid sedan and the Highlander Hybrid SUV:

- 2001–2003 Toyota Prius (1st generation)—US$3,649, minus US$1,350 "core credit" (for the returned old battery);
- 2004–2008 Toyota Prius (2nd generation)—US$3,649, minus US$1,350 "core credit;"
- 2009–present Toyota Prius (3rd generation)—US$3,939 minus US$1,350 "core credit;"
- Toyota Camry Hybrid—US$3,541, core credit deducted; and
- Toyota Highlander Hybrid—US$4,848, core credit deducted.

Toyota did not specify labor rates for the Camry or Highlander, but a pack in the second-generation Prius takes 1.7 hours to replace, and a third-generation Prius battery pack requires 1.6 hours of labor to replace.[52]

In contrast to these prices, second-hand and refurbished hybrid batteries sell on eBay for prices ranging from $300 to $1,500.[53]

3.5 EDV Battery Recycling and Processing System in North America

Environmentally sound management (ESM) of EOL EDV batteries involves processing for recycling at facilities that practice ESM. As discussed elsewhere in the report, the batteries are either NiMH or Li-ion. A small number of specialized companies in Canada and the US (none could be identified in Mexico during this study) recycle these two types of batteries. The companies identified are summarized in Table 12, with more details in the next section of this document. The specialized major processors of NiMH and Li-ion large-format batteries across North America are intricately linked and use each other's resources.

The processing of NiMH and Li-ion batteries is driven by the value of nickel (in NiMH batteries) and cobalt (in Li-ion batteries). Commodity values for these products are discussed earlier in this section. Where there is not sufficient value in EDV batteries as a result of these commodities, there is a cost involved in recycling.

Pure lithium metal is not recovered from the batteries by current processes as it is not expensive and is readily available through surface mining. When lithium becomes scarcer and the price of lithium increases, it may be worth recovering the lithium from EOL lithium-based batteries.[54]

The concentration of cobalt in Li-ion batteries is decreasing (because of its very high cost) as automakers move to other lithium-battery chemistries, which contain very little valuable material at end of life. This will change the market dynamics of EDV battery recycling over time, and will result in a net cost to recycle lithium-based EDV batteries. Newer European and Asian technologies (discussed in Section 5) focus more on battery-to-battery recycling and recovery of rare-earth metals as well as nickel and cobalt.

Batteries are sometimes broken apart manually or mechanically prior to processing. Approaches by different companies are described later in this text. In general, battery processors use either hydro-

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[52] Ingram, A. 2012. Toyota hybrid battery replacement cost guide. *Green Cart Reports.* <www.greencarreports.com/news/1078138_toyota-hybrid-battery-replacement-cost-guide>. (Accessed on 7 May 2014.)

[53] eBay. Hybrid batteries search. <www.ebay.com/bhp/hybrid-battery>. (Accessed on 7 May 2014.)

[54] Umicore staff. Personal communication with the author, 5 May 2014.

metallurgical (based on water and electrical processes) or a range of pyrometallurgical (based on heat) processes:

- Hydrometallurgy refers to the aqueous processing of metals. Hydrometallurgical processing of waste batteries involves a mechanical step and a chemical step. In the mechanical phase, the batteries are shredded in order to separate the metals, paper, plastic and the black mass. The black mass is further chemically processed to produce a solution, which undergoes electrolysis, or other treatment, in order to separate out the dissolved metals.[55]
- Pyrometallurgy uses high temperatures to transform, separate and purify metals. There is no generic method for recycling batteries pyrometallurgically and each of the existing methods is unique to the company involved.[56]

Table 12 presents a list of facilities that process EOL batteries from EDVs in Canada and the US. EOL EDVs from Mexico may be consolidated and sent to these facilities for final processing, as EDV manufacturers set up reverse supply chains across North America to recapture these batteries.

Our preliminary research indicates that very few EDVs have been sold in Mexico to date; therefore, the number of batteries at EOL will be modest for the foreseeable future. It is likely that auto manufacturers (like Toyota, Honda and GM, among others) will work with auto dismantlers to consolidate loads of EDV batteries collected through the auto recycling/dismantling infrastructure to be shipped to Canada or the US for processing, likely at a Retriev facility (see Table 12). Discussions with Honda staff in Mexico indicate that to date they have received about 20 returned hybrid batteries that were not operating properly. These were shipped to the US for processing.

[55] Fisher, K., E. Wallen, P.P. Laenen, and M. Collins. 2006. *Battery waste management life cycle assessment.* <www.epbaeurope.net/090607_2006_Oct.pdf>. (Accessed on 21 April 2015.)

[56] Ibid.

Table 12. Recycling Facilities Processing End-of-life Batteries from Electric-drive Vehicles (EDVs) in Canada and the US

Company Name, Address, Contact Details, Website	Types of EDV Batteries Recycled and Processed
RMC (Raw Materials Company, Inc.) 17 Invertose Drive Port Colborne, ON, Canada L3K 5V5	NiMH from HEVs. Li-ion from all EDVs sent to Retriev, BC.
Retriev Technologies (formerly Toxco[a]) 9384 Highway 22A Trail, BC, Canada V1R 4W6 <www.retrievtech.com/batteries/electric-and-hybrid-vehicles>	Li-ion from all EDVs.
Glencore Xstrata Sudbury, ON, Canada	Any nickel- or cobalt-bearing batteries, depending on metal content. Includes NiMH from HEVs and Li-ion (which contain cobalt) from all EDVs.
Inmetco One Inmetco Drive Ellwood City, PA, USA 16117 <www.inmetco.com/services_battery.htm>	Nickel-based batteries—includes NiMH from EVs. Li-ion (from all EDVs) generally sent to other smelters (e.g., Glencore Xstrata, among others).
Metal Conversion Technologies (MCT) 1 East Porter ST, Cartersville, GA, USA 30120 678-721-0022 <www.metalconversion.com>	NiMH from HEVs and Li-ion from all EDVs. Processed into nickel remelt alloy and cobalt alloys on-site in patented high-temperature metal reclamation system.
Retriev Technologies <www.retriev.com>	Will build second Li-ion recovery facility, for Li-ion only, SE of Columbus OH. Li-ion is used in all PHEVs and EVs, and in some HEVs. Taking electronics and automotive spent batteries, which it is able to do because of electronics. Retriev has a research and development facility in Folcroft, PA.
Retriev Technologies 125 East Commercial St. A Anaheim, CA, USA 92801	West Coast consolidation point for all batteries destined for a Retriev recycling facility. Accepts NiMH and Li-ion for shipment to other facilities. Fully permitted (in name "Kinsbursky Bros"). Permitted to process lead-acid batteries (LABs) at this location.
Retriev Technologies 265 Quarry Rd SE Lancaster, OH, USA 43130	This site processes all EDV batteries, and will process consumer and industrial NiMH, lead-acid batteries, and nickel cadmium batteries. Fully permitted. Once expanded, will be future home to advanced large-format-battery recycling lines, which are being built-out using $9.5 million in matching funds awarded by the Department of Energy to promote sustainable EDV batteries.
Retriev Technologies 8090 Lancaster-Newark Rd NE Baltimore, OH 43105 USA	Large Quantity Universal Waste Handling Facility —specializes in sorting, identification, packaging and shipment of Alkaline, NiCad, NiMH, LAB, Li-ion and other less common battery types.
Umicore 17182 Airport Road Maxton, NC USA www.batteryrecycling.umicore.com	Consolidate, pre-treat and dismantle NiMH batteries for shipment to ultra-high-temperature process in Hoboken, Belgium (capacity 7,500 t/year—150,000 vehicle batteries).

Note: a. London Metals Exchange value, 31 May 2014.

Each of these companies is described in separate sections for each North American country below.

3.6 EDV Battery Recyclers in Canada

There are three specialized battery recyclers in Canada which can process NiMH and Li-ion batteries from EDVs. They are described in this section.

3.6.1 Retriev (Toxco)—Trail, British Columbia, Canada

The Retriev (formerly Toxco) facility in Trail, BC, operates a comprehensive lithium battery processing facility. Customers include the US military, and oil service companies around the globe. Directional drilling equipment used by oil companies employs lithium batteries, which Retriev processes and recycles.

The Trail BC facility has been in business for 20 years. It accepts all batteries, then sorts them and sends the chemistries that they do not process at the site to other partners. Nickel-based batteries are sent to Retriev (formerly Toxco) in Ohio.

The company started out processing lithium primary batteries only, mostly from the US military and navy. Much of their initial efforts were as a result of a contract to recycle large lithium batteries from nuclear-weapon silos in the US, where large lithium batteries were used as a fourth backup power system. The Trail facility is still focused mostly on lithium batteries—all lithium battery chemistries, which include primary (non-rechargeable) and rechargeable lithium-based batteries.

Retriev has had contracts with EDV manufacturers for a number of years, in anticipation of an increased number of lithium batteries in EDVs over time.

Retriev has developed a database for all cells, modules and packs received to date as many battery manufacturers have multiple different packs, depending on the vehicle for which the battery was designed. To date, Retriev has disassembled, analyzed, and processed over 90 distinctly different battery packs for EDVs. Some of these have been one-of-a-kind experimental designs which did not go into full production. The battery design and manufacturing companies responsible for these want to ensure that the prototypes are fully destroyed.

Hydrometallurgy is the primary process used to recycle EDV Li-ion batteries. The steps used at the Retriev facility in Trail are outlined as follows:

- Batteries are sorted and fed via conveyor into a hammermill crusher in a lithium brine–process solution, consisting of dissolved electrolytes and lithium salts.
- The process stream is then separated from the lithium-ion “fluff,” which is a mixture of plastics and some steel. If the steel content is sufficient it is sent for steel recovery; otherwise, it is disposed of. The steel content may sometimes be as high as 65 percent, depending on the feedstock.
- The process stream then passes through a shaker table to produce a copper-cobalt product: a mixture of copper (Cu), aluminum (Al) and cobalt (Co). This product is sold to primary-metal producers.
- The slurry is then added to a mix tank and /or holding tank.
- The slurry is passed through a filter press to produce a cobalt filter cake: a mixture of cobalt and carbon (C). This product is sold to primary-metal producers.
- The remaining slurry is sent to the primary process line to recover lithium in the form of lithium carbonate.

Four streams are produced:

1. Li-ion "fluff"—mix of plastics and some steel
2. Copper-cobalt product (Cu, Al, and Co)
3. Cobalt filter cake (Co and C)
4. Lithium brine slurry—dissolved electrolytes and lithium salts.

All of these materials have end markets. High-grade lithium could go back to the pharmaceutical industry but this product is not produced at the Trail, BC, facility. Interviews with industry members indicate that lithium is currently plentiful and not expensive; at current prices, therefore, it is not worth recovering in a pure form through the recycling operation. The technical-grade lithium carbonate (>99 percent purity)[57] produced at the Trail facility is generally sold to a steel manufacturer.

The estimated recycling efficiency rate throughout the process ranges from 65 to 80 percent of the incoming battery weight, depending on the batteries processed.

Retriev has 15 employees at the Trail, BC, facility.

Retriev generally receives a battery pack from a supplier or manufacturer for initial analysis. A full report is issued on the steps and time required to disassemble the pack down to the cell level. The cells are processed within the Trail, BC, system. Retriev also conducts full analysis on each cell to determine the contained metal values, which are used in the valuation process. Depending on metal content and current metal market values, it is then determined if a tipping fee must be charged or a credit given. Retriev generally charges by the pound for processing. Most lithium batteries are charged a tipping fee. Due to lower values for nickel and cobalt than in the past, a tipping fee is now charged for most Li-ion batteries, whereas in the past these batteries were sometimes processed for a credit, whereby the generator was paid for the metal value minus a processing fee.

3.6.2 Raw Materials Company, Inc.—Port Colborne, Ontario, Canada

Raw Materials Company, Inc. (RMC) is a private corporation which operates a battery recycling facility in Port Colborne, Ontario and one in Buffalo, New York (which acts as shipping and receiving facility for US customers). Loads can be consolidated into one notice-for-Environment-Canada report at the Buffalo location and then shipped across the US border to Port Colborne for processing.

Batteries are not categorized as a hazardous waste or a hazardous recyclable in Ontario or the US. The company handles NiMH and Li-ion batteries from consumers, as well as EDVs. They have seen up to 100 EDV batteries to date from a variety of sources.

NiMH batteries are processed on-site. RMC grinds the batteries and mechanically extracts nickel-bearing materials, which are sold to the coatings industry. They use an all-mechanical process that includes milling, screening, drying, and agitation. There are two processes to separate metal-containing powder from the battery. A nickel concentrate is produced on-site which is sold North America–wide to the coatings and chemical industry for resistant coatings and a variety of applications.

RMC also produces and recovers the metal and plastic components.

RMC processes Li-ion batteries on-site in a process similar to that used for NiMH batteries. A cobalt material is produced which is sold for reclamation. Lithium carbonate cobalt is a marketable material for a range of industries. This material is sent for use as a feedstock for industrial applications or for

[57] Prices are not readily available publicly, but have been in the range of $1,500 to $4,500 per tonne in the past.

the recovery of cobalt. There are many coatings manufacturers in Canada and the US which used cobalt, for its blue colour as well as its intrinsic properties. The coatings industry uses lithium as well.

RMC has significant excess capacity. The recycling facility can be operated three shifts per day, seven days per week, to process 10,000 tonnes per year (20 million pounds of total mix). Market value is paid for nickel metal hydride batteries and cobalt. Non-cobalt-containing lithium batteries are processed for a fee.

3.6.3 Glencore/Xstrata—Sudbury, Ontario

Glencore/Xstrata operates a large copper and nickel smelter in Sudbury (formerly Falconbridge), Ontario, with a capacity of 550,000 tonnes per year. The smelter has 300 employees. Glencore/Xstrata has a niche in cobalt processing. Batteries make up a very small part of the total processed at the site, but are a niche market for Glencore/Xstrata (G/X), which wants to increase it. The company's specialty is cobalt-bearing batteries. It invested C$30 million (US$32.4 million) in a rotary kiln incinerator at the Sudbury site a few years ago, to allow for the processing of a wider range of batteries.

The smelter recovers nickel, cobalt and copper. Batteries are processed in one of two ways: they are either introduced directly to a converter, or to a rotary kiln. Processing options for loads of batteries packaged in plastic are limited by the flammability of the plastic; these loads are directed to the rotary kiln, where plastics are burned off, and all off-gases are treated through the afterburner to ensure that no dioxins are released.

Steel cases, along with the cobalt produced from the recycling operation, are introduced to the converter for further processing. As the temperature in the molten metal bath is 1300 degrees Celsius (2372 degrees Fahrenheit), the battery components are broken down. Lithium is captured in the slag (and is lost), and cobalt goes to the matt phase. Cobalt matt is produced through a hydrometallurgical chlorine process. The cobalt metal output is sold into global commodity markets.

G/X has stringent safety policies for evaluating new materials. Marketing staff identify where to sell nickel and cobalt, and what strategies the company can use to get the material back to recycle. They have put pressure on large-battery designers and manufacturers to consider end of life when designing batteries and new battery chemistries.

G/X processes mostly small, portable batteries, but has researched handling large-format EDV batteries. It considers EDV batteries to present a much higher risk because of the range of chemistries involved. As an example, the lithium iron phosphate battery (manufactured by A123) is very different from other lithium-ion battery chemistries, and does not contain a lot of metals of interest to G/X. The company would not process these batteries unless there was a tipping fee.

EDV batteries are not a big proportion of what G/X processes. The company usually deals with collectors, and asks collectors to pre-treat the batteries to de-activate them, as well as break them down into small components (battery packs with 6 or 12 cells, or individual battery cells) due to the input feed size limitations of the rotary kiln. The cells or packs (when a suitable size) are introduced to the kiln/calciner for metals recovery in a pyrometallurgical process.

G/X continues to be interested in both nickel and cobalt. As an example, the battery from the standard Tesla 18620 (which is a cylindrical battery pack with high cobalt content, manufactured by Panasonic) is an example of a battery that G/X would be interested in processing.

The matt produced in Sudbury is sent to Norway for further processing.

G/X imposes a "treatment charge" for processing. It offers a significant cobalt credit back to customers sending batteries. When a load comes in, staff has a rough idea of what the cobalt content should be, but G/X pays based on an assay carried out at an on-site laboratory. Some lithium batteries used to contain 18 to 22 percent cobalt, if the plastic is taken away, but as discussed previously in this report, this number is dropping rapidly. If the processed batteries are in the original package, they have extra paper and packaging. G/X takes the weight, but the load has a lower cobalt content when the weight of paper and packaging is subtracted.

3.7 EDV Battery Recycling and Processing Infrastructure in Mexico

Mexico has one recycling facility which processes EOL batteries from EDVs, and a second company dedicated to electronic waste which has potential capacity to collect and export Li-ion batteries.

3.7.1 Sitrasa—Irapuato, Guanajuato, México

Sitrasa has an official Sermarnat permit to treat hazardous industrial waste.[58] It is the only company that recycles and treats household batteries from consumer recycling programs. The company charges a tipping fee for receiving these batteries. On its website, Sitrasa states that it also receives and processes different types of EDVs batteries and recycles the metals for different uses. The available information does not identify whether the facility has refining and smelting operations in place in Mexico.

3.7.2 TES-AMM Latin America—Cuautitlán Izcalli, México

TES-AMM collects sorts and exports electronic waste at its plant in Singapore. Sorting includes Li-ion batteries, which are exported and recycled using a patented mechanical hydrometallurgical process. TES-AMM works in a joint venture with Recupyl using an innovative process for recycling batteries and recovering valuable metals.

Another possible option in the future for recycling batteries for EDVs in Mexico is Johnson Controls International (JCI), which has two facilities in Mexico dedicated to recycling spent lead-acid batteries imported from the US. JCI has announced investments in the US, for creating quality products, services and solutions for optimizing advanced and advanced lead-acid batteries for EDVs (various chemistries).

Estimates developed during this study indicate that very few EDV batteries are likely to be produced in Mexico prior to 2022. Even then, the quantity will be small for a number of years, based on current sales projections and the long lifespan of EDV batteries. Developing infrastructure and capacity to recycle EDV batteries in Mexico could evolve in one of the following ways:

- Emergence of companies (included scrap dealers) who will collect EOL batteries temporarily for their future resale or export.
- Emergence of companies that collect batteries for pre-processing and send them to larger, specialized processing facilities, either in Canada or the United States, or to other countries.
- Development in Mexico of specialized battery processing operations to recycle batteries generated in the country and also import batteries from other countries to be processed domestically.

[58] Semarnat. 2014. *Empresas autorizadas para el manejo de residuos peligrosos*. <www.semarnat.gob.mx/transparencia/transparencia-focalizada/residuos/empresas-autorizadas-para-el-manejo-de-residuos>. (Accessed on 30 September 2014.)

Should any hazardous waste result from EDV battery management, there are facilities for hazardous industrial waste management in Monterrey and Coahuila states.

It is also likely that auto manufacturers like Toyota, Honda, GM and others will work with auto dismantlers to consolidate loads of EOL EDV batteries collected through the auto maintenance, recycling and dismantling infrastructure, to be shipped to Canada or the US for processing.

3.8 EDV Battery Recycling Companies in the US

Our research identified four companies in the US which recycle NiMH and Li-ion batteries from EDVs. They are described in this section.

3.8.1 Inmetco (International Metal Company)—Elwood City, Pennsylvania, US

Inmetco is located in Ellwood City, Pennsylvania, 35 miles northwest of Pittsburgh. The company is a subsidiary of Vale Inco (originally Inco, which was purchased by Vale, a Brazilian mining company, in 2007) and has been in business since 1978. It is a fully permitted recycling facility, with US RCRA (Resource Conservation and Recovery Act) Part B hazardous waste storage status. There are about 110 employees at the site.

Although Inmetco does not process all battery types, it accepts all battery types at the site as a service to its clients. Batteries that are not processed at the site are sent to another reputable, properly permitted, recycling facility. As an element of environmentally sound management, environmental audits of all third-party sites are completed before any shipments are made.

Inmetco has always been the sole processing source for all batteries collected by the Rechargeable Battery Recycling Corporation, now Call 2 Recycle (C2R). Through C2R, Inmetco receives post-consumer batteries from across the US from sources that municipalities as well as retailers.

Inmetco processes a range of metal-rich waste streams, including:

- KO61 baghouse dust (which is high in nickel);
- mill scale;
- SWARF (from metal grinding); and
- batteries.

Ingots, which are sold to the stainless steel industry, are the key output from the recycling process. Nickel, chrome, and iron from spent batteries are recycled at Inmetco and are processed and reclaimed into a stainless steel remelt alloy product. The input is mixed with coke and sent through a two-step furnace (rotary hearth). The output is a 25-pound (11-kilogram) metal bar (referred to as a pig) which is 13 percent nickel and 13 percent chrome, with the balance consisting of iron. The nickel and chrome are expensive and are essential to the stainless steel–making process. Any battery with nickel is therefore valuable to Immetco.

Since Inmetco focuses on metal recovery, with primary attention given to nickel, chrome, iron and cadmium, other materials are not processed at the site. Plastics and other battery packaging are separated and sent off-site to a properly permitted facility for incineration, or are consumed in the process furnaces. A hammermill and a thermal oxidizer remove plastic and contaminants before metal reclamation.

All Inmetco processes have appropriate pollution control devices, which are checked and monitored regularly by independent contractors and reported to the Pennsylvania Department of Environmental Protection.

Inmetco sorts and sends lithium-ion batteries to Glencore/Xstrata Sudbury for cobalt recovery and recycling. Vanadium in lithium batteries is not good for Inmetco's process, and cobalt is not good for its product. Batteries containing small amounts of lithium, silver oxide, or zinc carbonate, and every other battery type can be sent to Inmetco for recycling. These batteries are either consumed through the stainless steel recycling process or, if large quantities are involved, are sent off-site.

Inmetco accepts EDV batteries for recycling. Ideally it would like the batteries broken down to the cells, or to small packs (six cells together). It has processed some EDV batteries that were delivered while still mounted on the frame or in the steel casing. This caused problems for Inmetco, as it thereby received unwanted copper—the company imposes a charge for this because of the manual labor involved in removing copper wiring from the EDV battery before smelting. Inmetco makes a remelt alloy for the steel industry, and copper is a contaminant in the steel-making process.

Inmetco does a considerable business in recycling Li-ion batteries; these are consolidated in mixed loads and sent to the smelter.

The company is concerned about the lithium-iron-phosphate batteries that are entering the market. It is not interested in processing them, as they have no metal value.

Prices charged by Inmetco reflect the comparative value or handling cost to the company for different batteries. It pays for some batteries, based on the nickel content and current value. It charges for other batteries. The costing structure for battery recycling and processing depends on the battery and the value of the recovered metal. Inmetco charges or pays for batteries depending on the chemistry. It generally provides a credit for nickel-bearing batteries if the value is sufficiently high.

3.8.2 Retriev (formerly Kinsbursky Brothers /Toxco)—Ohio, US

Retriev operates two large battery processing facilities in Ohio:

- A universal waste facility in Baltimore, Ohio, is a consolidation site for all battery chemistries from the East Coast. When 40,000 pounds (18,143 kilograms) of batteries have been accumulated, they are shipped to Retriev's facility (formerly known as Toxco) in Trail, BC, Canada. This facility also does some handling; staff goes through each drum of batteries to make sure no lithium batteries are going into the furnace.
- Retriev operates a US RCRA Part B–permitted treatment, storage, and disposal (TSD) facility in Lancaster, Ohio, 30 minutes outside Columbus. The universal waste facility currently processes NiMH batteries to recover nickel, and also lanthanum and yttrium (known as Misch metals—rare-earth metals). The facility also consolidates and provides logistics support for East Coast and Southern US battery recycling. The Lancaster facility is currently constructing a new Li-ion battery recycling line, with support of a US$9.5 million grant from the US Department of Energy.

In Ohio, steel mills take the ferrous case material. Residual ferronickel is very high-grade scrap. Output from the facility is sold to rare-earth, stainless steel, or specialty alloy companies, e.g., aerospace companies, where corrosion resistance is essential. Stainless steel contains 13 to 16 percent nickel (with 13 to 16 percent chromium).

The company has a corporate objective to be the best battery recycler in North America, with battery recycling as its core business; it sees battery recycling as a growth opportunity.

3.8.3 Umicore—Maxton, North Carolina, US

Umicore is a complex-metals recycling company with 80 manufacturing and recycling facilities and 14,000 employees, globally. The company has been in business since the 1880s. Umicore has a consolidation facility for EDV batteries in Maxton, North Carolina, which accepts both NiMH and Li-ion batteries from EDVs. Dismantling of EDV batteries is carried out manually, to remove metals which can easily be recycled locally (steel casings and copper wiring). After pre-treatment and dismantling, battery packs and/or battery cells (depending on size) are consolidated for shipment to the Umicore facility in Hoboken, Belgium, where they are processed in the Umicore smelter (which has a patented design accommodating high temperature). Outputs from the smelter include:

- slags, which contain aluminum, manganese, lithium, and rare-earth metals; and
- alloys, which contain cobalt, nickel, copper, and ferrous metal.

Slags are used in construction projects, and rare-earth metals are sent for further refining. Alloys are sent for alloy refining in Olen, Belgium, and from there are sold to battery manufacturers, to be made into new batteries.

The smelter includes specially designed gas treatment (a confidential Umicore design) to ensure full dust removal and no formation of volatile organic compounds (VOCs).

Lithium is not currently recovered from the slag, as it does not make economic sense to do so. Should the price of lithium increase in the future, Umicore would evaluate additional processes to recover lithium in a pure form. Ultimately, when EOL EDV battery volumes are sufficiently high, Umicore plans to locate three facilities globally (one each in Europe, North America, Asia) to consolidate EDV batteries for shipment to Belgium.

Figure 11. Dismantling of EDV Batteries at Umicore Facility in North Carolina, US

Source: Pederson, M. 2013. Umicore battery recycling dismantling (H)EV battery packs in Maxton, North Carolina, US. Presentation.

3.8.4 MCT—Atlanta Area, Georgia, US

MCT Georgia process both NiMH and Li-ion batteries from consumer recycling programs, as well as industrial batteries. MCT has seen a few EOL batteries from EDVs, to date. The batteries have arrived intact as well as dismantled. Where intact batteries have been delivered to the facility, there is a process in place for safe dismantling. The company charges a tipping fee for large-format batteries but, depending on battery chemistry, there may be a credit to the customer.

End products produced are:

- nickel remelt alloy from NiMH batteries, and
- cobalt alloys from lithium batteries.

3.9 Current Legislation Targeting EDV Batteries

Spent lithium-containing batteries being shipped for recycling or disposal are a waste classified under the international Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal and should be managed when shipped across international boundaries in accordance with its requirements.[59] Under the Convention, hazardous wastes containing Annex I constituents to an extent to render them hazardous (i.e., to exhibit an Annex III characteristic) and

[59] Secretariat of the Basel Convention. 2014. *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal*. <www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf>. (Accessed on 21 April 2015.)

other wastes listed in Annex II are required to follow Basel procedures. Specifically, EDV batteries are commonly exported under code A1170 ("Unsorted waste batteries...") of the Basel Convention and OECD waste code. These procedures include notification by the exporter to the importing country's "Competent Authority," and, upon receipt of a consent letter from the importing country's Competent Authority, shipping the waste batteries in accordance with all applicable regulations. As well, the exporting party should retain all documentation of approval. Canada and Mexico are both Parties to the Basel Convention. While the US is a signatory but not a Party to the Convention, it is considered a best practice in ESM to take the Basel Convention's requirements into consideration during policy development

Specific legislation related to EDV batteries in each country is described separately below.

3.9.1 Canada

A variety of federal, provincial, territorial and municipal laws may apply to the management of end-of-life EDV batteries in Canada. These include laws and other legal requirements (e.g., approvals, permits, etc.) that address hazardous and general wastes, environmental protection, and recycling and disposal operations. Examples of federal regulations that may apply to movements of used and waste EDV batteries include the Import of Hazardous Waste and Hazardous Recyclable Material Regulations, the Interprovincial Movement of Hazardous Waste Regulations, and the Transportation of Dangerous Goods Regulations.

3.9.2 Mexico

The General Law for the Prevention and Integral Management of Waste (the Spanish acronym is LGPGIR), which came into effect on 8 January 2004, addresses all types of hazardous and solid wastes, including batteries.

The Secretariat of the Environment and Natural Resources amended the General Law on 19 March 2014.[60] In Article 19, the LGPGIR provides a list of special management wastes, including "batteries that contain lithium, nickel, mercury, cadmium, manganese, lead, zinc, or any other element that permits the generation of energy, at such levels that they are not considered hazardous wastes in the corresponding Official Mexican Standard." Other types of wastes included in the list are: technological waste from computing industries; manufactures of electronic products or motor vehicles; and others which after their useful life require specific management approaches due to their characteristics.

Special management waste is defined as "waste generated in production processes, which does not meet the criteria to be considered as hazardous or as urban solid waste, or that is produced by large generators of urban solid waste."

In Article 27, the LGPGIR introduces the concept of management plans for certain types of wastes and generators. The objectives of these plans are to promote: waste minimization; waste recovery; shared responsibility for waste management; and technological innovations to develop economically viable waste management. Another objective of the plans is to meet the specific needs of generators of wastes with special characteristics.

The General Law also adds a new paragraph to Article 28, which lists responsible entities for the formulation and execution of waste management plans for special management wastes. Large

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[60] Secretariado de Gobernación. Decreto por el que se reforman y adicionan diversas disposiciones de la Ley General para la Prevención y Gestión Integral de los Residuos. *Diario Oficial de la Federación*. <www.dof.gob.mx/nota_detalle.php?codigo=5337505&fecha=19/03/2014>.

generators and producers, importers, exporters, and distributors of electrical batteries that are considered special management wastes in the corresponding Official Mexican Standard will be required to develop take-back plans.

The Mexican regulatory framework has adequate elements to manage end-of-life (EOL) NiMH and Li-ion batteries from EDVs, as well as the EDVs themselves when they reach the end of their useful lives.

Legal instruments that regulate the transboundary movement of waste in Mexico are based on national laws and international conventions signed by Mexico, in the area of transboundary movements of hazardous waste. These include:

- the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (Basel Convention);
- the Decision C(2002)107 (FINAL) of the Organization for Economic Cooperation and Development (OECD);
- Annex III of the Convention (La Paz Treaty) between Mexico and the United States on cooperation for the protection and improvement of the environment in the border area—this Annex referred to as the Cooperation Agreement between Mexico and the United States on transboundary movements of hazardous wastes and hazardous substances; and
- Mexico's General Law for the Prevention and Integral Management of Waste, and other national regulatory instruments related to wastes.[61]

The transboundary movement of spent EDV batteries (either into or out of Mexico) for treatment or recycling is viable, as long as the importing and exporting countries are in compliance with the laws and conventions governing the transboundary movement of waste, listed above.

Therefore, while Mexico has not passed any specific regulation pertaining to the recycling and/or EOL management of hybrid or electric vehicle batteries, these batteries can be properly handled at EOL under the legislation and regulations discussed above.

3.9.3 United States

In the United States, the management of nickel-cadmium (Ni-Cd) and small, sealed lead-acid (SSLA) batteries is covered by the Mercury-Containing and Rechargeable Battery Management Act, which established uniform labeling requirements and facilitates the recycling of these batteries.[62] Under the Act, Ni-Cd and SSLA batteries must be managed under the Universal Waste Rules. This Act, however, does not cover Li-ion or NiMH batteries.

Li-ion batteries would not be considered to be hazardous waste unless they remained reactive or contained other constituents, such as heavy metals, that would cause them to be toxic. When hazardous, these batteries can be managed under the Universal Waste regulations, which provide a streamlined management system to encourage proper collection of batteries in order to ensure that they are kept out of the municipal solid waste stream and are properly recycled or disposed of.

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[61] Semarnat. N.d. *Guía para la importación y exportación de residuos en México.* <http://tramites.semarnat.gob.mx/Doctos/DGGIMAR/Guia/07-029AF/guia_Import_Export_RP.pdf>. (Accessed on 21 April 2015.)

[62] US EPA. 1997. *Implementation of the Mercury-Containing and Rechargeable Battery Management Act.* <www.epa.gov/osw/hazard/recycling/battery.pdf>. (Accessed on 21 April 2015.)

Generally, under US federal and state law, sealed, non-leaking NiMH batteries are considered dry cell batteries and therefore non-hazardous waste. These batteries are regulated under US Department of Transportation (DoT) regulation 49 CFR 172.101. NiMH batteries that are found to be leaking are regulated as hazardous waste under both federal and state regulations, and as a hazardous material under DoT. NiMH batteries with other damage may also be regulated under hazardous waste laws, Recycling companies can accept these batteries, but additional measures must be taken by the shipper to transport and dispose of them. In California, NiMH batteries must be managed under California Universal Waste Rules.

3.10 Costs of EDV Battery Recycling

None of the recycling companies interviewed for the study would share information on recycling costs. They stated that a credit is provided for recycling of some batteries for which the value of the metal extracted is sufficiently high to cover processing costs. In other cases, a tipping fee is charged for battery recycling. With the chemistry of Li-ion batteries changing to lower-value materials (and away from cobalt), it is likely that there will be a net cost for recycling EDV batteries in the future.

4 ESM and Best Practices in Managing End-of-life EDV Batteries

This section addresses various aspects of environmentally sound management (ESM) of end-of-life (EOL) electric-drive vehicle (EDV) batteries.

4.1 Environmental Pathways for Constituents of HEV, PHEV and EV Batteries

When sealed, Li-ion and NiMH batteries pose a limited risk to the environment and human health. Should the seal be broken and the various constituents of these batteries are released to the environment, there is a risk of some environmental impacts.

This section presents the potential impacts of separate constituents of EDV batteries as stand-alone elements. In most cases they are found in EDV batteries as compound elements, and the potential impacts and pathways would be different.

4.1.1 Nickel Metal Hydride (NiMH) Batteries

NiMH batteries consist of several component materials, including steel, zinc, manganese, nickel, cobalt, other metals, alkali, water, and other non-metals. Some of these materials can be harmful to human health if exposure occurs at high levels. This is not expected for NiMH batteries from EDVs, but for the purpose of supplying information, potential impacts of high levels of exposure to the two main materials found in NiMH batteries (nickel and manganese) are presented below in Table 13.

About 80 percent of HEVs currently use NiMH batteries (Toyota Prius, Toyota Highlander, Ford Escape, Honda Insight, etc.). Nickel makes up between 24 and 35 percent of NiMH batteries, depending on the design. Nickel is also used in some Li-ion batteries.

Nickel and nickel metal compounds, and manganese and manganese compounds are used in Li-ion batteries such as: lithium-manganese oxide; nickel-cobalt-manganese (NCM); nickel-cobalt-aluminum (NCA); and manganese oxide spinel (MnO) batteries.[63]

[63] Berman, B. 2008. The hybrid car battery: A definitive guide. *Hybrid Cars.* <www.hybridcars.com/hybrid-car-battery/>. (Accessed 21 April 2015.)

Table 13. Potential Environmental Impacts of NiMH Battery Constituents

Nickel and Nickel Compounds[a]		
Potential Environmental Impacts	**Potential General Human Health Impacts**	**Potential Occupational Health Impacts**
A lot of nickel released into the environment ends up in soil or sediment, where it strongly attaches to particles containing iron or manganese. Under acidic conditions, nickel is more mobile in soil and might seep into groundwater. Nickel does not appear to concentrate in fish. Studies show that some plants can take up and accumulate nickel. However, it has been shown that nickel does not accumulate in small animals living on land that has been treated with nickel-containing sludge.	The International Agency for Research on Cancer (IARC) has determined that metallic nickel is possibly carcinogenic to humans (Group 2B). The general population can be exposed to nickel via inhalation, and oral and dermal routes of exposure. Based on occupational exposure studies, reports of allergic contact dermatitis, and animal exposure studies, the primary targets of toxicity appear to be the respiratory tract, following inhalation exposure; the immune system, following inhalation, oral, or dermal exposure; and possibly the reproductive system and the developing organism, following oral exposure.	The most serious harmful health effects from exposure to nickel, such as chronic bronchitis, reduced lung function, and cancer of the lung and nasal sinus, have occurred in people who have breathed dust containing certain nickel compounds while working in nickel refineries or nickel-processing plants. The levels of nickel in these workplaces were much higher than usual (background) levels in the environment. Lung and nasal sinus cancers occurred in workers who were exposed to more than 10 mg nickel/m^3 in the form of nickel compounds that were hard to dissolve (such as nickel subsulfide).
Manganese and Manganese Compounds[b]		
Potential Environmental Impacts	**Potential General Human Health Impacts**	**Potential Occupational Health Impacts**
Like other elements, manganese cannot break down in the environment. It can only change its form or become attached or separated from particles. The chemical state of manganese and the type of soil determine how fast it moves through the soil and how much of it is retained in the soil. In water, most of the manganese tends to attach to particles in the water or settle into the sediment. Although certain water sources in the United States are contaminated with excess manganese, there is little risk of excessive exposure to manganese through ingestion of fish or shellfish from contaminated waters, unless the manganese levels in the fish are extremely high and/or the fish are eaten as subsistence. Manganese in water may be significantly bioconcentrated at lower trophic levels. A bioconcentration factor (BCF) relates the concentration of a chemical in plant and animal tissues to the concentration of the chemical in the water in which they live.	Although low levels of manganese intake are necessary for human health, exposures to high manganese levels are toxic. Reports of adverse effects resulting from manganese exposure in humans are associated primarily with inhalation in occupational settings. Inhaled manganese is often transported directly to the brain before it is metabolized by the liver. The symptoms of manganese toxicity may appear slowly over months and years. Studies in children have suggested that extremely high levels of manganese exposure may produce undesirable effects on brain development, including changes in behavior and decreases in the ability to learn and remember. In some cases, these same manganese exposure levels have been suspected of causing severe symptoms of manganism disease (including difficulty with speech and walking). It is not known for certain that these changes are caused by manganese alone. It is not known if these changes are temporary or permanent.	The most common health problems in workers exposed to high levels of manganese involve the nervous system. These health effects include behavioral changes and other nervous system effects, such as movements that may become slow and clumsy. This combination of symptoms when sufficiently severe is referred to as "manganism." Other less severe nervous system effects, such as slowed hand movements, have been observed in some workers exposed to lower concentrations in the work place. The inhalation of a large quantity of dust or fumes containing manganese may cause irritation of the lungs which could lead to pneumonia. Loss of sex drive and sperm damage have also been observed in men exposed to high levels of manganese in workplace air. The manganese concentrations that cause effects such as slowed hand movements in some workers are approximately twenty thousand times higher than the concentrations normally found in the environment.

Note: mg = milligram(s); m^3 = cubic meter(s).

Sources:

a. Data source for nickel: ATSDR 2005. Toxicological profile for nickel. US Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry. <www.atsdr.cdc.gov/toxprofiles/tp15.pdf>.

b. Data source for manganese: ATSDR 2012. Toxicological profile for manganese. US Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry. <www.atsdr.cdc.gov/toxprofiles/tp151.pdf>.

4.1.2 Lithium-ion Batteries

Li-ion batteries have a three-layer structure consisting of an anode, a cathode, and a porous separator (placed between the anode and cathode layers). The anode is typically made out of graphite and other conductive additives, while the cathode is typically composed of layered, transition metal oxides (e.g., lithium cobaltite [$Li\text{-}CoO_2$] and lithium iron phosphates [$Li\text{-}Fe\text{-}PO_4$]).[64]

A study completed for the USEPA[65] in 2012 by Abt Associates assessed three Li-ion battery chemistries for an electric vehicle (EV) and two chemistries for a long-range plug-in hybrid electric vehicle (PHEV) with a 40-mile all-electric range. The battery chemistries assessed included:

- lithium-manganese oxide ($Li\text{-}MnO_2$);
- lithium-nickel-cobalt-manganese-oxide ($LiNi_{0.4}\text{-}Co_{0.2}\text{-}Mn_{0.4}\text{-}O_2$), and
- lithium-iron phosphate ($Li\text{-}Fe\text{-}PO_4$).

In addition, a single-walled, carbon nanotube (SWCNT) anode technology was assessed for possible future use in these batteries.

Among the study's findings was the observation that batteries that use cathodes with nickel and cobalt, as well as solvent-based electrode processing, are the most likely to have adverse environmental impacts (e.g., resource depletion, global warming, ecological toxicity, and human health impacts).[66] The processes most responsible for these negative impacts are those associated with the production, processing, and use of cobalt and nickel metal compounds, which may lead to adverse respiratory, pulmonary, and neurological problems in individuals exposed at high concentrations. These impacts can be reduced through a number of means; for example, cathode material substitution, solvent-less electrode processing, and recycling of metals from the batteries.[67] Potential impacts of the two main materials found in Li-ion batteries (lithium and cobalt) are described in Table 14. For nickel and manganese see Table 13 (above).

[64] US EPA. 2012. *Lithium-ion batteries and nanotechnology for electric vehicles: A life cycle assessment*. Office of Pollution Prevention and Toxics, and National Risk Management Research Laboratory Office of Research and Development. <http://nepis.epa.gov>. (Accessed on 21 April 2015.)

[65] Ibid.

[66] Ibid.

[67] Ibid.

Table 14. Potential Environmental Impacts of Lithium-ion Battery Constituents

Lithium and Lithium Compounds[a]		
Potential Environmental Impacts	**Potential Human Health Impacts**	**Potential Occupational Health Impacts**
Environmental impacts of lithium production are associated with energy production, release of other (more toxic) minerals and the natural intrusion at the site of production.[b] Elemental (metallic) lithium is easily oxidized in strongly exothermic reactions. Reaction with water is particularly dangerous because of simultaneous heat development and formation of hydrogen gas, which can result in explosion or fire.[c]	Lithium affects the nervous system, and is a widely prescribed drug used for the treatment of bipolar affective illness. Previous reports on its effects on sperm motility and male fertility are conflicting. A case of acute lithium-ion intoxication was reported in which the main clinical feature was respiratory failure, secondary to pulmonary edema, possibly due to myocardial depression associated with profound stupor.	Elemental lithium causes severe eye and skin burns. Industrial exposures to lithium may occur during extraction of lithium from its ores, preparation of various lithium compounds, welding, brazing, enameling, and the use of lithium hydrides. Lithium belongs to the alkali metals and is highly reactive.[d]
Cobalt and Cobalt Compounds[e]		
Potential Environmental Impacts	**Potential General Human Health Impacts**	**Potential Occupational Health Impacts**
There is sufficient evidence for the carcinogenicity of cobalt(II) oxide in experimental animals. The primary exposure pathways to cobalt that are of concern for the general population are food and drinking water. Generally, cobalt compounds that dissolve easily in water are more harmful than those that are hard to dissolve in water. Cobalt deposited on soil is often strongly attached to soil particles and therefore would not travel very far into the ground. However, the form of the cobalt and the nature of the soil at a particular site will affect how far cobalt will penetrate into the soil. Both in soil and sediment, the amount of cobalt that is mobile will increase under more-acidic conditions. Ultimately, most cobalt ends up in the soil or sediment.	Nonradioactive cobalt has not been found to cause cancer in humans or in animals following exposure in the food or water. Cancer has been shown, however, in animals who breathed cobalt or when cobalt was placed directly into the muscle or under the skin. The Agency for Research on Cancer (IARC) has determined that cobalt is possibly carcinogenic to humans (Group 2B). Exposure to cobalt compounds (metal, salts, or hard metal) has been shown to produce clastogenic (capable of causing breakage of chromosomes) effects in mammalian cells, including human lymphocytes.	The primary effects of cobalt on respiratory tissues are seen following inhalation exposure, and include diminished pulmonary function, increased frequency of cough, respiratory inflammation, and fibrosis; reported effect levels in occupationally-exposed humans have been in the range of 0.015–0.13 mg Co/m^3. Exposure to cobalt-containing dust, either as cobalt metal or as hard metal, is believed to result in cardiomyopathy characterized by functional effects on the ventricles, and enlargement of the heart, but the exposure levels associated with cardiac effects of inhaled cobalt in humans have not been determined. Dermatitis is a common result of dermal exposure to cobalt in humans.

Note: mg = milligram(s); m^3 = cubic meter(s).

Sources:

a. National Library of Medicine HSDB Database. 2007. Lithium compounds. <http://toxnet.nlm.nih.gov/cgi-bin/sis/search/a?dbs+hsdb:@term+@DOCNO+6900>.

b. Gaines, L., and R. Cuenca. 2000. *Costs of lithium-ion batteries for vehicles*. United States Department of Energy, Center for Transportation Research: Energy Systems Division, Argonne National Laboratory, Argonne, Illinois.

c. Ekermo, V. 2009. Recycling opportunities for Li-ion batteries from hybrid electric vehicles. Master of Science thesis in Chemical Engineering. Department of Chemical and Biological Engineering, Industrial Materials Recycling. Chalmers University of Technology. Göteborg, Sweden.

d. Ibid.

e. ATSDR. 2004. Toxicological profile for cobalt. US Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry. <www.atsdr.cdc.gov/toxprofiles/tp33.pdf>.

4.2 Best Technical Practices for Recycling of EDV Batteries

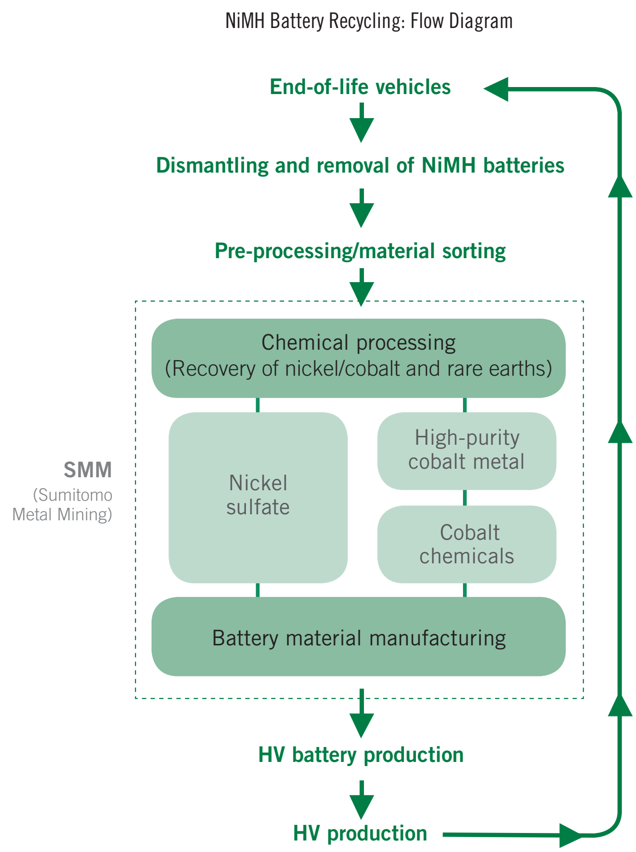
A number of leading-edge recycling operations for EDV batteries are in place in Europe and Asia. A representative selection is described in this section.

4.2.1 Leading-edge Best Practices for Recycling of EDV Batteries in Asia

The first company to recycle nickel in used NiMH batteries from HEVs for use in new NiMH batteries was Sumitomo Metal Mining (SMM) Corp. in Japan. This initiative was launched in 2010.

In conjunction with Toyota Motor Corporation (TMC), SMM developed a high-precision nickel sorting and extraction technology, allowing materials to be introduced directly into the nickel-refining process, thus achieving "battery to battery" recycling. TMC is currently looking at introducing this recycling system overseas. This system is illustrated in Figure 12 below.

Figure 12. Process Flow Chart for Nickel Metal Hydride Battery Recycling—Sumimoto Metal Mining Corporation, Japan

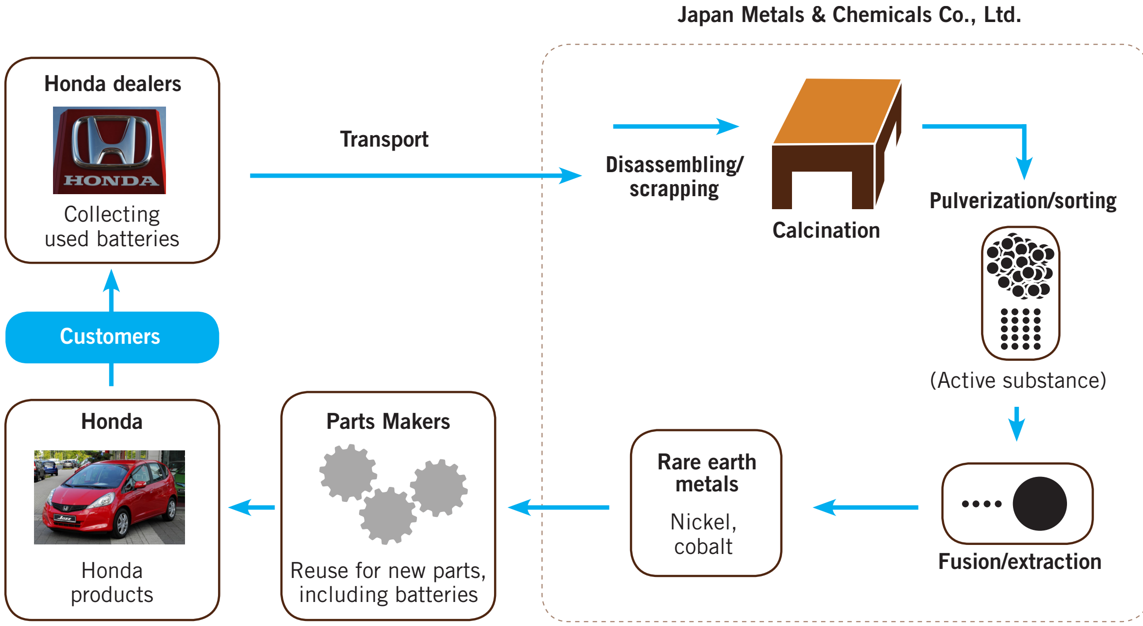


Source: Sumitomo Metal Mining Co. 2013. *CSR Report 2013*. <www.smm.co.jp/E/csr/report/pdf/csr2013_allpages.pdf>. (Accessed on 30 September 2014.)

Prior to this development, NiMH batteries were recovered by car dealers and vehicle dismantling businesses and were subjected to reduction treatment, and scrap containing nickel was recycled as a raw material for stainless-steel manufacturing.

In 2012, following the March 2011 earthquake and tsunami in Japan, Honda instituted at Japan Metals & Chemicals (JMC) a new process of extracting oxides containing rare-earth metals (mischmetal) from used NiMH batteries. Since March 2013, the extracted rare-earth metals are being supplied from JMC to a battery manufacturer, which will re-use them as negative-electrode materials for NiMH batteries for HEVs. To extract the mischmetals in the recycling process: once the battery is dismantled, the mischmetal mix is fired at high temperature and pulverized. The rare-earth metal portion melts and can then be extracted. Unlike the current recycling approach, which involves treating NiMH batteries with heat and using the resulting output as stainless steel scrap metal, this technology allows Honda to recover the stainless steel.[68,69] The process is illustrated in Figure 13.[70]

Figure 13. Honda Process for NiMH Battery Recycling with Rare-earth Metal Recovery



Source: Metalpedia. N.d. Asian Metal. Rare earths: *Recycling. Metalpedia*. <http://metalpedia.asianmetal.com/metal/rare_earth/recycling.shtml>. (Accessed on 31 March 2015.)

4.2.2 Leading-edge Best Practices for Recycling of EDV Batteries in Europe

In 2000–2003, Umicore (located in Belgium, and discussed separately in Section 3) developed a new recycling process called Val'Eas. This closed-loop process is the only industrial process dedicated to rechargeable NiMH and Li-ion batteries and is not derived from processes previously used for other battery types. It uses a combination of pyrometallurgical and hydrometallurgical processes.

Umicore's proprietary technology eliminates the necessity for hazardous pre-treatment of Li-ion, Li-polymer, and NiMH batteries. Batteries from HEVs, PHEVs and EVs are first dismantled in a dedicated dismantling line. The increase in temperature and the reducing (opposite of oxidation) conditions are closely monitored and managed, to prevent any explosions and to ensure that all of the cobalt, nickel, and steel is recovered in the metallic phase. The smelting process produces metal and slag fractions. The metal fraction contains nickel, cobalt, and other valuable metals. These metals are further refined and transformed into $Ni(OH)_2$ and $LiMe0_2$. These products are both active cathode

[68] Michelsen, C. 2012. Hybrid battery recycling works! according to Honda. *Clean Technica*. <http://cleantechnica.com/2012/04/24/hybrid-battery-recycling-works-according-to-honda/>. (Accessed 21 April 2015.)

[69] Els, F. 2013. Honda's starts recycling program to extract 80% of rare earths from used hybrid batteries. *InfoMine*. <www.mining.com/hondas-starts-recycling-program-to-extract-80-of-rare-earths-from-used-hybrid-batteries-43719>. (Accessed on 21 April 2015.)

[70] Integrity Exports. 2012. Honda introduces rare earth metal recovery tech for old hybrid car batteries. *Integrity Exports*. <http://integrityexports.com/2012/04/18/honda-introduces-rare-earth-metal-recovery-tech-for-old-hybrid-car-batteries/>. (Accessed 21 April 2015).

materials for batteries; therefore, this process closes the loop from battery to battery. The cobalt is used to make up LCO (lithium cobalt oxide), which can be resold to battery manufacturers.

Gas emissions are controlled by the gas cleaning installation, which ensures that no harmful dioxins or volatile organic compounds (VOCs) are produced. Fluorine from the electrolyte is collected in this installation and can be recovered.

Umicore’s recycling process is designed to manage any Li-ion and NiMH end-of-life batteries originating from hybrid and full electric vehicles, regardless of their specific cell chemistry. While the process is specifically designed to reach a high recycling efficiency, it can also be used to recycle other complex materials. Figure 14 illustrates how the process works.

The smelting operations are performed in Hoboken, Belgium, at Umicore’s industrial-scale recycling facility. Here, batteries are directly introduced into a furnace without any hazardous pre-processing (e.g., crushing).

A French metal recycling company, SNAM (*Société Nouvelle d’Affinage des Métaux*) can process up to 300 tonnes of Li-ion batteries annually. Once the batteries have been sorted, they undergo pyrolysis to eliminate plastic and paper materials. Cobalt, aluminum, copper, and iron are recycled but lithium is not currently recovered. SNAM recycles hybrid and EV batteries from brands that include Volkswagen, Audi, SEAT, and Skoda. SNAM has also signed an agreement with Honda for the recycling of batteries from its HEVs in Europe.[71]

Another French company, SAPRP Industries/Euro Dieuze**,** specializes in battery recycling—including the recovery of lithium—using a hydrometallurgical process. However, as it is a new process still undergoing research and development, the details are not yet publicly available.

Also in France, Recupyl treats spent batteries from HEVs, PHEVs and EVs using hydrometallurgy. Its patented technology of material valorization at low temperature is based on a closed-loop system where materials are re-used to produce new batteries.[72]

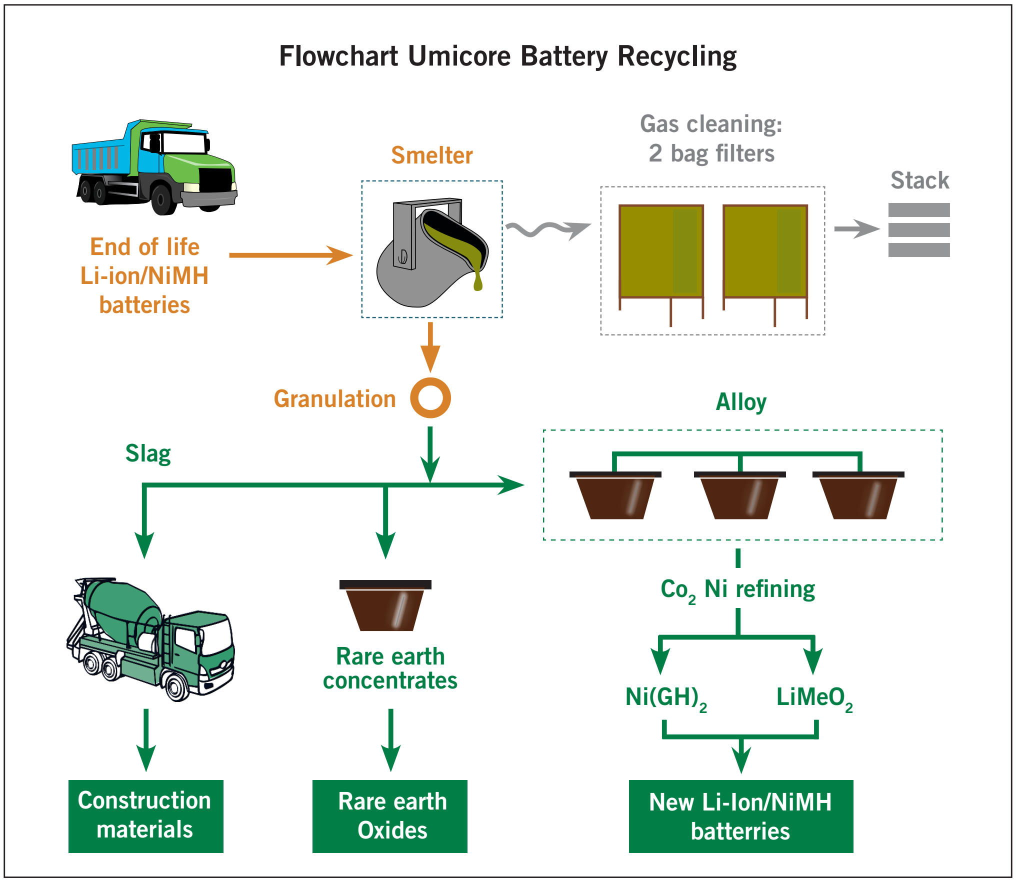
[71] Morris, C. 2014. Volkswagen Group France arranges for recycling of hybrid and EV batteries. *Charged.* <http://chargedevs.com/newswire/volkswagen-group-france-arranges-for-recycling-of-hybrid-and-ev-batteries/>. (Accessed 21 April 2015.)

Friends of the Earth Europe, Friends of the Earh England Wales and Northern Ireland. 2013. *Lithium.* <www.foeeurope.org/sites/default/files/publications/13_factsheet-lithium-gb.pdf>. (Accessed 21 April 2015.)

Toyota Motor Corporation. N.d. Toyota announces sustainable battery recycling agreement in Europe. Press release. <http://toyota.eu/about/pages/newsdetails.aspx?prid=688&prs=Corporate&prrm=pressrelease>. (Accessed 21 April 2015.)

[72] A more detailed description of the process can be found at: Vadenbo, Carl O. 2009. *Prospective environmental assessment of lithium recovery in battery recycling.* <www.uns.ethz.ch/pub/publications/pdf/1717.pdf>. (Accessed on 7 May 2014.)

Figure 14. Process Flow Chart for Umicore EDV Battery Recycling in Belgium



Source: Umicore. N.d. <www.batteryrecycling.umicore.com/UBR/process/process.jpg>. (Accessed on 21 April 2015.)

Other companies that process used EDV batteries in Europe include Batrec (in Switzerland) and AkkuSer (in Finland).

In Switzerland, Batrec operates a mechanical processing plant for Li-ion battery cells. The batteries are crushed in a CO_2 gas atmosphere, whereby the volatile organic electrolyte evaporates and is collected as non-usable condensate. The crushing operation is performed at room temperature in order to prevent any oxidation reaction from occurring. The next step is "neutralization" of metallic lithium by adding a controlled amount of an oxygen-containing reactant, such as air. After neutralization of lithium, the batteries are further crushed and undergo material separation. The different material fractions are sold as feedstock materials in other processes.[73]

In Finland, AkkuSer recycles hybrid and electric vehicle batteries using no chemicals, heat, or water. It has its own factory and uses a dry technology (crushing and gas treatment) to recycle the materials.[74] This method (dry-technology) is reported to have one of the highest degrees of material recovery from batteries, even on a global scale. In this process, rechargeable batteries are crushed and

[73] GlobalPSC. 2011. Batrec—Return Batteries and Accumulators. YouTube video clip. <www.youtube.com/watch?v=e6qyLT_x53o>. (Accessed 7 May 2014.)

[74] SYKLI Environmental School of Finland. N.d. Batteries. <www.sykli.fi/en/materials-and-tools/batteries-recycling/recycling>. (Accessed on 21 April 2015.)

the elements that can be re-used are separated, based on their physical properties (e.g., weight, magnetic qualities, etc.).[75] This process, which has been proven to be a best available technique (BAT), consumes relatively little energy (0.3 kWh/kg), yet achieves a very high recycling rate of over 90 percent.[76]

4.3 Research on Use of Spent EDVs as Energy Storage Devices

Groups such as the US Department of Energy (DoE), US National Renewable Energy Laboratories, the International Electric Power Research Institute (EPRI), and several universities (including Rochester Institute of Technology, UC Davis, UC Berkeley, among others) are exploring the potential to re-purpose used EDV batteries as energy storage, power management, and standby power devices. This work is partially focused on the broader use of large-format batteries as energy storage devices.

Various “second uses” identified (and some deployed) to date include:

- in conjunction with grid-based wind and solar power generating technologies, uses such as energy time shifting, renewables firming, service reliability and quality;
- telecommunications applications, such as cellular telephone towers;
- off-grid stationary applications, including for backup power and for remote installations;
- Non-light-duty vehicle mobile uses, including commercial idle-off, utility and recreational vehicles, and public transportation (various types of micro-hybridization);[77] and
- power sources for specialized applications such as server farms and agricultural needs, among others.

For example, the battery in an EDV may comprise 200 cells wired into eight electrically connected modules in the pack. At end of life, some or all of the modules in this pack will still hold sufficient charge for stationary applications (such as for a pump on a farm). The battery pack can be dismantled by a trained electrician or technician to “right-size” the modules for specific applications. This type of redeployment is attractive to formal organizations such as those named above, and to do-it-yourselfers and small “mom-and-pop” operations functioning in small-market niches. However, the Rechargeable Battery Association (PRBA) has expressed concerns about refurbishment of EDV batteries, due to safety issues. There are significant risks of electrical discharge and thus human health hazards related to refurbishing EDV batteries unless the refurbishment is undertaken by a well-trained individual.[78]

Other research underway includes the following:

- Nissan partnered with Sumitomo to initiate a business plan centered on recovering and reselling used automotive batteries.

[75] CTC-N. 2012. *Development of a recycling process for Li-Ion batteries*. Climate Technology Centre & Network. <http://ctc-n.org/content/development-recycling-process-li-ion-batteries>. (Accessed 30 September 2014.)

[76] AkkuSer. 2011. AkkuSer Ltd – Battery Recycling – Dry Technology. YouTube video clip. <www.youtube.com/watch?feature=player_embedded&v=HD1dB7zI7Ec>. (Accessed on 7 May 2014.)

[77] Neubauer, J., and A. Pesaran. 2010. *PHEV/EV li-ion battery second-use project* (NREL/PR-540-48018). National Renewable Energy Laboratory. <www.nrel.gov/docs/fy10osti/48018.pdf>. (Accessed on 18 March 2014.)

[78] Kerchner, George A. Personal communication with the author, 13 March 2014.

- An energy company is working with Itochu to develop energy storage systems for apartment buildings, to "help develop a secondary market" for used batteries.

Standards concerning the refurbishing of EDV batteries after end of first life may be needed in order for this industry to concurrently optimize value capture and ensure human and environmental safety. Further, if EDV batteries are re-purposed for subsequent non-EDV uses, there are unresolved questions concerning liability that might flow back through the vehicle and/or the battery manufacturers (or vehicle owners) should the batteries or cells fail in a way causing significant harm to human health or the environment.

A strong re-use market for EDV batteries after their first use would lengthen the number of years before these batteries would show up in the recycling stream. This potential has not been taken into consideration in the lifespan model used to produce EOL estimates in Section 3, as there is still some uncertainty over whether these "second use" applications will work in North America. Experts interviewed for this project suggested that third-world urban households (where there are frequent, lengthy power outages) might be a good market for using EOL EDV batteries as energy storage devices. There was also concern that because the batteries were initially designed for vehicle use they may not be ideal in an energy storage application.

4.4 Best Practices Legislation for ESM of EDV Batteries

Europe is a leader when it comes to legislation pertaining to battery recycling. The European Batteries Directive, first adopted in 1991, sets clear targets on collection and recycling rates for all types of batteries. While the Directive does not include battery-recycling requirements specifically tailored to EDV batteries, its requirements do apply. The main objective of this Directive is to minimize the negative impact of batteries and accumulators and waste batteries and accumulators on the environment, thus contributing to the protection, preservation and improvement of the quality of the environment.[79]

The Directive stipulates a number of battery recycling requirements, including, for example, that all collected batteries must be recycled; that the use of mercury is restricted; that batteries cannot be disposed of in landfills or by incineration; that batteries must be labeled with a picture of a crossed-out wheeled bin; that battery producers or third parties acting on their behalf cannot refuse to take back waste batteries; and that recycling processes must achieve a minimum efficiency of 50 percent for lithium-ion and nickel metal hydride batteries. The Directive also stipulates that batteries must be readily removable from appliances, and that all appliances (including vehicles) containing batteries must be accompanied by instructions showing how the batteries can be safely removed.

EDV batteries are considered industrial batteries (not automotive batteries) under the EU Battery Directive, which requires the collection rate for spent batteries to reach 25 percent by September 2012 and 45 percent by September 2016. EU member states are free to require higher collection rates within their territories. Germany set a 35 percent rate for September 2012. An EU recycling efficiency rate of 50 percent for "commonly used battery chemistries" has also been set.[80]

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[79] Toshiba of Europe Ltd. 2013. Legal directives in Europe. <www.toshiba.eu/eu/Environmental-Management/Legal-directives-in-Europe/>. (Accessed on 21 April 2015.)

[80] VARTA. n.d. Environmentally-friendly substances and recycling. <www.varta-consumer.com/en/Company/Environment/EU-battery-directive-and-Battery-recycling.aspx>. (Accessed on 21 April 2015.)

The Directive also sets a number of other requirements pertaining to mandatory take-back and to recycling efficiency targets. Some examples of specific text follow:[81]

- **Collection schemes:** "Member States shall ensure that producers of industrial batteries and accumulators, or third parties acting on their behalf, shall not refuse to take back waste industrial batteries and accumulators from end-users, regardless of chemical composition and origin. Independent third parties may also collect industrial batteries and accumulators."
- **Removal of waste batteries and accumulators:** "Member States shall ensure that manufacturers design appliances in such a way that waste batteries and accumulators can be readily removed. Appliances into which batteries and accumulators are incorporated shall be accompanied by instructions showing how they can be removed safely and, where appropriate, informing the end-user of the type of the incorporated batteries and accumulators. These provisions shall not apply where, for safety, performance, medical or data integrity reasons, continuity of power supply is necessary and requires a permanent connection between the appliance and the battery or accumulator".

Battery recycling is also regulated under the European Union's End-of-Life Vehicles Directive (ELV) (2000/53/EC). As stated in the Batteries Directive, "batteries and accumulators used in vehicles should meet the requirements of Directive 2000/53/EC, in particular Article 4 thereof. Therefore, the use of cadmium in industrial batteries (including NiMH and Li-ion batteries) should be prohibited, unless they can benefit from an exemption on the basis of Annex II to that Directive." In spring, 2014, the Province of Ontario issued a draft End-of-life Vehicle Guideline for consultation. The Draft Guideline would require proper removal of all batteries from vehicles prior to shredding.

In addition to the above Directives, in April 2010 the European Commission issued a communication for a "European Strategy on Clean and Energy-Efficient Cars." The strategy, recognizing the potential for expansion of the clean and energy-efficient vehicle market globally, contains a number of recommendations to "provide an appropriate and technology neutral policy framework for clean and energy efficient vehicles." Proposals in the strategy include looking at what changes will need to be made to existing battery legislation to adapt to new market circumstances; promoting European programs on recycling and reusing batteries; and reviewing options for changing the rules governing the transportation of batteries.[82]

Management of complex engineered products at EOL is increasingly coming under what is commonly called "product stewardship" laws and regulations around the world. This is a policy model whereby the makers of a product are asked to pay for the cost of responsible management of the product at end of life. Currently in North America these laws—which exist typically at a provincial or state rather than federal level in the Canada and the US, but national level in Mexico—apply to EOL electronics, paint, pesticides, tires, gas cylinders, carpet, radioactive devices, fluorescent lighting, mercury-containing devices (thermostats), and other product categories. Produce stewardship legislation is often passed when local waste management systems realize they are excessively burdened by the hazardous constituents found in these complex products, and are seeking to shift costs back to the product makers (and by extension, to the consumers of those products). It is

[81] European Union. 2013. Directive 2013/56/EU of the European Parliament and of the Council of 20 November 2013 amending Directive 2006/66/EC of the European Parliament and of the Council on batteries and accumulators and waste batteries and accumulators as regards the placing on the market of portable batteries and accumulators containing cadmium intended for use in cordless power tools, and of button cells with low mercury content, and repealing Commission Decision 2009/603/EC. *Official Journal of the European Union*. <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013L0056&from=EN>. (Accessed on 21 April 2015.)

[82] Eurobat. 2010. Other legislation. <www.eurobat.org/other-legislation>. (Accessed on 21 April 2015.)

considered very unlikely that EDV batteries will end up in municipal waste streams, because their large size and weight make them very visible and difficult to dispose of unnoticed.

Industry executives interviewed for this study generally concur that product stewardship laws are not the correct model for this product class. Executives hope to see a robust voluntary system, much as has been developed by Call 2 Recycle (formerly the Rechargeable Battery Recycling Corporation—RBRC) for smaller rechargeable batteries. In this system, manufacturers pay in to a third-party non-profit organization (Call 2 Recycle), based on quantity and type of batteries put on the market. These fees cover the cost of setting up collection points around the country and having the batteries recycled. Stakeholders would prefer not to see national legislation addressing the EDV battery class of products.

4.5 Best Practices Policies

There are many policies that encourage the purchase of EDVs and thereby reduce GHG emissions and environmental footprints (as long as the EOL vehicle is managed in an environmentally sound manner). They generally encourage the purchase of EDVs through various rebate incentives. Some policies include the following:

1. Cheaper or free parking for hybrid vehicles—has been implemented by cities such as Albuquerque (NM), Austin (TX), Baltimore (MD), Ferndale (MI), Huntington (NY), Los Angeles (CA), New Haven (CT), Salt Lake City (UT), San Antonio (TX), San Jose (CA), Santa Monica (CA), Vail (CO), Westchester (NY), among others.
2. Mandatory hybrids for taxi cabs—City of Vancouver, BC, Canada, and others.
3. Various green fleet EDV purchasing targets.
4. EDVs get to travel in high-occupancy lanes; EDVs are exempt from emission-testing requirements; owners of EDVs receive utility rate reductions or tax credits; and other incentives.

A detailed list of incentives is presented in Appendix B.

Some auto manufacturers offer cash incentives to encourage consumers to bring back EOL EDV batteries. In addition to offering a US$100 cash rebate when a recovered HEV battery is returned, Toyota Motor Corporation Australia offers a discount of US$500 off the purchase of a new replacement HEV battery when you return the old battery. The rebate or discount can be claimed at all Toyota dealers around Australia. Also, to ensure that every battery comes back to the company and is not simply discarded by the dealer, Toyota offers a US$200 bounty to dealerships for each EOL Prius battery.[83] Honda offers a refundable "core deposit" in the amount of US$500 that is returned to the customer when they ship in their old EDV battery to receive a new one.[84]

4.6 Best Practices Technical Approaches to ESM

Environmentally sound management (ESM) of EDV batteries must be addressed at every stage of the life cycle of the battery, to ensure protection of human health and the environment at EOL. This section presents suggestions collected from people interviewed for the study research.

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[83] Carbon Pig. N.d. Electric cars don't use fossil fuel, but what's the environmental impact and life cycle of the batteries? *Carbon Pig.* <http://carbonpig.com/article/electric-cars-dont-use-fossil-fuel-whats-environmental-impact-and-life-cycle-batteries>. (Accessed on 21 April 2015.)

[84] Bumblebee Batteries LLC. N.d. MAX-IMA replacement IMA battery for Honda Civic Hybrid. <http://bumblebeebatteries.com/hybrid-batteries/honda-civic-hybrid-battery>. (Accessed 21 April 2015.)

4.6.1 ESM of EDV Batteries in the Design Stage

The first best practice for ESM of EDV batteries is to design the EDV multi-cell batteries themselves with active safeguards to mitigate or prevent failures and safety risks, and also to design the batteries so they are easier to dismantle at EOL. Given the thermal instability of active materials within the battery at high temperatures and the possible occurrence of internal short circuits that may pose risks, products should be designed with extensive risk analysis, using proven industrial design tools such as failure modes and effects analysis and fault tree analysis. Safety risks associated with EDV batteries are addressed in a number of standards and testing protocols that can guide manufacturers on how to more safely construct and use Li-ion batteries.

Relevant safety standards in North America are typically developed through a consensus process, which relies on participation by representatives from regulatory bodies, manufacturers, industry groups, consumer advocacy organizations, insurance companies and other key safety stakeholders. Underwriters Laboratories (UL) has recently strengthened its Li-ion battery standards.[85] There are a number of current standards and testing protocols used to assess some of the safety aspects of Li-ion batteries in the design stage.[86]

4.6.2 ESM of Electric-drive Vehicle (EDV) Batteries through Labeling

A number of recyclers commented that it would be helpful if EDV batteries were clearly labeled as to their specific chemistry. Labeling of batteries as to chemistry, risks, and proper handling should be put into effect during the design stage as it helps ensure safety, correct usage, and optimal value recovery during all subsequent stages in the life cycle. It should be done in a way to protect the battery maker's proprietary formulas but give enough information so parties handling EOL EDV batteries know the hazards as well as the potential value (e.g., cells with a high concentration of cobalt, which is very valuable to recyclers).

Two anecdotes discussed during the study research underscore the need for proper labeling:

- A large North American auto shredder chain reports that it will not accept EDV batteries (nor will it accept hybrid or electric vehicles that have not had the batteries removed). Its policy was stated as "in addition to environmental issues, they present a serious safety issue and fire issue. We've had near electrocution and some small fires at a couple of our facilities associated with these kinds of batteries." This company decided to not receive EDV batteries for the foreseeable future. It will refer people with those vehicles to their mechanic or the dealership to remove the battery and then the auto shredder will receive the vehicle after the battery has been removed.[87]
- Lead-acid battery smelters report that they have had safety issues with lithium-ion batteries—which have very similar factors on their forms to those of lead-acid batteries—getting mixed in with the lead-acid batteries and causing explosions or other problems.[88]

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[85] Reuters. 2013. Standards are tightened for lithium-ion batteries. *The New York Times.* <www.nytimes.com/2013/06/13/business/lithium-ion-battery-standards-are-tightened.html?_r=0>. (Accessed on 21 April 2015.)

[86] Underwriters Lab. 2012. *Safety issues for lithium-ion batteries.* <www.ul.com/global/documents/newscience/whitepapers/firesafety/FS_Safety%20Issues%20for%20Lithium-Ion%20Batteries_10-12.pdf>. (Accessed on 11 March 2014.)

[87] Confidential large North American auto shredder chain. Personal communication with the author, 17 March 2014.

[88] Confidential large US lead smelter. Personal communication with the author, 10 March 2014.

The PRBA is working on labeling for EDV batteries, and the Automotive Battery Recyclers Association has recently sent a letter to the Society for Automotive Engineers asking for it to develop a method and standard for consistently identifying Li-ion batteries.[89] Labels must be physically attached to the battery, as it is unrealistic to expect busy recycling operations to look up each serial number to determine chemistry and risks. Unlabeled EDV batteries could present a barrier to the growth of the EOL value-recovery infrastructure.

4.6.3 ESM of Electric-drive Vehicle (EDV) Batteries during Transport

Correct handling during transport has separate requirements for new versus used EDV batteries. There is a fairly mature system of regulations governing the international transportation of hazardous wastes, covering all modes of transportation. The United Nations brings Parties together to set these regulations.

A Lithium Battery Working Group has been formed out of the UN Sub-Committee of Experts on the Transport of Dangerous Goods. This group met in early February 2014 in Brussels to address proposed changes to the testing requirements and definitions in the UN's *Manual of Tests and Criteria*, applicable to large-format lithium batteries. The meetings are co-hosted by the Rechargeable Battery Association (PRBA), the Council on Safe Transportation of Hazardous Articles (COSTHA) and the European Association for Advanced Rechargeable Batteries (RECHARGE). Participants included government officials from the United States, the United Kingdom (UK), Germany, France and Canada as well as leading battery and automobile industry experts from Japan, Germany, China, Korea, France and the US.[90]

The UN regulations will be incorporated into the International Maritime Organization's (IMO) Dangerous Goods Code, which regulates all types of dangerous goods shipped by sea. For example, if a company such as Tesla ships a battery to Japan for recycling, it will have to comply with this code.

At this time, Canada has no regulations on transport of EOL Li-ion batteries. It has been recommended that Canada update its transportation regulations with regard to waste Li-ion batteries.[91]

4.6.4 ESM of Electric-drive Vehicle (EDV) Batteries in the Battery Manufacturing and Installation Stage

The next stage in the battery's life cycle that will affect safety at EOL is proper installation in the EDV. Currently, there are international standards organizations working to improving vehicle and battery manufacturer product compatibility with integrated Li-ion batteries by including appropriate performance testing in applicable standards. An example of such an approach to performance testing can be found in IEC 60950-1 (UL 60950-1), Information Technology Equipment, Safety – Part 1.[92]

However, one concern several industry stakeholders voiced is that there can be the best standards and regulations concerning the design, marking, and transport of EDV batteries in the world, and the

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[89] Confidential battery recycling industry executive. Personal communication with the author, 11 March 2014.

[90] Rechargeable Battery Association. 2014. *Working group makes progress on updating UN testing requirements for large lithium batteries.* <www.prba.org/general/working-group-makes-progress-on-updating-un-testing-requirements-for-large-lithium-batteries-804/>. (Accessed 13 March 2014.)

[91] Kerchner, George. Personal communication with the author, 13 March 2014.

[92] Underwriters Lab. 2012. *Safety issues for lithium-ion batteries.* <www.ul.com/global/documents/newscience/whitepapers/firesafety/FS_Safety%20Issues%20for%20Lithium-Ion%20Batteries_10-12.pdf>. (Accessed on 11 March 2014.)

leading, "name brand" battery makers (e.g., Panasonic, Sanyo) will adhere to these standards and requirements conscientiously, but the next tier of battery manufacturers who are not "name brand"—and these exist already, often in cheaper labor markets—will ignore these best practices, and the overall EDV industry will have "sub-standard" batteries enter the market and be placed into electric-drive vehicles. This free market situation can be very difficult to address, and requires diligence on the part of all parties in the purchasing chain (from auto makers to auto dealers to vehicle owners, etc.) to ensure the best quality and standards have been adhered to.

4.6.5 ESM of Electric-drive Vehicle (EDV) Batteries in the Use Stage

It is critical that all parties which might come in contact with an EDV battery other than when it is smoothly running be properly trained in management and handling. This includes guidance for many stakeholders, including dealers, auto repair operations, vehicle owners, first-responders (in the event of accidents and fires), and auto salvage operations (where vehicles destroyed in accidents get hauled). EDV batteries hold a charge of 200 volts, compared to lead-acid batteries, which only hold a charge of 12 volts. Guidance documents have been developed by many of these stakeholders, including fire chiefs associations, and the auto after-market industry.[93]

4.6.6 ESM of Electric-drive Vehicle (EDV) Batteries in the End-of-life (EOL) Stage.

There are a variety of standard industrial hygiene approaches for assuring environmentally sound management of EOL EDV batteries, which includes protection of worker health and safety. These approaches have been proven and tested at existing lead-acid battery recyclers in North America. Environmental health and safety (EH&S) controls include:

- ongoing EH&S training for all employees, especially including electrical hazard training;
- engineering controls for assuring proper operation of all equipment in order to protect the environment and worker health and safety; and
- requirements for personal protective equipment, which is appropriately tested for all hazards in the facility.

These controls should be used not just at battery recycling facilities but at all intermediate facilities dealing with situations where an EDV reaches end of life: the auto dealer getting a returned vehicle, the independent used-vehicle dealer getting a trade-in, an auto salvage yard getting a wrecked EDV, and with any dismantlers. If an EDV is crushed at an auto shredder/crusher operation with the battery still in it, it can pose fire and electrocution dangers. However, an after-market auto industry specialist noted that the parties that crush vehicles are generally the same parties that first remove all marketable parts, and at this time it appears that the market for used batteries is currently strong enough that dismantlers are removing the EDV batteries for monetary gain. Advertisements are already on online recycling market boards offering EDV batteries for sale.

One unknown issue in planning for environmentally safe management of EDV EOL batteries is the use of nanoscale materials in their manufacture. Single-walled carbon nanotubes (SWCNTs) are being embedded in an increasing number of manufactured products, including in anodes in some lithium-ion batteries. Nanoscale materials behave differently under thermal, chemical and mechanical forces from their "normal-size" counterparts. They can become airborne and pose a respiratory risk

[93] Cars Direct. 2013. How to properly recycle used hybrid car batteries. *Cars Direct*. <www.carsdirect.com/green-cars/how-to-properly-recycle-used-hybrid-car-batteries>. (Accessed on 18 March 2014.)

when products with SWCNTs are shredded (as may be the case in pre-processing of Li-ion batteries at EOL). Research on the overall toxicity characteristics—for both human health and the environment—of SWCNTs and other nanoscale materials is in the early stages. As this research grows and becomes better understood, it may add to labeling and marking requirements that should be provided on EDV batteries.

5 Conclusions and Recommendations

5.1 Summary of Findings

1. HEVs were introduced into the Canadian, Mexican and American markets in 2000, 2006 and 2000, respectively. In 2013, unit sales of HEVs were an estimated 23,000 in Canada, 1,000 in Mexico, and 495,500 in the US, for a total of approximately 520,000 in North America. These values are expected to rise significantly in the coming years.
2. It is estimated that there were 2 million HEVs in the US at the end of 2013.
3. PHEVs and EVs were introduced to the North American market in December 2010. Sales are currently modest, but are increasing rapidly. PHEV and EV unit sales combined in 2013 were approximately 2,200 in Canada, 12 in Mexico and 96,900 in the US, for a total of almost 100,000 in North America in 2013.
4. There are a number of barriers to broad adoption of electric vehicle technology; one is the lack of charging stations and charging infrastructure, which limits the range of these vehicles today. These barriers are being addressed through the establishment of charging infrastructure in many locations, incentives for the purchase of electric vehicles, and developments in battery technology which are lowering the purchasing costs of electric vehicles.
5. Projections of future EDV sales depend on a number of factors, including purchasing specifications by fleet managers, the price of gasoline, the high price to purchase a HEV compared to a traditional vehicle, CO_2 policies of governments, and incentives provided by various levels of government to purchase HEVs.
6. All EDV batteries have long lifespans (eight years or longer) and manufacturer warranties (eight years or 100,000 to 150,000 miles, depending on the make and model of the vehicle).
7. Failure rates for EDV batteries are reported to be low (about 1 percent). Where the failures occur within the battery warranty period, the auto manufacturers replace the batteries.
8. As of end of 2013, about 80 percent of HEVs use nickel metal hydride (NiMH) batteries. About 20 percent of HEVs and all PHEVs and EVs use Li-ion batteries, because Li-ion batteries have the different characteristics needed to meet the charging requirements for fully electric vehicles.
9. The number of EDV batteries at EOL in North America was estimated at 115,000 units in 2013. This value is expected to reach about 380,000 units by 2020, 849,000 units by 2025 and almost 1.5 million units by 2030.
10. The constituents of EDV batteries (mostly nickel from NiMH batteries and cobalt from Li-ion batteries) provide an economic incentive for recycling at this time. Battery designs are changing so that they contain less-valuable materials; this is a concern for the economics of future recycling efforts.
11. Large auto manufacturers such as Toyota and Honda are establishing reverse supply chains to ensure that EOL EDV batteries are recovered and properly recycled.
12. Companies already in the battery recycling business (Retriev, RMC, Umicore, Glencore/Xstrata, etc.) can process large-format NiMH and Li-ion batteries as long as they are broken down to smaller components (cells or packs). Companies with smelting operations (sometimes large global companies such as Umicore, Glencore/Xstrata, etc., with global supply chains) are interested in recycling EDV batteries because of their metal content.
13. The economics of recycling EDV batteries depends on the value of the metals and other materials which can be recovered. In some cases, companies pay a credit against a processing fee. In other cases a tipping fee is charged.
14. The recycling/processing infrastructure for EDV batteries is in its infancy, but large players are already in the market and are assessing options for future expansion. It is likely that more players will emerge over time as the supply of EOL EDV batteries increases.

5.2 Conclusions and Recommendations

1. The supply of end-of-life electric-drive vehicles will increase significantly in North America in the coming years, from 115,000 units at the end of 2013 to 380,000 by 2020, 849,000 by 2025, and almost 1.5 million by 2030.
2. Most of the end-of-life electric-drive vehicle batteries will be produced in the United States, with much smaller numbers in Canada, and minimal numbers in Mexico, until the year 2022 and later.
3. Recycling options are already available in North America for the two types of batteries currently used in electric-drive vehicles (NiMH and Li-ion). The business is currently driven by the value of nickel and cobalt in these batteries, but the economics will change as the battery design changes to less-valuable materials.
4. The impacts of the changing battery chemistries currently being explored by battery designers, on the recycling system dynamics, need to be assessed to ensure that environmentally sound management of end-of-life electric-drive vehicle batteries continues.
5. Governments need to ensure that appropriate legislation is in place to ensure environmentally sound management of electric-drive vehicle batteries at end of life.
6. The assumptions on which sales and end-of-life projections presented in this report are based are likely to change over time. Therefore, these estimates need to be updated periodically.

Appendix A – Description of Lifespan Model Used to Develop EOL Estimates for EDV Batteries in North America

An Excel Workbook–based model (the Lifespan Model) is an analytical tool used by Kelleher Environmental in many projects, to develop estimates of end-of-life (EOL) products entering the waste and recycling stream. Most recently the Lifespan Model was used to estimate the flow of large appliances through the waste management system in British Columbia, Canada (2014). The Lifespan Model is used by Alberta Recycling Management Authority (ARMA) on an ongoing basis to estimate the flow of designated electronics through the recycling system in Alberta, Canada, and to compare actual amounts recycled with the amounts predicted to be at EOL by the Lifespan Model.

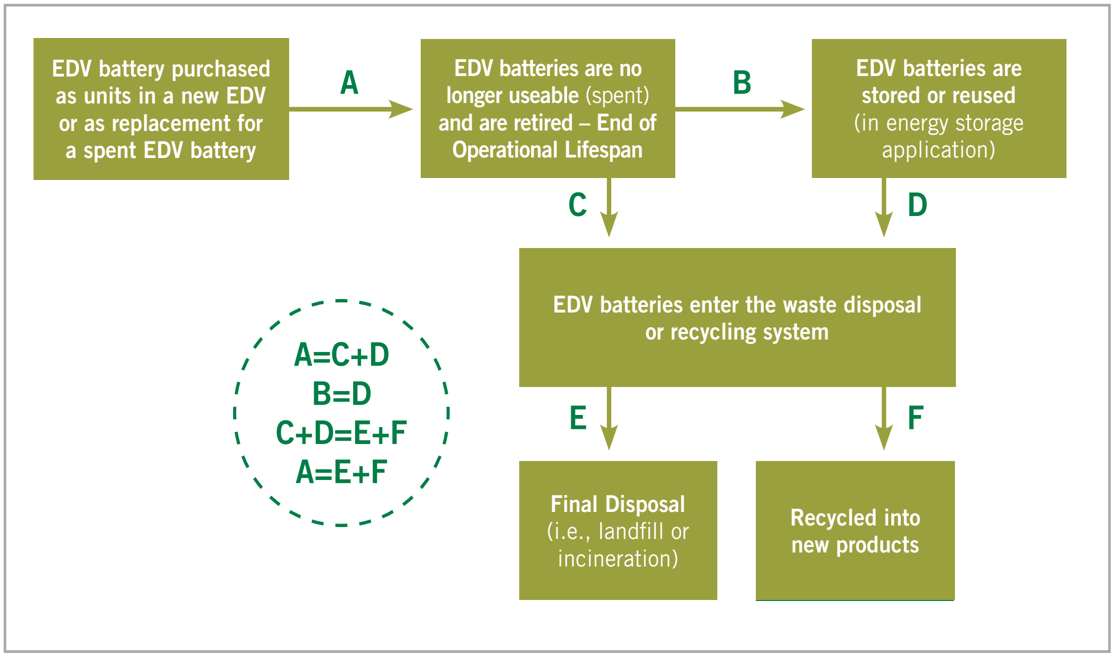
The Lifespan Model includes the following key inputs:

- Annual unit sales data, by product type (described in Section 2)
- Weight data, by battery type (described in Section 2)
- Lifespan of different battery types (described in Section 3)
- The amount of time each battery type is likely to be stored or re-used before disposal (discussed in Section 3)

The Lifespan Model is constructed to reflect the typical flow of nickel metal hydride (NiMH) and lithium-ion (Li-ion) batteries through the North American waste management system, as shown in Figure A1, and to take into account the various possible pathways.

The flow pathway is simple at this stage, given how few of these large-format batteries have reached EOL to date. Once batteries are purchased (generally in a new EDV), they are usually kept until spent. A few reach EOL because of early failures (estimated at only 1 percent of EDV batteries) or through accidents. At that time the batteries are stored, re-used (through some refurbishing), or discarded. When discarded they are either directed to recycling or disposal. Given their size, it is likely that most or all will be recycled.

Figure A1. Schematic of Mass Flow of EDV Batteries through the North American Recycling and Waste Management System, Used in the Lifespan Model to Estimate End-of-life Quantities



Note:

"A" represents the tonnage of electric-drive vehicle (EDV) batteries purchased. All "A" units will in time become retired, spent, or reach the end of their lifespan.

"B" represents EDV batteries that are stored or re-used for a period of time and eventually become discarded as well, but not immediately after they have been retired by their first owner.

"C" represents EDV batteries that are sent immediately either to a recycling facility or a waste management facility for incineration or landfilling.

The mass flow of electric-drive vehicle (EDV) batteries is determined by the simple formulae shown above.

The sum of "E" and "F" will equal "A."

All end-of-life batteries ("C" plus "D") are either recycled (i.e., "F" in Figure A1) or they are sent to final disposal in a landfill or incinerator ("E" in Figure A1).

Appendix B – Summary of Policy Instruments in Canada, Mexico and US to Encourage Purchase of EDVs

Policies Which Promote Purchase of Electric-drive Vehicles in Canada

Canada's Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations are likely to encourage the growing use of all electric vehicle types in the years to come. These national emission standards, which are the first regulated national greenhouse gas (GHG) emission standards in Canada, were established under the authority of the Canadian Environmental Protection Act and are administered by Environment Canada.[94] They took effect beginning in the 2011 model year, and are expected to become more stringent over the 2011 to 2016 model years. As a result of these regulations, it is anticipated that the average GHG emission of new vehicles in the 2016 model year will be about 25 percent lower than that of the new vehicles sold in Canada in 2008.[95]

It should be noted that while new vehicles sold in Canada must meet national emissions and safety standards administrated by the federal government, most of Canada's federal regulations for motor vehicles do not distinguish EDVs from conventional, combustion-engine vehicles.[96]

There is currently no Federal incentive program in Canada for plug-in electric vehicles (PHEVs) and all-electric vehicles (EVs).

Several Canadian provinces have implemented initiatives to support the adoption of electric-drive vehicles (EDVs, including policies to encourage the purchase, lease, or use of hybrid electric vehicles (HEVs), PHEVs, and EVs. A summary of these incentives is provided in Table B1 below.

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[94] International Energy Agency (IEA). 2012. *Hybrid and electric vehicles: The electric drive captures the imagination.* Hybrid & Electric Vehicle Implementing Agreement. <www.ieahev.org/assets/1/7/IA-HEV_2011_annual_report_web.pdf>. (Accessed 21 April 2015.)

[95] International Energy Agency (IEA). N.d. Canada: Policies and legislation. Hybrid & Electric Vehicle Implementing Agreement. <www.ieahev.org/by-country/canada-policy-and-legislation/>. (Accessed on 21 April 2015.)

[96] International Energy Agency (IEA). 2012. *Hybrid and electric vehicles: The electric drive captures the imagination.* Hybrid & Electric Vehicle Implementing Agreement. <www.ieahev.org/assets/1/7/IA-HEV_2011_annual_report_web.pdf>. (Accessed on 21 April 2015.)

Table B1. Summary of Incentives to Support Electric-drive Vehicles in Canada

Province	Policy Instrument
Quebec	**Purchase or Lease Rebate Program**[a] • The Drive Electric Program offers a purchase/lease rebate for individuals, businesses, non-profit organizations, and Quebec municipalities wishing to acquire an EV, PHEV, HEV, or low-speed electric vehicle (LSEV). • The rebate granted for an all-electric or plug-in hybrid vehicle is C$500, C$4,000 or C$8,000. (Note: The amount of the rebate is calculated according to the capacity of the vehicle's electric battery and the terms of the lease if applicable, and the vehicle must be included in the list of eligible vehicles.) • The rebate for a non-plug-in hybrid vehicle is C$500. (Note: Only hybrid vehicles registered since 1 November 2013 are eligible for a rebate at the time of purchase. This section of the program will be in effect until 31 December 2016 or until 15,000 rebates for hybrid vehicles have been granted.) • The rebate for low-speed electric vehicles is C$1,000. Those eligible for the program are those authorized to operate on Quebec roads. • The Drive Electric Program was launched on 1 January 2012 and will expire on 31 December 2016 or when the available funds are exhausted. **Charging Station Rebate** • As of 1 January 2012, until December 31st 2016, individuals who have purchased or leased an all-electric or plug-in hybrid vehicle can receive a subsidy for the purchase and installation of a 240-volt charging station at their home. The amount of the subsidy corresponds to the lesser of the following amounts: 50 percent of eligible expenses; or C$1,000.[b] • As of 1 November 2013, until 31 March 2017, subsidies for charging station in the workplace correspond to the lesser of the following amounts: 75 percent of eligible expenses; or C$5,000.[c] **Green License Plate**[d] • The license plate features green lettering and the electric vehicle pictogram and is used to identify an EV to help ensure that only EVs are parked in locations equipped with charging stations. **Electric vehicles in the government**[e] • A government directive asks that every new or replaced car should be either all electric or a plug-in hybrid. **Other** • Recharging manual, published in February 2012; designed for electricians, construction contractors, etc.[f] • Changes to the Quebec building code for new buildings: Objective is to require the installation of basic recharging infrastructure (240V) in new buildings.[g] • EVs are granted public transportation lane access on one highway through a pilot project in Quebec City.[h] • Development plan for the charging infrastructure—The Electric Circuit project—was announced in January 2012 and inaugurated on 30 March. It met its objective of having 150 recharging stations in operation by 2013. The goal is to reach 785 recharging stations in December 2016, including 60 fast charge stations.[i] • Some transit societies are to stop buying 100-percent diesel and instead choose hybrid and electric buses, to start by 2025.[j] • Subsidies to help transit companies develop and try electric buses,[k] also project with school buses.[l] • A new Electrification of Transports Action Plan with more measures will be made public in the fall of 2015 (including help for the electrification of taxis, funding to the industrial and research sectors, etc.)

Note: mg = milligram(s); m^3 = cubic meter(s).

Sources:

a. Gouvernement du Québec (Government of Quebec). 2012. Purchase or Lease Rebate Program. <http://vehiculeselectriques.gouv.qc.ca/english/particuliers/rabais.asp>. (Accessed on 21 April 2015.)

b. Gouvernement du Québec (Government of Quebec). 2012. Charging Station Rebate. <http://vehiculeselectriques.gouv.qc.ca/english/particuliers/remboursement.asp>. (Accessed on 22 July 2015.)

c. Gouvernement du Québec (Government of Quebec). 2012. Business, municipalities, organizations. <http://vehiculeselectriques.gouv.qc.ca/english/entreprises/entreprises.asp>. (Accessed on 22 July 2015.)

d. Gouvernement du Québec (Government of Quebec). 2011. *Plan d'action 2011–2020 sur les véhicules électriques*. Appendix 3: Measures for users. <www.mern.gouv.qc.ca/english/press/ev_annexe3.pdf>. (Accessed on 21 April 2015.)

e. Gouvernement du Québec (Government of Quebec). 2015. Centre de gestion de l'equippement roulant. Électrification des transports. Électrification du parc gouvernemental. <www.cger.mtq.gouv.qc.ca/virage-ecologique/electrification-des-transports/electrification-parc-gouvernemental.aspx>. (Accessed on 21 July 2015.)

f. Ibid.

g. Ibid.

h. Gouvernement du Québec (Government of Quebec). 2015. Covoiturage sur les voies réservées de l'autoroute Robert-Bourassa. Pourquoi un projet pilote? < www.mtq.gouv.qc.ca/usagers/reseauroutier/covoiturage-aut-Robert-Bourassa/Pages/default.aspx>. (Accessed on 23 July 2015.)

i. Electric circuit. 2015. <http://lecircuitelectrique.com/index.en.html> (Accessed on 23 July 2015.)

j. Societé de Transport de Montréal. 2015. Électrification du réseau de surface. *La mobilité de demain complètement électrique*. <www.stm.info/fr/a-propos/grands-projets/electrification-du-reseau-de-surface>. (Accessed on 23 July 2015.)

k. Le Huffington Post. 2015. *Québec lance un projet de 73 millions$ pour développer un autobus électrique*. <http://quebec.huffingtonpost.ca/2012/03/07/quebec-subvention-autobus-lectrique_n_1326581.html>. (Accessed on 23 July 2015.)

l. Gouvernement du Québec (Government of Quebec). 2015. Portail Québec. *Électrification des transports - Le gouvernement du Québec remet 2 M$ pour la mise en service d'autobus scolaires québécois 100 % électriques*. <www.fil-information.gouv.qc.ca/Pages/Article.aspx?aiguillage=ajd&idArticle=2302276777>. (Accessed on 23 July 2015.)

Table B1 (cont.). Summary of Incentives to Support Electric-drive Vehicles in Canada

Province	Policy Instrument
Ontario	**Electric Vehicle Incentive and Charging Incentive Program**[m] • Starting 1 July 2010, Ontario consumers (individuals, businesses, municipalities, nongovernmental organizations (NGOs), and non-profit groups) are eligible for an incentive ranging from C$5,000 to C$8,500 towards the purchase or lease of a new plug-in hybrid electric or battery electric vehicle. • The value of the incentive is based on the vehicle's battery capacity: C$5,000 for a 4 kWh battery, C$8,500 for a 17 kWh battery. • The value of the incentive for leased vehicles is scaled to the term of the lease. **Green License Plates**[n] • Special green license plates are available for eligible plug-in hybrid vehicles and battery electric vehicles. Vehicles with green plates have priority access to Ontario's high-occupancy vehicle (HOV) lanes until 30 June 2015, even if these is only one person in the vehicle. HOV lanes are otherwise restricted to vehicles carrying two or more people. • Gives access to future public charging facilities and parking at selected GO Transit lots. **City of Toronto**[o] • In February 2014, City of Toronto Council voted 31 to 12 in favor of implementing the Toronto Taxicab License (TTL), which would replace the existing standard and Ambassador licenses. Under the new system, all taxis will have to be replaced with alternative fuel or hybrid vehicles at the end of the mandatory five-year life cycle. The TTL was in effect as of 1 July 2014 and drivers will have up to 30 June 2024 to transfer over to the new license.
Manitoba	**Manitoba's Electric Vehicle Roadmap**[p] • Launched in April 2011, the Electric Vehicle Road Map aims to help the province adopt electric and hybrid vehicles; reduce its dependence on fossil fuels; and take advantage of the economic opportunities of electric transportation. • Includes Plug-in partnerships with auto manufacturers (such as Nissan Canada and Mitsubishi Motor Sales of Canada), electric technology providers, Manitoba Hydro, Manitoba companies, and academic institutions. • Proposes to create an Electric Vehicle Advisory Committee to suggest recommendations to government on the best ways to prepare for and accelerate the adoption of electric and hybrid vehicles. • Proposes to create an Electric Vehicle Learning and Demonstration Centre where various electric and plug-in electric vehicles and associated recharging equipment can be demonstrated. **Hybrid Electric Vehicle Rebate Program**[q] • Ended on 31 October 2010 (program began on 15 November 2006), it provided a C$2000 rebate on purchase of hybrid vehicle.
Alberta	**Rebate Program for Taxi Owners and Operators**[r] • Taxi owners and operators who purchase a gasoline-electric hybrid vehicle are eligible for a rebate of up to C$3,000 (retroactive to 1 July 2008).

Note: mg = milligram(s); m^3 = cubic meter(s).

Sources:

m. Ontario Ministry of Transportation. n.d. Electric vehicle incentive program. <www.mto.gov.on.ca/english/vehicles/electric/electric-vehicle-incentive-program.shtml>. (Accessed 21 April 2015.)

n. Ibid.

o. Chubb, C. 2013. Council votes in favour of Toronto taxicab licence. *CityNews Toronto*. <www.citynews.ca/2014/02/19/council-votes-in-favour-of-toronto-taxicab-licence/#__federated=1>. (Accessed on 21 April 2015.)

p. Government of Manitoba. 2011. *Manitoba's electric vehicle road map: Driving toward fossil fuel freedom*. <www.gov.mb.ca/ia/energy/transportation/images/elec_vehicle_road_map.pdf>. (Accessed on 21 April 2015.)

q. The Winnipeg Free Press. 2010. Province ending $2,000 rebate on hybrid vehicles. *The Winnipeg Free Press*. <www.winnipegfreepress.com/breakingnews/Province--104163053.html>. (Accessed on 21 April 2015.)

r. Government of Alberta. N.d. Energy efficiency rebates: Part of Alberta's climate change plan. <www.insulspan.com/newsletter/0509news/AlbertaEnvironmentEnergyRebateCard.pdf>. (Accessed on 21 April 2015.)

Table B1 (cont.). Summary of Incentives to Support Electric-drive Vehicles in Canada

Province	Policy Instrument
British Columbia	**Renewable and Low-Carbon Fuel Requirement Regulation**[s] • Requires a 10 percent reduction in transportation fuels by 2020, promoting increased sales of electricity to the transportation sector. **Clean Energy Act**[t] • Allows government to approve utility-prescribed undertakings that reduce emissions, including utility investments to increase the use of EVs and for the construction and operation of fuelling infrastructure **Electric Vehicle Charging Infrastructure Deployment Guidelines**[u] • Serve as a reference guide for utilities, creating a comprehensive plan for the emerging electrical vehicle market. **City of Vancouver**[v] • Requires all new single-family homes and off-street bicycle storage rooms to have dedicated electric plug-in outlets, and requires charging infrastructure for 20 percent of all parking stalls in new multi-unit residential buildings. • Eco-friendly taxi policy: requires all new taxis to be hybrid. **City of Kelowna**[w] • Eco-Pass Program: An Eco-Pass rewards anyone who drives a fuel-efficient hybrid vehicle by giving them free on-street parking for one year at any on-street parking meters in downtown Kelowna. **Clean Energy Vehicle Program** On 5 November 2011, the BC Government announced funding of C$14.3million for a new Clean Energy Vehicle (CEV) Program. The CEV program is a comprehensive program designed to provide British Columbians with a variety of clean and green choices for their transportation needs.[x] It included a number of incentives:[y] • CEV for BCTM Point-of-Sale Incentive Program: Provides a rebate of up to C$5,000 off the advertised price for qualifying new battery electric, fuel cell electric, plug-in hybrid electric, and compressed natural gas vehicles. • Residential Electric Vehicle Charging Station Rebate Program: Provides rebates of up to C$500 per unit for eligible residential electric charging stations. • CEV Infrastructure Program: Provides C$6.3 million for charging infrastructure and fueling infrastructure, including investments in upgrading hydrogen fueling infrastructure and the delivery of a 1,000-point Charging Infrastructure Project, with community, private sector, non-government, academic and utility partners. The CEV Point of Sale Incentive Program reached its budget limit and is fully depleted, effective 14 February 2014. The residential rebates for purchase of qualifying electric vehicle charging equipment were available until 31 March 2014. The fund for the CEV Infrastructure Program targeted the deployment of up to 570 Level 2 EV Charging stations across BC communities by 31 March 2013.[z]
Prince Edward Island	**Hybrid Vehicle Tax Refund** • Provincial Sales Tax (PST) refund up to a maximum of C$3,000 on the purchase (or 12-month-minimum lease) of a HEV. This program, the most generous in Canada, was canceled as of 1 April 2013.[aa]
Saskatchewan	**Green Rebate** • In 2012, the Saskatchewan Government vehicle insurance program canceled its green rebate for people who drive eco-friendly vehicles. Under the program, owners of hybrid (gas/electric) vehicles, as well as owners of highly fuel-efficient vehicles on a Transport Canada list, qualified for rebates. People who qualified got a 20 percent reduction on their insurance and registration. On average, SGI was paying out rebates of $210 each to 14,000 drivers in 2011.[bb]

Note: mg = milligram(s); m^3 = cubic meter(s).

Sources:

s. International Energy Agency (IEA). 2012. *Hybrid and electric vehicles: The electric drive captures the imagination*. Hybrid & Electric Vehicle Implementing Agreement. <www.ieahev.org/assets/1/7/IA-HEV_2011_annual_report_web.pdf>. (Accessed on 21 April 2015.)

t. Ibid.

u. Electric Transportation Engineering Corporation. 2009. *Electric vehicle charging infrastructure—Deployment guidelines: British Columbia*. Version 1.0. <www.ceati.com/files/ev/BC%20EV%20Charging%20Infrastructure%20Guidelines.pdf>. (Accessed on 21 April 2015.)

v. International Energy Agency (IEA). 2012. *Hybrid and electric vehicles: The electric drive captures the imagination*. Hybrid & Electric Vehicle Implementing Agreement. <www.ieahev.org/assets/1/7/IA-HEV_2011_annual_report_web.pdf>. (Accessed on 21 April 2015.)

w. City of Kelowna. 2009. Eco-pass. <www.kelowna.ca/CM/page1649.aspx>. (Accessed on 21 April 2015.)

x. Government of British Columbia. 2013. Clean energy vehicle incentive program extended. <www.newsroom.gov.bc.ca/2013/03/clean-energy-vehicle-incentive-program-extended.html>. (Accessed on 21 April 2015.)

y. International Energy Agency (IEA). 2012. *Hybrid and electric vehicles: The electric drive captures the imagination*. Hybrid & Electric Vehicle Implementing Agreement. <www.ieahev.org/assets/1/7/IA-HEV_2011_annual_report_web.pdf>. (Accessed on 21 April 2015.)

z. Government of British Columbia. N.d. Transportation rebates and incentives. *Live Smart BC*. <www.livesmartbc.ca/incentives/transportation/>. (Accessed on 21 April 2015.)

aa. Prince Edward Island Department of Finance and Energy. 2013. Revenue tax (PST) refund. <www.taxandland.pe.ca/index.php3?number=17274&lang=E>. (Accessed on 21 April 2015.)

bb. CBC. 2012. SGI green rebate program ends. CBC News. <www.cbc.ca/news/canada/saskatchewan/sgi-green-rebate-program-ends-1.1181246>. (Accessed on 21 April 2015.)

Sources of information on Canadian Policies

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- <www.ieahev.org/assets/1/7/IA-HEV_2011_annual_report_web.pdf>
- <http://negc.org/uploads/file/AFV Conference/11-ADaneau_PAVE_MRNF_Eng.pdf>
- <www.mto.gov.on.ca/english/vehicles/electric/about-electric-vehicle.shtml>
- <www.cbc.ca/news/canada/saskatchewan/sgi-green-rebate-program-ends-1.1181246>
- <www.gov.mb.ca/ia/energy/transportation/images/elec_vehicle_road_map.pdf>
- <www.fleetcarma.com/canada-electric-vehicle-policies/>
- <www.insulspan.com/newsletter/0509news/AlbertaEnvironmentEnergyRebateCard.pdf>
- <www.livesmartbc.ca/incentives/transportation/ - cevinbc>
- <www.ptboard.bc.ca/documents/2013_Eco_Friendly_Taxi_Guide.pdf>
- <www.hybridcars.com/region-by-region/>
- <www.blogto.com/city/2014/02/5_things_to_know_about_the_new_toronto_taxi_rules/>
- <www.citynews.ca/2014/02/19/council-votes-in-favour-of-toronto-taxicab-licence/>

Policies Which Promote Purchase of Electric-drive Vehicles in Mexico

The publication in June 2013 of the "Official Mexican Standard (NOM) 163, Carbon Dioxide emissions from light-weight vehicles' exhaust pipelines and their equivalence in terms of fuel economy, applicable to new automotive vehicles with a gross weight of up to 3,857 kilograms"[97] is likely to encourage the purchase of EDVs. This NOM aims to harmonize fuel economy standards for new vehicles in Mexico with applicable standards in Canada and the United States, at 14.9 kilometers per liter (35 miles per gallon).[98] This standard would meet environmental regulations in Canada and the US, where the majority of exported vehicles produced in Mexico are sold.

Although this standard does not make any reference to HEVs, and it is intended to provide incentives to automotive manufacturers to increase fuel efficiency, in the near term it is anticipated that manufactures may start introducing their HEV models in Mexico. The standard applies to 2014 models, and is expected to become more stringent for the 2015 to 2016 model years.

Some HEVs are exempt from the Mexico City Vehicular Inspection Program (referred to as the "Not Circulating Today" Program), and can travel all days of the week. The Program Agreement sets out measures to limit the movement of motor vehicles in the Federal District, in order to control and reduce air pollution and environmental impacts of vehicle traffic. Vehicles exempted from emissions testing requirement and restricted travel through the Not Circulating Today programs are listed in Table B2 below.

[97]Norma Oficial Mexicana. 2013. *Emisiones de bióxido de carbono (CO_2) provenientes del escape y su equivalencia en términos de rendimiento de combustible, aplicable a vehículos automotores nuevos de peso bruto vehicular de hasta 3 857 kilogramos (NOM-163-SEMARNAT-ENER-SCFI-2013), 21 June 2013*. <http://diariooficial.gob.mx/nota_detalle.php?codigo=5303391&fecha=21/06/2013>. (Accessed 21 April 2015.)

[98]Mexican Automotive. 2010. Questions on Official Mexican Standard 163 and its continued suspension. <http://mexicanautomotive.com/en/home/84-october-2012/364--questions-on-official-mexican-standard-163-and-its-continued-suspension>. (Accessed on 30 April 2014.)

Table B2. EDVs Exempted from the Vehicle Emissions Testing and “Not Circulating Today” Programs in Mexico

Make	Model
Hyundai	Blue City Hibrido (natural gas-electric)
Hyundai	HD 120 (natural gas)
Hyundai	Super Aero City (natural gas)
Toyota	Prius (electric-gasoline)
Vehizero	Ecco C (electric-gasoline)
Nissan	Leaf (electric)
BMW	ActiveHybrid 5 (electric-gasoline)
BMW	X6 ActiveHybrid (electric-gasoline)
BMW	Series 3 active hybrid
BMW	Mini E
Porsche	Cayenne hybrid V6 3.0
Volkswagen	Touareg hybrid V6 3.0

Source:
Secretaría del medio ambiente. N.d. Hoy No Circula. (Not Circulating Today.) Adapted from <www.sedema.df.gob.mx/sedema/index.php/component/content/article/80-verificacion-vehicular-hoy-no-circula/185-verificacion-vehicular>. (Accessed on 30 April 2014.)

Note that Honda HEV models are not included in the table above, and some of the vehicles included are not yet available commercially in Mexico. It is expected that this list will include new models in the future.

Vehicular inspection and Not Circulating Today programs also have been implemented in fifteen Mexican states: Aguascalientes, Chihuahua, Distrito Federal, Guanajuato, Hidalgo, Jalisco, Estado de México, Michoacán, Morelos, Oaxaca, Nuevo León, Puebla, Querétaro, Tlaxcala, Veracruz and Yucatán.

Economic incentives to encourage purchases of EDV have not been implemented to date in Mexico. Initiatives such as federal income tax credit for EDV purchases; reduction in the Tax on New Cars (*Impuesto sobre Automóviles Nuevos*—ISSAN); or reduction in the rates of financing for the purchase of vehicles are not in place. To implement these economic policies in Mexico would require agreement among key sectors, such as: automotive manufacturers and dealers; and the ministries of Finance (*Secretaría de Hacienda y Crédito Público*—SHCP), Environment and Natural Resources (*Secretaría de Medio Ambiente y Recursos Naturales*—Semarnat), and Health (*Secretaría de Salud*—SSa); and other, local authorities.

Policies that Promote Purchase of Electric Drive Vehicles in the United States

Many states are considering a variety of incentives to promote hybrid and plug-in electric vehicle adoption.[99] As of November 2013, 39 states and the District of Columbia have implemented incentives that would provide high-occupancy vehicle lane exemptions, monetary incentives, vehicle inspections or emissions test exemptions, parking incentives, or utility rate reductions. Monetary incentives, including tax credits and registration fee reductions, are some of the most popular ways to promote adoption. State rebates or tax credits range from US$1,000 in Maryland to US$6,000 in Colorado. At least 94 bills in 20 states were pending in 2013 that encourage the purchase and increased use of hybrids and PEVs. In New Jersey, at least 38 bills introduced in 2013 encouraged the development of alternative vehicle infrastructure, such as charging stations, providing monetary incentives for alternative vehicle purchases, and establishing additional parking for hybrids and PEVs. Additionally, utilities in Minnesota offer electricity rate reductions but no incentives enacted by the state legislature. Federal incentives help to boost hybrid and PEV use.

A federal tax credit of US$7,500 is available in addition to state incentives for electric vehicles. The tax credit will expire once 200,000 qualified PEVs have been sold by each automotive manufacturer. Other incentives include electric charging infrastructure tax credits, research project grants, alternative fuel technology loans, and establishing requirements for federal fleets.

Note: The material in this section has been compiled from the following sources:

- Hartman, K. 2015. *National Conference of State Legislatures.* "State efforts promote hybrid and electric vehicles." <www.ncsl.org/research/energy/state-electric-vehicle-incentives-state-chart.aspx#hybrid>. (Accessed on 21 April 2015.)
- Berman, B. 2010. Hybrid and plug-in incentives and rebates: Region by region. *Hybrid Cars.* <www.hybridcars.com/region-by-region/>. (Accessed on 21 April 2015.)

Hybrid and Plug-in Incentives in the US, by State[100,101]

Alabama

Equipment Tax Credit: Maximum of US$75 available to individuals for installation of EV charging outlets.

Plug-in Electric Vehicle Charging Rate Incentive: Alabama Power offers special rates for electricity purchased to charge PEVs used for residential and non-residential purposes.

Arizona

HOV Lane Exemption: Qualified alternative fuel vehicles may use designated HOV lanes regardless of the number of occupants in the vehicle.

Electric Vehicle Equipment Tax Credit: Maximum of US$75 available to individuals for installation of EV charging outlets.

Reduced Alternative Fuel Vehicle License Tax: Reduction in the annual vehicle license tax for an electric vehicle, to a minimum of US$5 per year.

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[99] Hartman, K. 2015. State efforts to promote hybrid and electric vehicles. National Conference of State Legislatures. <www.ncsl.org/research/energy/state-electric-vehicle-incentives-state-chart.aspx>. (Accessed on 21 April 2015.)

[100] Ibid.

[101] Berman, B. 2010. Hybrid and plug-in incentives and rebates: Region by region. *Hybrid Cars.* <www.hybridcars.com/region-by-region/>. (Accessed on 21 April 2015.)

Plug-in Electric Vehicle Charging Rates: Glendale Water and Power offers an electricity bill discount of US$0.33 per day to residential and commercial customers who own qualified PEVs. Also, the Arizona Public Service Company offers an electricity rate option to residential customers who own a qualified PEV.

California

HOV Lane Exemption: Qualified EVs and PHEVs may use designated HOV lanes regardless of the number of occupants in the vehicle. EVs and PHEVs are also exempt from toll fees in High Occupancy Toll (HOT) lanes.

Clean Vehicle Rebate Project (CVRP): Offers rebates for the purchase or lease of qualified vehicles. The rebates offer up to US$2,500 for light-duty, zero-emission and plug-in hybrid vehicles that the California Air Resources Board (ARB) has approved or certified.

California Alternative Energy and Advanced Transportation Financing Authority (CAEATFA): Provides financing for property used to develop and commercialize advanced transportation technologies that reduce pollution and energy use and promote economic development.

Drive Clean! Rebate Program: The San Joaquin Valley Air Pollution Control District administers the Drive Clean! Rebate Program, which provides rebates of up to US$3,000 for the purchase or lease of eligible new vehicles, including qualified natural gas and plug-in electric vehicles.

Insurance Discount: Several insurance providers offer a discount of up to 10 percent on certain insurance coverage for HEV and AFV owners.

Alternative Fuel and Vehicle Incentives: Through the Alternative and Renewable Fuel Vehicle Technology Program, the California Energy Commission provides financial incentives for businesses, vehicle and technology manufacturers, workforce training partners, fleet owners, consumers, and academic institutions, with the goal of developing and deploying alternative and renewable fuels and advanced transportation technologies.

Free EV parking: Sacramento offers free parking to individuals or small businesses certified by the city's Office of Small Business Development who own or lease EVs with an EV parking pass in designated downtown parking garages and surface lots. Vehicles must be 100 percent electric to qualify.

Free EV parking: Free metered parking in San Jose, Hermosa Beach, and Santa Monica for electric vehicles displaying a Clean Air decal.

Alternative Fuel Vehicle Parking: The California Department of General Services (DGS) and California Department of Transportation (DOT) must provide 50 or more parking spaces and park-and-ride lots owned and operated by DOT to incentivize the use of alternative-fuel vehicles.

Colorado

Alternative Fuel and Advanced Vehicle Technology Tax Credit: An income tax credit of up to US$6,000 is available for a motor vehicle that uses or is converted to use an alternative fuel, is a hybrid electric vehicle, or has its power source replaced with one that uses an alternative fuel.

Plug-in Electric Vehicle and Electric Vehicle Supply Equipment Grants: The Colorado Energy Office (CEO) and Regional Air Quality Council (RAQC) provide grants to support PEV adoption in fleets. RAQC grants cover 80 percent of the incremental cost of a qualified PEV, up to US$8,260. Both CEO and RAQC grants fund 80 percent of the cost of EVSE, up to US$6,260.

Electric Vehicle Grant Fund: Provides grants to local governments, landlords of multi-family apartment buildings, and communities to install recharging stations for electric vehicles.

Connecticut

Alternative Fuel Vehicle Funding: The Connecticut Clean Fuel Program provides funding to municipalities and public agencies which purchase, operate, and maintain alternative fuel and advanced technology vehicles, including those that operate on compressed natural gas, propane, hydrogen, and electricity.

Alternative Fuel and Hybrid Electric Vehicle Parking: Free parking on all city streets for qualified AFVs and HEVs registered in New Haven, CT.

Delaware

Vehicle-to-Grid Energy Credit: Retail electricity customers with at least one grid-integrated electric vehicle may qualify to receive kilowatt-hour credits for energy discharged to the grid from the EV's battery at the same rate that the customer pays to charge the battery.

District of Columbia

Alternative Fuel and Fuel-Efficient Vehicle Title Tax Exemption: Qualified alternative fuel vehicles are exempt from the excise tax imposed on an original certificate of title.

Reduced Registration Fee: A new motor vehicle with an average city fuel economy, estimated by the US Environmental Protection Agency, of at least 40 miles per gallon is eligible for a reduced vehicle registration fee of US$36 for the first two years of registration.

Florida

HOV Lane Exemption: Qualified EVs and PHEVs may use designated HOV lanes regardless of the number of occupants in the vehicle. The vehicle must display a decal issued by the Florida Division of Motor Vehicles, which is renewed annually. Vehicles with decals may also use any designated HOV toll lane without paying the toll.

Electric Vehicle Supply Equipment Financing: Property owners may apply to their local government for funding to help finance EVSE installations on their property or enter into a financing agreement with the local government for the same purpose.

Electric Vehicle Insurance Regulation: Protects an electric vehicle owner from premium surcharges by insurance companies.

Georgia

HOV Lane Exemption: Qualified EVs and PHEVs may use designated HOV lanes regardless of the number of occupants in the vehicle.

Alternative Fuel Vehicle Tax Credit: An income tax credit is available to individuals who purchase or lease a new dedicated AFV or convert a vehicle to operate solely on an alternative fuel. The amount of the tax credit is 10 percent of the vehicle cost, up to US$2,500.

Zero Emission Vehicle Tax Credit: An income tax credit is available for 20 percent of the cost or up to $5,000 for individuals who purchase or lease a new zero-emission vehicle.

Electric Vehicle Supply Equipment Tax Credit: An income tax credit is available for 10 percent of the cost of the electric vehicle charging equipment, up to $2,500.

Hawaii

HOV Lane Exemption: Qualified EVs and PHEVs may use designated HOV lanes regardless of the number of occupants in the vehicle.

Parking Fee Exemption: EVs with electric vehicle license plates are exempt from certain parking fees charged by any non-federal government authority.

Parking Requirement: Public parking systems with 100 parking spaces or more must include at least one designated parking space for EVs and provide an EV charging system.

Idaho

Vehicle Inspection Exemptions: HEVs and EVs are exempt from state motor vehicle inspection and maintenance programs.

Illinois

Alternative Fuel Vehicle and Alternative Fuel Rebates: The Illinois Alternate Fuels Rebate Program provides a rebate of up to US$4,000 of the cost of purchasing an alternative-fuel vehicle.

Electric Vehicle Supply Equipment Rebates: The Illinois Department of Commerce and Economic Opportunity provides rebates to offset the cost of Level 2 EVSE. The maximum possible total rebate award is US$49,000 or 50 percent of the total project cost for up to 15 EVSE, whichever is less.

Electric Vehicle Registration Fee Reduction: The owner of an EV may register for a discounted registration fee not to exceed US$35 for a two-year registration period or US$18 for a one-year registration period.

Plug-in Electric Vehicle and Infrastructure Grants: Car-sharing organizations located and operating in Illinois may be eligible for grants of up to 25 percent of qualifying project costs, including the cost of purchasing new PEV and building charging infrastructure.

Indiana

Plug-in Electric Vehicle Charging Rate Incentive: Indianapolis Power & Light Company (IPL) offers special plug-in EV charging rates for residential and fleet customers who own a licensed electric or plug-in electric vehicle.

Electric Vehicle Supply Equipment Credit and Charging Incentive: NIPSCO's IN-Charge Electric Vehicle Program offers a credit of up to US$1,650 to purchase and install residential EVSE, as well as free plug-in electric vehicle charging during off-peak hours.

Iowa

Alternative Fuel Vehicle Demonstration Grants: The Iowa Department of Natural Resources conducts marketing and education outreach to encourage the use of alternative fuels and, contingent upon funding, awards demonstration grants to individuals who purchase vehicles that operate on alternative fuels, including electricity.

Reduced Registration Fee: The annual registration fee for an EV is US$25 unless the vehicle is more than five model years old, in which case the annual registration fee is reduced to US$15.

Louisiana

Alternative Fuel Vehicle and Fueling Infrastructure Tax Credit: An income tax credit is available for 50 percent of the cost of converting or purchasing an alternative fuel vehicle or constructing an alternative fueling station. Alternatively, a tax credit of 10 percent of the cost of the motor vehicle, up to US$3,000 is available for alternative fuel vehicles registered in the state.

Authorization for Alternative Fuel Vehicle Loans: The Louisiana Department of Natural Resources will administer the AFV Revolving Loan Fund to provide loan assistance to local government entities, including cities, parishes, school boards, and local municipal subdivisions for the cost of converting conventional vehicles to operate on alternative fuels, or the incremental cost of purchasing new alternative-fuel vehicles (AFVs).

Maine

Provision for Establishment of Clean Fuel Vehicle Insurance Incentives: An insurer may credit or refund any portion of the premium charged for an insurance policy on a clean fuel vehicle in order to encourage its policyholders to use clean fuel vehicles.

Maryland

Plug-in Electric Vehicle Tax Credit: Effective 1 July 2013 through 30 June 2014, a tax credit of up to US$1,000 is available against the excise tax imposed for the purchase of a qualified plug-in electric vehicle.

Electric Vehicle Supply Equipment Tax Credit: The Maryland Energy Administration (MEA) offers an income tax credit equal to 20 percent of the cost of qualified EVSE. The credit may not exceed the lesser of US$400 or the state income tax imposed for that tax year.

Michigan

Electric Vehicle Supply Equipment Rebate: Indiana Michigan Power provides rebates of up to US$2,500 to residential customers who purchase or lease a new plug-in electric vehicle and install a Level 2 EVSE with a separate meter. Customers must also sign up for the Indiana Michigan Power PEV time-of-use rate. The rebate is available to the first 250 qualified customers who submit a completed application. Consumers Energy provides qualified customers with a reimbursement of up to US$2,500 to cover the purchase, installation, and wiring for qualified Level 2 electric vehicle supply equipment. Additionally, DTE Energy will provide up to US$2,500 for the purchase and installation of separately metered EVSE to the first 2,500 qualified customers who purchase PEVs and enroll in the DTE PEV rate.

Plug-in Electric Vehicle Charging Rate Reduction: Indiana Michigan Power and Consumers Energy offer a special time-of-use rate option to residential customers who own a qualified PEV. DTE Energy offers a reduced electricity rate to qualified residential customers for charging PEVs during off-peak hours.

Vehicle Inspection Exemption: Alternative fuel vehicles are exempt from emissions inspection requirements.

Minnesota

Plug-in Electric Vehicle Charging Rate Reduction: Dakota Electric offers a discounted rate for electricity used to charge electric vehicles during off-peak times.

Mississippi

Revolving Loan Fund: Effective 3 July 2013, the Mississippi Development Authority must establish a revolving loan program to provide zero-interest loans for public school districts and municipalities to purchase alternative fuel school buses and other motor vehicles, convert school buses and other motor vehicles to use alternative fuels, purchase alternative fuel equipment, and install fueling stations.

Missouri

Vehicle Inspection Exemption: Alternative fuel vehicles are exempt from state emissions inspection requirements.

Montana

Alternative Fuel Vehicle Conversion Tax Credit: Businesses or individuals are eligible for an income tax credit of up to 50 percent of the equipment and labor costs for converting vehicles to operate using alternative fuels.

Nebraska

Alternative Fuel Vehicle and Fueling Infrastructure Loans: The Nebraska Energy Office administers the Dollar and Energy Saving Loan Program, which provides low-cost loans for a variety of alternative fuel projects, including the replacement of conventional vehicles with AFVs, the purchase of new AFVs, the conversion of conventional vehicles to operate on alternative fuels, and the construction or purchase of a fueling station or equipment.

Nevada

HOV Lane Exemption: Qualified EVs and PHEVs may use designated HOV lanes regardless of the number of occupants in the vehicle.

Plug-in Electric Vehicle Charging Rate Incentive: NV Energy offers discounted electricity rates to residential customers who charge electric or plug-in hybrid electric vehicles during off-peak hours.

Hybrid Taxicab Exemption: Qualified electric vehicles operating as taxicabs may remain in operation for an additional 24 months beyond the existing limits. Existing limits restrict vehicles used as taxicabs to operate for a period of up to 67 months for new vehicles or 55 months for used vehicles with less than 30,000 miles on the odometer.

Vehicle Inspection Exemption: AFVs are exempt from emissions testing requirements. A new HEV is exempt from emissions inspection testing for the first six years, after which the vehicle must comply with emissions inspection testing requirements on an annual basis.

Parking Fee Exemption: All local authorities with public metered parking areas within their jurisdiction must establish a program for AFVs to park in these areas without paying a fee.

New Jersey

HOV Lane Exemption: Qualified vehicles may use the HOV lanes located between Interchange 11 and Interchange 14 on the New Jersey Turnpike.

Vehicle Toll Incentive: The New Jersey Turnpike Authority offers a 10 percent discount on off-peak toll rates on the New Jersey Turnpike and Garden State Parkway through NJ EZ-Pass for drivers of vehicles that have a fuel economy of 45 miles per gallon or higher and meet the California Super Ultra Low Emission Vehicle standard. Discount will expire 30 November 2013.

Zero Emissions Vehicle Tax Exemption: ZEVs sold, rented, or leased in New Jersey are exempt from state sales and use tax.

New York

HOV Lane Exemption: Through the Clean Pass Program, eligible hybrid and EVs may use the Long Island Expressway HOV lanes.

Alternative Fuel Vehicle Recharging Tax Credit: S.B. 2609 and A.B. 3009, passed in 2013, provide a tax credit for 50 percent of the cost, up to US$5,000, for the purchase and installation of alternative fuel vehicle refueling and electric vehicle recharging property. The credit is available through 31 December 2017.

North Carolina

HOV Lane Exemption: Qualified EVs and PHEVs may use designated HOV lanes regardless of the number of occupants in the vehicle.

Electric Vehicle Financing: The Local Government Federal Credit Union offers green vehicle loans to purchase qualified new and used fuel-efficient vehicles. The loan interest rates are 0.5 percent lower than traditional new or used vehicle loan rates.

Vehicle Inspection Exemption: Qualified PEVs are exempt from state emissions inspection requirements.

Ohio

Alternative Fuel and Fueling Infrastructure Incentives: The Alternative Fuel Transportation Grant Program provides grants and loans for up to 80 percent of the cost of purchasing and installing fueling facilities offering alternative fuels.

Oklahoma

Alternative Fueling Infrastructure Tax Credit: For tax years beginning before 1 January 2015, a tax credit is available for up to 75 percent of the cost of alternative fueling infrastructure, including electric vehicle charging stations.

Alternative Fuel Vehicle Tax Credit: For tax years beginning before 1 January 2015, a one-time income tax credit is available for 50 percent of the incremental cost of purchasing a new original equipment manufacturer AFV or converting a vehicle to operate on an alternative fuel. The state also provides a tax credit for 10 percent of the total vehicle cost, up to US$1,500, if the incremental cost of a new AFV cannot be determined or when an AFV is resold, as long as a tax credit has not been previously taken on the vehicle.

Vehicle Manufacturing Tax Credit: Vehicle manufacturers are eligible for a tax credit for EVs, including low- and medium-speed EVs, manufactured on or after 1 July 2010. EVs that can legally be operated on interstate highways and turnpikes in the state are eligible for a US$2,000 credit per vehicle.

Oregon

Alternative Fueling Infrastructure Tax Credit for Residents: Through the Residential Energy Tax Credits program, qualified residents may receive a tax credit for 25 percent of alternative fuel infrastructure project costs, up to US$750.

Alternative Fueling Infrastructure Tax Credit for Businesses: Business owners and others may be eligible for a tax credit of 35 percent of eligible costs for qualified alternative fuel infrastructure projects.

Pollution Control Equipment Exemption: Dedicated original equipment manufacturer natural gas and electric vehicles are not required to be equipped with a certified pollution control system.

Alternative Fuel Vehicle Loan Program: S.B. 583 establishes the Alternative Fuel Vehicle Revolving Fund, which permits public bodies to borrow from the fund to purchase alternative fuel vehicles.

Pennsylvania

Alternative Fuel Vehicle Funding: The Alternative Fuels Incentive Grant (AFIG) Program provides financial assistance for qualified projects and information on alternative fuels, including plug-in hybrid electric vehicles. The AFIG Program also offers Alternative Fuel Vehicle Rebates to assist with the incremental cost of the purchase of new AFVs. Rebates of US$3,000 are available for qualified EVs and PHEVs.

Plug-in Electric Vehicle Rebate: PECO provides rebates of US$50 to residential customers who purchase a new, qualified PEV.

Rhode Island

Alternative Fuel Vehicle Tax Exemption: The town of Warren may allow excise tax exemptions of up to US$100 for qualified AFVs registered in Warren.

South Carolina

Plug-in Hybrid Electric Vehicle Tax Credit: For taxable years before 2017, an income tax credit is available for the in-state purchase or lease of a new PHEV. The credit is equal to US$667, plus US$111 if the vehicle has at least five kWh of battery capacity, plus an additional US$111 for each additional kWh, with a maximum allowed credit of US$2,000.

Fuel Cell Vehicle Tax Credit: Residents who claim the federal fuel cell vehicle tax credit are eligible for a state income tax credit equal to 20 percent of the federal credit.

Tennessee

HOV Lane Exemption: Qualified EVs and PHEVs may use designated HOV lanes regardless of the number of occupants in the vehicle.

Texas

Alternative Fueling Infrastructure Grants: The Texas Commission on Environmental Quality administers the Alternative Fueling Facilities Program, which provides grants for 50 percent of eligible costs, up to US$500,000 to construct, reconstruct, or acquire a facility to store, compress, or dispense alternative fuels, including electricity, in Texas air quality nonattainment areas.

Electric Vehicle Supply Equipment Incentive: Austin Energy customers who own a plug-in electric vehicle are eligible for a rebate of 50 percent or up to US$1,500 of the cost to purchase and install a qualified Level 2 EVSE.

Free Hybrid Parking: Free metered parking at all downtown parking meters in San Antonio. Vehicles must display hybrid vehicle placard.

Utah

HOV Lane Exemption: Qualified vehicles may use designated HOV lanes regardless of the number of occupants in the vehicle. Vehicles must display a special clean fuel decal issued by the Utah Department of Transportation.

Alternative Fuel Tax Exemption: Propane, compressed natural gas, liquefied natural gas, and electricity used to operate motor vehicles are exempt from state fuel taxes.

Alternative Fuel and Fuel Efficient Vehicle Tax Credit: H.B. 96, enacted in 2013, provides that new clean fuel vehicles that meet air quality and fuel economy standards may be eligible for a credit of US$605, including certain electric and hybrid electric vehicles. An income tax credit is also available for 50 percent or up to US$2,500 of the cost to convert a vehicle to run on propane, natural gas, or electricity.

Free Electric Vehicle Parking: Free metered parking in Salt Lake City for electric vehicles displaying a Clean Air license plate.

Vermont

Alternative Fuel and Advanced Vehicle Research and Development Tax Credit: Vermont businesses that qualify as a high-tech business involved exclusively in the design, development, and manufacture of alternative-fuel vehicles, hybrid electric vehicles, all-electric vehicles, or energy technology involving fuel sources other than fossil fuels are eligible for up to three of the following tax credits: 1) payroll income tax credit; 2) qualified research and development income tax credit; 3) export tax credit; 4) small business investment tax credit; and 5) high-tech growth tax credit.

Virginia

HOV Lane Exemption: For HOV lanes serving the I-95/I-395 corridor, only registered vehicles displaying Clean Special Fuel license plates issued before 1 July 2006 are exempt from HOV lane requirements. For HOV lanes serving the I-66 corridor, only registered vehicles displaying Clean Special Fuel license plates issued before 1 July 2011 are exempt from HOV lane requirements.

Alternative Fuels Grants and Loans: The Alternative Fuels Revolving Fund is used to distribute loans and grants to state and local government agencies to support AFV programs, pay for AFV maintenance, operation, evaluation, or testing, pay for vehicle conversions, or improve alternative fuel infrastructure.

Plug-In Electric Vehicle Charging Rate Reduction: Dominion Virginia Power offers discounted electricity rates to residential customers who charge electric vehicles during off-peak hours.

Alternative Fuel Vehicle Conversion Fund: Assists state agencies with the incremental cost of converting of an existing state-owned vehicle to use an alternative fuel, or with the cost differential between a traditional vehicle and one that uses alternative fuel.

Vehicle Inspection Exemption: Alternative fuel and hybrid electric vehicles are exempt from emissions testing.

Washington

Alternative Fuel Vehicle Tax Exemption: New passenger cars, light-duty trucks, and medium-duty passenger vehicles that are dedicated alternative fuel vehicles are exempt from the state motor vehicle sales and use taxes.

Plug-in Electric Vehicle Demonstration Grants: The Washington Department of Commerce administers the Vehicle Electrification Demonstration Grant Program, part of the Energy Freedom Program. Eligible applicants are state agencies, public school districts, public utility districts, or political subdivisions of the state. Grants may be awarded for projects involving the purchase or conversion of existing vehicles to PEVs for use in an applicant's fleet or operations.

Electric Vehicle Infrastructure and Battery Tax Exemptions: Public lands used for installing, maintaining, and operating EV infrastructure are exempt from leasehold excise taxes until 1 January 2020. Additionally, the state sales and use taxes do not apply to EV batteries; labor and services for installing, repairing, altering, or improving EV batteries and EV infrastructure; and the sale of property used for EV infrastructure.

Vehicle Inspection Exemption: Alternative fuel and hybrid electric vehicles are exempt from emissions testing.

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