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FINAL PROJECT REPORT

THE MARKET IMPACT OF STANDARDIZED DESIGN IN COMMERCIAL PEV BATTERY PACK PURCHASE AND DISPOSAL

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Transportation

The Market Impact of Standardized Design in Commercial PEV Battery Pack Purchase and Disposal is the final report for the CEC-PIR-12-005 project conducted by Electricore, Inc., Ricardo, Inc., Center for Sustainable Energy (CSE) formally California Center for Sustainable Energy (CCSE), San Diego Gas & Electric, and BMW of North America, LLC. The information from this project contributes to PIER's Transportation Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

Plug-in electric vehicles (PEVs) face market barriers due to the high cost of battery packs. Standardized design methods are necessary in order to optimize the performance of commercial PEV battery systems and to reduce the cost of purchasing, repurposing, and disposing of them. The California Energy Commission has identified the need for a techno-economic assessment of PEV battery system standards. In the past, standardization of battery system design created potential for battery life cycle cost savings, improved reliability , and greater quality control[1].

Focusing on Class 3 through 8 commercial vehicles, the quantitative and measurable goals of this project include:

- Translate stakeholder requirements into battery system design requirements
- Estimate the life-cycle cost impacts of the design and process changes required for standardized designs, including the impact on commercial vehicle manufacturing and design, commercial vehicle competitiveness with other technologies, and battery removal and re-manufacturing costs.
- Examine the holistic impact of design standardization on the cost of Commercial PEV batteries in dollars per kilowatt hour ($/kWh).
- Collect and describe lessons learned on battery system standardization efforts from Original Equipment Manufacturers (OEMs), utilities, Energy Services Companies (ESCOs), and battery pack manufacturers.
- Determine the stakeholder requirements for a standardized commercial PEV battery system that will be repurposed into a stationary application after it has completed its useful life in the vehicle.
- Make recommendations on methods to implement PEV system standards.

The objectives of this project are to:

- Evaluate how standard system designs compare to the current state non-standard systems in their ability to meet OEM, vehicle customer, remanufacturer, and second use requirements: performance; form factor; manufacturability and re-manufacturability; cost; and longevity.
- Quantify the impact on battery system cost in $/kWh of standardization for each stakeholder in the battery pack value chain.
- Identify the barriers to standardizing battery system design.
- Quantify the size of the secondary market for battery packs sold to ESCOs.

[1] According to "Study Into the Impact of Standardization" - a report by the Impacts of Standards Users Group

- Quantify the added value for a standard system compared to a non-standard system when sold to secondary applications markets.
- Identify and evaluate potential pathways for implementation of PEV battery pack standards.

Keywords: battery, standardization, second use, standardized design, plug-in electric vehicle, PEV, battery pack, stationary application, battery recycling

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TABLE OF CONTENTS

Acknowledgements ..... **i**

PREFACE ..... **ii**

ABSTRACT ..... **iii**

TABLE OF CONTENTS ..... **v**

LIST OF FIGURES ..... **viii**

EXECUTIVE SUMMARY **1**

Project Purpose 1

CHAPTER 1: Market Analysis: Supply vs. Demand **12**

1.1 Executive Summary 12

1.1.1 Employ Adoption Rate Model to Forecast Second use Supply 12

1.1.2 Employ Market Research to Forecast Second use Demand 19

1.1.3 Forecast of Utility Grid Lithium-Ion Battery Energy Storage Demand 20

1.1.4 Comparison: Supply vs. Demand 20

1.2 Overview: Market Analysis: Supply vs. Demand 21

1.2.1 Supply of Second use Commercial, Electric-Drive Vehicle Batteries 21

1.2.2 Demand Side Analysis: Forecast of Utility Grid Need for Lithium-Ion Battery Energy Storage Through 2025 146

1.2.3 Chapter 1 Summary and Conclusions 155

1.3 Chapter 1 References 159

CHAPTER 2: Barriers Analysis: Industry Reluctance **168**

2.1 Executive Summary 168

2.1.1 Identification of Key Barriers to Module/Battery System Standardizaton 168

2.1.2 Approaches to Overcoming Identified Barriers 169

2.2 Barriers Analysis: Industry Reluctance Overview 170

2.3 Supply Side Industry Interviews 173

2.4 Supply Side Barriers 179

2.4.1 Technical and Commercial Barriers: Results of Interviews and Literature Review 179

2.4.2 Overcoming Identified Supply-Side Barriers to Standardization 184

2.5 Demand Side Barriers 197

2.5.1 Suitability of Range of Voltages and Watt-Hours for Utility Second use Applications 197

2.5.2 Resistance Range and State of Battery Health 198

2.5.3 Alternative Approaches to Integration without Standardization 199

2.6 Demand Side Industry Interviews 200

2.7 Demand Side Evaluation of Alternative Approaches 200

2.8 Chapter 2 Barriers Analysis Summary and Conclusions 202

2.9 Chapter 2 References 205

CHAPTER 3: Design Concepts: Standards Design 206

3.1 Executive Summary 206

3.2 Introduction to Design Concepts: Standardized Design Scope of Work 208

3.3 Development of Standardized Lithium-Ion Module Design Concepts 210

3.3.1 Standardized Module and Battery System Requirements 212

3.3.2 Module BMS Interface - Digital 216

3.3.3 Module BMS Interface – Analog 216

3.4 Benchmark Current Designs and Map Current Communications Protocols 217

3.4.1 Battery System Specifications 218

3.4.2 Communications and Serial Data Interfaces 230

3.4.3 Module Specification Summary 230

3.5 Cost/Benefit Analysis of Standardization Impacts on First use Li-Ion Battery System 233

3.5.1 Cost/Benefit Analysis of Standardization Value Chain Analysis 233

3.6 Design for Second use and Recycling: Demonstration of Second use Battery Energy Storage System 245

3.6.1 BMS Architecture Overview 245

3.6.2 BMW UC San Diego B2L System Overview 246

3.6.3 Communications Protocols 248

3.6.4 Project Implications for B2L Standardization 249

3.7 Evaluation of Pathways for Implementing PEV Battery Pack Standards 249

3.8 Chapter 3 Summary and Conclusions 250

3.9 Chapter 3 References 252

CHAPTER 4: Value Analysis: Financial Benefit 255

4.1 Executive Summary 255

4.1.1 Sub-Task 1: Impact of Standardization on Each Stage of Value Chain 257

4.1.2 Sub-Task 2: Evaluation of Incentives and Disincentives to Each Stakeholder for Adopting Standardized Designs 258

4.1.3 Sub-Task 3: Assign Generalized Recommendations for Each Suggested Configuration of Standardized Modules 259

4.1.4 Sub-Task 4: Evaluating Pathways for Implementing Standardized Modules 260

4.2 Sub-Task 1: Impact of Standardization on Each Stage of Value Chain: Economic Benefits, Standardized Compared to Non-Standardized Modules and Battery Systems 262

4.2.1 Industry Interviews: Overview 262

4.2.2 Industry Interviews: Cost and Performance Impacts of Standardization and Battery Safety 263

4.2.3 Industry Interviews: Value Impact of Standardization on Industry Stakeholders 264

4.2.4 Impact of Standardization on Module and Battery System First Use Price Projections 265

4.2.5 Research Results: Assessment of Battery Prices at Start of First Use Application 266

4.2.6 Determination of Residual Value of Battery Systems at End of First Use 267

4.2.7 Value Analysis: Second Use Module and Battery Systems 272

4.3 Sub-Task 2: Evaluation of Incentives and Disincentives to Each Stakeholder for Adopting Standard Designs 300

4.3.1 Industry Interviews: Non-Cost Impacts of Standardization on Industry Stakeholders 301

4.3.2 Other Comments Regarding Incentives and Disincentives for Adopting Standardized Designs 302

4.3.3 Current Industry Standards for Rechargeable Energy Storage Systems 303

4.4 Sub-Task 3: Assign Generalized Recommendations for Each Suggested Configuration of Standardized Modules 306

4.4.1 Guidelines: Designing Li-Ion Modules and Battery Systems for Recyclability 306

4.4.2 Generalized Recommendations for First Use Standardized Modules and Battery Systems 307

4.5 Sub-Task 4: Evaluation of Potential Pathways for Implementing Standardized Modules and Battery Systems 309

4.5.1 Industry Interviews: Pathways for Implementing Standards 309

4.5.2 Potential Pathways to Lithium-Ion System Standardization 309

4.6 Chapter 4 Summary and Conclusions 310

References 313

ESCT Model References 317

Glossary 318

APPENDIX A: Market Analysis: Supply vs. Demand A-1

APPENDIX B: Alternative Technical Approaches to Integration without Standardization .. B-1

APPENDIX C: Value Analysis C-1

LIST OF FIGURES

Figure 1: United States and California Icons 13

Figure 2: Vehicle Vocations included in current study 13

Figure 3: Projected Number of Second use Battery Packs by Year through 2025 Originating from Selected Vehicle Vocations (Entire US) 15

Figure 4: Number of Battery Packs Available for Second use by Year through 2025 Originating from Selected Vehicle Vocations (Entire US) 15

Figure 5: Projected Energy Capacity of Second use Battery Packs by Year through 2025 Originating from Selected Vehicle Vocations (Entire US) 16

Figure 6: Energy Capacity of Battery Packs Available for Second use (GWh) by Year through 2025 Originating from Selected Vehicle Vocations (Entire US) 16

Figure 7: Projected Number of Second use Battery Packs by Year through 2025 Originating from Selected Vehicle Vocations within California 17

Figure 8: Number of Battery Packs Available for Second use by Year through 2025 Originating from Selected Vehicle Vocations within California 17

Figure 9: Projected Energy Capacity of Second use Battery Packs by Year through 2025 Originating from Selected Vehicle Vocations within California 18

Figure 10: Energy Capacity of Battery Packs Available for Second use (MWh) by Year through 2025 Originating from Selected Vehicle Vocations within California 18

Figure 11: Summary of Lithium-Ion Energy Storage Systems Demand through 2025 19

Figure 12: Comparison of Projected Second use Lithium-Ion Battery Systems Originating with Commercial Vehicles to Stationary Energy Storage Systems Demand through 2025 20

Figure 13: Projected Second use Battery Pack Supply vs. Projected Second use Demand for Entire US 21

Figure 14: Approach to Developing Supply Forecast 21

Figure 15: Task Interaction: Supply Side Second use Battery Forecast 23

Figure 16: Example Populations of Various Vehicle Vocations: California Market Segments 24

Figure 17: United States Light Vehicle Classifications by GVW 24

Figure 18: Vehicle Classification Definitions 25

Figure 19: Total CA Vehicle Population and Annual CA New Vehicle Registrations 26

Figure 20: Candidate Sources of Vehicle Battery Packs: Electric Commercial Vehicles (ECVs) ... 28

Figure 21: Other Candidate Sources of Vehicle Battery Packs: (Excluded from Current Study) . 28

Figure 22: Total New Vehicle Registrations: 2012, Commercial Vehicles Classes 3-7, for Entire US 29

Figure 23: New Vehicle Registrations by Year, Classes 3-7, for Entire US 30

Figure 24: New Vehicle Registrations by Year, Classes 3-7, for Entire US 30

Figure 25: Analysis of 2012 United States New Vehicle Registrations 31

Figure 26: Commecial Vehicle Vocations associated with IHS (Polk) Vehicle Registration Data Base 31

Figure 27: Data Base Categories Corresponding to Selected Vocations 32

Figure 28: Annual Miles Traveled for Indicated Vocations 32

Figure 29: Portion of Miles Traveled within Defined Speed Ranges (Bins) 33

Figure 30: Ricardo's TCO and Adoption Rate Determination Process 34

Figure 31: Vehicle TCO 34

Figure 32: Total Cost of Ownership Model Input Parameters for Selected Vocational Vehicles . 35

Figure 33: Total Cost of Ownership includes Infrastructure Requirements for ECVs and PHECVs 36

Figure 34: Number of Second use Batteries and Capacities for Selected Commercial Vehicle Vocations 36

Figure 35: Duty Cycle and Battery Pack Capacity Determines Number of Charge/Discharge Cycles and Depth of Discharge 37

Figure 36: Additional Inputs to TCO Model 37

Figure 37: Example Duty Cycle for Class 4-6 Urban Delivery Trucks 38

Figure 38: Additional Inputs to Total Cost of Ownership Models 39

Figure 39: California Incentive Programs for Commercial EVs, PHEVs, and HEVs 40

Figure 40: United States Incentive Programs for Commercial EVs, PHEVs, and HEVs 41

Figure 41: United States Incentive Programs for Commercial EVs, PHEVs, and HEVs 42

Figure 42: End Use Prices (nominal cents per kilowatt-hour): All Sector Average 43

Figure 43: Pack Specific Cost Projections – PHEV / EV's (Li-ion) 44

Figure 44: Battery Cost Forecasts: Input to TCO Model 45

Figure 45: Payback Periods for Incremental Cost of EV, HEV, or PHEV Drive Systems based on output of Total Cost of Ownership Models. 46

Figure 46: Adoption Rate Categories 47

Figure 47: Adoption Rate Model 48

Figure 48: Class 3 Service Van Sales (ECV's and PHECVs) without Incentives, Entire US 49

Figure 49: Class 3 ECV and PHECV Service Vans Projected New United States Vehicle Registrations without Incentives 50

Figure 50: Class 3 Service Van Sales (ECVs and PHECVs) with Incentives, Entire US 51

Figure 51: Class 3 ECV and PHECV Service Vans Projected New Vehicle Registrations with Incentives, Entire US 52

Figure 52: Class 6 Box Truck Sales (ECVs and PHECVs) without Incentives, Entire US 53

Figure 53: Class 6 ECV and PHECV Box Trucks Projected New Vehicle Registrations without Incentives, Entire US 54

Figure 54: Class 6 Box Truck Sales (ECVs and PHECVs) with Incentives, Entire US 55

Figure 55: Class 6 ECV and PHECV Box Trucks Projected New Vehicle Registrations with Incentives, Entire US 56

Figure 56: Class 4-6 Urban Delivery (ECVs) without Incentives, Entire US.....57

Figure 57: Class 4-6 ECV Urban Delivery Trucks Projected New Vehicle Registrations without Incentives, Entire US.....58

Figure 58: Class 4-6 Urban Delivery Sales (ECVs) with Incentives, Entire US.....59

Figure 59: Class 4-6 ECV Urban Delivery Trucks Project New Vehicle Registrations with Incentives, Entire US.....60

Figure 60: Class 7-8 City Transit Bus Sales (ECVs, HCEVs and PHECVs) without Incentives, Entire United States 61

Figure 61: Class 7-8 ECV, PHECV, and HECV City Transit Bus Projected New Vehicle Registrations without Incentives, Entire US 62

Figure 62: Class 7-8 Transit Buses (ECVs, HCEVs and PHECVs) with Incentives, Entire US.....63

Figure 63: Class 7-8 ECV, PHECV, and HECV City Transit Bus Projected New Vehicle Registrations with Incentives, Entire US 64

Figure 64: Class 4-6 Work Truck Sales (PHECVs) without Incentives, Entire US 65

Figure 65: Class 4-6 PHECV Work Trucks Projected new Vehicle Registrations without Incentives, Entire US.....66

Figure 66: Class 4-6 Work Truck Sales (PHECVs) with Incentives, Entire US 67

Figure 67: Class 4-6 PHECV Work Trucks Projected New Vehicle Registrations with Incentives, Entire US.....68

Figure 68: Class 3-6 Shuttle Bus Sales (ECVs and PHECVs) without Incentives, Entire US.....69

Figure 69: Class 3-6 ECV and PHECV Shuttle Buses Projected New Vehicle Registrations without Incentives, Entire US.....70

Figure 70: Class 3-6 Shuttle Bus Sales (ECVs and PHECVs) with Incentives, Entire US.....71

Figure 71: Class 3-6 ECV and PHECV Shuttle Buses Projected New Vehicle Registrations with Incentives, Entire US.....72

Figure 72: Examples of Electric Drive Vehicles and Manufacturers.....73

Figure 73: Manufacturers of Commercial Electric Vehicles (1 of 2).....74

Figure 74: Manufacturers of Commercial Electric Vehicles (2 of 2).....75

Figure 75: Commercial Hybrid Electric and Plug-In Hybrid Electric Commercial Vehicles (1 of 2) 76

Figure 76: Commercial Hybrid Electric and Plug-In Hybrid Electric Commercial Vehicles (2 of 2) 77

Figure 77: Available or Upcoming Plug-in Vehicles (1 of 2) 78

Figure 78: Available or Upcoming Plug-in Vehicles (2 of 2) 79

Figure 79: California Truck Registrations by Vehicle Model Year: Data for Calendar Year 2012 80

Figure 80: Class 3, 6, and 8 Vehicles Account for Approximately 2/3 of Medium and Heavy Duty CV Populations in California 81

Figure 81: California Truck Registrations by Model Year 81

Figure 82: Heavy Duty and Medium Duty Electric Commercial Vehicle Populations 2003 – 2011, Entire US 82

Figure 83: California New Class 3 Commercial Vehicle Registrations 83

Figure 84: California New Class 4 Commercial Vehicle Registrations 83

Figure 85: California New Class 5 Commercial Vehicle Registrations 84

Figure 86: California New Class 6 Commercial Vehicle Registrations 84

Figure 87: California New Class 7 Commercial Vehicle Registrations 85

Figure 88: California New Class 8 Commercial Vehicle Registrations 86

Figure 89: ECV Registrations in California from 2002 to 2012 87

Figure 90: California Class 3 Service Van New Vehicle Registrations by Calendar Year 88

Figure 91: California Class 3-6 Shuttle Bus New Vehicle Registrations by Calendar Year 89

Figure 92: California Class 6 Box Truck New Vehicle Registrations by Calendar Year 90

Figure 93: California Class 4-6 Urban Delivery Truck New Vehicle Registrations by Calendar Year 90

Figure 94: California Class 7-8 Transit Buses (including school buses) New Vehicle Registrations by Calendar Year 91

Figure 95: California Class 7-8 Transit Buses (excludes school buses) New Vehicle Registrations by Calendar Year 92

Figure 96: California Class 4-6 Work Truck New Vehicle Registrations by Calendar Year 92

Figure 97: United States Class 3 New Vehicle Registrations by Calendar Year, Entire United States 93

Figure 98: United States Class 4 New Vehicle Registrations by Calendar Year 94

Figure 99: United States Class 5 New Vehicle Registrations by Calendar Year 94

Figure 100: United States Class 6 New Vehicle Registrations by Calendar Year 95

Figure 101: United States Class 8 New Vehicle Registrations by Calendar Year 96

Figure 102: Class 3 Service Van New Vehicle Registrations by Calendar Year, Entire United States 97

Figure 103: Class 3-6 Shuttle Buses New Vehicle Registrations by Calendar Year, Entire United States 98

Figure 104: Class 6 Box Trucks: New Vehicle Registrations by Calendar Year, Entire United States 99

Figure 105: Class 4-6 Urban Delivery Trucks: New Vehicle Registrations by Calendar Year, Entire United States 99

Figure 106: Class 7-8 Transit Buses (all buses): New Vehicle Registrations by Calendar Year, Entire United States 100

Figure 107: United States Class 7-8 Transit Buses (excludes school buses) New Vehicle Registrations by Calendar Year 101

Figure 108: United States Class 4-6 Work Trucks: New Vehicle Registrations by Calendar Year 101

Figure 109: Automotive Battery System Specifications 102

Figure 110: Automotive Battery System Specifications 103

Figure 111: Automotive Battery System Specifications 103

Figure 112: Automotive Battery System Specifications 104

Figure 113: Automotive Battery Packs Specifications (dimensions, cooling systems) 104

Figure 114: Automotive Battery Packs Specifications (dimensions, cooling systems) 105

Figure 115: Commercial Vehicle Battery Specifications Commercial Vehicles 105

Figure 116: Commercial Vehicle Battery Chemistries and Suppliers Commercial Vehicles: Battery Types and Suppliers 106

Figure 117: Commercial Vehicle Battery Specifications 106

Figure 118: Commercial Vehicle Battery Specifications Commercial Vehicles 107

Figure 119: Second use Battery Availability Forecasts: Class 3 Service Vans, No Incentives, Entire United States 109

Figure 120: Second use Battery Availability Forecasts, Class 6 Box Trucks, No Incentives, Entire United States 109

Figure 121: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery, No Incentives, Entire United States 110

Figure 122: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, No Incentives, Entire United States 110

Figure 123: Second use Battery Availability Forecasts, Class 7-8 CityTransit Buses, No Incentives, Entire United States 111

Figure 124: Second use Battery Availability Forecasts, Class 3-6 Shuttle Buses, No Incentives, Entire United States 111

Figure 125: Without Incentives, Projected Energy Capacity of Second use Batteries from Selected Vocational Vehicles for entire United States is 2.5 GW-hr through 2025 112

Figure 126: Second use Battery Availability Forecasts, Class 3 Service Vans, Unlimited Incentives, Entire United States 113

Figure 127: Second use Battery Availability Forecasts, Class 6 Box Trucks, Unlimited Incentives, Entire United States 113

Figure 128: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery, Unlimited Incentives, Entire United States 114

Figure 129: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, Unlimited Incentives, Entire United States 114

Figure 130: Second use Battery Availability Forecasts, Class 7-8 City Transit Buses, Unlimited Incentives, Entire United States 115

Figure 131: Second use Battery Availability Forecasts, Class 3-6 Shuttel Buses, Unlimited Incentives, Entire United States 115

Figure 132: Projected Energy Capacity of Second use Batteries from Selected Vocational Vehicles 116

Figure 133: Determination of Available Grant and Incentive Awards for Six Selected Vocations, Entire United States 117

Figure 134: Second use Battery Availability Forecasts, Class 3 Service Vans, Limited Incentives, Entire United States 118

Figure 135: Second use Battery Availability Forecasts, Class 6 Box Trucks, Limited Incentives, Entire United States 118

Figure 136: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery Trucks, Limited Incentives, Entire United States 119

Figure 137: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, Limited Incentives, Entire United States 119

Figure 138: Second use Battery Availability Forecasts, Class 7-8 City Transit Buses, Limited Incentives, Entire United States 120

Figure 139: Second use Battery Availability Forecasts, Class 3-6 Shuttel Buses, Limited Incentives, Entire United States 120

Figure 140: With Limited Incentives, Projected Energy Capacity of Second use Batteries from Selected Vocational Vehicles for Entire United States is 2.7 GW-hr through 2025..... 121

Figure 141: Impact of Incentives on Availability of Second use Battery Packs (Number of Batteries), Selected Vocational Vehicles, Entire United States 122

Figure 142: Impact of Incentives on Availability of Second use Battery Packs (Capacity), Selected Vocational Vehicles, Entire United States..... 122

Figure 143: Class 3 Service Van Sales (ECV's and PHECVs) without Incentives, California 124

Figure 144: Class 3 Service Vans Projected New Vehicle Registrations without Incentives, California..... 125

Figure 145: Class 6 Box Truck Sales (ECV's and PHECVs) without Incentives, California 126

Figure 146: Class 6 Box Trucks Projected New Vehicle Registrations without Incentives, California..... 127

Figure 147: Class Class 4-6 Urban Delivery Truck Sales (ECVs) without Incentives, California128

Figure 148: Class 4-6 Urban Delivery Trucks Projected New Vehicle Registrations without Incentives, California..... 129

Figure 149: Class 7-8 City Transit Bus Sales (ECVs, HECVs, and PHECVs, does not include school buses) without Incentives, California 130

Figure 150: Class 7-8 City Transit Bus Projected New Vehicle Registrations without Incentives, California..... 131

Figure 151: Class 4-6 Work Truck Sales (PHECVs) without Incentives, California 132

Figure 152: Class 4-6 Work Trucks Projected New Vehicle Registrations without Incentives, California..... 133

Figure 153: Class 3-6 Shuttle Bus Sales (ECVs and PHECVs) without Incentives, California 134

Figure 154: Class 3-6 Shuttle Buses Projected New Vehicle Registrations without Incentives, California..... 135

Figure 155: Second use Battery Availability Forecasts, Class 3 Service Vans, No Incentives, California Vehicles..... 136

Figure 156: Second use Battery Availability Forecasts, Class 4-6 Box Trucks, No Incentives, California Vehicles..... 136

Figure 157: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery Trucks, No Incentives, California Vehicles..... 137

Figure 158: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, No Incentives, California Vehicles 137

Figure 159: Second use Battery Availability Forecasts, Class 3 Service Vans, No Incentives, California Vehicles 138

Figure 160: Second use Battery Availability Forecasts, Class 3-6 Shuttle Buses, No Incentives, California Vehicles 138

Figure 161: Without Incentives, Projected Energy Capacity of Second use Batteries from Selected Vocational Vehicles is 294 MW-hr through 2025 139

Figure 162: Determination of Available Grant and Incentive Awards for Six Selected Vocations, California 140

Figure 163: Second use Battery Availability Forecasts, Class 3 Service Vans, Limited Incentives, California Vehicles 141

Figure 164: Second use Battery Availability Forecasts, Class 6 Box Trucks, Limited Incentives, California Vehicles 141

Figure 165: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery Trucks, Limited Incentives, California Vehicles 142

Figure 166: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, Limited Incentives, California Vehicles 142

Figure 167: Second use Battery Availability Forecasts, Class 7-8 City Transit Buses, Limited Incentives, California Vehicles 142

Figure 168: Second use Battery Availability Forecasts, Class 3-6 Shuttle Buses, Limited Incentives, California Vehicles 143

Figure 169: With Limited Incentives, Projected Energy Capacity of Second use Batteries from Selected California Vocational Vehicles is 310 MW-hr through 2025 144

Figure 170: Number of Battery Packs Available for Second use, Originating with Six Vehicle Vocations, Limited Incentives, California 145

Figure 171: Energy Storage Capacity of Battery Packs Available for Second use, Originating with Six Vehicle Vocations, Limited Incentives, California 146

Figure 172: Equations to standardize each publication and governmental procurement estimate by geographical scope 148

Figure 173: Discharge Durations by Application 148

Figure 174: Original dates through which each resource's projections are made 149

Figure 175: Projection values based on market factors shown pictorially as subsets 150

Figure 176: Original and Scaled Data Characteristics 151

Figure 177: Results Summary of Utility Li-ion Battery Energy Storage Demand Projection 152

Figure 178: United States Utility Energy Storage Demand (All Technologies) Through 2020 with CSE Projections to 2025 (Maximum Market Potentials 152

Figure 179: United States Li-Ion Energy Storage Demand Forecast Projections to 2025 (Market Proposals Only) 153

Figure 180: Overall United States Li-Ion Energy Storage Demand Forecast Projections to 2025 (All Projections) 154

Figure 181: United States Li-Ion Energy Storage Demand Forecast Projections to 2025 (Market Estimates Only) 155

Figure 182: Summary of Lithium-Ion Energy Storage Systems Demand through 2025 158

Figure 183: Comparison of Projected Second use Lithium-Ion Battery Systems Originating with Commercial Vehicles to Stationary Energy Storage Systems Demand through 2025 159

Figure 184: Identification of Technical and Commercial Barriers 170

Figure 185: Stages of Battery Life Cycle 171

Figure 186: Identified Barriers Prompt Technical Solutions 171

Figure 187: Analysis: Barriers to Supply-Side Standard Cells and Modules 172

Figure 188: Approach to Interview Process 173

Figure 189: Industry Interviews: Participant Titles and Organizations 173

Figure 190: Topic Categories and Questions 174

Figure 191: The Interview Process 175

Figure 192: Interview Form: Vehicle OEMs 176

Figure 193: Interview Form: Battery Suppliers 178

Figure 194: Vehicle OEMs Input: Technical Barriers 179

Figure 195: Vehicle OEMs Input: Commercial Barriers 180

Figure 196: Battery Suppliers Input: Technical Barriers 181

Figure 197: Battery Suppliers Input: Commercial Barriers 183

Figure 198: Examples of Unique Automotive Battery System Designs 187

Figure 199: GM Pouch Cell and German VDA Prismatic Cell 188

Figure 200: Variations in Automotive Battery Systems Designs 188

Figure 201: Example Battery Management System (BMS) 190

Figure 202: Example Electric-Drive Automotive Electronics and Control Systems 191

Figure 203: Battery Thermal Management Methods 192

Figure 204: Example Battery Pack Cooling Systems (Air and Liquid Cooling) 193

Figure 205: Typical Frame Design for Commercial Truck 195

Figure 206: Concept Standarized Battery System Design: Prismatic Pouch 196

Figure 207: Concept Standardized Battery System Design, Prismatic Can 196

Figure 208: Voltage Range (According to Existing Industry Modules) 198

Figure 209: Watt-hour Range (According to Existing Industry Modules) 198

Figure 210: Summary of alternative technical approaches to integration without standardization interview responses 200

Figure 211: Structure and list of questions for alternative technical approaches to integration without standardization interviews 202

Figure 212: Design Concepts Approach 206

Figure 213: Design Process 209

Figure 214: Conduct Design and Analysis for Standard Modules 210

Figure 215: Energy Storage System Design Priorities by Application 211

Figure 216: Packaging Options for a Class 4 Truck 213

Figure 217: VDA PHEV2 5 kWh 23S2P Standard Module Design Concept 214

Figure 218: VDA PHEV2 25 kWh 23S2P Battery System Design Concept 214

Figure 219: GM Pouch Cell, A123, 5 kWh Standard Module Design Concept 215

Figure 220: GM Pouch Cell (A123) 25 kWh Battery Pack Design Concept 215

Figure 221: Examples of Battery Systems with Modules that Employ Digital BMS Interface 216

Figure 222: Digital Module BMS Interface: Required Signals 216

Figure 223: Examples of Battery Systems with Modules that Employ Analog BMS Interface 217

Figure 224: Analog Module BMS Interface: Required Signals 217

Figure 225: Benchmark Current Designs and Map Current Communications Protocols: Nominal Voltage 219

Figure 226: Benchmark Current Designs and Map Current Communications Protocols: Module Energy 220

Figure 227: Benchmark Current Designs and Map Current Communications Protocols: Capacity (Ah) 220

Figure 228: Benchmark Current Designs and Map Current Communications Protocols: Continuous Charge Current (A) 221

Figure 229: Benchmark Current Designs and Map Current Communications Protocols: Continuous Discharge Current (A) 221

Figure 230: Benchmark Current Designs and Map Current Communications Protocols: Length 222

Figure 231: Benchmark Current Designs and Map Current Communications Protocols: Height 223

Figure 232: Benchmark Current Designs and Map Current Communications Protocols: Width 224

Figure 233: Benchmark Current Designs and Map Current Communications Protocols: Volume 224

Figure 234: Benchmark Current Designs and Map Current Communications Protocols: Weight 225

Figure 235: Benchmark Current Designs and Map Current Communications Protocols: Energy Density Gravimetric (Wh/kg) 225

Figure 236: Benchmark Current Designs and Map Current Communications Protocols: Energy Density Volumetric (kWh/m^3) 226

Figure 237: Benchmark Current Designs and Map Current Communications Protocols:Min Optimal Operating Temp (Celsius) 227

Figure 238: Benchmark Current Designs and Map Current Communications Protocols: Max Optimal Operating Temp (Celsius) 228

Figure 239: Benchmark Current Designs and Map Current Communications Protocols: Minimum Operating Temp (Celsius) 229

Figure 240: Benchmark Current Designs and Map Current Communications Protocols: Max Operating Temp (Celsius) 229

Figure 241: Communication Serial Data Interfaces for Stationary Storage Modules 230

Figure 242: Benchmark Current Designs and Map Current Communications Protocols:Battery System Specifications 231

Figure 243: Benchmark Current Designs and Map Current Communications Protocols: Battery Specifications (cont.) 231

Figure 244: Benchmark Current Designs and Map Current Communications Protocols: Battery Specifications (cont.) 232

Figure 245: Benchmark Current Designs and Map Current Communications Protocols: Image of Modules 233

Figure 246: Relationships of Design Concepts and Value Analysis to Battery Life Cycle 234

Figure 247: Procedure for Determining the Impact of Standardization on the Value Chain 234

Figure 248: Inputs to Lithium-Ion Battery Manufacturing Cost Model 235

Figure 249: Inputs to Manufacturing Plant Process Expense Portion of Model 235

Figure 250: Additional Cost Inputs Related to Manufacturing Facility Operations 236

Figure 251: Determination of Unit Costs, System Costs, and Sales Price to Vehicle OEM 236

Figure 252: Unit Cell Manufacturing Cost Input Variables 237

Figure 253: Purchased Materials Manufacturing Cost Input Variables 238

Figure 254: Manufacturing Rate Input Variables 238

Figure 255: Manufacturing Rate Input Variables 239

Figure 256: Manufacturing Investment Costs 239

Figure 257: Battery System Unit Costs 239

Figure 258: Profit and Warranty Costs 240

Figure 259: Battery Pack Integration System Costs 240

Figure 260: Thermal Control System Costs 240

Figure 261: Baseline Li-Ion Battery Manufacturing Plant Diagram 241

Figure 262: Impact of Standardization on Battery Assembly Costs 241

Figure 263: Impact of Standardization on Battery Assembly Costs 242

Figure 264: Summary of Lithium Ion Battery System Manufacturing Costs (as percent of price to vehicle OEM) 242

Figure 265: First use Cost Breakdown Detail: Cost Components as a Percentage of Price to Vehicle OEM 243

Figure 266: Cost Impact of Standardization on Selected Categories 244

Figure 267: Impact of Standardization on First use Cells, Modules, and Packs 244

Figure 268: BMW UC San Diego B2L Project System Overview 246

Figure 269: BMW UC San Diego B2L Project Functional Architecture 247

Figure 270: Communication Standards Relevant to Vehicle Grid Communication 248

Figure 271: Four Key Sub-Tasks of the Value Analysis 255

Figure 272: Key Activities Associated with Sub-Task 1: Impact of Standardization on Each Stage of Value Chain 258

Figure 273: Key Activities Associated with Sub-Task 2: Evaluation of Incentives and Disincentives to Each Stakeholder for Adopting Standardized Module and Battery System Designs 259

Figure 274: Key Activities Associated with Sub-Task 3: Assignment of Generalized Recommendations for Each Suggested Configuration of Second Use Standardized Modules and Battery Systems 260

Figure 275: Key Activities Associated with Sub-Task 4: Evaluation of Pathways for Implementing Standardized Modules and Battery Systems 260

Figure 276: Relationship of Task 5 to Stages of the Battery Value Chain 261

Figure 277: Resource Utilization: Assignment of Sub-Tasks 261

Figure 278: Types of Organizations Included in Task 5 Industry Interviews 262

Figure 279: Relationship of Interview Questions to Task 5 Sub-Tasks 262

Figure 280: Multiple Battery Pack Cost Projections 267

Figure 281: Determine Residual Value of Battery at End of First Use 268

Figure 282: Residual Values of Light Duty Electric Vehicles after 5 Years 269

Figure 283: Residual Value Factors 270

Figure 284: Residual Value Research Results 271

Figure 285: Method for Calculating First Use Residual Value Based on Second Use Application 272

Figure 286: Relationship of Second Use Value Analysis to Sub-Task 1: Impact of Standardization on Each Stage of Value Chain 272

Figure 287: Applications for Second Use Batteries 273

Figure 288: Methods Used for each Benefit 274

Figure 289: Impact of Standardization on Input Costs 275

Figure 290: Top Level ESCT ACM Cost Inputs 276

Figure 291: Battery Integration Cost Input Breakdown 277

Figure 292: Battery Integration Cost Component Breakdown 277

Figure 293: Repurposing Cost Input Breakdown 278
Figure 294: Installation Cost Input Breakdown 278
Figure 295: Installation Cost Component Breakdown 279
Figure 296: Operation Cost Input Breakdown 279
Figure 297: Multiple-Application Scenario Overview 280
Figure 298: ESCT DIM Cost Inputs 280
Figure 299: Potential Benefits 282
Figure 300: Electric Service Reliability Benefit Inputs 283
Figure 301: Emissions Rate Inputs 284
Figure 302: Emissions Rate Inputs (Ibs/MWh) by Fuel 285
Figure 303: Assumptions and Dollarized Benefit Analysis (SDF = Standardized Discount Factor) 285
Figure 304: Scenarios Labeling Legend 286
Figure 305: ESCT Module Results Summary 287
Figure 306: ESCT Non-Standard Module Results (25 kWh Size) 289
Figure 307: ESCT Standardized Module Results (25 kWh Size) 289
Figure 308: ESCT Non-Standard Module Results (250 kWh Size) 290
Figure 309: ESCT Standardized Module Results (250 kWh Size) 290
Figure 310: ESCT Non-Standard Module Results (1000 kWh Size) 291
Figure 311: ESCT Standardized Module Results (1000 kWh Size) 291
Figure 312: ESCT Non-Standard Module Results (20000 kWh Size) 292
Figure 313: ESCT Standardized Module Results (20000 kWh Size) 292
Figure 314: Dollarized Net Benefit with Respect to Second Use Battery Cost and Standardized Discount Factor (Electric Service Reliabilty Scenerio) 293
Figure 315: Dollarized Net Benefit with Respect to Second Use Battery Cost and Standardized Discount Factor (Electric Service Reliability Scenario) (TOU_Reliability_Quality Scenario) 294
Figure 316: Dollarized Net Benefit with Respect to Second Use Battery Cost and Standardized Discount Factor (Renewable_Reliability_Quality Scenario) 295
Figure 317: Dollarized Net Benefit with Respect to Second Use Battery Cost and Standardized Discount Factor (DCM_Reliability_Quality Scenario) 296

Figure 318: Illustration of Method B: Impact of Standardization 297

Figure 319: Breakdown of Repurposing and Repackaging Cost Impacts..... 298

Figure 320: Repurposing and Repackaging Cost Impact Exercise Summary Table..... 299

Figure 321: Impacts of Second-Life Battery Cost Components 300

Figure 322: Determination of Incentives and Disincentives is Part of Sub-Task 2 301

Figure 323: SAE Vehicle Electrification Standards..... 304

Figure 324: Industry Standards for Rechargeable Energy Storage Systems..... 305

Figure 325: Industry Standards for Rechargeable Energy Storage Systems, continued 305

Figure 326: Industry Standards for Rechargeable Energy Storage Systems, continued 306

Figure 327: Sub-Task 2: Generalized Recommendations Were Generated for Standarized Modules..... 306

Figure 328: Battery Packs Associated with Electric Drive Commercial Vehicles 309

Figure 329: Sub-Task 4 Evaluate Potential Pathways for Implementing Standardized Modules and Battery Systems..... 309

Figure 330: Review of the individual assumptions and characterization of each resource 1

Figure 331: Grid applications assumed in the Sandia National Laboratories' Report..... 5

Figure 332: Table of CPUC mandated energy storage procurement targets for by application and IOU 6

Figure 333: Time durations for grid applications..... 7

Figure 334: Microgrid-islanded test system schematic..... 2

Figure 335: ESCT Architecture Overview..... 1

Figure 336: ESCT Asset Characterization Module (ACM)..... 2

Figure 337: ESCT Asset Characterization Module (ACM) (continued)..... 2

Figure 338: ESCT Data Input Module (DIM) 3

Figure 339: Benefits Definitions 4

Figure 340: Benefits Definitions 5

EXECUTIVE SUMMARY

This study consisted of four main technical tasks. The technical tasks and goals are described below and will be discussed throughout this report.

Chapter 1: Market Analysis: Supply vs. Demand
The goal of this task is to conduct market analysis through primary research, market reports, and selected interviews. The analysis will facilitate the identification of lessons learned from previous and current standardization efforts as they pertain to Class 3 – 8 commercial vehicles.

Chapter 2: Barriers Analysis: Industry Reluctance
The goals of this task are to conduct analyses of OEMs and battery suppliers, identify technical and commercial barriers to standard modules and packs, and evaluate alternative technical approaches to integration of modules/packs as they pertain to Class 3 – 8 commercial vehicles.

Chapter 3: Design Concepts: Standards Design
The goal of this task is conduct design and analysis for standard modules and to perform a cost/ benefit analysis of standardization for vehicle OEMs.

Chapter 4: Value Analysis: Financial Benefit
The goals of this task are to determine the financial benefit of standard modules and packs in second use, and to estimate life cycle cost impacts from standardizing battery pack parameters,

Project Purpose

Chapter 1 – Market Analysis: Supply vs. Demand

Supply Side Analysis Summary
To determine the number and capacity of battery systems originating with electric-drive commercial vehicles and becoming available for second use stationary energy storage applications, the following approach was taken. Adoption rates were calculated for selected vocations (chosen based on favorable total cost of ownership) both with and without government incentives and grants.

1. Using a Total Cost of Ownership model, determine the payback period associated with the incremental cost of the electric or hybrid drive components compared to baseline costs associated with conventional diesel or gasoline powertrains.

2. The adoption rate for the ECV, PHECV, or HECV is determined based on the payback period.

3. For example if the incremental cost of an advanced technology system is less than three years, it is a candidate for adoption by a majority of new vehicle purchasers. Other categories include early adopters (payback periods >8 years) and late adopters (payback periods between 3 and 8 years).

4. Apply the adoption rate to projected new vehicle registrations (based on historical new vehicle registration data) to determine the number of ECV, PHECV, and HECV purchases for each selected vocation through 2020. Predictions for new vehicle

registrations through 2022 were developed for each of the selected vehicle vocations based on historical registration data for the time period 2003-2012 and expected economic drivers.

5. Based on duty cycle, battery capacity degradation, and expected vehicle life, determine the number of second use batteries to become available, the capacity of the batteries as they enter second use, and the year the batteries become available for second use for each selected vehicle vocation.

6. Determine the total number of batteries and total second use energy capacity (kw-hrs) of the batteries expected to become available prior to 2025.

Research was completed regarding currently-available and approved government grants and incentives for purchase of ECVs, PHECVs, and HECVs. For 2014, the cumulative value of these awards is approximately $50M. Based on an average award of $33,000 per vehicle, the awards would support the purchase of approximately 1,500 vehicles. For 2014, the cumulative value of these awards for California is approximately $14M. Based on an average award of $33,000 per vehicle, the awards would support the purchase of approximately 425 vehicles.

Commercial vehicles were a key focus of study because owners of these vehicles are key early adopters of PEV and HEV technologies, the construction of commercial vehicles facilitates implementation of standardized battery systems, battery systems associated with commercial vehicles are expected to have capacities (kW-hr or kWh) larger than those for passenger cars, and the increased residual value of battery systems for ECVs, HECVs, and PECVs reduces payback periods and increases cost justification for adopting electric drive technologies.

Significant numbers of battery systems from ECVs, PHECVs, and HECVs are expected to become available for second use applications within California and the remaining states beginning in 2019. Current incentive programs provide limited funds and thus impact less than 1 percent of projected California sales and ½ percent of projected United States sales of ECVs, PHECVs, and HECVs, for identified vocational vehicles through 2025.

The cumulative number of second use battery systems for the entire US, originating with the six selected vehicle vocations, is expected to be greater than 50,000 by 2025, with the average energy capacity per pack equal to 52 kWh. The cumulative number of second use battery systems available within California is expected to be approximately 6,000 by 2025, with the average energy capacity per system equal to 50 kWh.

Cumulative Energy Capacity of available second use battery systems for the entire United States is expected to be between 2.5 and 4.3 GWh by 2025. Cumulative Energy Capacity of available second use battery systems becoming available in California is expected to be between 295 and 311 MW-hrs by 2025.

Demand Side Analysis Summary

A market analysis of utility demand for Li-Ion energy storage in the United States included the following information sources: industry publications, technical journals, interviews with industry stakeholders, procurement target proposals, and company reports. Data found in texts

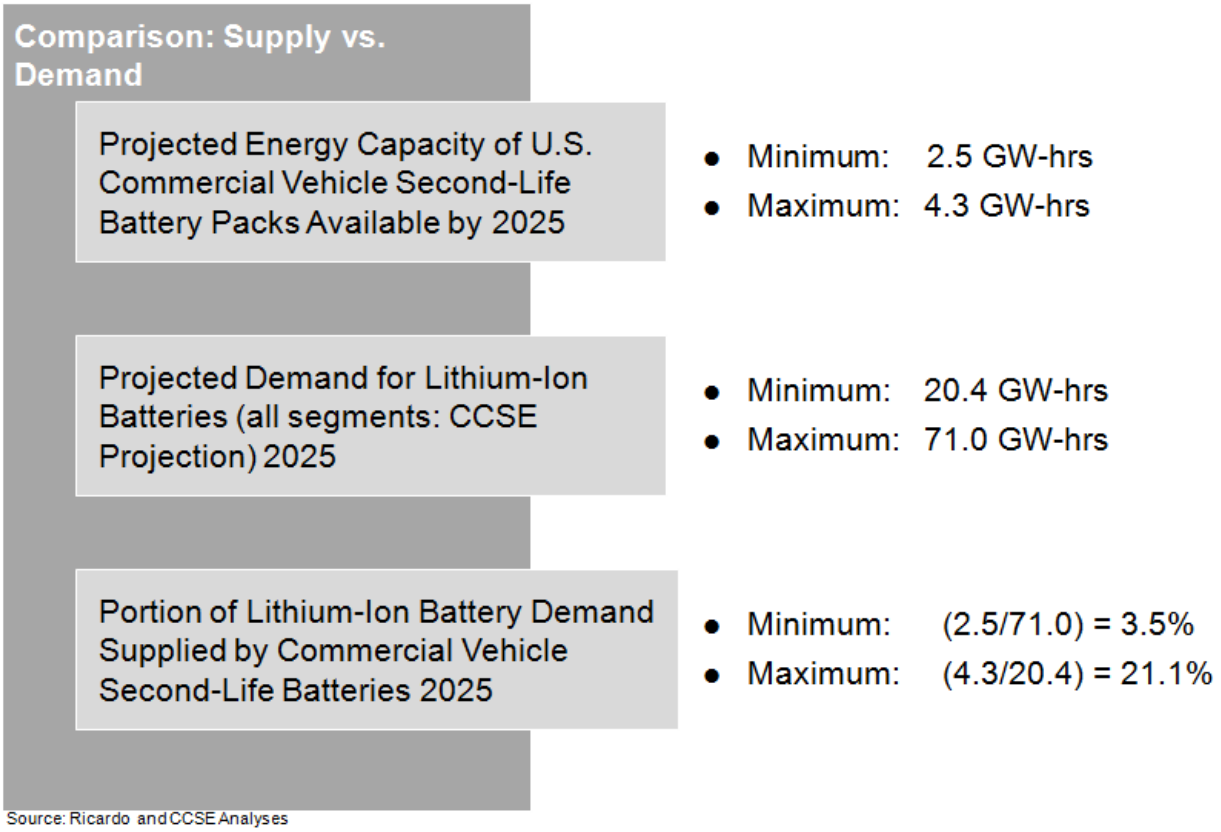
by the CPUC (California Public Utilities Commission), CESA (California Energy Storage Alliance), KEMA Inc., Lux Research Inc., Navigant Consulting Inc., Pike Research, and Sandia National Laboratory (SNL) were normalized to United States geospatial boundaries using Peak Load Growth proportional relationships. Once normalized, the data was converted to energy units (GWh) and narrowed to utility-scale applications and Li-Ion battery energy storage. The various identified approaches projected data to different future dates: 1) CPUC to 2020; 2) CESA to 2020; 3) KEMA, Inc. to 2017; 4) Lux Research, Inc. to 2017; 5) Navigant Consulting (Pike Research), Inc. to 2022; and 6) Sandia National Laboratory to 2020. For the current study the market analysis employed single order exponential regressions to project Li-Ion utility energy storage demand through 2025 from the given data.

The predictions for stationary litihium ion energy storage capacity demands through 2025, originating with Sandia National Laboratory (based on Maximum Market Potentials approach) were noted to be significantly larger than those originating with other researchers. This is thought to be related to the larger number of energy storage applications considered by SNL[1].

Sandia's NL Maximum Market Potentials were employed as the basis for the demand projections developed during the current study. The CPUC and CESA market forecasts were also higher than the average estimates, based on the assumption of strong grant and incentive programs for the adoption of utility-scale energy storage. The projections for the current study were based on exponential growth patterns and are in line with identified government mandates for utilities to adopt energy storage. The CPUC energy storage forcast data should be updated with these newly found projections to better reflect current government storage orders.

Comparisons of the supply side versus demand side forecasts are summarized in figure below. It is projected that second use lithium-ion battery systems have the potential to supply between 3.5 percent and 21.1 percent of the stationary lithium-ion energy storage demand by the utility industry through 2025.

Figure A: Comparison of Projected Second use Lithium-Ion Battery Systems Originating with Commercial Vehicles to Stationary Energy Storage Systems Demand through 2025



Chapter 2 - Barries Analysis: Industry Reluctance

Barriers Analysis Summary and Conclusions

Technical and commercial barriers to standardized battery modules and packs were identified for both supply (first use automotive applications) and demand (second use energy storage applications). Resources employed in the study included a literature review and interviews with industry stakeholders. Stakeholders included representatives of vehicle OEMs, battery suppliers, researchers, as well as standards organizations and regulators.

The results of the Barriers Analysis were employed during the Design and Analysis for Standard Modules (see Chapter 3), along with battery performance requirements, to design and analyze standard modules for both first and second use applications.

Supply Side: The project team identified key demand-side technical barriers divided into two categories: technical and commercial for both vehicle OEMs and battery suppliers. Identified barriers include:

1. Packaging location and space requirements.
2. Electrical, electronic, thermal, and communications protocols for each application.

3. Durability.
4. Charge acceptance.
5. Safety.
6. Integration with second use requirements.
7. Remanufacturing requirements.

Key commercial barriers include:

1. Impacts of perceived safety issues.
2. Predictable and sustainable supply of cells, modules, packs and associated ancillary systems.
3. Uncertainty in costs.
4. Remanufacturing issues (standard vs. non-standard, and comparisons to bespoke battery packs).
5. Industry resistance to risk and change.
6. Uncertainty in maintenance requirements and responsibilities, variation in system longevity.
7. Electrical & electrochemical compatibility.
8. Intellectual Property and competitive position issues.
9. The total cost of the storage systems need to be cost competitive with alternative non-storage options available to electic utilities (including subassembly, installation, and integration costs)[2].

Key approaches to overcoming these barriers include:

1. Continuing with development of electric vehicle battery standards such as those now published by ISO/IEC, UL and GM.
2. Improved education regarding industry requirements for both first and second use applications.
3. Promotion of cost savings and performance improvements resulting from standardization.
4. Development of cells and modules which are compatible with a wide range of battery chemistries and performance specifications (voltage, watt-hours, resistance).

[2] According to the "Grid Energy Storage" report from December 2013 written by the Department of Energy.

5. Establishment of acceptable module specifications to facilitate a "building block" approach to both vehicle and stationary energy storage applications. This could include the use of 'middlemen' (3rd party, the original battery manufacturer, or the car manufacturer for example) that verify the quality of the electric vehicle owner's battery before it is accepted for use as a stationary energy storage device.
6. Development of thermal management systems that are compatible with multiple vehicle applications as well as stationary energy storage environments.
7. Development of expanded communications and battery management systems containing options to facilitate a range of vehicle and energy storage applications.
8. Development of modules that facilitate remanufacturing processes for stationary energy storage.

Demand Side: Based on industry interviews, advantages and disadvantages were identified for the various technical approaches to integrating current design, non-standardized battery systems into second use stationary energy storage applications. A key disadvantage was the additional cost associated with the non-standardized designs, which must be modified for each application and thus cannot take advantages of the cost reductions associated with large scale production volumes. There are also non-recurring labor and design costs for this approach.

Other technical approaches to integrating PEV battery systems into second use, stationary energy storage applications include:

1. Non-standard use of separate DC-DC converter for each system
2. Options to preserve systems intact after removal from vehicle
3. Combining like systems (e.g. from same model vehicle) into second use systems.
4. Adaption/replacement of BMS for modules that are reconfigured into second use systems
5. Develop partnerships between battery and vehicle OEMs to allow reconfigurable BMS to be employed during both first and second use applications
6. Employing standardized end-of-first use testing and validation programs, to allow for the selection of systems for second use based on key performance paramenters.
7. Developing systems that enable extension of vehicle-to-grid (V2G) interfaces into second use applications.
8. Develop customized (one-off) systems based on characteristics of available battery systems for second use applications.

This study also produced recommendations for facilitating integration of used electric vehicle battery systems into stationary storage applications and methods to reduce the cost of this repurposing. These included:

1. Establish standard *module-level* anode and cathode locations, physical attachment sites, thermal management system interfaces, communication port pin-assignments and communications protocols.
2. Do not restrict implementation of electrical or themal management algorithms or topologies.
3. Establish a standard sequence for the allocation of control variable in CANbus communications
4. Design safety systems to be internally integrated. Manufacturers to make available certain documentation to enable adaptation of of control parameters for second use applications by the repurposer.
5. Establish industry-wide standardized acceptance testing protocols to validate battery state of health at end of first use with conditionals for distinct cell types and manufacturers.

Chapter 3: Design Concepts: Standards Design Conclusions

The Design Concepts portion of the study included development of standardized design concepts for lithium-ion battery systems, evaluation of currently available lithium-ion battery system specifications and communication protocols, determination of the cost impact of standardization on the price of batteries delivered to vehicle OEMs, design and demonstration of a second use battery energy storage system, and the evaluation of pathways for implementing PEV battery pack standards.

In keeping with the application focus of the current study, two standard battery pack designs were developed for commercial vocational vehicles. The packs were based on the following design parameters:

1. Module energy of 5kWhr: Supports 25 kWhr battery pack energy increments and allows reasonable series and parallel cell configuration in module
2. Cell types: GM standard pouch cell (A123 and LG Chem cells) and VDA PHEV2 prismatic cell
3. Module dimension: Keep to minimum to maintain energy density

The standardized battery pack communication systems and BMS interfaces were also defined.

A market research study was completed for commercially available energy storage modules of varying size, voltages, energy capacities and etc. The market research was conducted to give an overview on the specifications of many different existing energy storage modules (totaling over 20 modules from 9 different companies). The research included tabulation of specifications and identification of trends and patterns of available energy storage modules to facilitate development of the standardized EV battery modules.

A cost/benefit analysis was completed based on a value chain assessment of the battery life cycle beginning with the battery manufacturing process, the first use vehicle application, and the transfer from vehicle to stationary energy storage application.

The impact of standardization on EV OEM module and battery price (delivered price to vehicle OEM) was determined using a lithium-ion manufacturing cost model. Individual component costs were defined as a function of the delivered battery price to the vehicle manufacturer. In Chapter 4, the impact of standardization on battery price for second use applications was quantified, along with the value derived from the individual players in the supply chain.

The battery manufacturing cost model included both unit (module/battery) costs as well as system (thermal and battery management systems, cables, connectors, and housing) costs to determine the sales price to the vehicle OEM.

Each cost component was evaluated to determine the impact of standardization. This included assessments of variable costs, fixed expenses, profit warranty, pack integration, and addition of thermal and battery management systems.

Materials and purchased items were found to range from 45 percent to 76 percent of the delivered battery price, depending upon battery chemistry and topology. It was determined that standardization could reduce these costs between 3 percent and 12 percent of the delivered battery price.

Direct labor represents between 0.4 percent and 7 percent of the delivered battery price, again depending upon battery chemistry and topology. Standardization can reduce direct labor costs between 0.4 percent and 1 percent of the delivered battery price.

Other cost components, such as GSA, R&D, overhead, depreciation, and warranty are projected to be impacted by standardization within the range of 0.4 percent to 1.6 percent.

Addition of thermal management systems and pack integration adds between 20 percent and 29 percent to the delivered battery price. Standardization can reduce these between 2.5 percent and 5.75 percent of the delivered battery price.

Standardization thus has the potential to reduce the delivered battery price to the vehicle OEM by 3 percent to 15 percent.

BMW led the development of a grid-tied stationary energy storage system located at the University of California San Diego which integrates six used MINI E high-voltage Li-Ion battery packs. The system architecture was dictated by the goals of design for commercialization and reuse of vehicle components. The system safety concept relies on each battery to be self-protecting, reducing the need for higher level safety measures and enabling a standard interface to any proprietary vehicle BMS design. The introduction of the "Super BMS" system between the vehicle BMS's and the site controller and inverter is another key to enabling communication interface standardization.

Based on a literature search and interviews with industry stakeholders, potential pathways to implementing PEV battery pack standards were identified and included:

1. Participation in standards committees for OEM and stationary battery industry organizations, such as SAE, ISO/IEC, IEEE, and IEC.
2. Improved education regarding industry requirements for both first and second use applications.
3. Preparing and presenting technical papers containing results of battery standardization analyses.
4. Promotion of cost savings, savings, and performance improvements resulting from standardization.
5. Development of cells and modules that are compatible with a wide range of battery chemistries and performance specifications (voltage, watt-hours, resistance).
6. Identification of acceptable module specifications to facilitate "building block" approach to both vehicle and energy storage applications and preparation of "Draft" specifications for delivery to standards organizations.
7. Development of expanded communications and battery management systems containing option to facilitate a range of vehicle and energy storage applications.
8. Development of modules that facilitate remanufacturing processes for stationary energy storage and remain compatible for EV use.

Chapter 4: Value Analysis: Financial Benefit Conclusions

1) Determination of the impact of standardization on each stage of the value chain: this included research on the residual value of battery systems at the end of first use and an economic analysis of second use, stationary energy storage applications.

Additional interviews were conducted with industry stakeholders (vehicle OEMs, battery manufacturers, national laboratories, and battery recyclers) to obtain comments on the impact of standardization from both commercial and technical perspectives, as well as views regarding the impact of standardization on residual value of first use battery systems and definition of incentives and disincentives to standardization.

It is projected that significant cost reductions due to module and battery design standardization will not occur until production volumes exceed 100,000 units per year, at which time price reductions on the order of 10 percent to 15 percent are expected relative to current first use battery system prices. It is noted that continuing improvements in lithium-ion chemistries for the electric vehicle market are likely to reduce prices to below $300/kWh by 2020, assuming large-volume production facilities are put in place. Leading battery developers, such as Tesla, are estimated to achieve a 35 percent reduction to $172/kWh for lithium-ion battery packs by the year 2025[3].

[3] According to "Electric Vehicles Market Set for Big Boost as Li-ion Battery Costs Hit $172/kWh in 2025", article from May 2015 written by Lux Research.

It is the opinion of the industry experts interviewed during this portion of the study that standardization will lead to improved battery safety, through the implementation of improved separators, coatings, thermal management systems, and housing designs.

Industry stakeholders are recommending that a family of up to four design standards be implemented to account for differences in applications, chemistries, and performance specifications. Currently, economic and technical considerations dictate that assembled second use modules and packs will contain like cells. As standard designs become available, this assumption can be relaxed.

The residual value of lithium-ion batteries at the end of their first use was determined using a variety of methods, including: 1) scrap materials prices, 2) battery recycle values, 3) results of research conducted that the national laboratories, 4) vehicle battery pack trade-in values, and 5) evaluation of second use value based on economics of second use grid energy storage applications. The resulting values ranged from -$30/kWh (battery owner must pay to have battery recycled) to +$150/kWh (based on high value second use application).

The suitability of the standardized module/battery system configurations for different grid applications was assessed and compared to the suitability of the current non-standardized PEV system architectures. An energy storage economics model was utilized to determine the dollarized benefit of selected grid/storage scenarios for both non-standardized and standardized battery designs. It was determined that, in general, all applications show potential for net benefit results if battery modules are standardized. Key grid applications that will benefit from battery energy storage include electric service reliability, renewable time shift, and power quality. The maximum, economically feasible installed battery costs (below this cost the system is has a favorable return on investment) range from $183/kWh to over $1,000/kWh.

2) Evaluation of incentives and disincentives to each stakeholder for adopting standard designs: the purpose of this sub-task was to inform recommendations for standardization.

A list of incentives and disincentives for implementing standardized battery designs for electric-drive commercial vehicles was assembled. Many of the stakeholders expressed concern regarding possible negative impacts on battery development if design standards are imposed too early in the maturation of the industry.

3) Assignment of generalized recommendations for each suggested configuration of standardized modules: this sub-task included promoting recyclability and defining financial benefits.

Organizations such as SAE, FMVSS (NHTSA), UNMTC (UNECE), FreedomCAR, and ISO, have already put in place many components and testing standards for rechargeable energy storage systems, but have not yet addressed design standards. It is recommended that these organizations be approached regarding support for design standards aimed at commercial vehicle modules and packs.

Standardized modules will facilitate recycling because 1) there will be fewer module types and chemistries, 2) construction will favor disassembly, 3) components may be labeled with bar

codes to enable identification and machine sorting, and 4) future packs are anticipated to be larger (energy capacity) and available in larger volumes, thus promoting recycling operations

Commercial vehicles have been identified as primary candidates for standardized module/pack designs because of the favorable economics associated with electric drive systems, the packaging options available for implementing standardized packs, and the projected supply of second use batteries originating from these vehicles.

As described in Chapter 3, example module and pack designs have been developed based on energy capacity increments of 25 kW-hrs that meet the identified duty cycles. These are intended to establish a basis for developing a family of module and pack design standards applicable to the commercial vehicle industry. It is projected that three to four sets of designs standards can eventually be developed for various electric drive vehicle categories (design standards for HEVs are expected to be different than those for BEVs, for example).

The design standards are to include sections on accommodations of 1) repurposing and second use applications and 2) recycling.

It is recommended that initial module and pack design standardization activity be focused on commercial vehicle applications.

Module production volumes for application to commercial vehicles are projected to exceed 100,000 units during 2018. Significant cost reductions associated with large volumes and standardized designs occur at this production level.

Thus, design activity associated with standard modules and packs aimed at the commercial vehicle market should begin during 2015.

4) Evaluation of pathways for implementing standardized modules based on research and industry interviews.

Pathways to implementing standardized modules and battery systems, in addition to those defined in Chapter 3, were identified and include:

- Identify commercial and technical advantages of standard designs for all portions of the module/pack life cycle.
- Include monetary incentives for implementing standardized battery designs as part of government-funded battery-electric vehicle adoption rate programs (based on clear benefits to entire value chain).
- Improve supply chain reliability – the supply chain has been erratic in recent years as a result of changes in ownership and strategy. To effectively implement design standards, an improvement in supply chain coordination and cooperation will be required.

CHAPTER 1:
Market Analysis: Supply vs. Demand

The goal of the *Market Analysis: Supply vs. Demand* task was to employ primary research, market reports, modeling, and selected industry interviews to determine the availability of second use commercial PEV lithium-ion battery systems through 2025 and to compare the results to the projected demand by the utility industry for battery energy storage for the same time period. The analysis facilitated the identification of lessons learned from previous and current standardization efforts.

1.1 Executive Summary

The market analysis and assessment of second use battery supply vs. demand included two primary subtasks: 1) employ an adoption rate model to predict sales through 2020 of commercial vehicles having electric drives and from this model, determine supply through 2025 of second use battery systems applicable to energy storage applications, and 2) complete a demand side analysis with the objective of forecasting electric utility demand for lithium-ion battery energy storage capacity through 2025.

1.1.1 Employ Adoption Rate Model to Forecast Second use Supply

An adoption rate model was employed to predict sales of commercial electric drive vehicles through 2020 and determine supply of second use lithium-ion battery systems through 2025.

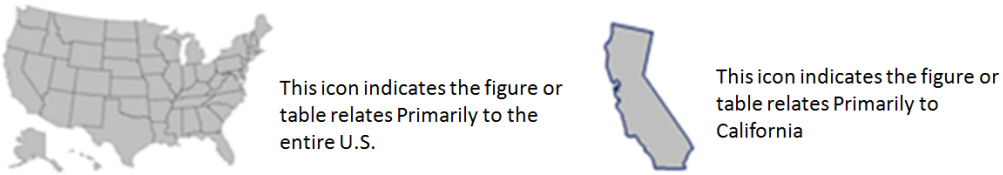
Commercial vehicle vocations were chosen for the adoption rate forecast based on several criteria. The US EPA defines the commercial vehicle sector into three distinct categories: 1) combination tractor/trailers, 2) heavy-duty pickups and vans, and 3) vocational vehicles, which includes all other vehicle types, including buses, refuse trucks, shuttle buses, construction vehicles, delivery trucks, etc. (reference 114).

The commercial vehicle vocations were chosen based on several criteria including:

1. Duty cycles that lend themselves to electrification and hybridization (and incorporate battery packs favorable for second use applications).
2. Vocations for which vehicle manufacturers currently offer or are planning to offer PEV or HEV products.
3. Vehicles eligible for government incentive programs.
4. Vehicles for which the total cost of ownership is significantly reduced when PEV and HEV drive systems are employed.
5. Vocations that have a large enough population to significantly impact the second-use energy storage market.
6. Vehicles that are favored by early adopters of new technology.

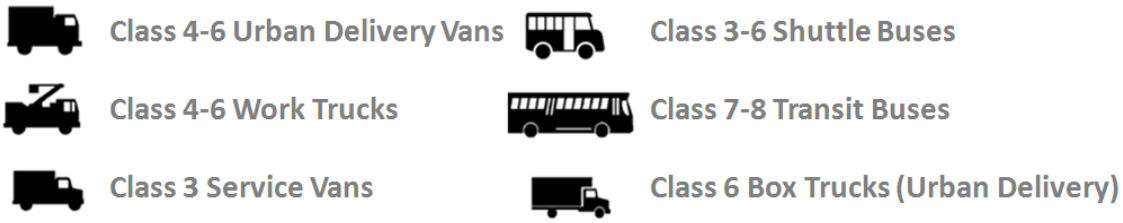
The study included analysis of current vehicle population data for both California and the entire United States Icons have been placed on the various plots and tables to indicate the range of the data.

Figure 1: United States and California Icons



To select candidates for the commercial vehicles to be evaluated during the study, a basic spreadsheet-based modeling procedure was utilized. The procedure included evaluation of sales data for commercial vehicles (Classes 3 through 8) within California and the entire United States, duty cycles for selected vocations, capital and operational cost data, and a rudimentary adoption rate model. The vocations were selected based on favorable economics associated with incorporation of electric drive systems, including battery electric commercial vehicles (ECVs), hybrid electric commercial vehicles (HECVs), and plug-in hybrid electric commercial vehicles (PHEVCs). The selected vehicle populations were then subjected to a more rigiorous analysis using proprietary modeling tools to determine payback periods for the incremental cost of new technologies (Total Cost of Ownership –TCO) and predicting market penetration of selected powertrain technologies into defined market segments (Vehicle Adoption Rate). Figure 2 shows the vehicle vocations that are included in the current study.

Figure 2: Vehicle Vocations included in current study



Future populations for ECVs, HECVs, and PHECVs for the entire US, and separately for California, were determined using the TCO and Vehicle Adoption Rate models.

Characteristics of the selected vocational vehicles were defined based on information available in the literature as well as interviews with industry representatives and include duty cycles, battery pack specifications, infrastructure costs, maintenance, incremental costs for the ECV, PHECV, or HECV drive systems, applicable incentive programs, fuel costs, and residual value of vehicle and battery pack at end of first use.

It was found that current incentive programs provide limited funds and thus impact less than 0.5 percent of projected United States sales of ECVs, PHECVs, and HECVs, for identified vocational vehicles during 2015 and beyond.

Adoption rates were calculated for each of the selected vocations both with and without government incentives and grants. The adoption rates were based on the following procedure:

1. From the Total Cost of Ownership model, determine the payback period associated with the incremental cost of the electric or hybrid drive components compared to baseline costs associated with conventional diesel or gasoline powertrains.
2. The adoption rate for the ECV, PHECV, or HECV is determined based on the payback period. For example if the incremental cost of an advanced technology system is less than three years, it is a candidate for adoption by a majority of new vehicle purchasers. Other categories include early adopters and late adopters.
3. Apply the adoption rate to projected new vehicle registrations (based on historical new vehicle registration data) to determine the number of ECV, PHECV, and HECV purchases for each selected vocation through 2020.
4. Based on duty cycle, battery capacity degradation, and expected vehicle life, determine the number of second use batteries to become available, the capacity of the batteries as they enter second use, and the year the batteries become available for second use for each selected vehicle vocation.
5. Determine the total number of batteries and total second use energy capacity (kWh) of the batteries expected to become available prior to 2025.

The availability of automotive battery packs for second use applications was determined based on:

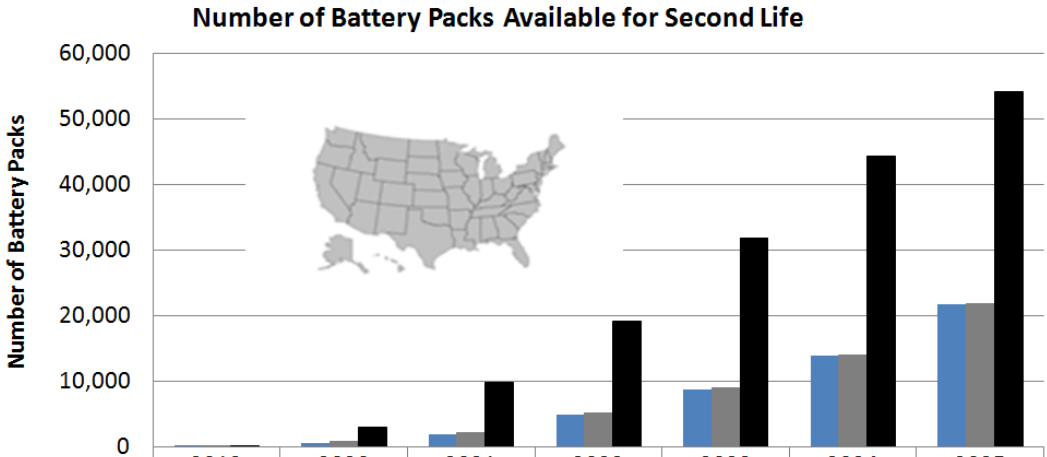
- Sales forecasts of commercial electric, hybrid commercial electric and plug-in hybrid commercial electric vehicles
- New-technology-vehicle adoption rates determined by comparing the total cost of ownership to conventional diesel and gasoline ICE vehicles

Second use battery packs from commercial vehicles are expected to become available starting in 2019. For the entire US, the cumulative number of second use battery packs, originating with vocational vehicles, is expected to be greater than 50,000 by 2025. The number of available second use batteries is expected to be greater if incentive and grant funding programs are increased over current levels.

Figure 3: Projected Number of Second use Battery Packs by Year through 2025 Originating from Selected Vehicle Vocations (Entire US)

Number of Battery Packs			
Year	Without Incentives	With Limited Incentives	With Unlimited Incentives
2019	35	37	72
2020	568	758	2,929
2021	1,921	2,174	9,717
2022	4,891	5,154	19,043
2023	8,678	8,968	31,793
2024	13,828	13,928	44,262
2025	21,629	21,856	54,107
Totals:	**51,550**	**52,875**	**161,923**

Figure 4: Number of Battery Packs Available for Second use by Year through 2025 Originating from Selected Vehicle Vocations (Entire US)



	2019	2020	2021	2022	2023	2024	2025
Without Incentives	35	568	1,921	4,891	8,678	13,828	21,629
With Limited Incentives	37	758	2,174	5,154	8,968	13,928	21,856
With Unlimited Incentives	72	2,929	9,717	19,043	31,793	44,262	54,107

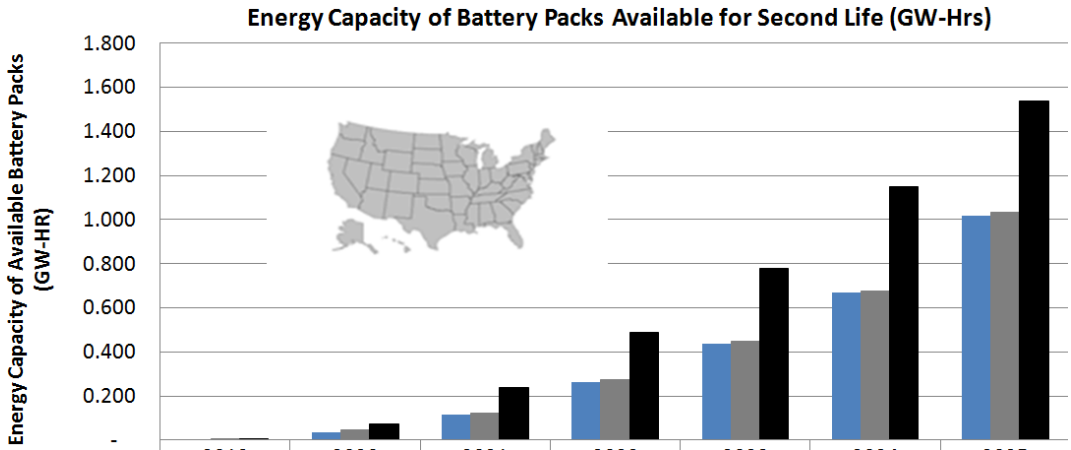
The availability of commercial vehicle battery systems for second use applications was determined based on a detailed evaluation of selected vocational vehicles. The vehicles were chosen based on economic evaluations of vehicle duty cycles and favorable ROIs associated with the incremental costs of incorporating electric, plug-in hybrid electric, and hybrid electric drive systems. The focus of the study was on commercial vehicles.

For the entire US, the cumulative energy storage capacity of second use battery packs, originating with vocational vehicles, is expected to be greater than 2.5 GWh. The available energy storage capacity of second use batteries is expected to be greater if incentive and grant funding programs are increased over current levels.

Figure 5: Projected Energy Capacity of Second use Battery Packs by Year through 2025 Originating from Selected Vehicle Vocations (Entire US)

Capacity of Battery Packs (GW-Hrs)			
Year	Without Incentives	With Limited Incentives	With Unlimited Incentives
2019	0.002	0.002	0.003
2020	0.036	0.045	0.074
2021	0.114	0.124	0.240
2022	0.264	0.274	0.486
2023	0.438	0.449	0.780
2024	0.667	0.676	1.150
2025	1.016	1.031	1.538
Totals:	**2.538**	**2.600**	**4.271**

Figure 6: Energy Capacity of Battery Packs Available for Second use (GWh) by Year through 2025 Originating from Selected Vehicle Vocations (Entire US)



	2019	2020	2021	2022	2023	2024	2025
Without Incentives	0.002	0.036	0.114	0.264	0.438	0.667	1.016
With Limited Incentives	0.002	0.045	0.124	0.274	0.449	0.676	1.031
With Unlimited Incentives	0.003	0.074	0.240	0.486	0.780	1.150	1.538

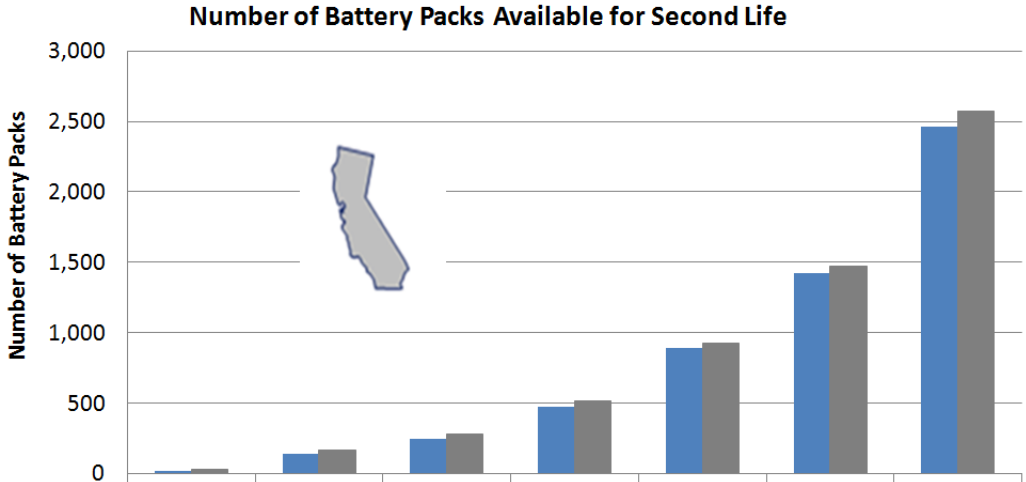
A second analysis was completed for vocational vehicles registered within California. Selected vehicles included battery packs with energy storage capacities greater than 10 kWh. Electric Commercial Vehicles (ECVs), Plug-In Hybrid Electric Commercial Vehicles (PHECVs), and Hybrid Electric Commercial Vehicles (HECVs) were included in the evaluation.

For California, the cumulative number of second use battery packs, originating with vocational vehicles, is expected to be approximately 6,000 by 2025. The number of available second use batteries is expected to be greater if incentive and grant funding programs are increased over current levels.

Figure 7: Projected Number of Second use Battery Packs by Year through 2025 Originating from Selected Vehicle Vocations within California

Number of Battery Packs		
Year	Without Incentives	With Limited Incentives
2019	21	28
2020	139	165
2021	246	284
2022	473	514
2023	895	922
2024	1,422	1,469
2025	2,464	2,575
Totals:	**5,660**	**5,957**

Figure 8: Number of Battery Packs Available for Second use by Year through 2025 Originating from Selected Vehicle Vocations within California



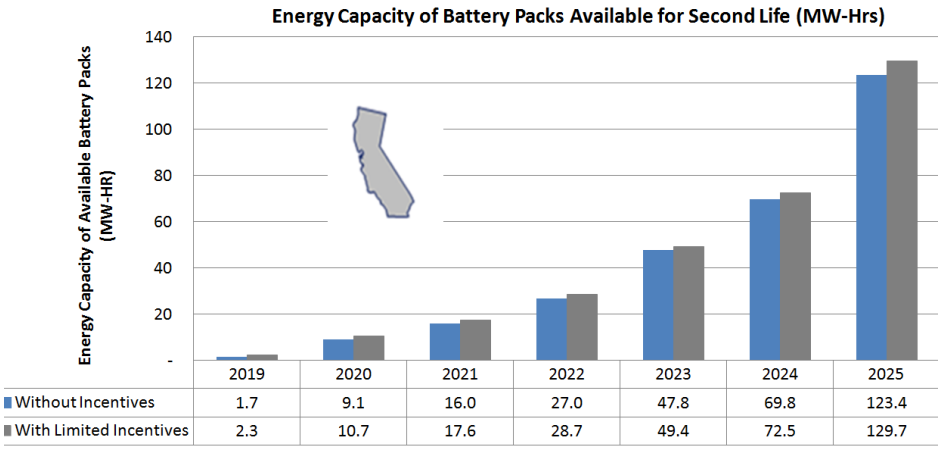
	2019	2020	2021	2022	2023	2024	2025
Without Incentives	21	139	246	473	895	1,422	2,464
With Limited Incentives	28	165	284	514	922	1,469	2,575

For California, the cumulative energy storage capacity of second use battery packs, originating with vocational vehicles, is expected to be greater than 0.3 GWh, approximately 12 percent of that predicted for the entire US. The available energy storage capacity of second use batteries is expected to be greater if incentive and grant funding programs are increased over current levels.

Figure 9: Projected Energy Capacity of Second use Battery Packs by Year through 2025 Originating from Selected Vehicle Vocations within California

Capacity of Battery Packs (MW-Hrs)		
Year	Without Incentives	With Limited Incentives
2019	1.7	2.3
2020	9.1	10.7
2021	16.0	17.6
2022	27.0	28.7
2023	47.8	49.4
2024	69.8	72.5
2025	123.4	129.7
Totals:	**294.9**	**310.9**

Figure 10: Energy Capacity of Battery Packs Available for Second use (MWh) by Year through 2025 Originating from Selected Vehicle Vocations within California



Significant numbers of battery packs from ECVs, PHECVs, and HECVs are expected to become available for second use applications within California and the remaining states beginning in 2019. Current incentive programs provide limited funds and thus impact less than 1 percent of projected California sales and ½ percent of projected United States sales of ECVs, PHECVs, and HECVs, for identified vocational vehicles through 2025.

The cumulative number of second use battery packs for the entire US, originating with the six selected vehicle vocations, is expected to be greater than 50,000 by 2025, with the average energy capacity per pack equal to 52 kWh. The cumulative number of second use battery packs available within California is expected to be approximately 6,000 by 2025, with the average energy capacity per pack equal to 50 kWh.

Cumulative Energy Capacity of available second use battery packs for the entire United States is expected to be between 2.5 and 4.3 GWh by 2025. Cumulative Energy Capacity of available second use battery packs becoming available in California is expected to be between 295 and 311 MWh by 2025.

1.1.2 Employ Market Research to Forecast Second use Demand

A market analysis of utility demand for Li-Ion energy storage in the United States includedthe following information sources: industry publications, technical journals, interviews with industry stakeholders, procurement target proposals, and company reports. Data found in texts by the CPUC (California Public Utilities Commission), CESA (California Energy Storage Alliance), KEMA Inc., Lux Research Inc., Navigant Consulting Inc., Pike Research, and Sandia National Laboratory (SNL) were normalized to United States geospatial boundaries using Peak Load Growth proportional relationships. Once normalized, the data was converted to energy units (GWh) and narrowed to utility-scale applications and Li-Ion battery energy storage. The various identified approaches projected data to different future dates: 1) CPUC to 2020; 2) CESA to 2020; 3) KEMA, Inc. to 2017; 4) Lux Research, Inc. to 2017; 5) Navigant Consulting (Pike Research), Inc. to 2022; and 6) Sandia National Laboratory to 2020. For the current study the market analysis employed single order exponential regressions to project Li-Ion utility energy storage demand through 2025 from the given data.

The results of the demand analysis are summarized in Figure 11 below.

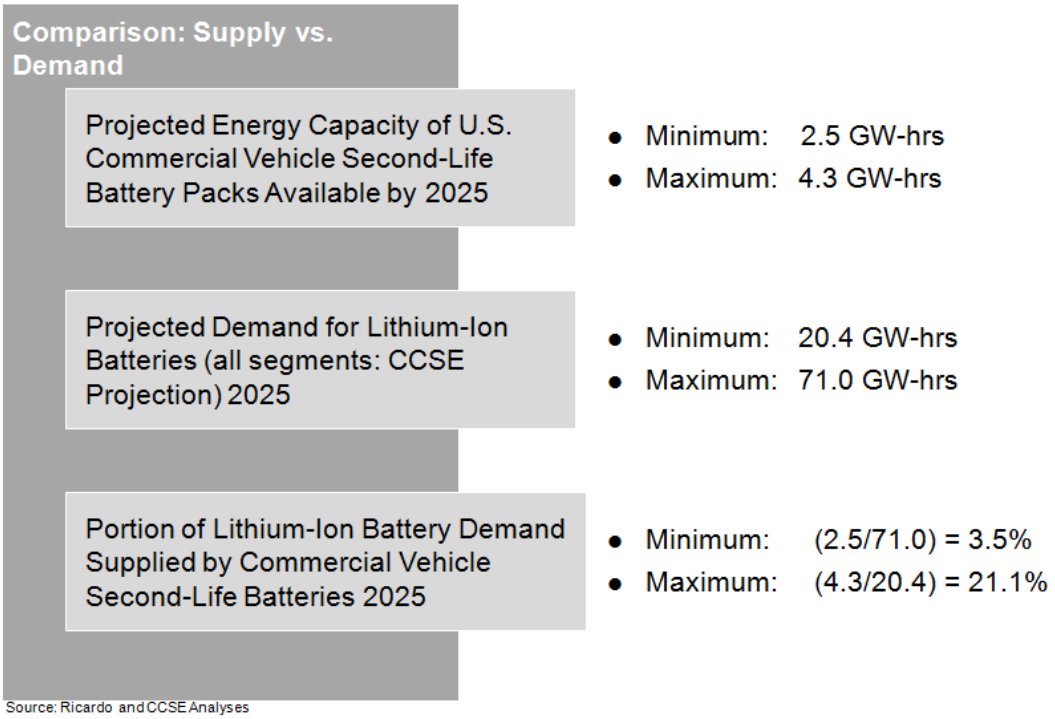
Figure 11: Summary of Lithium-Ion Energy Storage Systems Demand through 2025

Summary of U.S. Li-Ion Energy Storage Demand Forecast Projections to 2025						
Sources	2015 (GWh)	2017 (GWh)	2020 (GWh)	2022 (GWh)	2025 (GWh)	Estimation Scale
CPUC (Min)	0.98	1.5	2.9	3.3	4.3	Market Proposal
CPUC (Max)	3.05	4.5	8.9	10.2	13.2	Market Proposal
CESA (Min)	5.00	20.6	43.9	59.4	82.7	Market Proposal
CESA (Max)	32.60	74.0	136.1	177.5	239.6	Market Proposal
KEMA (Min. No Incentive)	0.32	0.5	0.8	1.1	1.8	Market Estimate
KEMA(Max. No Incentive)	0.90	1.3	2.2	3.2	5.6	Market Estimate
Kema(Min. With Incentive)	0.60	1.3	4.0	8.5	26.4	Market Estimate
Kema (Max. With Incentive)	1.59	3.4	10.4	22.0	67.6	Market Estimate
Lux	0.93	2.0	9.8	27.1	124.8	Market Estimate
Navigant (Min)	0.60	1.7	4.6	8.5	33.0	Market Estimate
Navigant (Max)	1.57	4.5	11.9	22.1	86.1	Market Estimate
Sandia (Min)	146	204	292	424	688	Maximum Market Potential
Sandia (Max)	290	406	580	844	1368	Maximum Market Potential

Comparisons of the supply side versus demand side forecasts are summarized in Figure 12. It is projected that second use lithium-ion battery systems have the potential to supply between 3.5

percent and 21.1 percent of the stationary lithium-ion energy storage demand by the utility industry through 2025.

Figure 12: Comparison of Projected Second use Lithium-Ion Battery Systems Originating with Commercial Vehicles to Stationary Energy Storage Systems Demand through 2025



1.1.3 Forecast of Utility Grid Lithium-Ion Battery Energy Storage Demand

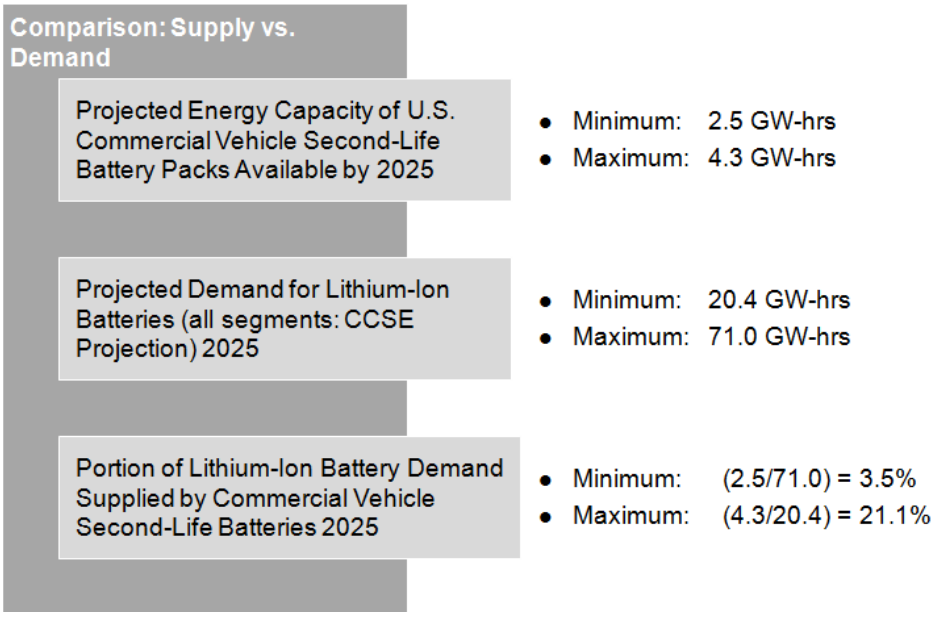
A wide range of information sources, including interviews with industry stakeholders, were utilized to assess the utility grid market for lithium-ion batteries. The standardized projections followed exponential growth patterns which are in line with the increase in government proposals for California investor-owned utilities to adopt energy storage.

The standardized projections for 2025 for Lithium-ion battery energy storage show a utility demand of between about 21 GWh (minimum average) and 74 GWh (maximum average), with an overall average at about 51 GWh. The range and average values were computed using the market estimates resources only.

1.1.4 Comparison: Supply vs. Demand

The results of the Supply and Demand Side Analyses are summarized in Figure 13. It is projected that second use modules originating from commercial electric-drive vehicles will provide between 3.5 percent and 21.1 percent of the stationary lithium-ion battery demand by 2025, based on the cumulative supply of batteries that become available between 2014 and 2025.

Figure 13: Projected Second use Battery Pack Supply vs. Projected Second use Demand for Entire US



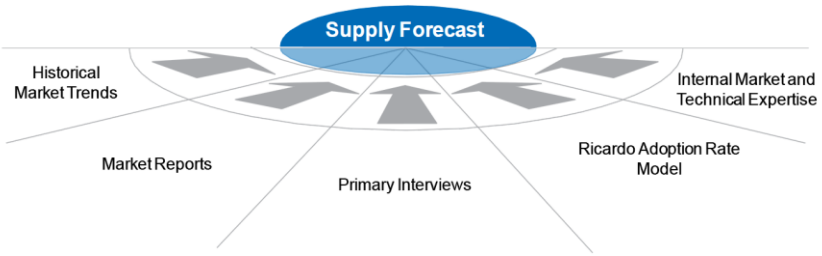
1.2 Overview: Market Analysis: Supply vs. Demand

The goal of the market analysis is to determine the degree of alignment between the first use commercial PEV battery supply and the second use utility market module/battery demand. This analysis incorporated an assessment of the technical product requirements in both markets as well as the alignment in the size of both markets between 2014 and 2025.

1.2.1 Supply of Second use Commercial, Electric-Drive Vehicle Batteries

A landscape of the supply side of the PEV battery market was developed, including growth forecasts and product descriptions through 2020. Information gathered during industry interviews with vehicle OEMs and battery suppliers was merged with data obtained from a literature search which included historical market trends, current market reports, internal technical and market expertise and Ricardo's technology adoption rate model to forecast the supply of PEV batteries available for secondary application within the utility industry. This process is illustrated in Figure 14.

Figure 14: Approach to Developing Supply Forecast

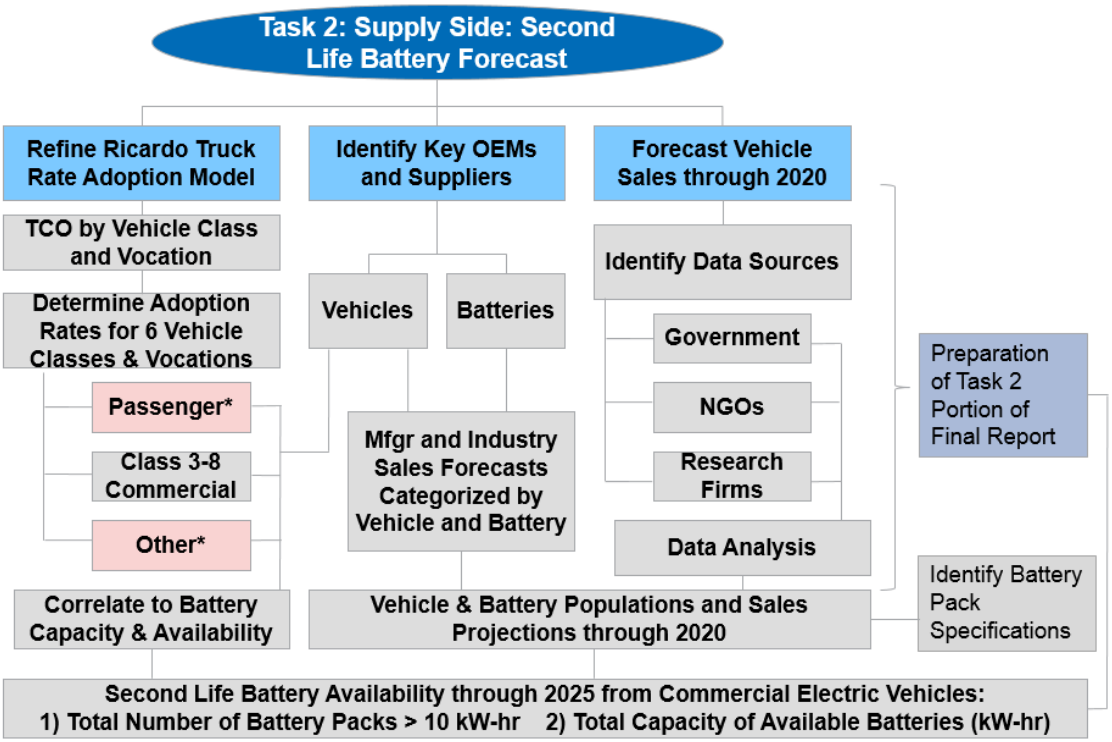


The focus of the battery supply study was on commercial vehicles. Commercial vehicle vocations were chosen based on several criteria including:

1. Vocational vehicles have duty cycles that lend themselves to electrification and hybridization (and incorporate battery packs favorable for second use applications).
2. Vehicle manufacturers currently offer or are planning to offer a wide range of electric drive products.
3. The increased residual value of battery packs for EVs, HECVs, and PECVs reduces payback periods and provides cost justification for incorporating electric drive technologies.
4. Vocational vehicles are eligible for government incentive programs
5. For many vocational vehicles, the total cost of ownership is significantly reduced when PEV and HEV drive systems are employed.
6. Many vocations have a population large enough to significantly impact the second use battery market.
7. Vocational vehicle fleet owners have been shown to be early adopters of new technology

The process for determining the availability of modules and battery systems originating from the selected vocational vehicles is illustrated in Figure 15.

Figure 15: Task Interaction: Supply Side Second use Battery Forecast



*Not included in current study

Information sources ranged from industry interviews to technical journals and commercially available data bases. Commercial vehicles were categorized by both vocation and weight class. Weight class categories are defined in Figure 17. The term vocational refers to vehicles with a defined commercial purpose, such as buses, refuse trucks, concrete mixers, etc. (and not combination tractors or heavy-duty pick-up trucks or vans, reference 114). An example of the vocation vehicle population study results, in this case for vehicles registered within California, is shown in Figure 16 (references 16, 17, 18, 93).

Figure 16: Example Populations of Various Vehicle Vocations: California Market Segments

Class	Category	Applications	Est. Vol.
Urban 7-8	HCV	Day/ Delivery Trucks	110,972
		Transit Buses	13,143
		Other	68,369
Urban 2b-6	MCV	Delivery Trucks	365,308
		Shuttle Buses	129,299
Worksite 4-8	M&HCV	Large Work Trucks	81,107
Worksite 1-3	L&MCV	Small Work Trucks	201,353
Rural 2b-6	MCV	Delivery and Shuttle	151,282

Figure 17: United States Light Vehicle Classifications by GVW[4]

US light vehicle classifications by GVW

US market definition	Light trucks			Trucks				
				Medium duty				Heavy duty
Truck class	1	2	3	4	5	6	7	8
GVW – Lbs	6,000 lbs or less	6,001 – 10,000 lbs	10,001 – 14,000 lbs	14,001 – 16,000 lbs	16,001 – 19,500 lbs	19,501 – 26,000 lbs	26,001 – 33,000 lbs	33,001 lbs or more
GVW – Kgs	2,722 kg or less	2,653 – 4,535 kg	4,536 – 6,350 kg	6,351 – 7,257 kg	7,258 – 8,845 kg	8,846 – 11,793 kg	11,794 – 14,968 kg	14,969 kg or more
Requires commercial driving license							●	●
Model example	BMW X5	Ford F-250	Isuzu NPR	UD 1400	GMC T5500	Mitsubishi Fuso FM-MR	Ford F-750	Freightliner FL-80

[4] Source: Ricardo Analysis

Commercial vehicles are divided into four categories and over 200 vocations as summarized below in Figure 18.

Figure 18: Vehicle Classification Definitions[5]

Vehicle Classification*	Definition (typical applications)*	North America* (based on US DOT Vehicle Inventory and Use Survey)
Light Commercial Vehicles (LCV)	Includes pick-up and delivery, utilities, airport operations, facilities management and several other vocational applications	Class 2-3 GVWR <= 14,000 lbs
Medium Commercial Vehicles (MCV)	Home delivery, logistics, parcel delivery, utilities, waste and recycle collection, airport operations, small and medium school and transit buses among others	Class 4-6 GVWR > 14,000 & <=19,500 lbs
Heavy Commercial Vehicles (HCV)	Line haul freight trucks, refuse trucks, mining & construction trucks, and other types of vocations that demand high GVWR trucks	Class 7 and 8 GVWR > 26,500 lbs
Bus	Urban public transport systems such as transit buses, school buses and motor coaches	GVWR higher than 14,000 lbs

Vocational vehicles are defined by their application. Examples include Urban Delivery, Construction, Service Vans, Box Trucks, Work Trucks, Heavy Haul, Line Haul, Logging, Mining, Refuse, Oil Field, Fire Service, Transit Coach, InterCity Bus, Airport Shuttles, Trolleys, School Bus, and Yard Tractors[6].

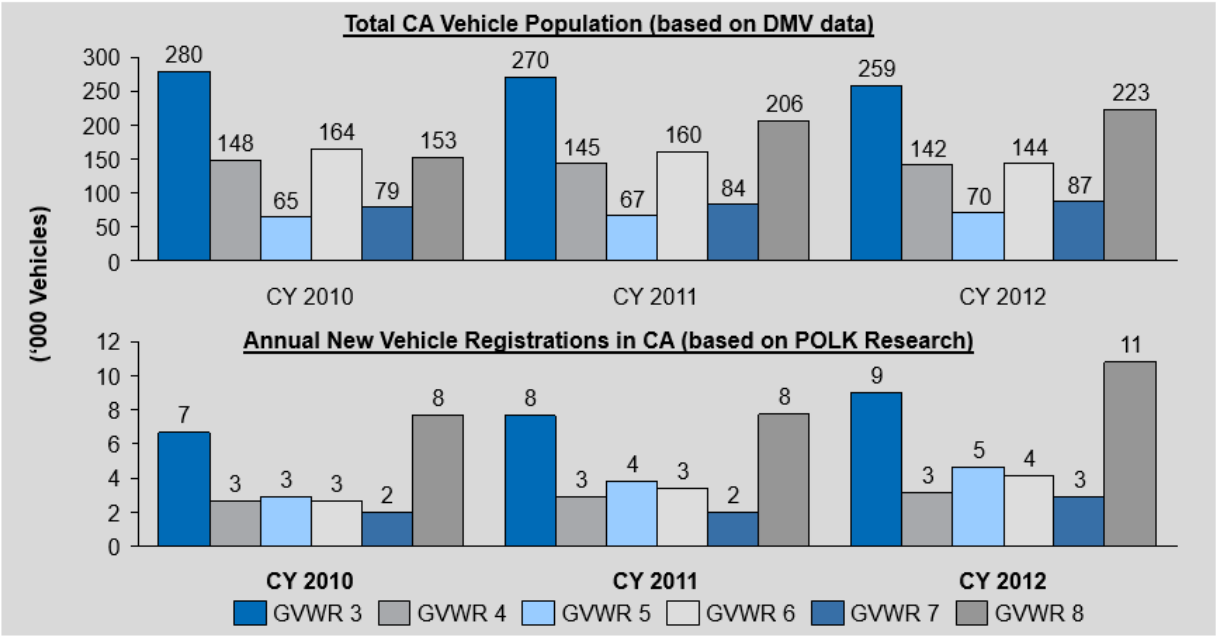
Classes 3, 4, 6, and 8 represent the largest Commercial Vehicle Registrations within California. California Truck Populations and New Registrations by Class (2010-12) show the following:

- Significant variations in populations are noted for commercial vehicle classes.
- Current populations and new vehicle sales were considered in selecting vocation weight classes for TCO and Adoption Rate Analyses

[5] Source – US Federal Highway Administration

[6] Eaton Warranty Guide, April 2013 (Document TCWY0900 EN-US)

Figure 19: Total CA Vehicle Population and Annual CA New Vehicle Registrations



1.2.1.1 Selection of Key Vocational Vehicle Categories

Prior to employing the detailed Total Cost of Ownership (TCO) model, a simplified payback analysis was performed to assist in selecting vehicle vocations for additional analysis. The following parameters were included in Simplified Payback Analysis[7]:

- Electric range (miles)
- Electric power ($kW_{average}$)
- Energy usage (kWh/mile)
- Battery size (kWh)
- Motor size (kW)
- Incremental price (relative to conventional diesel vehicle)
- Conventional vehicle efficiency (miles/gallon)
- Idle time (hours)
- Idle time fuel use (gallons/hour)
- Calculate fuel saved relative to conventional

[7] Source: Ricardo Analysis

- Determine cost of fuel saved
- Maintenance savings relative to conventional
- Determination of annual savings
- Calculation of payback period (years)

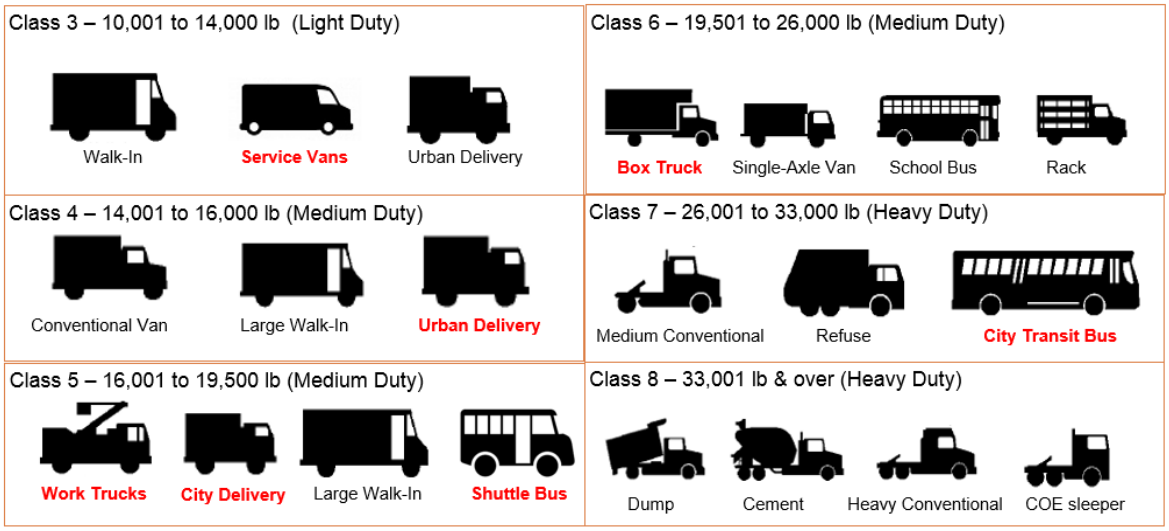
Note that this study does not include vehicle retrofit market (conversion of existing conventional vehicles to EVs).

Vehicle vocations were selected based on a simplified payback analysis. Based on the results of the initial evaluation of vocational vehicle duty cycles, incremental capital costs and operational costs, six vocational categories were selected for detailed analyses. These are highlighted in red font in Figure 20. The six selected vocations were found to have potential for favorable economic returns and thus positive incentive for fleet owners to incorporate the new technologies into future vehicle acquisitions.

It is noted that there are many other vehicles that are candidates for electric drive technologies and, hence, are possible sources for future second use modules and battery systems. These are shown in Figure 21. They were not included in the current analysis due to their lower populations, smaller capacity battery systems, or less-developed electric drive technologies.

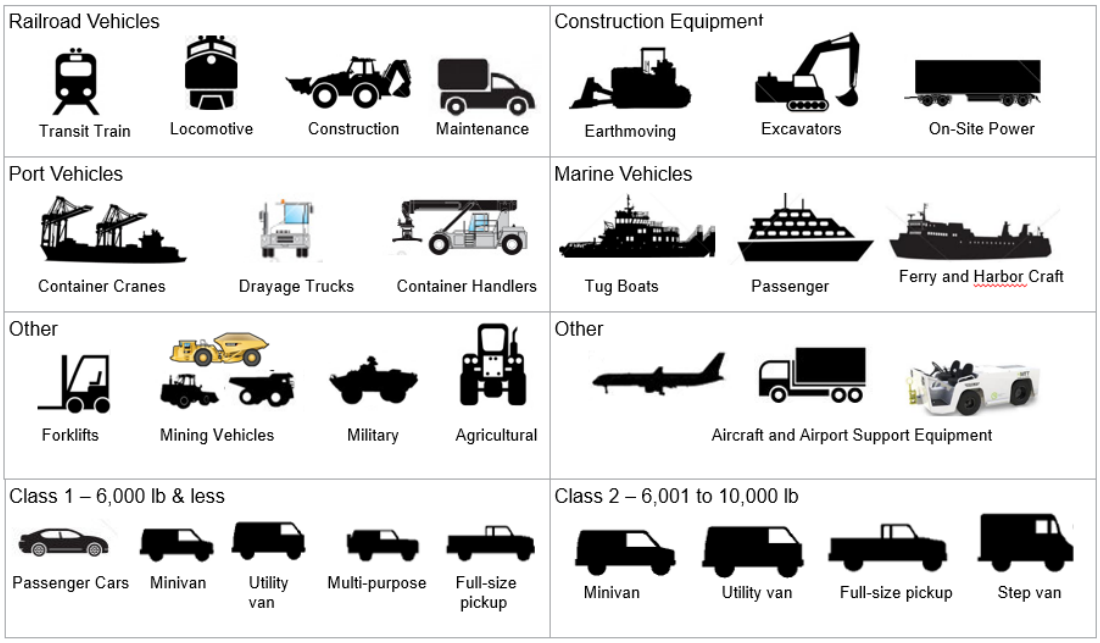
Vocational vehicle populations are significant, as shown in Figure 16 (total California vehicle registrations), Figure 22 (new vehicle registrations for entire United States), and (new vehicle registrations for entire United States, by year, categorized by vehicle weight class). These vehicles are candidates for supplying large numbers of modules and battery systems for second use stationary energy storage applications. As shown in Figure 25, new United States vocational vehicle registrations represent over 60 percent of commercial vehicle sales based on 2012 data (reference 93).

Figure 20: Candidate Sources of Vehicle Battery Packs: Electric Commercial Vehicles (ECVs)[8]



Vocations shown in red font were selected for Total Cost of Ownership and Adoption Rate Modeling.

Figure 21: Other Candidate Sources of Vehicle Battery Packs: (Excluded from Current Study)



[8] Sources – US Federal Highway Administration, NREL, National Academy of Sciences, R.L. Polk, California DMV, National Renewable Energy Laboratory, Oak Ridge National Laboratory, US Energy Information Agency, U.S. Doe Alternative Fuels Data Center, US EPA, National Research Council of the National Academis, and the Electric Power Research Institute.

The six selected vehicle vocations have significant populations and offer potential as sources for second use batteries.

Figure 22: Total New Vehicle Registrations: 2012, Commercial Vehicles Classes 3-7, for Entire US

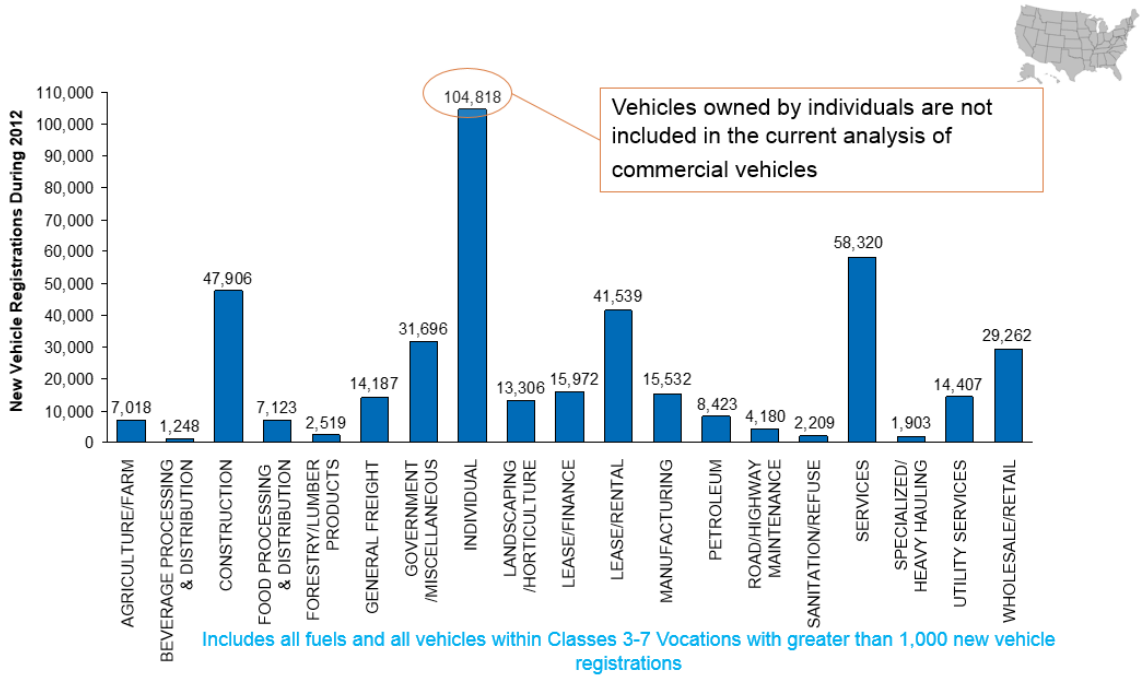
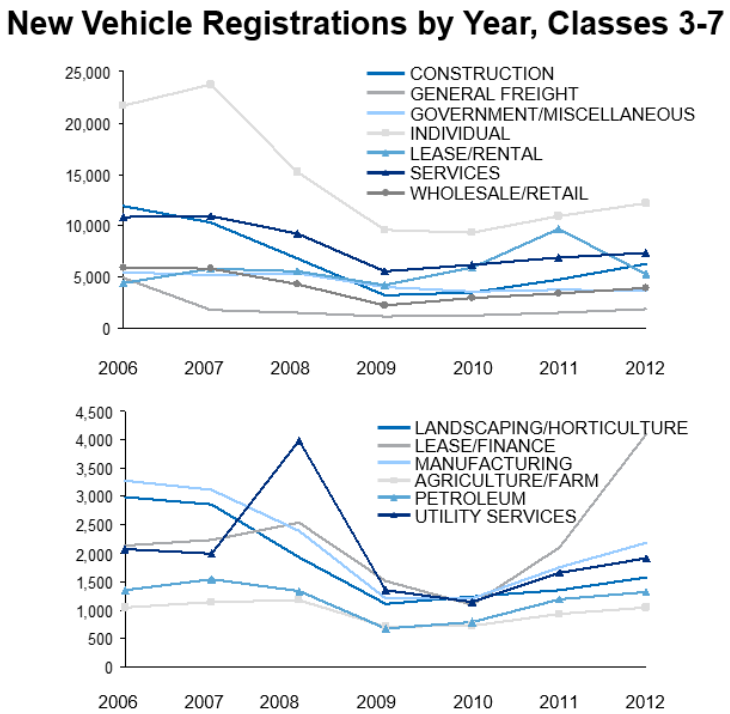


Figure 23: New Vehicle Registrations by Year, Classes 3-7, for Entire US



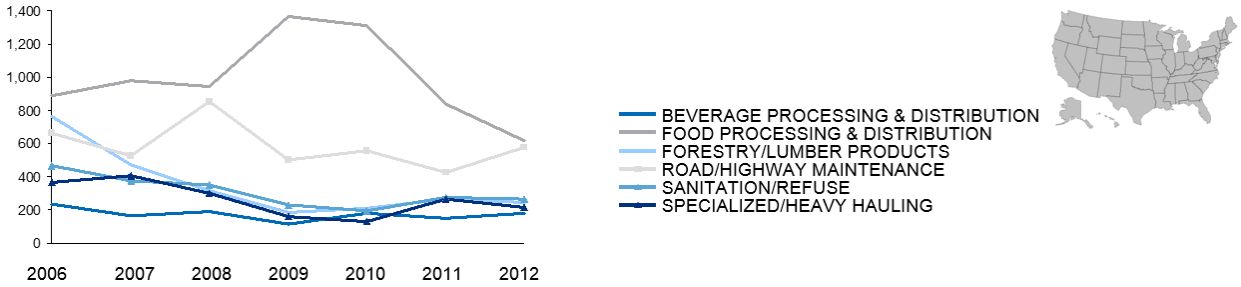
Weight Class	New Vehicle Registrations 2012
3	169,964
4	38,131
5	48,134
6-7	43,155
8	198,123
Total:	497,507

Total New Commercial Vehicle Registrations by Weight Class for 2012 (All Vehicles)

Vocation	New Vehicle Registrations 2012
Class 3 Service Vans	54,517
Class 3-6 Shuttle Buses	9,797
Class 6 Box Trucks	5,347
Class 4-6 Urban Delivery Trucks	14,240
Class 7-8 Transit Buses	19,134
Class 4-6 Work Trucks	13,902
Total	116,937

Total New Vehicle Registrations for 2012: Selected Vocations

Figure 24: New Vehicle Registrations by Year, Classes 3-7, for Entire US



New Vehicle Registrations by Year, Classes 3-7

As the table below indicates, the the six selected vocational vehicle cateogories chosen for further analysis represent 24 percent of all new United States commercial vehicle registrations and 37 percent of all new vocational vehicle registrations. Vocational vehicles represent 64 percent of new commercial vehicle registrations.

Figure 25: Analysis of 2012 United States New Vehicle Registrations[9]

Analysis of 2012 New Vehicle Registrations		Percent of New Commercial Vehicle Registrations	Percent of New Vocational Vehicle Registrations
New Commercial Vehicle Registrations	497,507		
New Vocational Vehicle Registrations	316,750	64%	
New Vehicle Registrations for Six Selected Vocations	116,937	24%	37%

To properly analyze the R.L. Polk (IHS) Vehicle Registration Data Base[10], it was necessary to match the vocational vehicle definitions used in the data base with those employed by US DOE and EPA. The IHS categories are shown in Figure 26. The corresponding DOE/EPA categories are shown in Figure 27.

Figure 26: Commecial Vehicle Vocations associated with IHS (Polk) Vehicle Registration Data Base

1. Agricultural/Farm
2. Beverage Processing & Distribution
3. Bus Transportation
4. Construction
5. Dealer
6. Emergency Vehicles
7. Food Processing and Distribution
8. Forestry/Lumber Products
9. General Freight
10. General Freight: Hazardous Materials
11. Government and Government Miscellaneous
12. Hazardous Materials
13. Individual
14. Landscaping/Horticulture
15. Lease/Finance
16. Lease/Manufacturer Sponsored
17. Lease/Rental
18. Manufacturing
19. Mining/Quarrying
20. Miscellaneous
21. Moving and Storage
22. Petroleum
23. Petroleum/Hazardous Materials
24. Road/Highway Maintenance
25. Sanitation/Hazardous Materials
26. Sanitation/Refuse
27. Services
28. Specialized and Heavy Hauling
29. Unclassified
30. Utility Services
31. Vehicle Transporter
32. Wholesale/Retail

The following data base vocations were included in the population and new vehicle registration analyses for the six selected vehicle categories.

[9] Source: Ricardo Analysis of New Vehicle Registrations

[10] Source – R.L. Polk (IHS)

Figure 27: Data Base Categories Corresponding to Selected Vocations

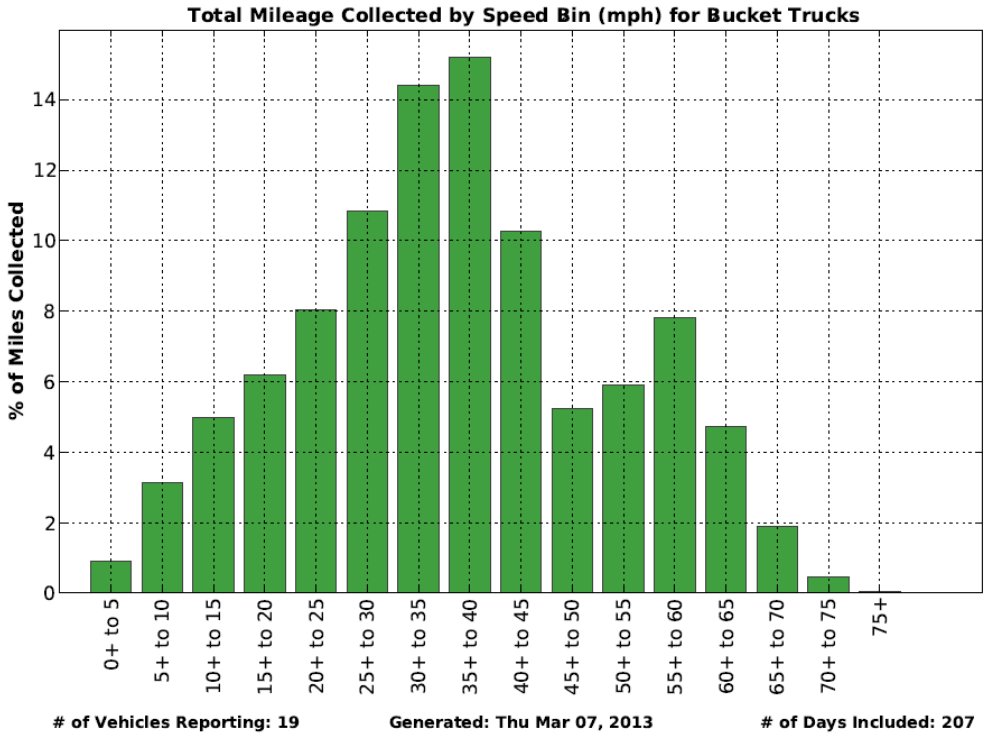
Class and Vocation	Corresponding Polk Vocations	Class and Vocation	Corresponding Polk Vocations
Class 3 Service Vans	BEVERAGE PROCESSING & DISTRIBUTION CONSTRUCTION FOOD PROCESSING & DISTRIBUTION GENERAL FREIGHT LANDSCAPING/HORTICULTURE LEASE/RENTAL MANUFACTURING MOVING AND STORAGE ROAD/HIGHWAY MAINTENANCE SERVICES UTILITY SERVICES WHOLESALE/RETAIL	**Class 4 to 6 Urban Delivery**	BEVERAGE PROCESSING & DISTRIBUTION FOOD PROCESSING & DISTRIBUTION GENERAL FREIGHT MOVING AND STORAGE WHOLESALE/RETAIL
Class 3 - 6 Shuttle Buses	BUS TRANSPORTATION	**Class 7 - 8 Transit Buses**	BUS TRANSPORTATION
Class 6 Box Trucks	BEVERAGE PROCESSING & DISTRIBUTION FOOD PROCESSING & DISTRIBUTION GENERAL FREIGHT MOVING AND STORAGE WHOLESALE/RETAIL	**Class 4-6 Work Trucks**	ROAD/HIGHWAY MAINTENANCE SANITATION/REFUSE SPECIALIZED/HEAVY HAULING UTILITY SERVICES

Duty cycle and annual miles traveled were additional criteria used for selecting vehicles for inclusion in the adoption rate analysis. Duty cycle data were collected from a number of sources. Examples are shown below.

Figure 28: Annual Miles Traveled for Indicated Vocations

Categories	Annual Miles Traveled
Class 8 Truck	66,768
Transit Bus	36,424
Refuse Truck	25,000
Shuttle (no fixed route)	24,680
Police	15,160
Light Truck	14,596
Delivery Truck	13,239
School Bus	12,000
Light-Duty Vehicle	11,318
Car	10,614
Motorcycle	2,221

Figure 29: Portion of Miles Traveled within Defined Speed Ranges (Bins)[11]

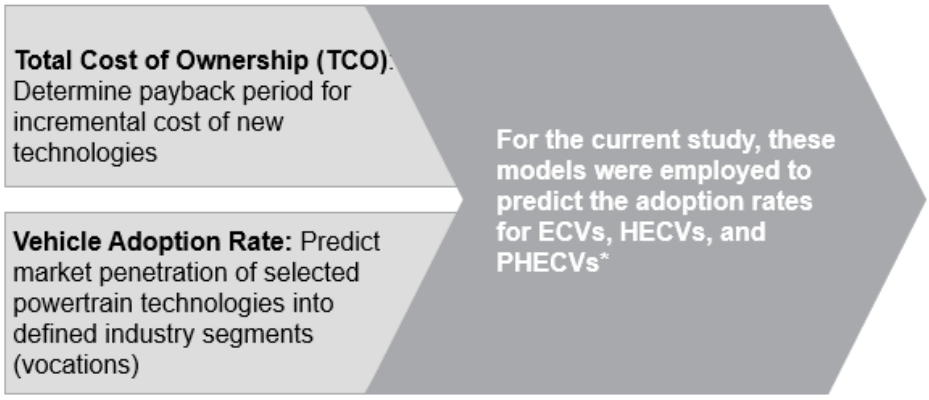


1.2.1.2 Adoption Rates by Vehicle Class and Vocation

A market analysis to identify lessons learned from previous standardization efforts was conducted. Ricardo's TCO Model was employed to determine payback periods for ECV, HECV, and PHECV technologies. Prior to the current study, Ricardo developed two proprietary, spreadsheet-based modeling tools to assess adoption rates of new vehicle technologies.

[11] Source: National Renewable Energy Laboratory: Fleet DNA Project Summary Report (7 March 2013): PR-5400-57992 (Work Trucks, Bucket Trucks)

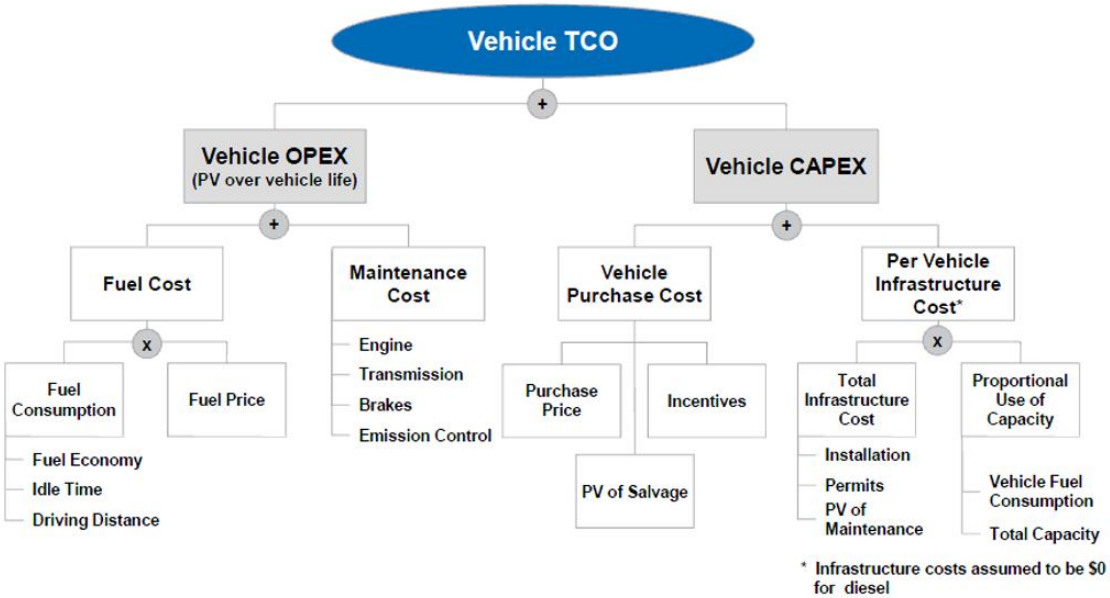
Figure 30: Ricardo's TCO and Adoption Rate Determination Process



* Electric Commercial Vehicles, Hybrid Electric Commercial Vehicles, and Plug-In Hybrid Electric Commercial Vehicles

The Vehicle TCO is modeled as the Present Value (PV) of the sum of both CAPEX and OPEX for the first ownership period. The residual value of the battery pack has a significant impact on commercial vehicle TCO. The primary components of the TCO modeling process are shown in Figure 31 below.

Figure 31: Vehicle TCO



The Total Cost of Ownership (TCO) model was used to assess economic viability of EV, PHEV, and HEV technologies for the six selected commercial vehicle vocations. These were compared to corresponding TCO information for conventional diesel and gasoline-fueled commercial

vehicles to determine the return on investment (ROI) associated with the incremental costs (and resulting savings) for the electric drive systems. Incremental costs for ECVs and PHECVs included the charging infrastructure (which also includes permitting and installation costs). The calculated payback period is an input to the ECV adoption rate model.

Inputs to TCO Model

Some of the inputs to the TCO model for the selected vocational vehicles are shown in the figures below. Additional information and details on chemistry types and expected lifetime will follow in later chapters.

Figure 32: Total Cost of Ownership Model Input Parameters for Selected Vocational Vehicles

Vehicle Vocation	Power Train Type	Weight Class	Duty Cycle Miles/day	Battery Capacity (kw-hrs)	Fuel Economy (miles/gallon)	Usage (days/year)	Time to Initial Battery Replacement (years)
Service Vans	EV	3	71	75	45	280	10.7
	PHEV			20	17	280	10.7
Box Truck	EV	6	80	120	31	280	>12
	PHEV			28.4	12	280	>12
Urban Delivery	EV	4 to 6	71	110	31	280	>12
	PHEV			No commercial PHEVs offered for this category			
City Transit Bus	EV	7 to 8	120	260	22	280	>12
	HEV			11.8	5.9	280	>12
	PHEV			90	9.3	280	>12
Work Trucks	EV	4 to 6	43	No commercial EVs offered for this category			
	PHEV			13	9.6	280	10.7
Shuttle Bus	EV	3 to 6	100	105	45.0	280	10.7
	PHEV			15	14.9	280	10.7

Note: Hybrid Electric Commercial Vehicles (HECVs) are offered by OEMs in each vocational category, however, only City Transit Buses in this category had battery pack capacities greater than 10 kw-hrs; vehicles with battery capacities less than this were excluded from the current analysis.

For the inputs shown in Figure 33, the electric drive fuel economy is measured in diesel gallons equivalent.

Figure 33: Total Cost of Ownership includes Infrastructure Requirements for ECVs and PHECVs

Vehicle Vocation	Power Train Type	Battery Capacity (kw-hrs)	Charger Type	Charging System Cost	Per Charger System Installation Cost*	Charger Installations Required per Vehicle
Service Vans (Class 3, 71 miles/day)	EV	75	Level 2	$ 850	$ 1,000	1
	PHEV	20	Level 2	$ 850	$ 1,000	1
Box Truck (Class 6, 80 miles/day)	EV	120	Level 2	$ 10,000	$ 4,468	1
	PHEV	28.4	Level 2	$ 850	$ 1,000	1
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	Level 2	$ 10,000	$ 4,468	1
	PHEV	No commercial PHEVs offered for this category				
City Transit Bus (Class 7-8) (120 miles/day)	EV	260	Level 2	$ 10,000	$ 4,468	1
	HEV	11.8	No Additional Infrastructure Required			
	PHEV	90	level 2	$ 10,000	$ 4,468	1
Work Trucks (Class 4-6, 43 miles/day)	EV	No commercial EVs offered for this category				
	PHEV	13	Level 2	$ 850	$ 1,000	1
Shuttle Bus (Class 3-6, 100 miles/day)	EV	105	Level 2	$ 850	$ 1,000	1
	PHEV	15	Level 2	$ 850	$ 1,000	1

* Charger Installation Costs Include:

1) Permitting, 2) Installation Labor, 3) Installation Materials, 4) Real Estate and Other Costs, and 5) Incentives and Rebates

An evaluation of applicable EV, HEV, and PHEV drive systems was completed and is summarized in Figure 34. Key goals for this task include: define the size of the originally-installed battery packs, the determination of the battery capacity (kw-hrs) at the time it is removed from the vehicle, the duration of the battery first use (length of time it is installed in the vehicle before it is removed), the useful life of the vehicle (for comparison to useful life of the battery), and, from this information, determine the number of times the batteries are replaced during the useful life of the vehicle, the number of second use batteries that become available for each vehicle, and the capacity (kWh) of the second use batteries.

Figure 34: Number of Second use Batteries and Capacities for Selected Commercial Vehicle Vocations

Vehicle Vocation	Power Train Type	Battery Capacity		Time to Initial Battery Replacement (years)	Vehicle Useful Life (years)	Number of Battery Replacements during Useful Life	Number of Second-Life Batteries/Vehicle	Capacity of Second-Life Batteries (kw-hr)
		Originally Installed (kw-hrs)	End of First Life (kw-hrs)					
Service Vans (Class 3, 71 miles/day)	EV	75	71	10.7	6	0	1	60
	PHEV	20	18	10.7	6	0	1	16
Box Truck (Class 6, 80 miles/day)	EV	120	89	>12	12	0	1	96
	PHEV	28.4	25	>12	12	0	1	23
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	71	>12	12	0	1	88
	PHEV	No commercial PHEVs offered for this category						
City Transit Bus (Class 7-8) (120 miles/day)	EV	260	133	>12	12	0	1	208
	HEV	11.8	21	>12	12	0	1	9
	PHEV	90	80	>12	12	0	1	72
Work Trucks (Class 4-6, 43 miles/day)	EV	No commercial EVs offered for this category						
	PHEV	13	11	10.7	15	1	2	22
Shuttle Bus (Class 3-6, 100 miles/day)	EV	105	89	10.7	6	0	1	84
	PHEV	15	13	10.7	6	0	1	12

Battery life is based on the vehicle duty cycle and the number of charge/discharge cycles. This is summarized in Figure 35 for each selected vocational vehicle.

Figure 35: Duty Cycle and Battery Pack Capacity Determines Number of Charge/Discharge Cycles and Depth of Discharge[12]

Vehicle Vocation	Power Train Type	Battery Capacity (kw-hrs)	Fuel Economy (miles/gal)	Number of Charge and Discharge Cycles During Vehicle Life	Vehicle Useful Life (years)	Battery Useful Life (years)	Vehicle Energy Usage (miles/kw-hr)	Depth of Discharge (DOD) Based on Duty Cycle (%)*
Service Vans (Class 3, 71 miles/day)	EV	75	45	1,680	6	10.7	1.19	80%
Box Truck (Class 6, 80 miles/day)	EV	120	31	3,360	12	>12	0.83	80%
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	31	3,360	12	>12	0.83	77%
City Transit Bus (Class 7-8, 120 miles/day)	EV	260	22	1,680	12	>12	0.58	79%
Shuttle Bus (Class 3-6, 100 miles/day)	EV	100	45.0	3,360	6	10.7	1.19	80%

Number of Battery Charge/Discharge Cycles = Vehicle Useful Life divided by Number of Days Vehicle is Used Per Year (280 days/year)
Depth of Discharge (DOD) =[(Duty Cycle miles/day)/(Vehicle Energy Usage miles/kw-hr)]/(Battery Capacity kw-hrs)

Note, that for this analysis the electric drive fuel economy is measured in diesel gallons equivalent. Actual sales data illustrating the accessibility of commercially available vehicles is discussed later in the report.

Additional TCO Model Inputs included (see Figure 36):

- Battery replacement costs for vehicles with useful life ratings that exceed the battery life expectancy
- Incremental cost of EV, PHEV, and HEV drive systems

Figure 36: Additional Inputs to TCO Model[13]

Vehicle Vocation	Power Train Type	Weight Class	Duty Cycle Miles/day	Battery Capacity (kw-hrs)	Vehicle Price Diesel Powertrain	Incremental Price (EV, PHEV, HEV)
Service Vans	EV	3	71	75	$ 40,000	$ 98,500
	PHEV			20		$ 27,000
Box Truck	EV	6	80	120	$ 65,000	$ 81,400
	PHEV			28.4		$ 36,380
Urban Delivery	EV	4 to 6	71	110	$ 65,000	$ 74,400
	PHEV			No commercial PHEVs offered for this category		
City Transit Bus	EV	7 to 8	120	260	$ 400,000	$ 442,000
	HEV			11.8		$ 155,760
	PHEV			90		$ 211,000
Work Trucks	EV	4 to 6	43	No commercial EVs offered for this category		
	PHEV			13	$ 140,000	$ 26,600
Shuttle Bus	EV	3 to 6	100	100	$ 40,000	$ 119,500
	PHEV			15		$ 23,500

[12] Reference: Ricardo TCO Model

[13] Reference: Ricardo TCO Model

Duty cycles were defined for each application (vocation) to determine battery requirements and electricity costs. An example duty cycle, for Class 4-6 Urban Delivery Trucks, is shown in Figure 37.

Figure 37: Example Duty Cycle for Class 4-6 Urban Delivery Trucks[14]

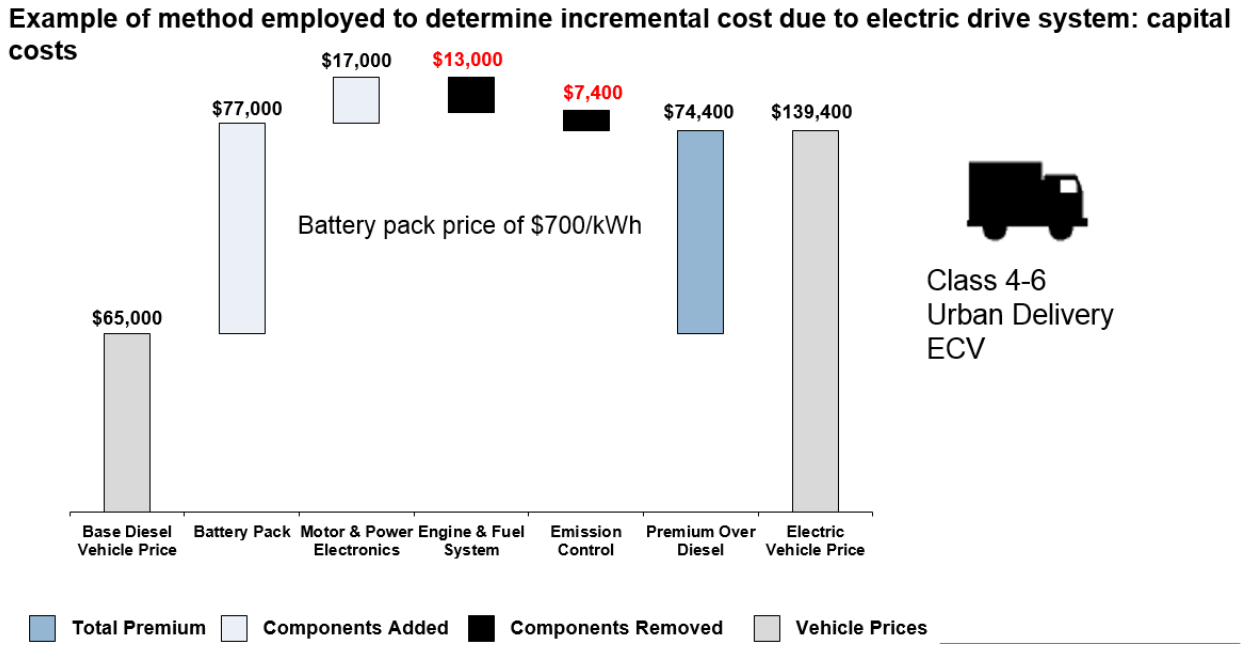
Class 4-6
Urban Delivery

Duty Cycle			
Duty Cycle Inputs	Days Used/year		280
	Operating Time (vehicle on)	hours/day	4
	Percent Time @ Idle	% Operating Time	13%
	2-10 mph	% Operating Time	20%
	11-20 mph	% Operating Time	30%
	21-30 mph	% Operating Time	15%
	31-40 mph	% Operating Time	6%
	41-50 mph	% Operating Time	7%
	51-60 mph	% Operating Time	5%
	61-70 mph	% Operating Time	4%
Total Operating Check	Total Operating Time Mix		100%
Total Annual Miles	Miles Driven - Yearly	miles/year	19,751
Idle Time Calculations	Idle Time - Daily	hours/day	0.52
	Idle Time - Yearly	hours/year	146
Duty Cycle Weighted Miles @ Speed Calculations	2-10 mph	miles/day	2.8
	11-20 mph	miles/day	9.6
	21-30 mph	miles/day	15.3
	31-40 mph	miles/day	8.5
	41-50 mph	miles/day	12.7
	51-60 mph	miles/day	11.1
	61-70 mph	miles/day	10.5
	Total Miles per day	miles/day	70.5
	Average Operating Speed	mph	23

The incremental cost of the electric drive system was determined for each of the six selected vocational vehicles. The incremental cost relative to a conventional diesel engine version of each vehicle includes both positive and negative increments. For the example shown in Figure 38, positive incremental elements include the price of the battery pack, motor, and power electronics. Negative increments (e.g. costs lower than those for a conventional diesel vehicle) include the engine and fuel system as well as emissions controls. Adding the positive and negative increments provides the net incremental cost associated with the advanced technology vehicle. Similar evaluations were completed for operational costs differences between the conventional and advanced technology versions of each vocational vehicle.

[14] Source: Ricardo TCO Model

Figure 38: Additional Inputs to Total Cost of Ownership Models



Grant and Incentive Programs and Impact on TCO

Incentives have a significant impact on adoption rates for ECVs, PHECVs, and HECVs. However, the incentive programs do not have adequate funding to support sales levels for majority adoption and will thus be applicable only during the first few years following introduction of a new technology vehicle or for longer time periods at much-reduced funding per vehicle levels[15]. A summary of current incentive programs is shown in the table of Figure 39.

[15] Source: Ricardo analysis and "Clean Commercial Truck Incentives", presented by Tom Brotherton of CALSTART at 6 March 2013 NTEA Truck Show

Figure 39: California Incentive Programs for Commercial EVs, PHEVs, and HEVs

Incentive Program	Region	Description	Notes
California HVIP Base Hybrid Voucher	California	GVW(lbs) 6,001-8,500 (plug-in hybrids only): $8,000 8,501-10,000 (plug-in hybrids only): $10,000 10,001-19,500: $15,000; 19,501-33,000: $20,000 33,001-38,000: $25,000; >38,000: $30,000	
California HVIP Base Zero-Emission Voucher	California	GVW(lbs) 5,001-8,500: $12,000; 8,501-10,000: $18,000 10,001-14,000: $30,000; 14,001-19,500: $35,000 19,501-26,000: $40,000; >26,000: $45,000	
San Joaquin Valley APCD HVIP Plus-Up Voucher	San Joaquin Air District	Hybrid Vehicle: +$15,000 Zero-Emission Vehicle (<8,500 lbs): +$12,000 Zero-Emission Vehicle (<8,500 lbs) manufactured in San Joaquin Valley: +$18,000 Zero-Emission Vehicle (>8,500 lbs): +$20,000 Zero-Emission Vehicle (>8,500 lbs) manufactured in San Joaquin Vally: +$30,000	Vehicles must be domiciled in the San Joaquin Air District
California HVIP Voucher Adders	California	**The first three vouchers received by a fleet are eligible for additional funding:** $2,000/vehicle <8,501 GVWR $5,000/vehicle 8,501 - 10,000 GVWR $10,000/vehicle >10,000 GVWR **Hydrogen Fuel Cell Vehicles:** 5,001-19,500 lbs: +$20,000 19,501-33,000 lbs: +$30,000 >33,000 lbs: +$40,000	
Incentive Program	**Region**	**Description**	**Notes**
California HVIP Hybrid Voucher Adders	California	GVW(lbs) 6,001-10,000 (plug-in hybrids only): School Bus $5,000 10,001-14,000: Plug-in or Hydraulic Hybrid $5,000, School Bus $5,000 14,001-33,000: Plug-in or Hydraulic Hybrid $10,000, School Bus $10,000, ARB Certification (full vehicle) $15,000 >33,001: Plug-in or Hydraulic Hybrid $10,000, School Bus $10,000, ARB Certification (full vehicle) $20,000	1 - The total of all advanced technology vehicle subsidies, including the HVIP Base Vehicle Incentive and voucher enhancements may not exceed the assumed vehicle incremental cost. 2 – Plug-in electric or hydraulic hybrid vehicles must demonstrate at least a 40 percent fuel economy benefit relative to their non-hybrid counterpart as part of their HVIP eligibility application. 3 - Zero-emission school buses also eligible for this voucher bump-up.
California HVIP OBD Voucher Adders	California	Vehicle GVWR (lbs) 14,001 - 26,000: Total Number of Hybrid-Related Deficiencies 10+ (2013/2014 MY): $12,000 <10 (2013/2014 MY): $16,000 9-14 (2015 MY): $8,000 5-8 (2015 MY): $12,000 <=4 (2015 MY): $16,000 Vehicle GVWR (lbs) >26,001: Total Number of Hybrid-Related Deficiencies 10+ (2013/2014 MY): $16,000 <10 (2013/2014 MY): $20,000 9-14 (2015 MY): $12,000 5-8 (2015 MY): $16,000 <=4 (2015 MY): $20,000	

On October 1, 2013, the California Air Resources Board (ARB) announced an additional $72.5 million in grants and loan funding[16]. The funding for Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project was increased by $10 million to $15 million. This program provides vouchers of up to $55,000 per vehicle. ARB's Truck Loan Assistance Program provides an additional $18 million to finance truck upgrades required under the ARB's In-Use Truck and Bus Regulation.

The following legislation was recently enacted in California[17]:

[16] Sources: Ricardo analysis and "Clean Commercial Truck Incentives", presented by Tom Brotherton of CALSTART at 6 March 2013 NTEA Truck Show, and the California Air Resources Board.

[17] Sources: Plug-In America Newsletter, October 2013, Page 1

- AB 8 continues funding of the Clean Vehicle Rebate Project along with other key state EV initiatives through 2023.
- SB 359, by Senator Corbett, funds the Clean Vehicle Rebate Project at full strength for 2014, helps small fleets finance upgrades, and supports a "cash for clunkers" incentive.
- SB 286 and AB 266 extend the solo California high-occupancy lane access for BEVs and PHEVs through the end of 2018.
- SB 454 opens access to public charging by mandating easy payment methods, and transparent pricing.
- AB 1092 incorporates rules for EV charging into California's building code.

Other United States incentive programs for ECVs, PHECVs and HECVs are included in Figure 40 and Figure 41.

Figure 40: United States Incentive Programs for Commercial EVs, PHEVs, and HEVs[18]

Incentive Program	Region	Description
California HVIP Voucher - ePTO	California	Aerial Boom Vehicles with ePTO: Can get voucher without hybrid driveline, Must be >26,000 GVWR. Lithium batteries $20,000 Lead-acid batteries $14,000
Incentives for Evs in New York State	New York State	Class 3-8 electric trucks. $9 million in incentives. Vouchers for 80% of incremental cost up to $60,000 per eligible vehicle. For 30 non-attainment counties. CMAQ funding from NY State DOT. For vehicles ordered after July 1, 2012. Expected spring 2013 launch.
Alt Fuel Vehicle in New York City	New York City	Class 3-8 CNG, hybrid, electric trucks. $6 million in incentives. Vouchers for 80% of incremental cost up to $40,000 per eligible vehicle. Private fleets only. Must domicile in NYC. CMAQ funding from NY City DOT. Will launch in 2013.
Metro Chicago	Chicago	Electric trucks. Launches spring 2013. Voucher amount based on battery size. Targets 60% of incremental cost. Private and public fleets. $15 million in CMAQ funds. Targets 250 vouchers.
Bill SB359	California	Saves the CA CVRP Rebate Program and provides additional funding to last through June 2014
Bill AB8	California	$2 billion for long-term state alternative fuels funding, including significant funding for EV related projects

The US Department of Transportation under 49 USC Section 5339/MAP-21 Section 20029 provides $65.5 M annually to replace, rehabilitate and purchase buses and related equipment and to construct bus-related facilities. Each state is eligible for up to $1.25 M and each territory (D.C. and Puerto Rico) receiving $500 K.

[18] Sources: 1) Ricardo analysis, 2) "Clean Commercial Truck Incentives", presented by Tom Brotherton of CALSTART at 6 March 2013 NTEA Truck Show , and 3) US FTA Fact Sheet: Bus and Bus Facilities, Section 5339 (www.fta.dot.gov/map21)

Figure 41: United States Incentive Programs for Commercial EVs, PHEVs, and HEVs[19]

Incentive Program	Region	Description
Commercial Electric Truck Vouchers	Oregon	Through the Commercial Electric Truck Incentive Program, the Oregon Department of Transportation provides vouchers to reimburse commercial fleets for $20,000 per qualified zero emission truck purchased.
Alternative Fuel Vehicle Tax Exemption, Vehicle Inspection Exemption	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. Vehicle Inspection Exemption: Alternative fuel and hybrid electric vehicles are exempt from emissions testing.
Plug-In Electric Vehicle Demonstration Grants	Washington	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.
Plug-in Electric Vehicle and Electric Vehicle Supply Equipment Grants	Colorado	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 $8,260. Both CEO and RAQC grants fund 80 percent of the cost of EVSE, up to $6,260.
Plug-In Electric Vehicle Charging Rate Incentive	Indiana	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.
Alternative Fuel Vehicle Revolving Loan Fund	Mississippi	Effective July 1, 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.
A.B. 795	New Jersey	A.B. 795 would provide a credit under the corporation business tax and gross income tax for costs of electric power infrastructure for use by heavy duty vehicles to reduce idling times. Incentives pending for 2013.

1.2.1.3 Additional Inputs to TCO Model

Three additional inputs required for the TCO model include: 1) price of electricity, 2) price of battery systems, and 3) impact of near-zero and zero-emission mandates.

Historical and projected end-use electricity pricess are shown inFigure 42. Projections for lithium-ion battery prices are shown in Figures 40 and 41 and include comparisons from a variety of sources.

1.2.1.4 Impact of Mandates and Incentives

California's Zero Emission Vehicle (ZEV) Mandate is undergoing revision; it is expected that medium-duty and heavy duty vehicles will be included in the revised program. "The Action Plan also calls for expanded ZEV usage within private vehicle fleets, including public transportation and freight transport."[20]

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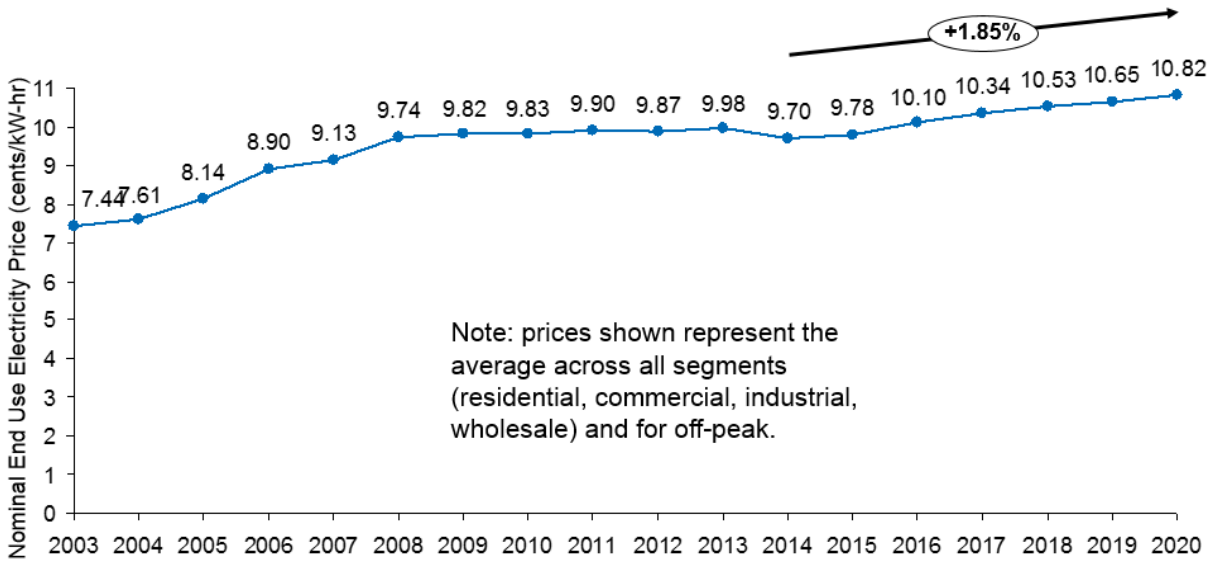
[19] Source: Ricardo analysis and "Clean Commercial Truck Incentives", presented by Tom Brotherton of CALSTART at 6 March 2013 NTEA Truck Show

[20] Ref 1.: 2012 ZEV Action Plan, Governor's Interagency Working Group on Zero-Emission Vehicles, September 2012)

The ARB Zero Emission Bus (Zbus) Regulation program began in 2000 when the State of California passed a regulation as part of the Fleet Rules for Transit Agencies--the core system of rules by which California transit agencies operate--mandating that agencies running fleets of more than 200 buses make at least 15 percent of their purchases or acquisitions from 2008 through 2015 zero emission buses. (BEV, Electric Trolley, or fuel cell)[21].

Electricity price projections through 2020 are shown below in Figure 42.

Figure 42: End Use Prices (nominal cents per kilowatt-hour): All Sector Average [22]



Ricardo has developed 2020 battery cost roadmaps for both energy (EV) and power (HEV) applications[23]. These are summarized in Figure 41.

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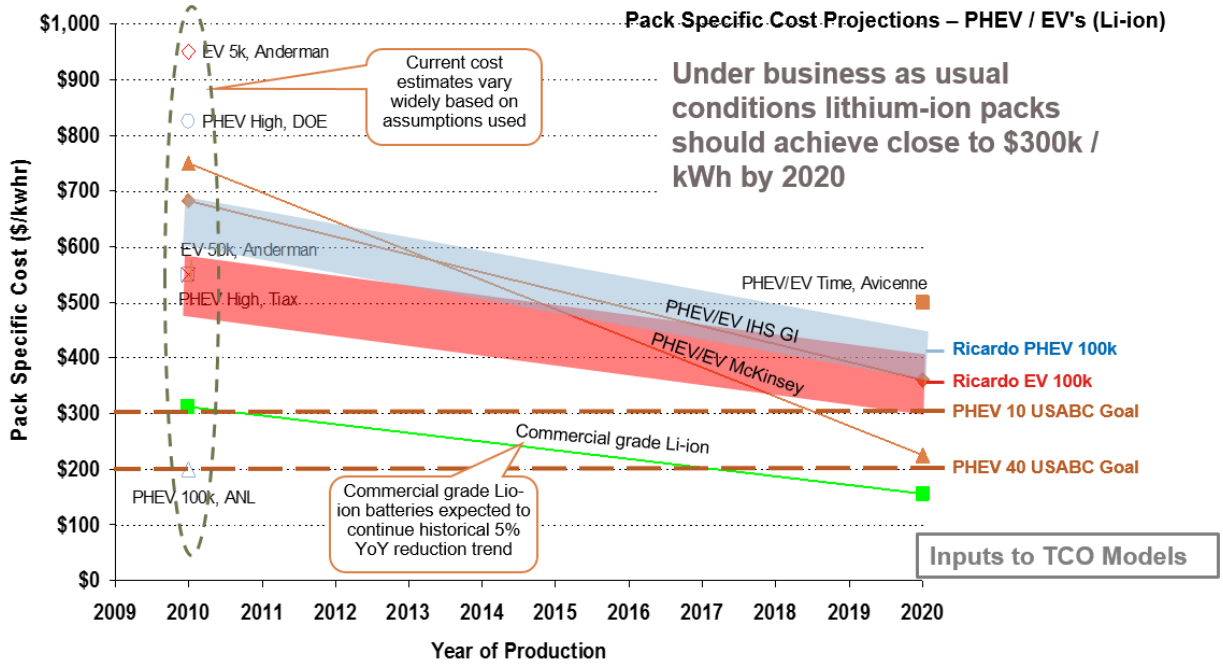
[21] (Ref 2: A Road Map for Fuel Cell Electric Buses in California, California Fuel Cell Partnership, March 2013)

[22] Source: EIA

[23] Sources: Ricardo Analysis, Anderman "Can Li-ion Batteries Support the Proliferation of Plug-in and Electric Vehicles? Status and prospects" from AABC 2010, Avicenne "Present and Future Market Situations for Batteries" from 2nd International Congress Advanced Battery Technologies 2009, DoE "Annual Merti Review - Energy Storage R&D and ARRA Overview" from DoE Annual Merit Review, June 2010, TIAX, LLC "PHEV Battery Cost Assessment" from DoE Annual Merit Review, June 2010, ANL "Factors Determining the Manufacturing Costs of Lithium Ion Batteries for PHEVs" from EVS24, May 2009, IHS Global Insight "Advanced Automotive Energy Storage Report", McKinsey "Electrifying cars: How three industries will evolve" from AABC, 2010

Figure 43: Pack Specific Cost Projections – PHEV / EV's (Li-ion)

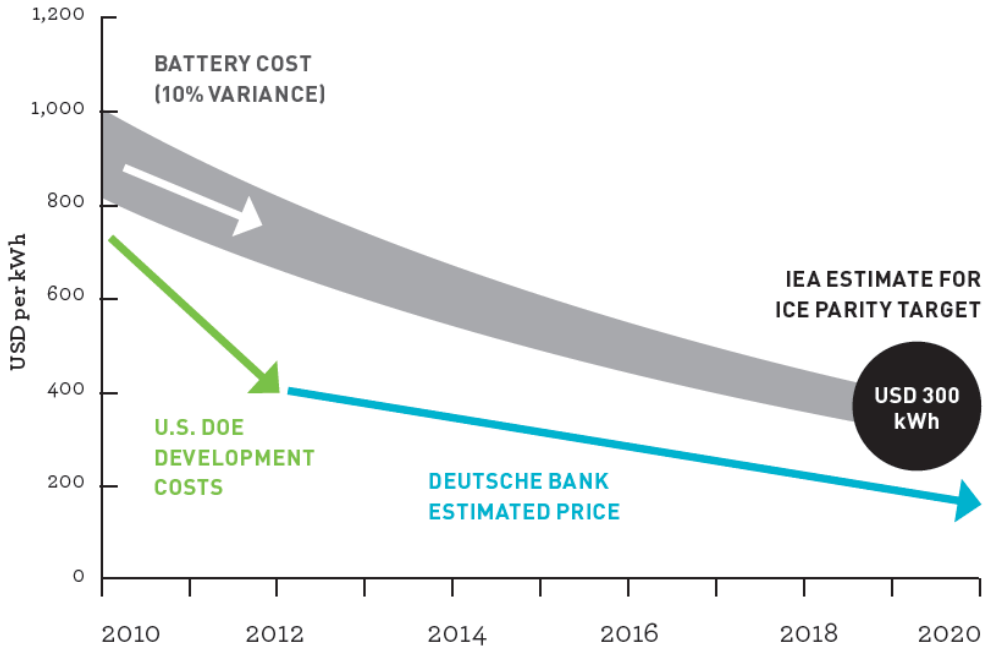


LG Chem predicts current Li-Ion battery costs will decrease by a factor of 2 prior to 2020 (*Automotive News*, 17 September 2013)[24] .

[24] Reference: Electric Vehicle Initiative: Global EV Outlook, April 2013

Source: IEA, U.S. DOE, Deutsche Bank.

Figure 44: Battery Cost Forecasts: Input to TCO Model[25]



Results of TCO Model

The results of the total cost of ownership analysis for the six selected vocational vehicles and three electric drive technologies (EV, HEV, PHEV) are shown in the table offigure 45. The table includes the calculated payback period (in years) associated with the incremental price of the electric drive systems. It is noted that the model includes a "ramp-up" period equal to three years following introduction of the advanced technology. This ramp-up period is associated with establishing manufacturing and supply operations to accommodate demand generated by favorable cost-of-ownership results.

It can be seen from the table in Figure 45 that incentives have a strong impact on payback periods. Projected reductions in future electric drive systems also have a strong influence on total cost of ownership and thus also significantly impact payback periods.

[25] Electric Vehicle Initiative: Global EV Outlook, April 2013, and IEA, U.S. DOE, and Deutsche Bank

Figure 45: Payback Periods for Incremental Cost of EV, HEV, or PHEV Drive Systems based on output of Total Cost of Ownership Models.

Incentive Programs Have a Significant Impact on Payback Periods

Vehicle Vocation	Power Train Type	Original Battery Capacity (kw-hrs)	Without Incentives: Payback Period (years) for Incremental Cost of EV, HEV, or PHEV Drive System for Vehicles Purchased During the Indicated Calendar Year										With Full Incentives: Payback Period (years) for Incremental Cost of EV, HEV, or PHEV Drive System for Vehicles Purchased During the Indicated Calendar Year									
			2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Service Vans (Class 3, 71 miles/day)	EV	75	18	15	13	11	9	8	7	6	5	4	9	7	6	4	3	2	1	1	1	1
	PHEV	20	30	30	30	18	14	11	9	7	6	5	6	4	3	2	1	1	1	1	1	1
Box Truck (Class 6, 80 miles/day)	EV	120	11	10	9	8	7	7	6	5	5	4	4	3	3	2	2	1	1	1	1	1
	PHEV	28.4	30	30	30	30	30	16	12	9	7	6	8	5	3	2	1	1	1	1	1	1
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	11	10	9	9	8	7	6	6	5	5	4	3	3	2	1	1	1	1	1	1
	PHEV	No commercial PHEVs offered for this category																				
City Transit Bus (Class 7-8) (120 miles/day)	EV	260	25	19	14	11	9	7	5	4	3	2	18	14	10	8	6	4	3	2	1	1
	HEV	11.8	15	15	14	13	12	11	10	10	9	8	12	11	10	9	8	8	7	6	6	5
	PHEV	90	22	19	17	15	13	11	10	9	8	3	16	14	12	11	9	8	7	6	5	3
Work Trucks (Class 4-6, 43 miles/day)	EV	No commercial EVs offered for this category																				
	PHEV	13	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Shuttle Bus (Class 3-6, 100 miles/day)	EV	100	15	13	11	10	8	7	6	5	5	4	9	7	6	5	4	3	2	1	1	1
	PHEV	15	30	30	30	30	18	12	9	8	6	5	6	4	2	1	1	1	1	1	1	1

Adopted by Majority
Late Adopters
Early Adopters

Adoption Rate Model

The adoption rate model was developed based on interviews with several managers of large fleets as well as representatives of trucking industry organizations. The goal was to develop a relationship between payback periods obtained from the TCO model and purchasing decisions for the fleet owners/managers.

The impacts of identified commercial vehicle purchase drivers & barriers were considered in developing market forecasts and adoption rates. Market drivers include:

- Fuel prices
- Fleet operating costs
- Government emissions regulations
- Government incentives
- "No Idle" rules
- Greening of fleets ("good neighbor" policies adopted by fleet owners)
- Marketing and sales considerations (promotion of "green image")

Market barriers include:

- Capital cost: incremental cost of advanced technology
- Operating cost (initial operating costs can be greater than conventional diesel due to immature technologies, and increased maintenance)

- Reliability
- Infrastructure requirements and costs
- Supply chain constraints
- Effective competing technologies (e.g. low-emission engines operating on biofuels)

The results of this analysis, which included industry interviews and the purchasing behavior of the fleet owners/managers, were divided into three categories. These are summarized in the table of Figure 46.

Figure 46: Adoption Rate Categories[26]

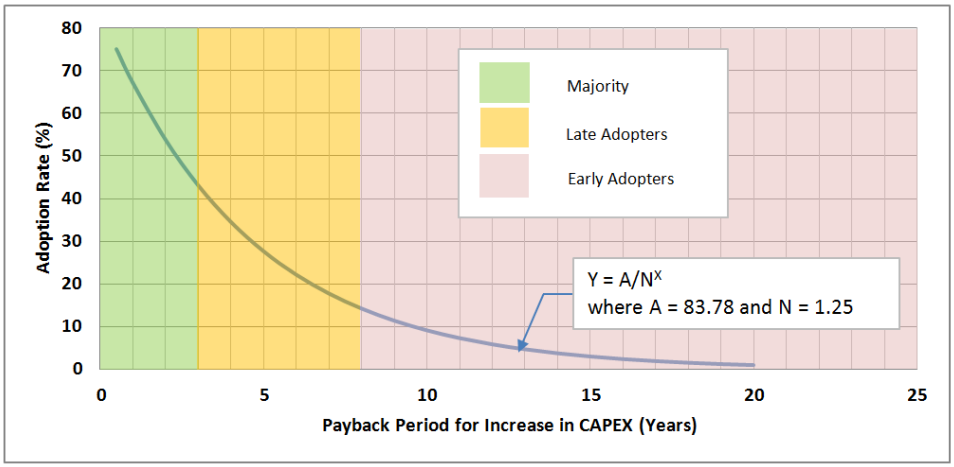
Designation	Early Adaptor	Late Adoptor	Majority
Reliability	System in production for less than 5 years	System is mature	System is mature
Incremental Price	100% of conventional vehicle price	60% of conventional vehicle Price	< 30% of conventional vehicle price

Early adoptors are defined as vehicle purchasers driven by the promise of new technologies and are willing to accept incremental Capital Expense (CAPEX) payback periods greater than eight years. Early adopters are often focused on reducing vehicle emissions compared to conventional diesel or gasoline technologies. Late adoptors are willing to accept payback periods of three to eight years and thus generally retain vehicles in their fleets for durations that exceed the payback period. Majority rates are associated with payback periods of less than three years and occur when a technology becomes the preferred option of vehicle purchasers. A curve fit of the purchasing decisions is shown in Figure 47. For this plot, the increase in CAPEX represents the difference in price of the new technology vehicle relative to the conventional technology vehicle[27].

[26] Source: CALSTART, Ricardo analysis

[27] Reference: North American Council for Freight Efficiency/ICCT Report Barriers to the Increased Adoption of Fuel Efficiency Technologies in the North American On-Road Freight Sector (July 2013).

Figure 47: Adoption Rate Model



Adoption Rate Forecasts for Selected Vocational Vehicles

Based on the predicted payback periods from the TCO model and the Adoption Rate Model, predictions can be made regarding adoption rates for each vocational vehicle and assocated electric drive technologies.

This was accomplished using the following procedure:

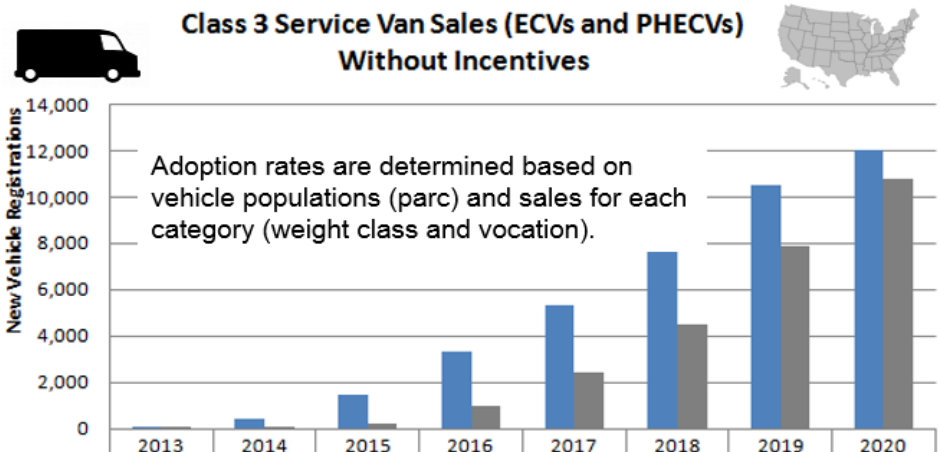
- Determine populations of each vocational vehicle type for the time period 2002 through 2013
- Prepare projections for vocational vehicle sales through 2020 based on historical sales data and projected market factors.
- Based on adoption rate forecasts determined from the TCO payback results and the adoption rate model, determine penetration of each electric drive technology through 2020 for each vocation, both with and without incentives.
- Once the adoption rates have been defined, the battery availability analysis (Figure 34) can be used to determine the number and capacity of second use batteries that will become available through the year 2025.

1.2.1.5 Class 3 Service Vans (Entire United States)

Without incentives, ECV + PHECV Class 3 Services Vans are projected to attain annual United States sales of 27,800 units by 2020.[28]

[28] Reference: Ricardo Analysis

Figure 48: Class 3 Service Van Sales (ECV's and PHECVs) without Incentives, Entire US



	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	20	450	1,450	3,300	5,300	8,000	10,500	12,000
PHECVs	6	20	200	952	2,409	4,500	7,906	10,800

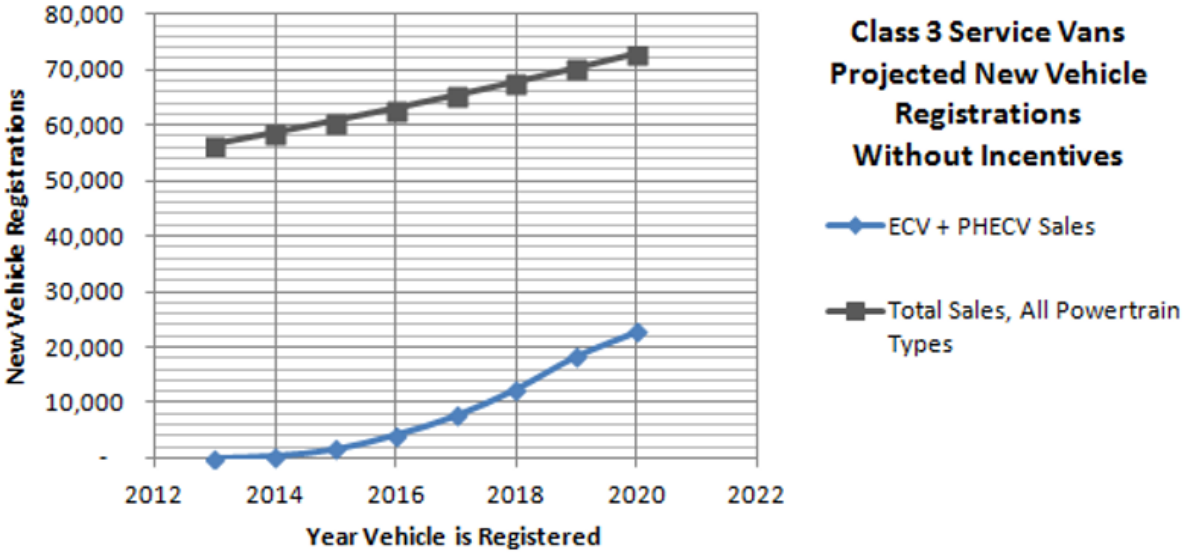
Based on Projected New Vehicle Sales for this Class and Vocation and the Results of Ricardo's Total Cost of Ownership Analysis

Without incentives, ECVs and PHECVs are projected to account for 31.3 percent of new United States Class 3 Service Van registrations by 2020[29].

[29] Reference: Ricardo Analysis

Figure 49: Class 3 ECV and PHECV Service Vans Projected New United States Vehicle Registrations without Incentives

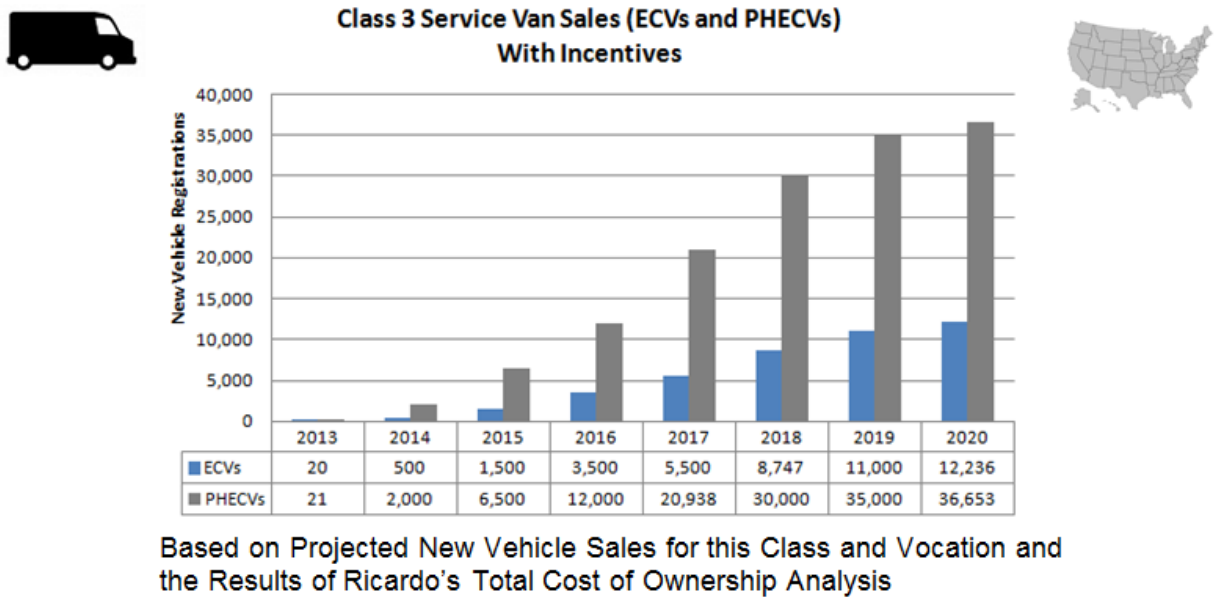
Year	Class 3 Service Van Sales without Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	56,535	20	6	26	0.0%
2014	58,628	450	20	470	0.8%
2015	60,798	1,450	200	1,650	2.7%
2016	63,049	3,300	952	4,252	6.7%
2017	65,382	5,300	2,409	7,709	11.8%
2018	67,803	8,000	4,500	12,500	18.4%
2019	70,312	10,500	7,906	18,406	26.2%
2020	72,915	12,000	10,800	22,800	31.3%



With incentives, ECV + PHECV Class 3 Service Vans are projected to attain annual United States sales of 48,900 units by 2020[30].

[30] Reference: Ricardo Analysis

Figure 50: Class 3 Service Van Sales (ECVs and PHECVs) with Incentives, Entire US



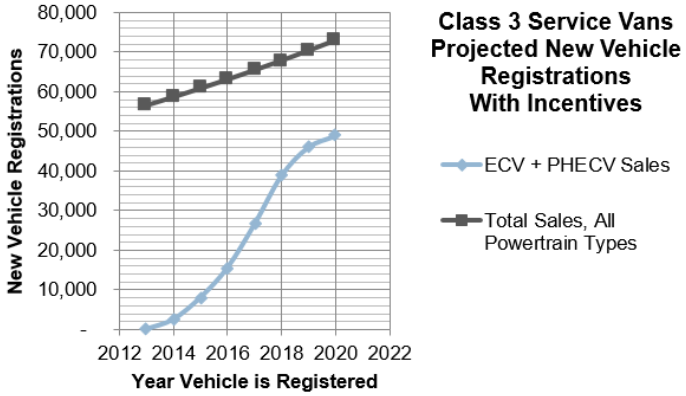
Note, projected sales shown in this graph are based on incentives remaining available for all vehicle purchased during the indicated time period. It is likely incentive payments per vehicle will be reduced or eliminated as adoption rates increase. Adoption rates are determined based on vehicle populations (parc) and sales for each category (weight class and vocation).

With incentives, ECVs and PHECVs are projected to account for 67 percent of new Class 3 Service Van United States registrations by 2020[31].

[31] Reference: Ricardo Analysis

Figure 51: Class 3 ECV and PHECV Service Vans Projected New Vehicle Registrations with Incentives, Entire US

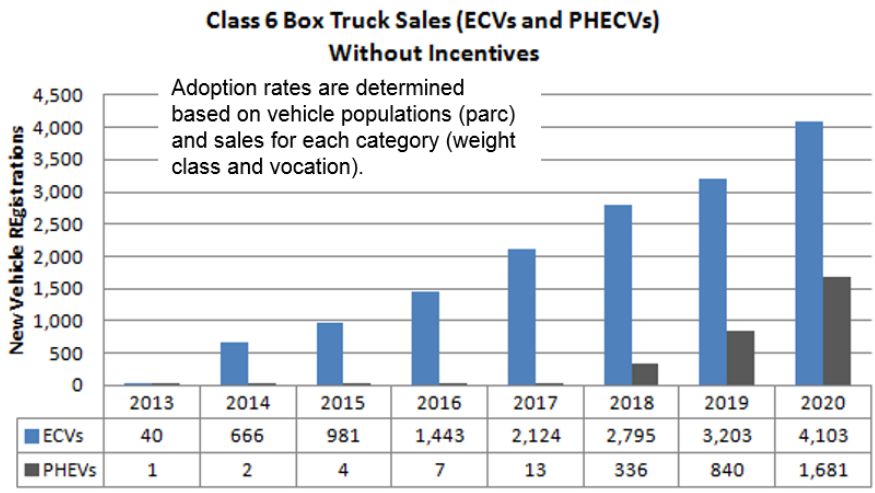
Year	Class 3 Service Van Sales with Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	56,535	20	21	41	0.1%
2014	58,628	500	2,000	2,500	4.3%
2015	60,798	1,500	6,500	8,000	13.2%
2016	63,049	3,500	12,000	15,500	24.6%
2017	65,382	5,500	20,938	26,438	40.4%
2018	67,803	8,747	30,000	38,747	57.1%
2019	70,312	11,000	35,000	46,000	65.4%
2020	72,915	12,236	36,653	48,889	67.0%



1.2.1.6 Class 6 Box Trucks (Entire United States)

Without incentives, ECV + PHECV Class 6 Box Trucks are projected to attain annual United States sales of 5,800 units by 2020.

Figure 52: Class 6 Box Truck Sales (ECVs and PHECVs) without Incentives, Entire US[32]



	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	40	666	981	1,443	2,124	2,795	3,203	4,103
PHEVs	1	2	4	7	13	336	840	1,681

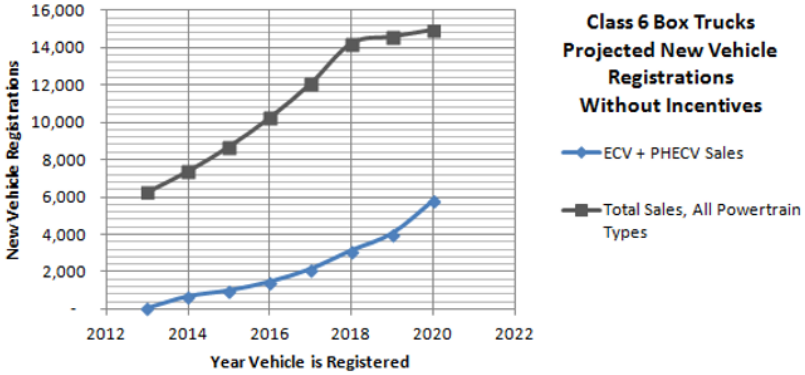
Based on Projected New Vehicle Sales for this Class and Vocation and the Results of Ricardo's Total Cost of Ownership Analysis

Without incentives, ECVs and PHECVs are projected to account for 38.7 percent of new United States Class 6 Box Truck registrations by 2020.

[32] Reference: Ricardo Analysis

Figure 53: Class 6 ECV and PHECV Box Trucks Projected New Vehicle Registrations without Incentives, Entire US[33]

Year	Class 6 Box Truck Sales without Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	6,294	40	1	41	0.7%
2014	7,409	666	2	668	9.0%
2015	8,722	981	4	985	11.3%
2016	10,267	1,443	7	1,450	14.1%
2017	12,086	2,124	13	2,137	17.7%
2018	14,227	2,795	336	3,131	22.0%
2019	14,583	3,203	840	4,043	27.7%
2020	14,947	4,103	1,681	5,784	38.7%

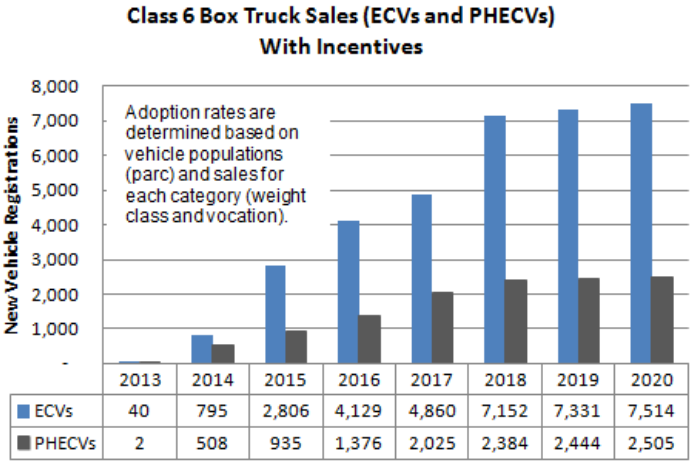


With incentives, ECV + PHECV Class 6 Box Trucks are projected to attain annual United States sales of 10,000 units by 2020[34].

[33] Reference: Ricardo Analysis

[34] Reference: Ricardo Analysis

Figure 54: Class 6 Box Truck Sales (ECVs and PHECVs) with Incentives, Entire US



	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	40	795	2,806	4,129	4,860	7,152	7,331	7,514
PHECVs	2	508	935	1,376	2,025	2,384	2,444	2,505

Based on Projected New Vehicle Sales for this Class and Vocation and the Results of Ricardo's Total Cost of Ownership Analysis

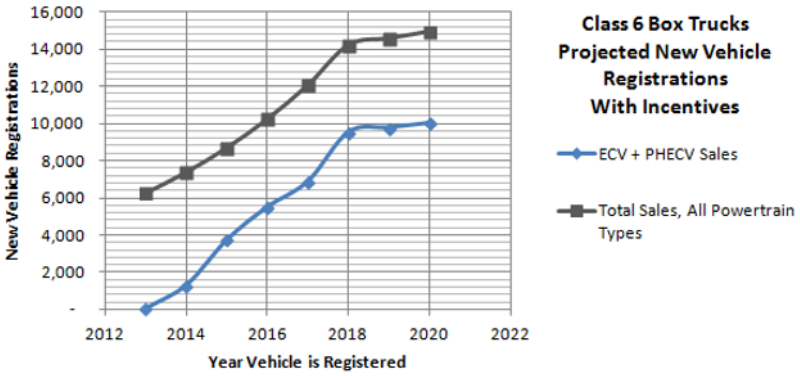
Note, projected sales shown in this graph are based on incentives remaining available for all vehicle purchased during the indicated time period. It is likely incentive payments per vehicle will be reduced or eliminated as adoption rates increase.

With incentives, ECVs and PHECVs are projected to account for 67 percent of new United States Class 6 Box Truck registrations by 2020[35].

[35] Reference: Ricardo Analysis

Figure 55: Class 6 ECV and PHECV Box Trucks Projected New Vehicle Registrations with Incentives, Entire US

Year	Class 6 Box Truck Sales with Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	6,294	40	2	42	0.7%
2014	7,409	795	508	1,303	17.6%
2015	8,722	2,806	935	3,741	42.9%
2016	10,267	4,129	1,376	5,505	53.6%
2017	12,086	4,860	2,025	6,885	57.0%
2018	14,227	7,152	2,384	9,536	67.0%
2019	14,583	7,331	2,444	9,775	67.0%
2020	14,947	7,514	2,505	10,019	67.0%

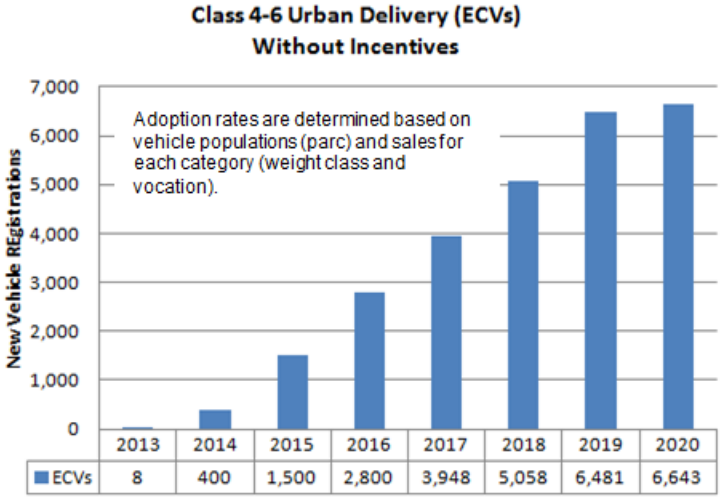


1.2.1.7 Class 4-6 Urban Delivery Trucks (Entire United States)

Without incentives, ECV Class 4-6 Urban Delivery Trucks are projected to attain annual United States sales of 6,643 units by 2020[36].

[36] Reference: Ricardo Analysis

Figure 56: Class 4-6 Urban Delivery (ECVs) without Incentives, Entire US



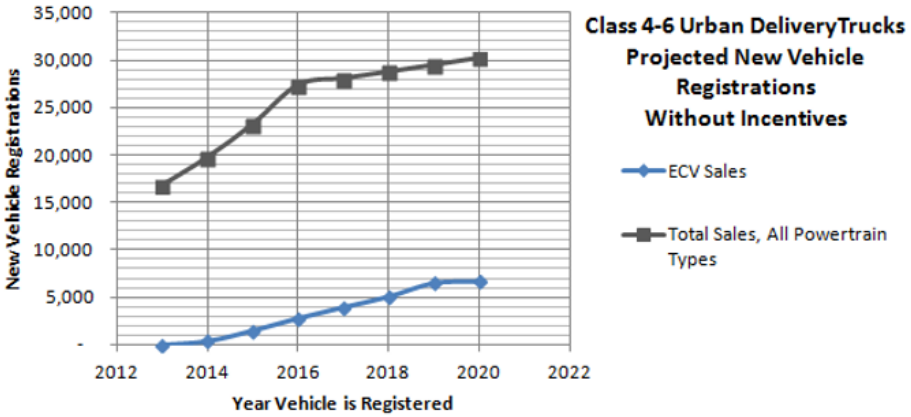
Based on Projected New Vehicle Sales for this Class and Vocation and the Results of Ricardo's Total Cost of Ownership Analysis

Without incentives, ECVs are projected to account for 22 percent of new United States Class 4-6 Urban Delivery Truck registrations by 2020[37].

[37] Reference: Ricardo Analysis

Figure 57: Class 4-6 ECV Urban Delivery Trucks Projected New Vehicle Registrations without Incentives, Entire US

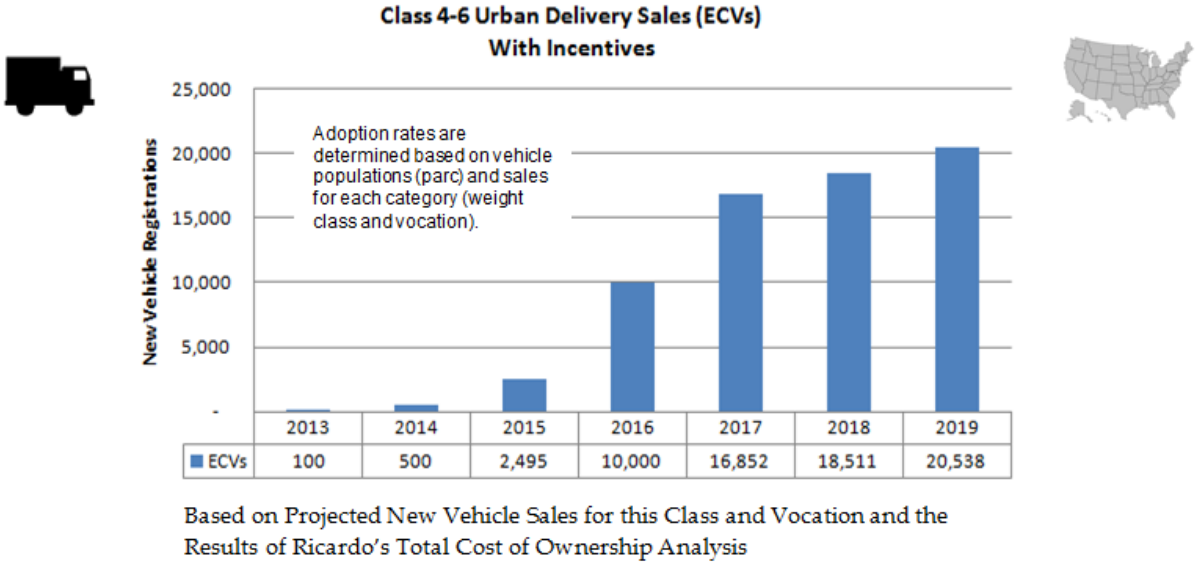
Class 4-6 Urban Delivery Truck Sales without Incentives			
Year	Total, All Powertrain Types	ECV Sales	ECV Sales as % of Total, All Powertrain Types
2013	16,772	8	0.0%
2014	19,753	400	2.0%
2015	23,265	1,500	6.4%
2016	27,401	2,800	10.2%
2017	28,086	3,948	14.1%
2018	28,788	5,058	17.6%
2019	29,508	6,481	22.0%
2020	30,246	6,643	22.0%



With incentives, ECV Class 4-6 Urban Delivery Trucks are projected to attain annual United States sales of 20,538 units by 2020[38].

[38] Reference: Ricardo Analysis

Figure 58: Class 4-6 Urban Delivery Sales (ECVs) with Incentives, Entire US



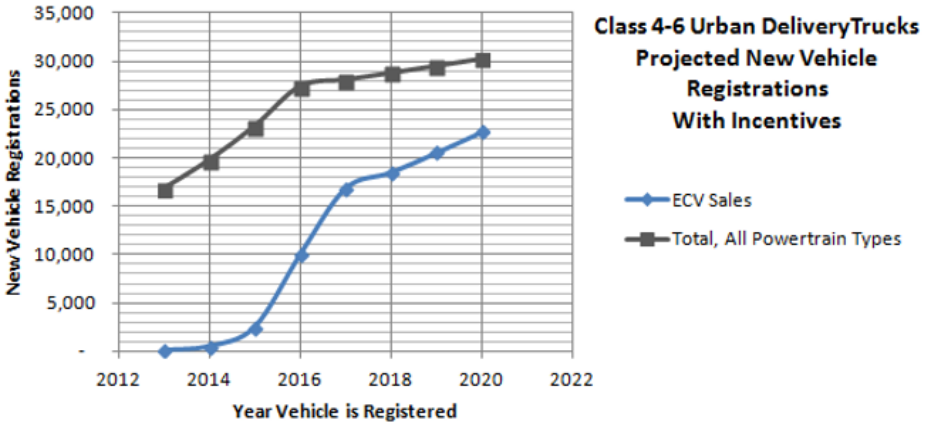
Note, projected sales shown in this graph are based on incentives remaining available for all vehicle purchased during the indicated time period. It is likely incentive payments per vehicle will be reduced or eliminated as adoption rates increase.

With incentives, ECVs are projected to account for 75 percent of new United States Class 4-6 Urban Delivery Truck registrations by 2020[39].

[39] Reference: Ricardo Analysis

Figure 59: Class 4-6 ECV Urban Delivery Trucks Project New Vehicle Registrations with Incentives, Entire US

Class 4-6 Urban Delivery Truck Sales with Incentives			
Year	Total, All Powertrain Types	ECV Sales	ECV Sales as % of Total, All Powertrain Types
2013	16,772	100	0.6%
2014	19,753	500	2.5%
2015	23,265	2,495	10.7%
2016	27,401	10,000	36.5%
2017	28,086	16,852	60.0%
2018	28,788	18,511	64.3%
2019	29,508	20,538	69.6%
2020	30,246	22,685	75.0%

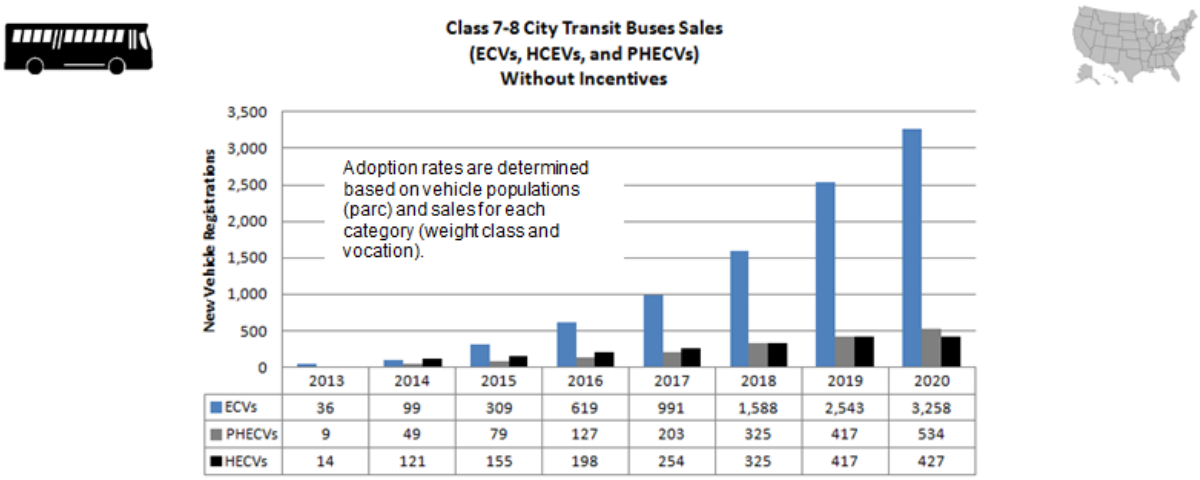


1.2.1.8 Class 7-8 Transit Buses (Entire United States)

Without incentives, ECV + PHECV + HECV Class 7-8 Transit Buses are projected to attain annual United States sales of 4,200 units by 2020[40].

[40] Reference: Ricardo Analysis

Figure 60: Class 7-8 City Transit Bus Sales (ECVs, HCEVs and PHECVs) without Incentives, Entire United States



	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	36	99	309	619	991	1,588	2,543	3,258
PHECVs	9	49	79	127	203	325	417	534
HECVs	14	121	155	198	254	325	417	427

Based on Projected New Vehicle Sales for this Class and Vocation and the Results of Ricardo's Total Cost of Ownership Analysis

Note, Figure 60 does not include Class 7-8 School Buses.

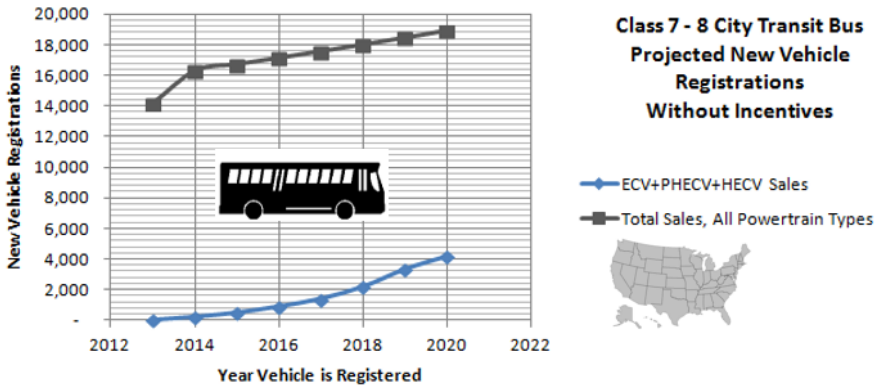
Without incentives, ECVs + PHECVs + HECVs are projected to account for 22 percent of new United States Class 7-8 city Transit Bus registrations by 2020[41].

[41] Reference: Ricardo Analysis

Figure 61: Class 7-8 ECV, PHECV, and HECV City Transit Bus Projected New Vehicle Registrations without Incentives, Entire US

Year	Class 7-8 City Transit Bus Sales without Incentives					ECV+PHECV+HECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	HECV Sales	ECV + PHECV + HECV Sales	
2013	14,243	36	9	14	59	0.4%
2014	16,373	99	49	121	269	1.6%
2015	16,783	309	79	155	543	3.2%
2016	17,202	619	127	198	944	5.5%
2017	17,632	991	203	254	1,448	8.2%
2018	18,073	1,588	325	325	2,238	12.4%
2019	18,525	2,543	417	417	3,377	18.2%
2020	18,988	3,258	534	427	4,219	22.2%

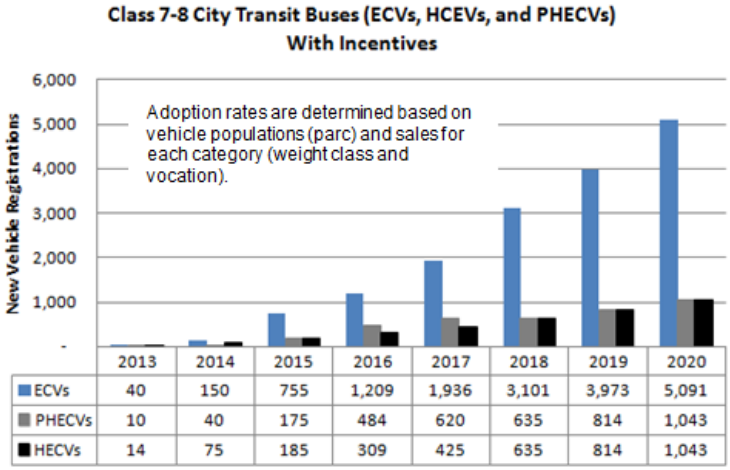
Note: Does not include Class 7-8 School Buses



With incentives, ECV + PHECV + HECV Class 7-8 Transit Buses are projected to attain annual United States sales of 7,177 units by 2020[42].

[42] Sources: 1) Ricardo analysis, 2) "Clean Commercial Truck Incentives", presented by Tom Brotherton of CALSTART at 6 March 2013 NTEA Truck Show , and 3) US FTA Fact Sheet: Bus and Bus Facilities, Section 5339 (www.fta.dot.gov/map21)

Figure 62: Class 7-8 Transit Buses (ECVs, HCEVs and PHECVs) with Incentives, Entire US



	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	40	150	755	1,209	1,936	3,101	3,973	5,091
PHECVs	10	40	175	484	620	635	814	1,043
HECVs	14	75	185	309	425	635	814	1,043

Note: Figure 62 does not include Class 7-8 School Buses.

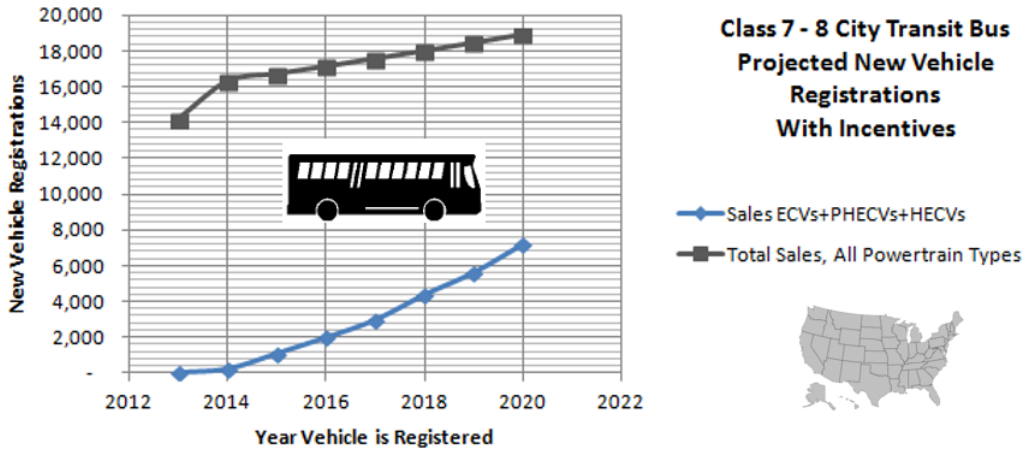
The US Department of Transportation under 49 USC Section 5339/MAP-21 Section 20029 provides $65.5 M annually to replace, rehabilitate and purchase buses and related equipment and to construct bus-related facilities. Each state is eligible for up to $1.25 M and each territory (D.C. and Puerto Rico) receiving $500 K.

With incentives, ECVs + PHECVs + HECVs are projected to account for 37.8 percent of new United States Class 7-8 City Transit Bus registrations by 2020[43].

[43] Reference: Ricardo Analysis

Figure 63: Class 7-8 ECV, PHECV, and HECV City Transit Bus Projected New Vehicle Registrations with Incentives, Entire US

Year	Class 7-8 City Transit Bus Sales with Incentives					ECV+PHECV+HECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	HECV Sales	ECV + PHECV + HECV Sales	
2013	14,243	40	10	14	64	0.4%
2014	16,373	150	40	75	265	1.6%
2015	16,783	755	175	185	1,115	6.6%
2016	17,202	1,209	484	309	2,002	11.6%
2017	17,632	1,936	620	425	2,981	16.9%
2018	18,073	3,101	635	635	4,371	24.2%
2019	18,525	3,973	814	814	5,601	30.2%
2020	18,988	5,091	1,043	1,043	7,177	37.8%



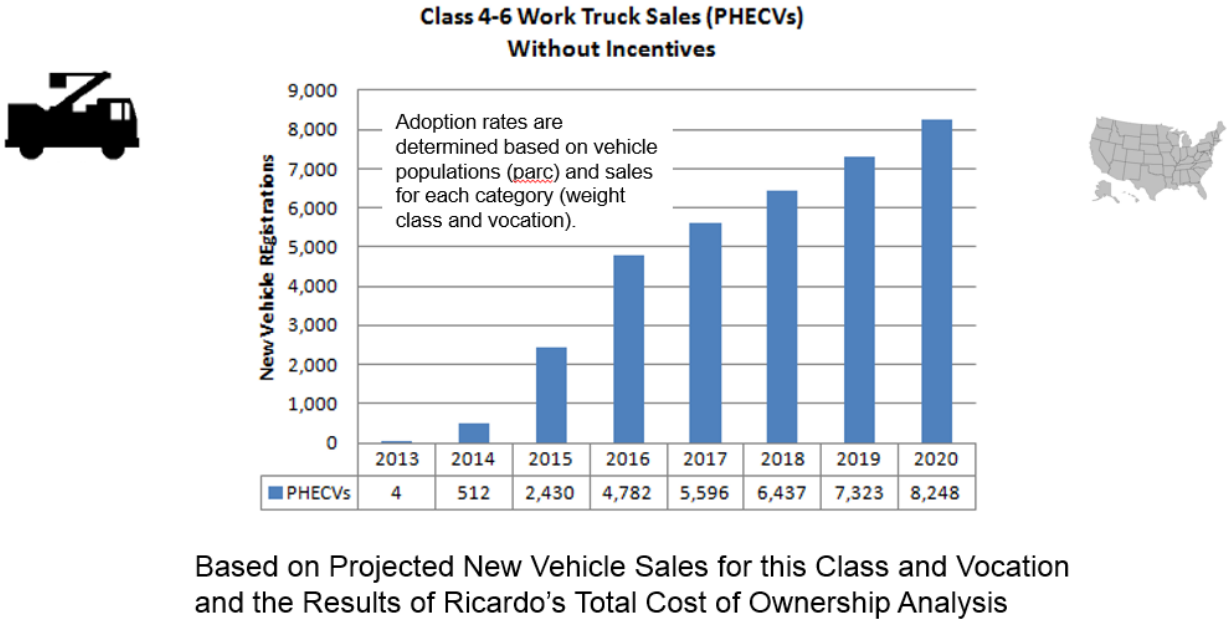
Note, Figure 63 does not include Class 7-8 School Buses.

1.2.1.9 Class 4-6 Work Trucks (Entire United States)

Without incentives, PHECV Class 4-6 Work Trucks are projected to attain annual United States sales of 8,248 units by 2020[44].

[44] Reference: Ricardo Analysis

Figure 64: Class 4-6 Work Truck Sales (PHECVs) without Incentives, Entire US

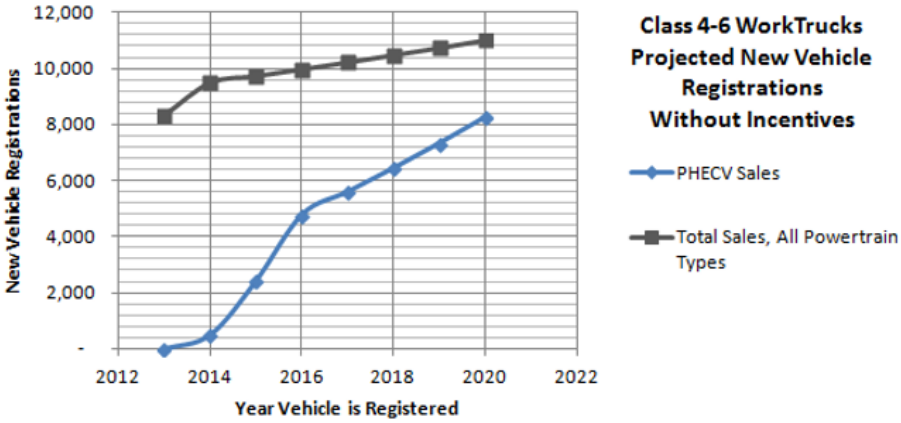


Without incentives, PHECVs are projected to account for 75 percent of new United States Class 4-6 Work Truck registrations by 2020[45].

[45] Reference: Ricardo Analysis

Figure 65: Class 4-6 PHECV Work Trucks Projected new Vehicle Registrations without Incentives, Entire US

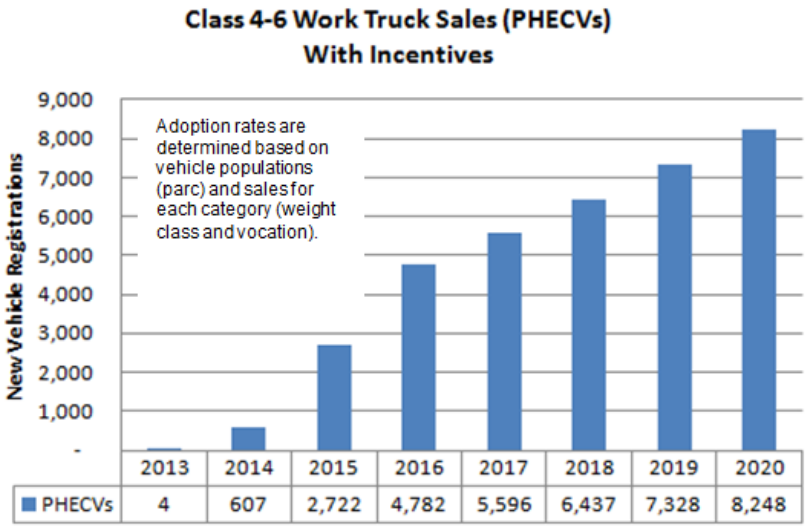
Class 4-6 Work Truck Sales without Incentives			
Year	Total, All Powertrain Types	PHECV Sales	PHECV Sales as % of Total, All Powertrain Types
2013	8,321	4	0.0%
2014	9,483	512	5.4%
2015	9,720	2,430	25.0%
2016	9,963	4,782	48.0%
2017	10,212	5,596	54.8%
2018	10,467	6,437	61.5%
2019	10,729	7,323	68.3%
2020	10,997	8,248	75.0%



With incentives, PHECV Class 4-6 Work Trucks are projected to attain annual United States sales of 8,248 units by 2020[46].

[46] Reference: Ricardo Analysis

Figure 66: Class 4-6 Work Truck Sales (PHECVs) with Incentives, Entire US



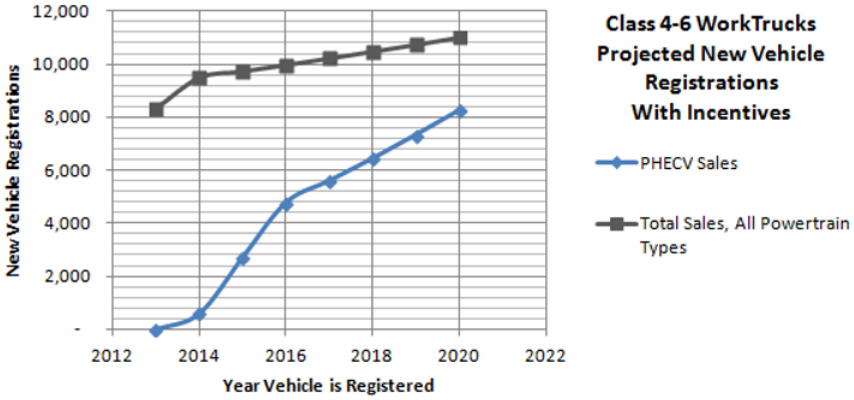
Economic drivers for adoption of Class 4-6 PHECV work trucks are not dependent upon Incentives.

With incentives, PHECVs are projected to account for 75 percent of new United States Class 4-6 Work Truck registrations by 2020[47].

[47] Reference: Ricardo Analysis

Figure 67: Class 4-6 PHECV Work Trucks Projected New Vehicle Registrations with Incentives, Entire US

Class 4-6 Work Truck Sales with Incentives			
Year	Total, All Powertrain Types	PHECV Sales	PHECV Sales as % of Total, All Powertrain Types
2013	8,321	4	0.0%
2014	9,483	607	6.4%
2015	9,720	2,722	28.0%
2016	9,963	4,782	48.0%
2017	10,212	5,596	54.8%
2018	10,467	6,437	61.5%
2019	10,729	7,328	68.3%
2020	10,997	8,248	75.0%

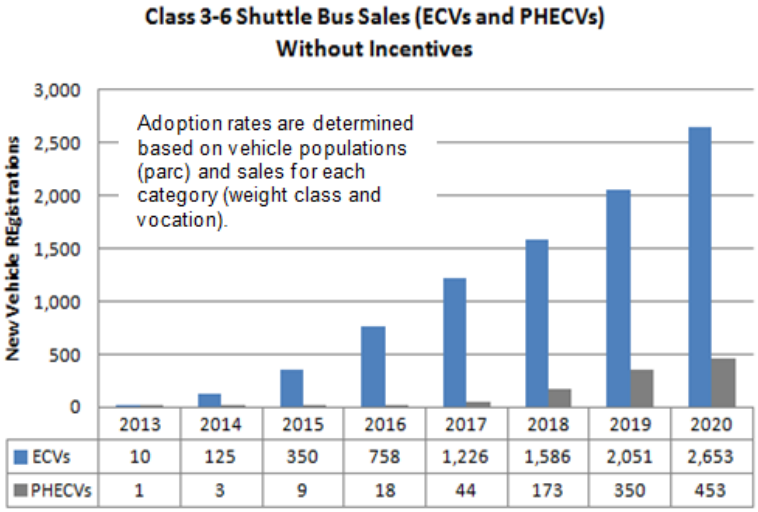


1.2.1.10 Class 3-6 Shuttle Buses (Entire United States)

Without incentives, ECV + PHECV Class 3-6 Shuttle Buses are projected to attain annual United States sales of 3,106 units by 2020[48].

[48] Reference: Ricardo Analysis

Figure 68: Class 3-6 Shuttle Bus Sales (ECVs and PHECVs) without Incentives, Entire US



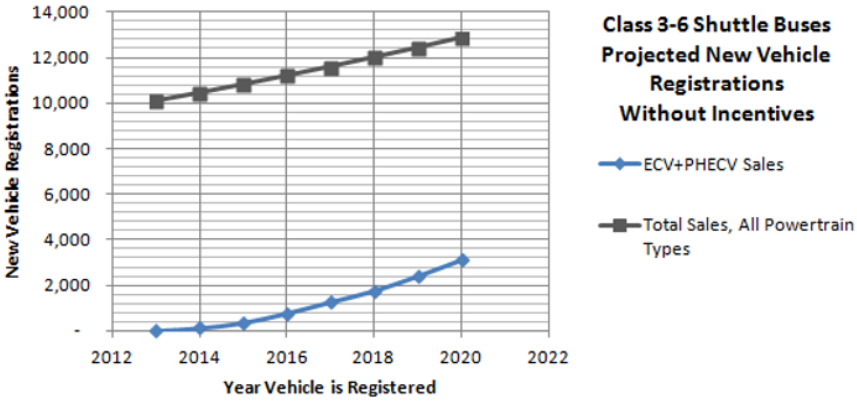
Without Incentives, ECVs provide an economic advantage over PHEVs for Class 3-6 Shuttle Bus Applications.

Without incentives, ECVs and PHECVs are projected to account for 24.1 percent of new United States Class 3-6 Shuttle Bus registrations by 2020[49].

[49] Reference: Ricardo Analysis

Figure 69: Class 3-6 ECV and PHECV Shuttle Buses Projected New Vehicle Registrations without Incentives, Entire US

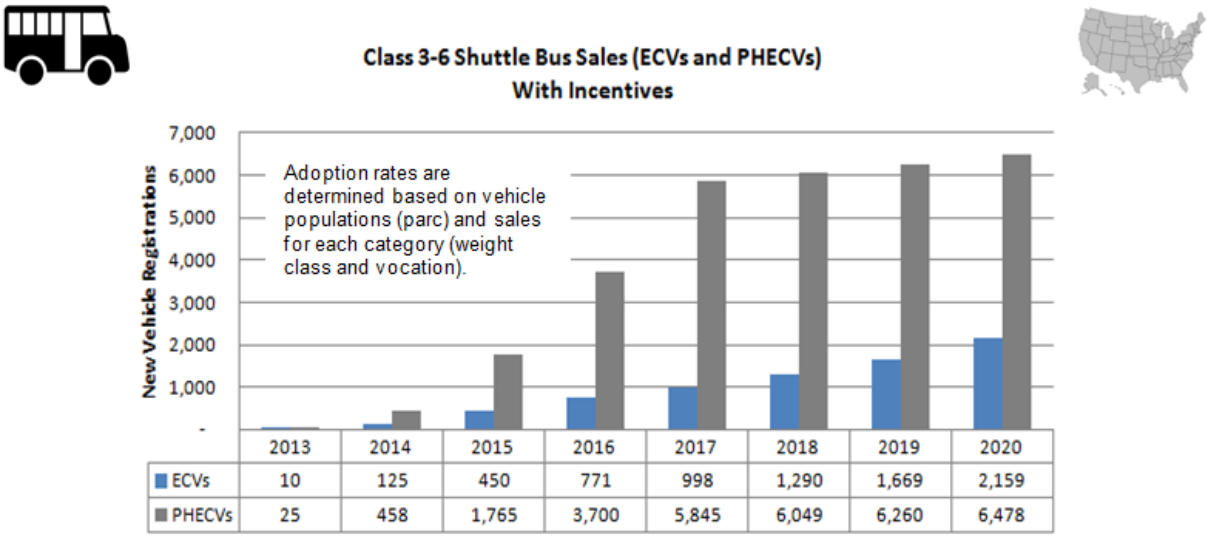
Year	Class 3-6 Shuttle Sales without Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	10,139	10	1	11	0.1%
2014	10,492	125	3	128	1.2%
2015	10,858	350	9	359	3.3%
2016	11,236	758	18	776	6.9%
2017	11,628	1,226	44	1,270	10.9%
2018	12,033	1,586	173	1,759	14.6%
2019	12,453	2,051	350	2,401	19.3%
2020	12,887	2,653	453	3,106	24.1%



With incentives, ECV + PHECV Class 3-6 Shuttle Buses are projected to attain annual United States sales of 8,637 units by 2020[50].

50

Figure 70: Class 3-6 Shuttle Bus Sales (ECVs and PHECVs) with Incentives, Entire US



	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	10	125	450	771	998	1,290	1,669	2,159
PHECVs	25	458	1,765	3,700	5,845	6,049	6,260	6,478

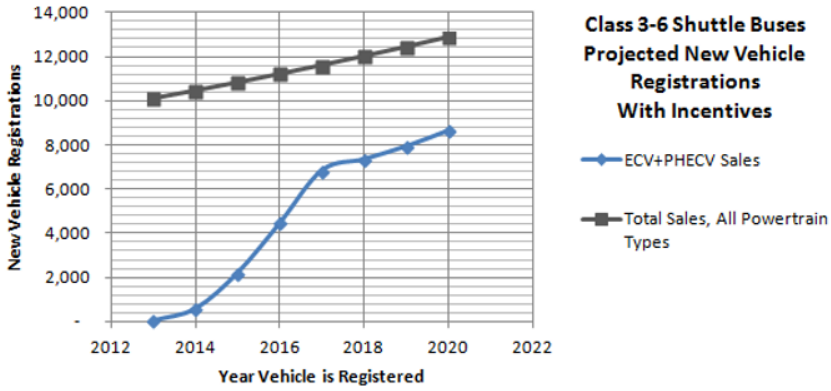
Incentives favor PHECVs for Class 3-6 Shuttle Bus Applications.

With incentives, ECVs and PHECVs are projected to account for 67 percent of new United States Class 3-6 Shuttle Bus registrations by 2020[51].

[51] Reference: Ricardo Analysis

Figure 71: Class 3-6 ECV and PHECV Shuttle Buses Projected New Vehicle Registrations with Incentives, Entire US

Year	Class 3-6 Shuttle Sales with Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	10,139	10	25	35	0.3%
2014	10,492	125	458	583	5.6%
2015	10,858	450	1,765	2,215	20.4%
2016	11,236	771	3,700	4,471	39.8%
2017	11,628	998	5,845	6,843	58.8%
2018	12,033	1,290	6,049	7,339	61.0%
2019	12,453	1,669	6,260	7,929	63.7%
2020	12,887	2,159	6,478	8,637	67.0%



1.2.1.11 Manufacturers and Battery Suppliers

Supply-Side Portion of Analysis of Battery Pack Availability

There are active manufacturers and users of ECVs in each of the key segments under consideration. Example vocations and associated manufacturers are shown in Figure 72.

Figure 72: Examples of Electric Drive Vehicles and Manufacturers

A survey of current manufacturers of commercial battery electric vehicles was completed and the results are shown in the tables of Figures 70 and 71. Current manufacturers of commercial hybrid electric and plug-in hybrid electric commercial vehicles are listeded in the tables of Figures 72 and 73. Current and pending manufacturers of plug-in electric-drive light duty and commercial vehicles are shown in the tables of Figures 74 and 75.

This survey provided input to the selection process for vocational vehicles evaluated during the current study. One criterion for the selection of these vocations was the technology readiness level of the selected electric drive system and associated battery system.

Figure 73: Manufacturers of Commercial Electric Vehicles (1 of 2)

OEM	Model	Battery Pack Supp.	Application	Motor Specs	GVW	Class	Avg. Range (Miles)	Battery Size (kW-Hr)	Battery Chemical	Battery Life
Modec	Chassis cab, Dropside and Box Van	Axeon (Lithium iron phosphate and NCM)	Chassis Cab, Dropside, Box Van, Refrigerated Box Van, Tail Lift, Tipper	Electric	12000	3	100		lead-acid	
Navistar	eStar	A123	Delivery Van	102 hp, 300 Nm electric motor	12100	3	60 to 100	80	Nanophosphate lithium-ion	Discontinued May 2013
Smith Electric	Newton	Valence, A123	Box, Aerial Lift, Stake/Flat Bed, Utility/Maintenance, Refrigerated Box, Shuttle Bus, Weapons Resent	180 bhp[134kW] Peak, 480 lb-ft [650 Nm] Peak, Brushless Permanent Magnet	16500, 22000, 26000	5, 6, 7	100	40,60,80,100,120	Lithium Iron Phospate	have a minimum of 80 per cent capacity after 3,000 cycles
BYD	eBus	BYD	Bus	AC Synchronous Motor (Brushless) - BYDTYC90A	39683	8	155	324 kWh / 600Ah	Fe Battery	more than 4000 recharging cycles in a life span
Balqon	Nautilus XE20	HIQAP	Terminal Tractor	200 hp 230 volt AC Induction motor	(GCW) 90000	8	90 (unloaded) 60 (fully loaded)	215	Lithium Iron Phospate	3000 cycles at 80 percent DOD
Balqon	Nautilus XE30	HIQAP	Tractor	200 hp 230 volt AC Induction motor	(GCW) 125000	8		250	Lithium Iron Phospate	2000 cycles at 80 percent DOD
Balqon	Mule M100	HIQAP	On-Road Truck	200 hp. rated 230 volt AC vector duty electric motor	52500	8	150 (unloaded)	220	Lithium Iron Phospate	1500 cycles at 80 percent DOD or 2500 cycles at 70 percent DOD
Balqon	MX30	HIQAP	On-road Tractor	325 hp peak rated 460 volt AC vector duty electric motor		8	150 (unloaded), 90 (fully loaded)	380	Lithium Iron Phospate	

Figure 74: Manufacturers of Commercial Electric Vehicles (2 of 2)

OEM	Model	Battery Pack Supp.	Application	Motor Specs	GVW	Class	Avg. Range (Miles)	Battery Size (kW-Hr)	Battery Chemical	Battery Life
Balqon (Ford E-450 chassis)	EQO 14	HIQAP	14-passenger Shuttle Bus (defined route used at airport, rental lots and shopping malls)	125 hp AC induction motor	up to 14,500	3	80	80	Lithium	2500 cycle life
EVI	EVI-MD	Valence Technology (Model: U-ChargeXP)	Freight Delivery, Ref. Freight, Beverage, Utility, Construction, Ground Support	AC Permanent Magnet	15000-25950	4,5,6	90	99	Lithium Iron Magnesium Phosphate (LiFeMgP04)	2800 cycles at 100% DOD (with 80% of start of life capacity)
EVI	EVI-WI (Walk-in Van)	Valence Technology (Model: U-ChargeXP)	Parcel Delivery, Food & Beverage, Utility, Landscaping, Ground Support		19500	4,5,6	90	99	Lithium Iron Magnesium Phosphate (LiFeMgP04)	2800 cycles at 100% DOD
Boulder	DV500		Delivery Van, Service Body Work Truck, Flatted Work Trucks & Vans, Passenger Shuttle	80 kW electric motor	11500	3	80 to 120	80	Lithium Iron Phospate	300,000 miles
Electrorides (based on Isuzu N series — flexible medium duty truck)	Zero-Truck	Dow Kokam	Utility, Dry freight	100 kW electric motor, 650 Nm peak torque and 150 kW power	12000-19500	4	65 to 75	65	Li-ion Polymer	2500+ full charges
FCCC MT-45 walk-in van	Enova Ze	Tesla	Walk-in step van	120 kW	10001-16000	3, 4	150	36	Lithium ion	
Proterra	EcoRide BE35	Altair Nano	Full size city bus	PM motor, 150 kW (100 kW cont) power and 650 Nm torque		8	30	72	Lithium ion	Up to 8-12 years depending on duty cycle & charging
AMP Electric Vehicles	E-100 (Workhorse)	AMP	Walk-in Step Van	160 kW moter	19500	3 to 6	100	100	Lithium Iron Phosphate	

Figure 75: Commercial Hybrid Electric and Plug-In Hybrid Electric Commercial Vehicles (1 of 2)

OEM	Model	Powertrain (P/T)	P/T Supplier	Application	Engine	Fuel	GVW	Class	Battery Chemical
Ford	E450	Hybrid Electric	AD Balance	Step Van, Shuttle Bus	5.4L EFI FFV V8	Gasoline	14,000	3	
Freightliner	Bus. Class M2e Hybrid	Hybrid Electric	Eaton	City Delivery, Utility, Delivery Tractor		Diesel	33000-55000	7, 8	Lithium-ion
Freightliner Custom Chassis	MT-45, MT-55	Hybrid Electric	Eaton	Walk-in Van		Diesel			
GMC	TC5500	Plug-in Hybrid Electric	Dueco Odyne	Utility	Vortec 8.1L MD	Gasoline	19500	5	
Kenworth	T270	Hybrid Electric	Eaton	Delivery, Utility	PACCAR PX-6	Diesel	25000	6	Lithium-ion
Kenworth	T370	Hybrid Electric	Eaton	Delivery, Utility	PACCAR PX-6	Diesel	33000	7	
Mack/Volvo	TerraPro Hybrid	Hybrid Electric		Refuse		Diesel		8	Lithium-ion
Navistar, Inc	DuraStar Hybrid (Truck)	Hybrid Electric	Eaton	Beverage, Box Van, Refrigeration, Landscape Dump, Utility, Crane, Tree Trimmer, Recovery Towing, Armored Vehicle, Stake Flat, Grapple, Road Patch Truck, Refined Fuels, Propane Tank	MaxxForce DT	Diesel	23,500-39,000	6, 7	
Navistar, Inc	4300	Plug-in Hybrid Electric	Dueco Odyne	Utility, Digger, Derrick, Air Compressor	MaxxForce DT	Diesel	25000-37000	6, 7, 8	
Navistar, Inc	DuraStar Hybrid (4x2)	Hybrid Electric	Eaton	Beverage Diminishing Load	MaxxForce DT	Diesel	Up to 55000	7	
Navistar, Inc	WorkStar Hybrid (Truck)	Hybrid Electric	Eaton	4x4 Utility, Landscape Dump, Snowplow, Digger Derrick, Utility, Crane, Stake Flat, Box Van, Recovery Towing, Refined Fuels, Propane Tank	MaxxForce DT	Diesel	23,500-39,000	6, 7	

Figure 76: Commercial Hybrid Electric and Plug-In Hybrid Electric Commercial Vehicles (2 of 2)

OEM	Model	Powertrain (P/T)	P/T Supplier	Application	Engine	Fuel	GVW	Class	Battery Chemical
Peterbilt	330 Hybrid	Hybrid Electric	Eaton	Delivery van	PACCAR PX-6	Diesel	26000	6	
Peterbilt	335 Hybrid	Hybrid Electric	Eaton					7	lithium-ion
Peterbilt	337 Hybrid	Hybrid Electric	Eaton	City Delivery, Fire & Rescue, Beverage, Municipal, Refuse, Utility	PACCAR PX-6	Diesel		6, 7	
Peterbilt	348 Hybrid	Hybrid Electric	Eaton	Municipal, Service, Utility	PACCAR PX-6	Diesel	33000+	7, 8	
Peterbilt	386 Hybrid	Hybrid Electric	Eaton	Long Haul		Diesel		8	
EVI	EVI-REEV	Plug-in Hybrid Electric		Utility, Construction, Tree Service, Logistics			16500-19500	5, 6	$LiFeMgPO_4$
IC Bus	CE Hybrid	Plug-in Hybrid Electric		School Bus					
New Flyer	Xcelsior	Plug-in Hybrid Electric		Bus		Diesel/Gasoline			
HINO	195h COE hybrid	Hybrid Electric				Diesel	19500	5	Ni-MH
HINO	195h-DC COE hybrid	Hybrid Electric				Diesel	19500	5	Ni-MH

Figure 77: Available or Upcoming Plug-in Vehicles (1 of 2)

Vehicle Manufacturer	Vehicle Model	Projected Year	Type	All-Electric Range (Miles)	Battery Size (kW-Hr)	Battery Chemical	Battery Sub Type	Battery Supplier
Audi	A3 eTron	2014	EV	92	26.5	Lithium-ion		
BMW	ActiveE		EV	94	32	Lithium-ion		
BMW	i3	2013	EV	100	22	Lithium-ion		SB LiMotive
BMW	i8	2014	PHEV	30	10.8	Lithium-ion		
BMW	Mini E			156	35	Lithium-ion	NMC	
BYD	e6 Wagon	2013	EV	250		iron-phosphate Fe		
BYD	F3DM	2013	PHEV	60	16	Lithium-ion		
Cadillac	ELR	2014	PHEV	35	16.5	Lithium-ion		
Chevrolet	Volt		PHEV	35	16	Lithium-ion	Manganese	LG Chem
Chevrolet	Spark EV	2013	EV		20	Lithium-ion	Iron-nano-phosphate	A123
Coda	Electirc Sedan			88	34	Lithium-ion		
Fiat	500e	2013	EV	80	24	Lithium-ion		SB LiMotive
Fisker	Karma		PHEV	32	22	Lithium-ion	Iron-nano-phosphate	A123
Ford	Focus Electric		EV	76	23	Lithium-ion		LG Chem
Ford	C-Max Energi		PHEV	21	7.6	Lithium-ion		Pansonic
Ford	Fusion Energi	2013	PHEV			Lithium-ion		Pansonic

Figure 78: Available or Upcoming Plug-in Vehicles (2 of 2)

Vehicle Manufacturer	Vehicle Model	Projected Year	Type	All-Electric Range (Miles)	Battery Size (kW-Hr)	Battery Chemical	Battery Sub Type	Battery Supplier
Honda	Fit EV		EV	82	20	Lithium-ion		Toshiba
Honda	Accord PHEV	2013	PHEV	10 to 15	6.7	Lithium-ion		Blue Energy
Mercedes-Benz	B-Class EV	2014	EV	125				
Mitsubishi	i-MiEV		EV	62	16	Lithium-ion		Lithium Energy Japan, Toshiba
Mitsubishi	Outlander Plug-in Hybrid	2014	PHEV			Lithium-ion		Lithium Energy Japan
Nissan	Leaf		EV	73	24	Lithium-ion	Manganese	AESC
Scion	iQ EV	2014		50	12	Lithium-ion		
Smart	ED	2013	EV	70	16	Lithium-ion		
Tesla	Roadster		EV	245	53	Lithium-ion	Cobalt	
Tesla	Model S		EV	300	85	Lithium-ion		Pansonic
Think Global	Think City	2011	EV	100	24.5	Lithium-ion	Nickel, manganese, and cobalt (NMC)	EnerDel
Toyota	Prius		PHEV	11		Lithium-ion		Primearth
Toyota	Rav4 EV		EV	100	42			Tesla
Volkswagen	E-Up!	2013		80	18			
Volvo	V70 Plug-in Hybrid	2013	PHEV	30	11.3			

1.2.1.12 Commercial Vehicle Populations and Forecasts: Supply-Side Portion Analysis of Battery Pack Availability

Information Sources for Vehicle Populations

A number of sources were included in the vehicle population and forecast analysis, including:

- Vehicle registration data (US and California).

- Government data bases (US and California).
- Published reports from research organizations, including national laboratories, government contractors, and consulting companies.

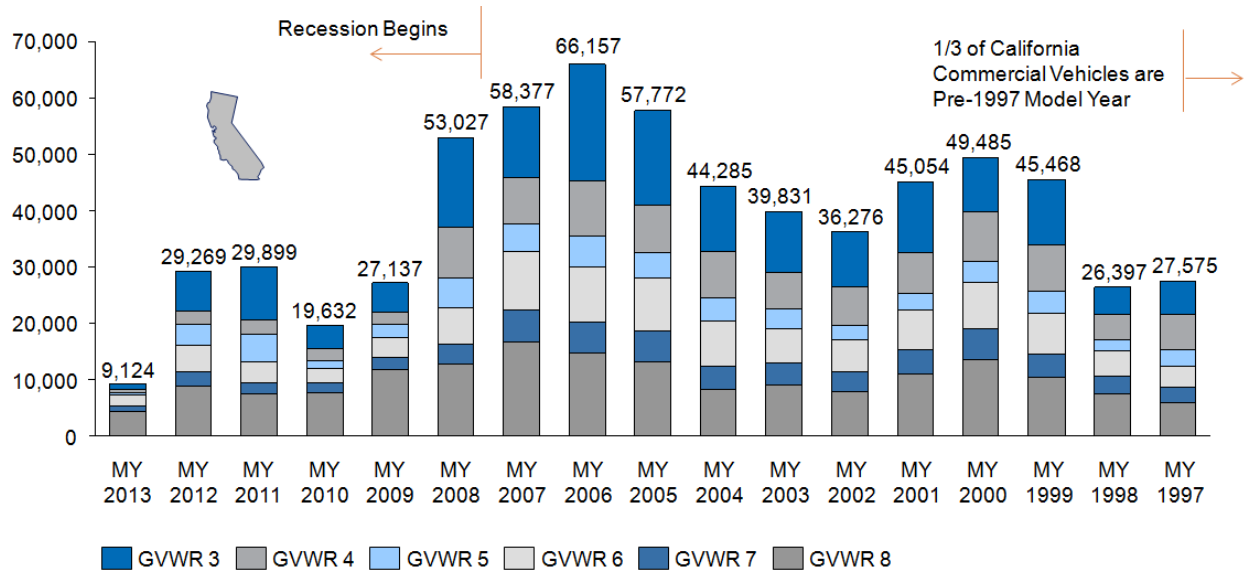
California Commercial Vehicle DMV Population Study

An assessment of the California Department of Motor Vehicles Vehicle Registration data base was completed with the assistance of CEC staff. Procedures were followed to ensure confidentiality of the data. Summaries of the registrations for model years 1997 through 2013 were completed and were categorized by vehicle weight class. The results of this analysis are displayed in Figure 79 and Figure 80. Conclusions that can be drawn from this analysis are:

- Class 3, 6, and 8 vehicles account for approximately 2/3 of medium duty and heavy duty commercial vehicle populations within California.
- It can be seen that the recession and additional EPA diesel emission requirements have large impacts on new vehicle registrations beginning in 2008[52].

California ECV Population Analysis

Figure 79: California Truck Registrations by Vehicle Model Year: Data for Calendar Year 2012

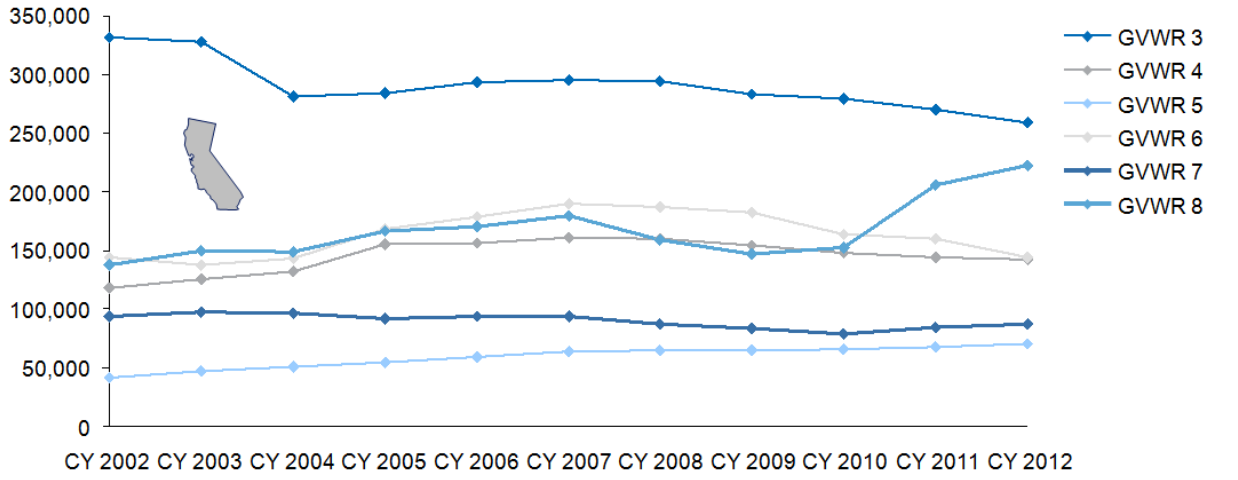


California commercial vehicle registrations by reporting year and class are shown below in Figure 80[53].

[52] Source: California DMV 2012

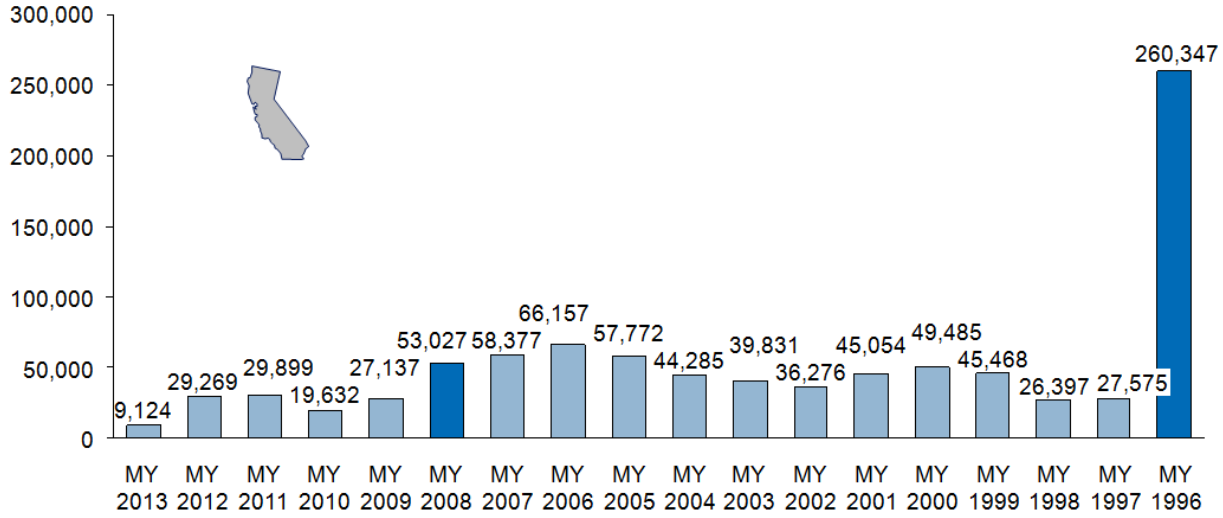
[53] Source: California DMV

Figure 80: Class 3, 6, and 8 Vehicles Account for Approximately 2/3 of Medium and Heavy Duty CV Populations in California



If pre-1997 model year vehicle registrations are included, it can be seen that approximately 1/3 of registered trucks in California are over 15 years old[54] as shown in Figure 81.

Figure 81: California Truck Registrations by Model Year



United States Commercial Vehicle Population Analysis Based on US DOE Data Base

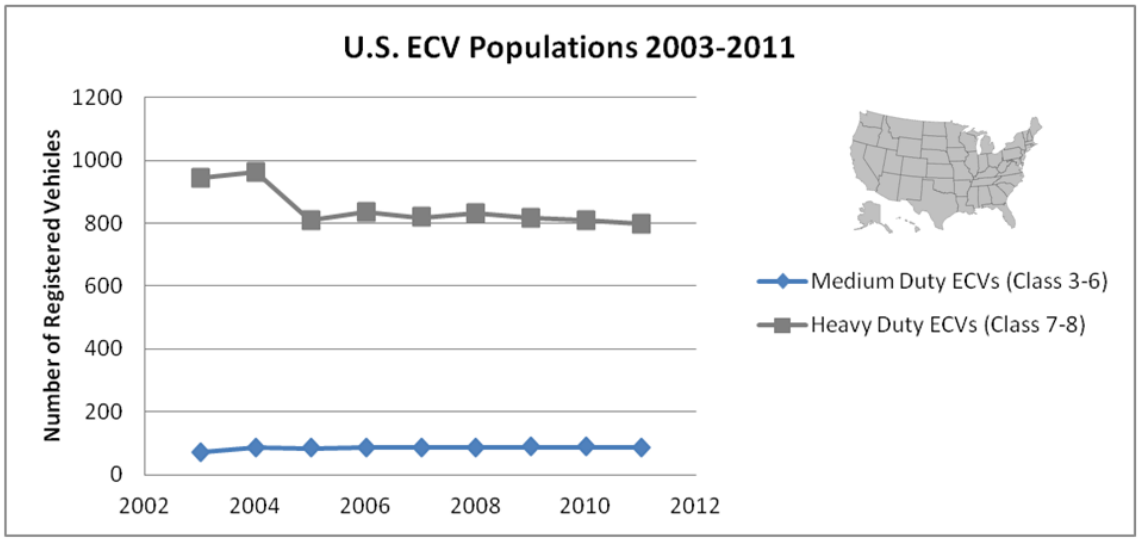
United States ECV populations have remained low and constant as shown inFigure 82.

.

[54] Source: California DMV

Figure 82: Heavy Duty and Medium Duty Electric Commercial Vehicle Populations 2003 – 2011, Entire US[55]

Category	2003	2004	2005	2006	2007	2008	2009	2010	2011
Medium Duty ECVs	71	85	84	85	86	87	88	88	87
Heavy Duty ECVs	943	962	808	836	819	832	817	808	799



It is noted that data are not consistent from the various sources listing ECV populations (e.g. US DOE and CA DMV), likely due to the small populations of ECVs, PHECVs, and HECVs as well as lack of appropriate data base categories for these vehicles.

California HECV Population Analysis

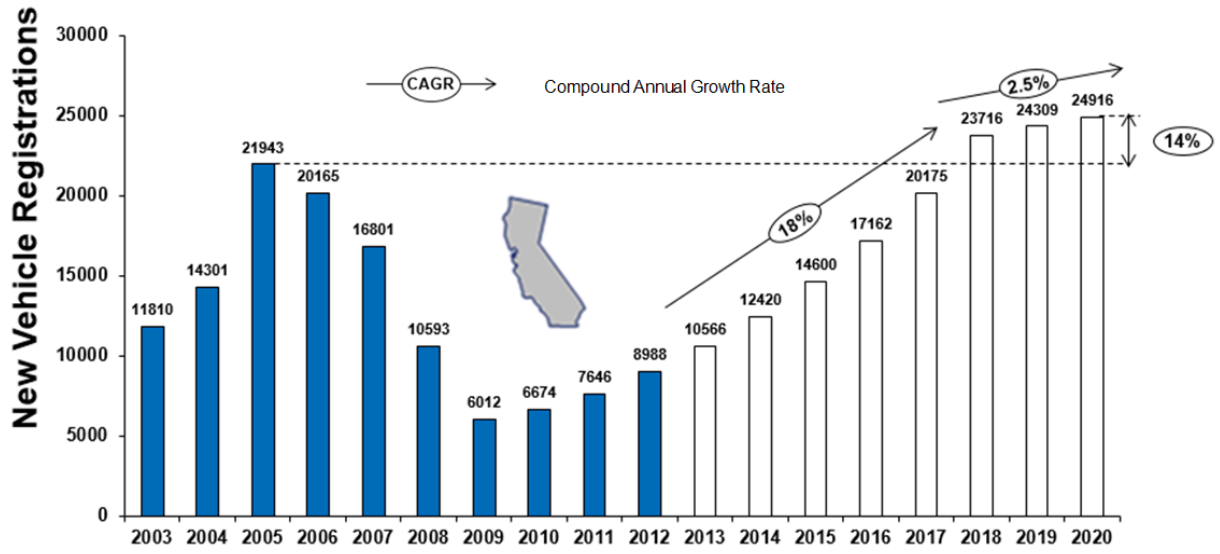
Commercial vehicle populations, new vehicle registrations, and forecasted sales by vocation were analyzed for both Californa-only and the entire US. New vehicle registration forecasts were then used as input to the adoption rate model to determine populations of battery electric, hybrid electric and plug-in hybrid electric vehicles by model year through 2020.

California Vehicle Population Analysis by Weight Class

For this portion of the study, all vehicles in each indicated weight class were evaluated. An analysis of new vehicle registrations for the selected six vocations was also performed. Class 3 vehicles are not forecasted to reach pre-recession peak volumes until 2018.

[55] Source: U.S. DOE, Energy Information Agency

Figure 83: California New Class 3 Commercial Vehicle Registrations



Note, all Class 3 vehicles are included (both conventional and advanced technology drive systems).

Figure 83 assumes a faster than Gross Domestic Product (GDP) growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 4 vehicles are not forecasted to reach pre-recession peak volumes even by 2020.

Figure 84: California New Class 4 Commercial Vehicle Registrations

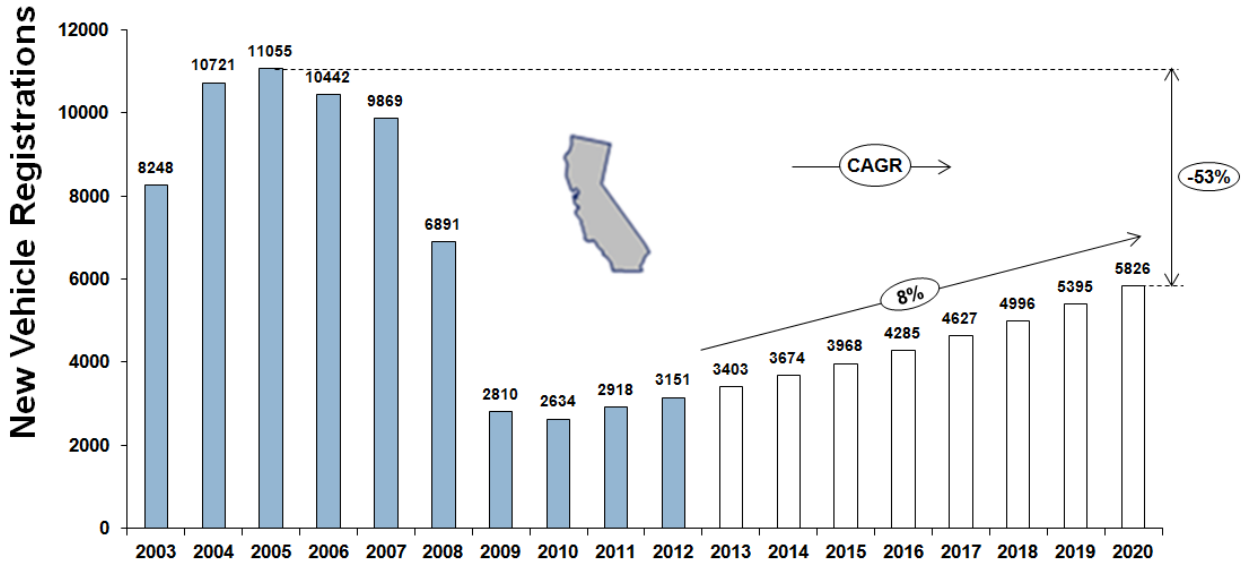


Figure 84 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 5 vehicles are forecasted to reach pre-recession peak volumes by 2014.

Figure 85: California New Class 5 Commercial Vehicle Registrations

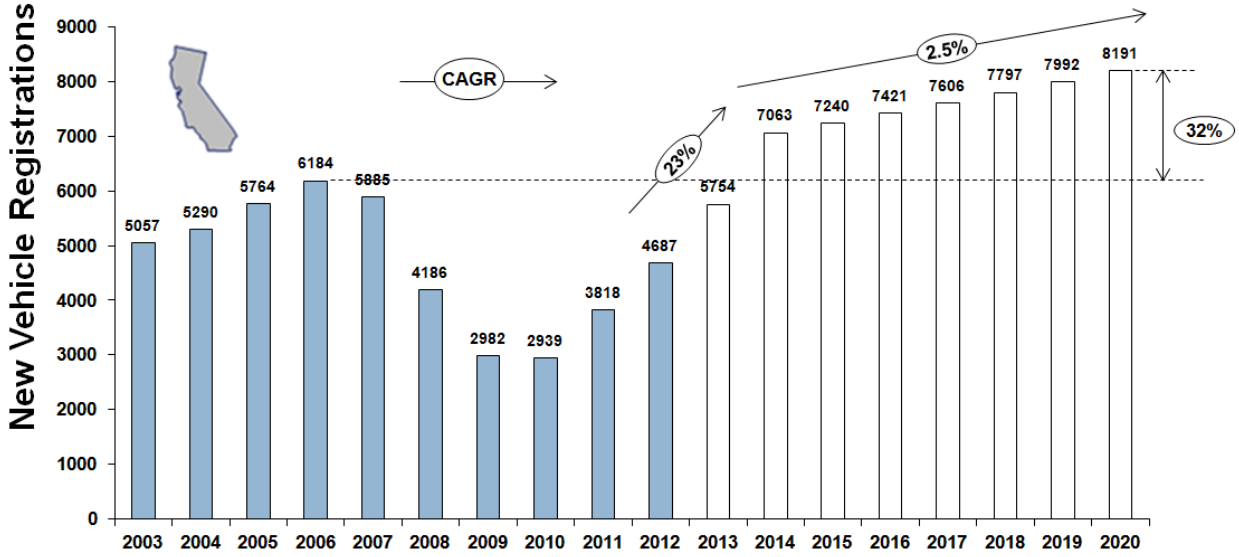
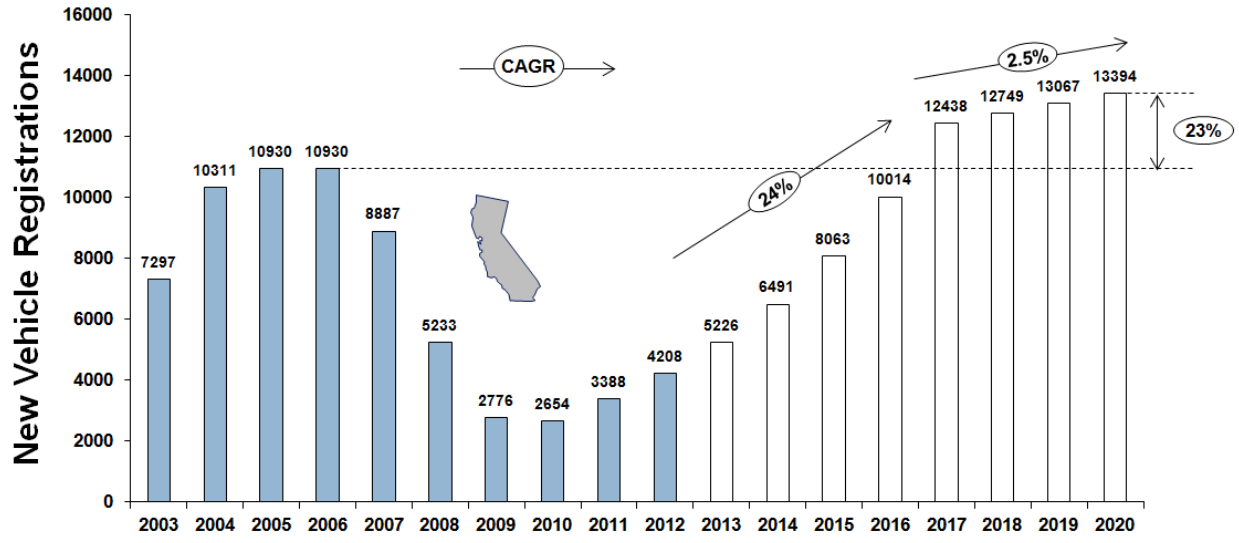


Figure 85 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 6 vehicles are not forecasted to reach pre-recession peak volumes until 2017.

Figure 86: California New Class 6 Commercial Vehicle Registrations

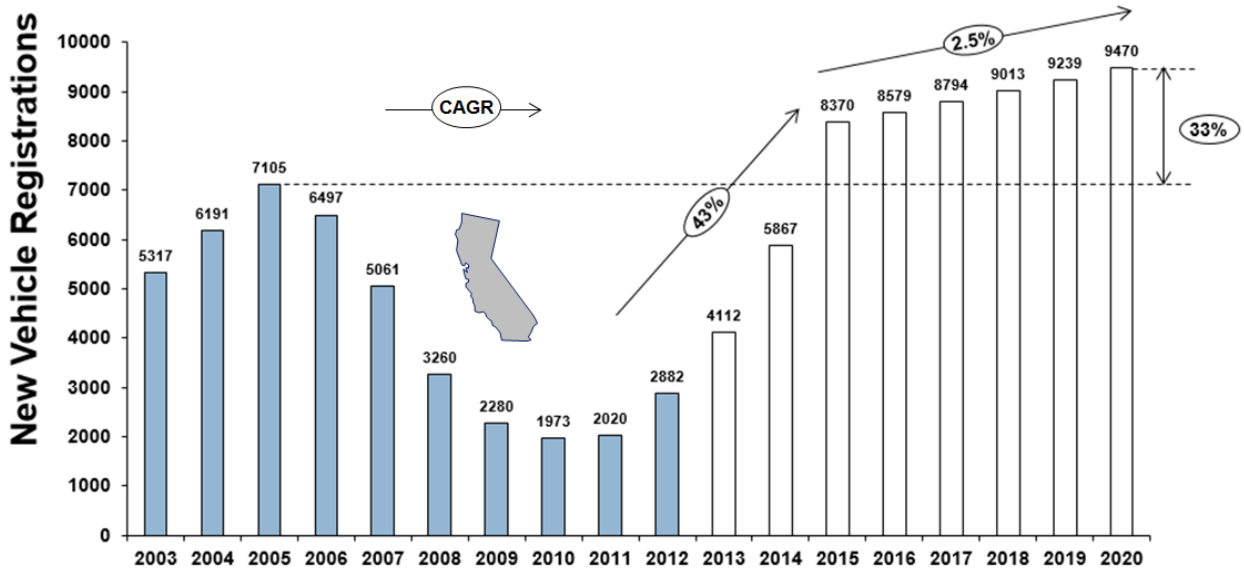


Note, all Class 6 vehicles are included (both conventional and advanced technology drive systems).

Figure 86 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 7 vehicles are not forecasted to reach pre-recession peak volumes until 2015.

Figure 87: California New Class 7 Commercial Vehicle Registrations

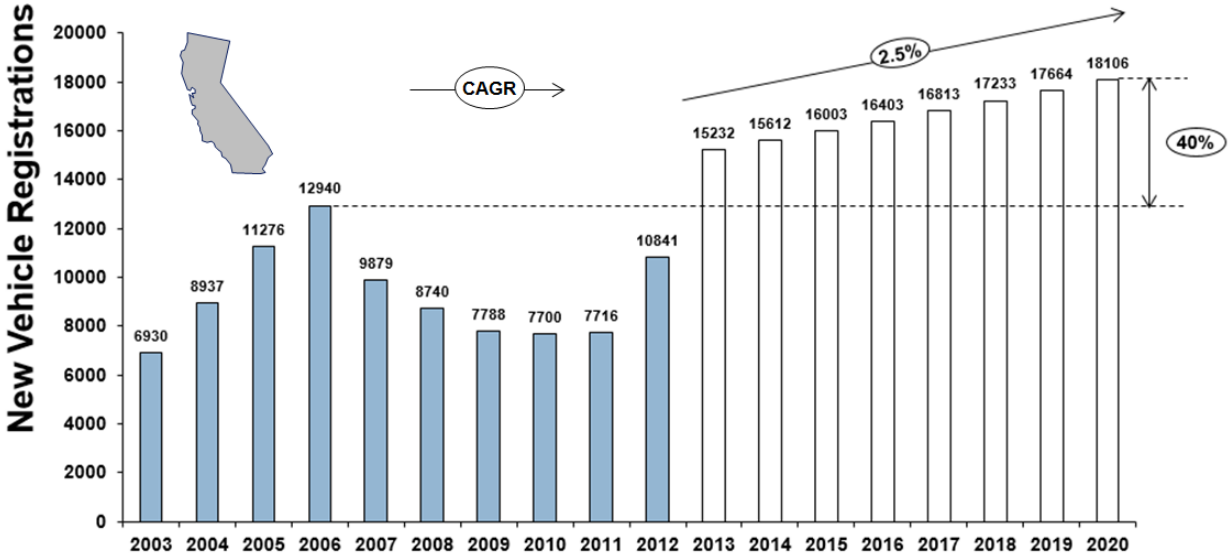


Note, all Class 7 vehicles are included (both conventional and advanced technology drive systems).

Figure 87 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 8 vehicles sales reached pre-recession peak volumes during 2013.

Figure 88: California New Class 8 Commercial Vehicle Registrations



Note, all Class 8 vehicles are included (both conventional and advanced technology drive systems).

Figure 88 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed

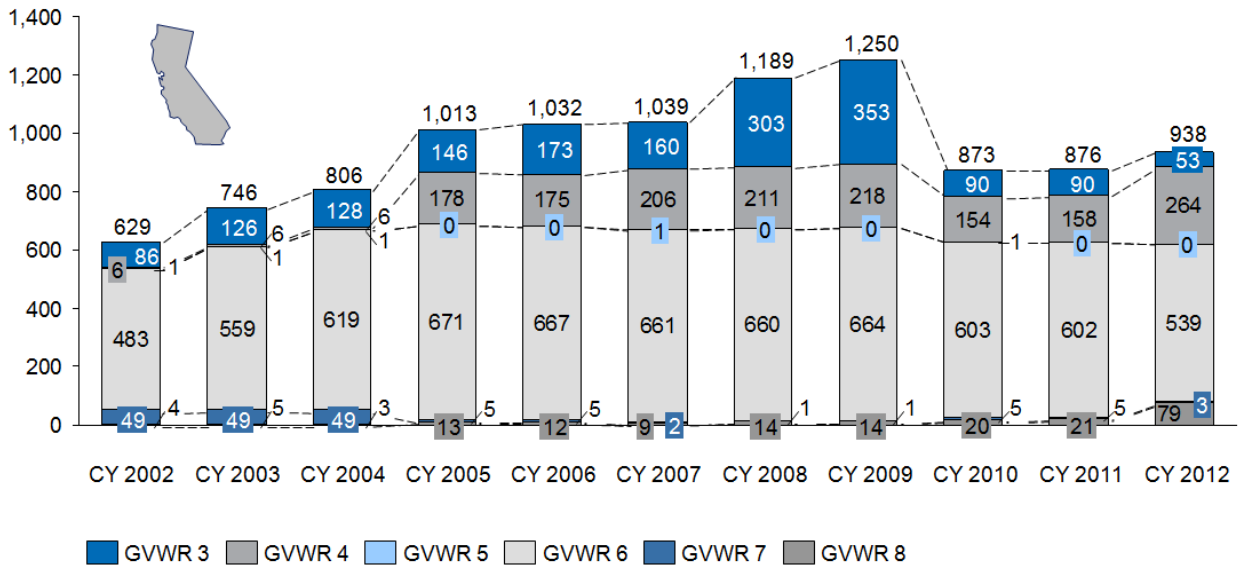
California ECV Registrations by Calendar Year

A separate analysis was conducted regarding the number of electric vehicle registrations in California for calendar years 2002 through 2012.

California ECV Registrations show:

- The number of vehicle registrations in this category has been small.
- Growth of ECVs within California was adversely affected by recession.

Figure 89: ECV Registrations in California from 2002 to 2012[56]



California Hybrid Electric Commercial Vehicle Registrations show:

- The number of vehicle registrations in this category has been small (less than 100 vehicles per year beginning in 2010).
- Growth of HECVs within California has been sporadic.

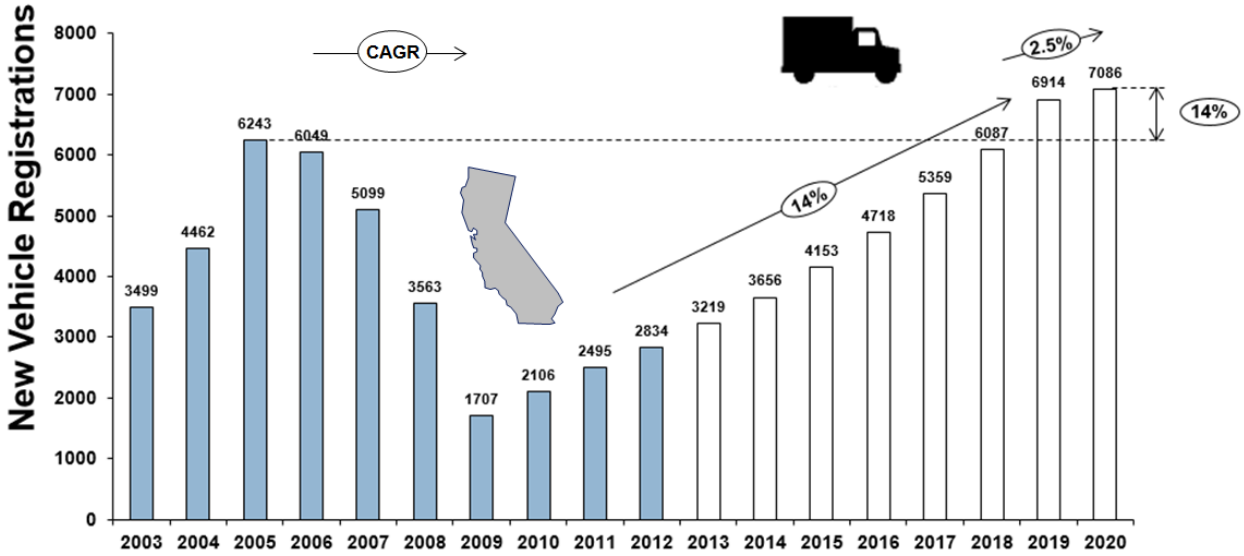
California New Vehicle Registration Forecasts by Vocation

This portion of the study focuses on the six selected vocational vehicle categories.

[56] Source: California DMV 2002-2012

Class 3 Service Vans (California)

Figure 90: California Class 3 Service Van New Vehicle Registrations by Calendar Year



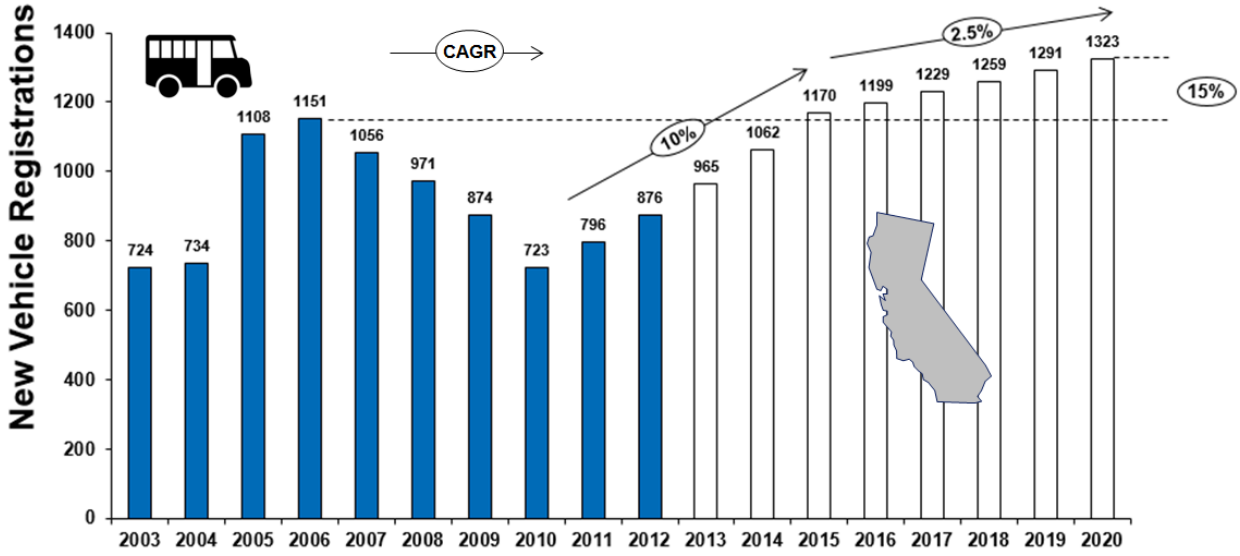
Class 3 service vans are forecasted to reach pre-recession peak sales volumes within California by 2019.

Note, for this and the following vocational vehicle sales projections, all powertrain types are included (e.g., gasoline, diesel, and electric drive versions).

Figure 90Figure 90 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 3-6 Shuttle Buses (California)

Figure 91: California Class 3-6 Shuttle Bus New Vehicle Registrations by Calendar Year

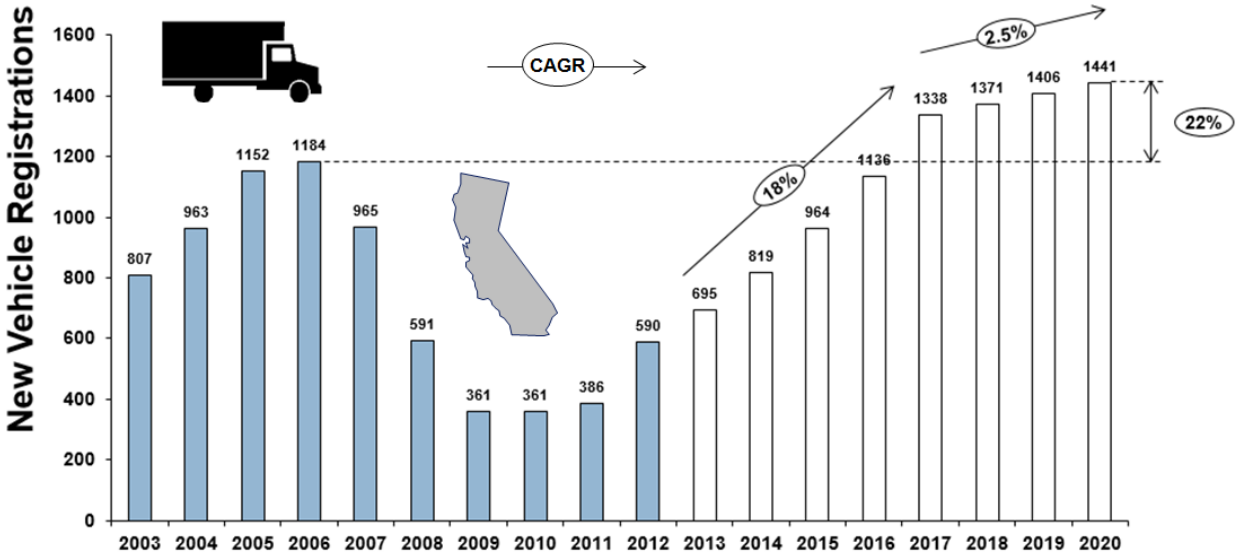


Class 3 – 6 shuttle buses are not forecasted to reach pre-recession peak volumes until 2015.

Figure 91 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 6 Box Trucks (California)

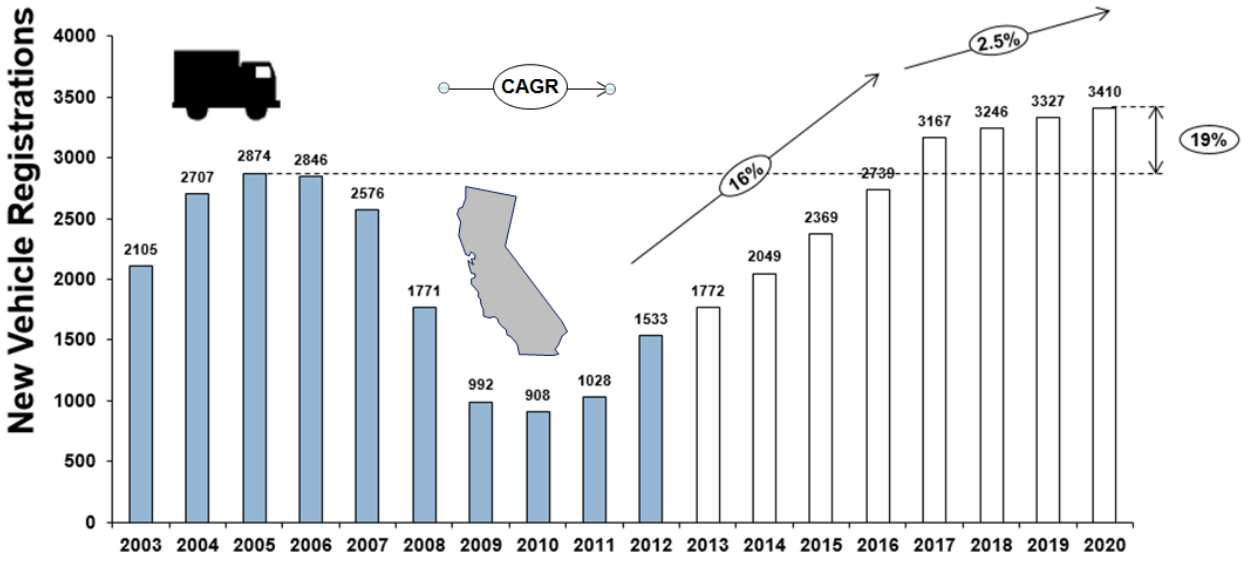
Figure 92: California Class 6 Box Truck New Vehicle Registrations by Calendar Year



Class 6 box trucks are forecasted to reach pre-recession peak volumes by 2017. Figure 92 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 4-6 Urban Delivery Trucks (California)

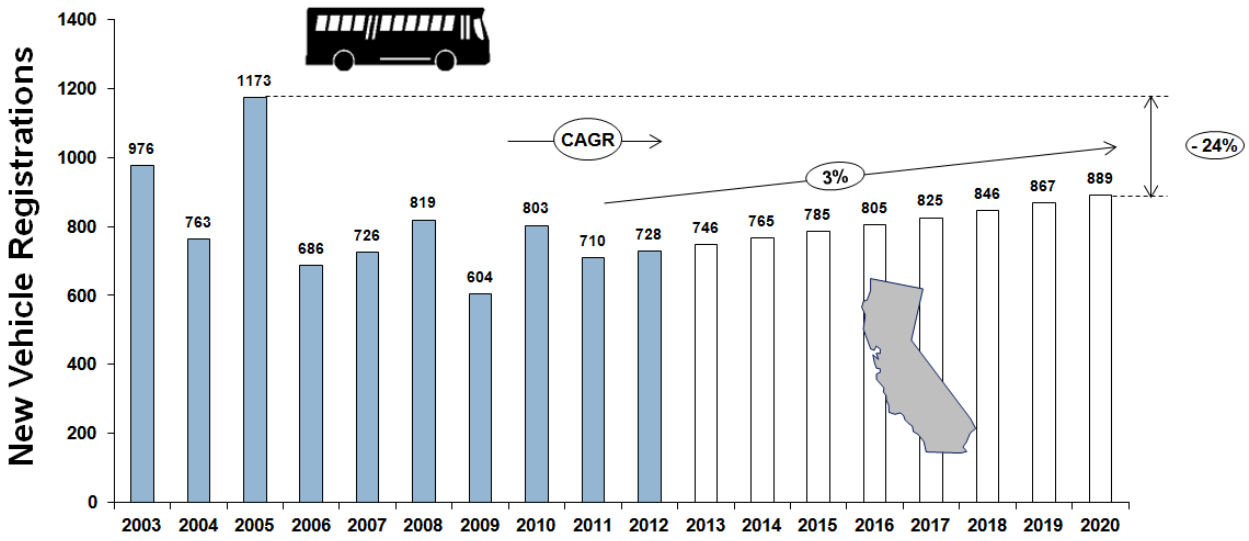
Figure 93: California Class 4-6 Urban Delivery Truck New Vehicle Registrations by Calendar Year



Class 4 to 6 urban delivery trucks are forecasted to reach pre-recession peak volumes by 2017. Figure 93 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

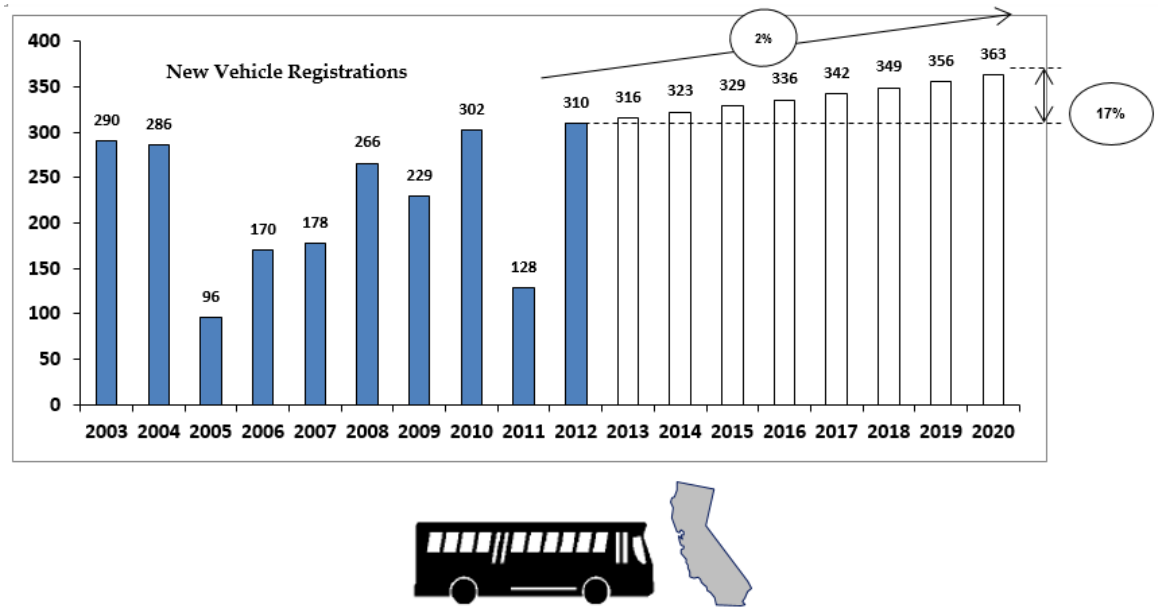
Class 7-8 Transit Buses (California)

Figure 94: California Class 7-8 Transit Buses (including school buses) New Vehicle Registrations by Calendar Year



Class 7 to 8 transit buses (including school buses) are not forecasted to reach pre-recession peak volumes even by 2020. Figure 94 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

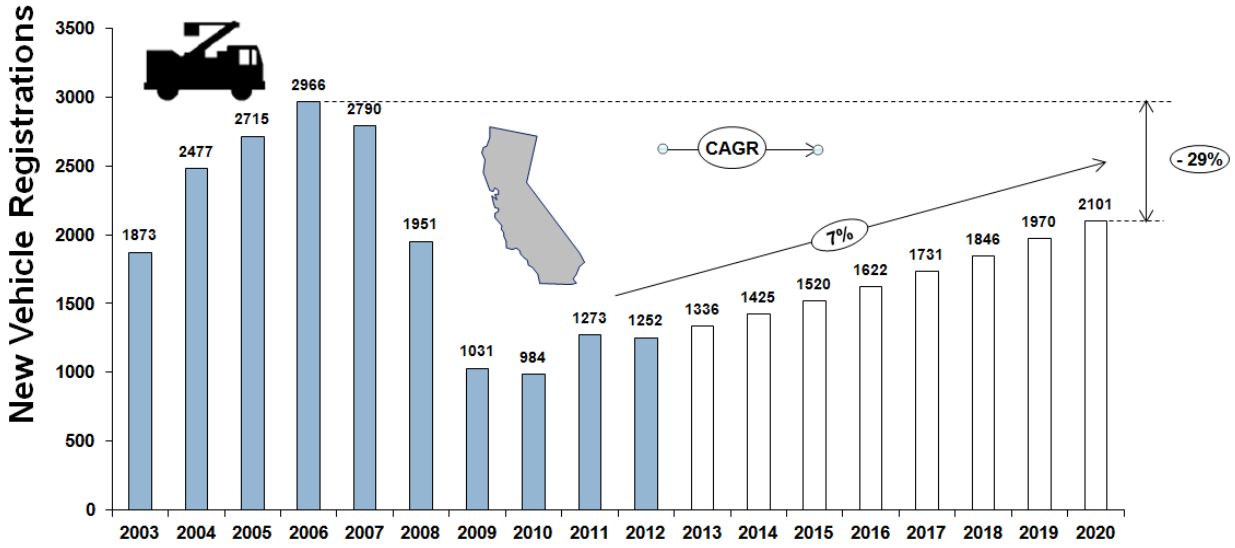
Figure 95: California Class 7-8 Transit Buses (excludes school buses) New Vehicle Registrations by Calendar Year



Class 7 to 8 transit buses (excludes school buses) are already at highest level in 10 years; modest growth is forecast over next 10 years. Figure 95 shows nine year CAGR (2003-2012) is only ~1 percent; growth forecast ssumes a modest 2 percent annual growth rate, which is an average of GDP forecast and GAGR over the past nine years.

Class 4-6 Work Trucks (California)

Figure 96: California Class 4-6 Work Truck New Vehicle Registrations by Calendar Year

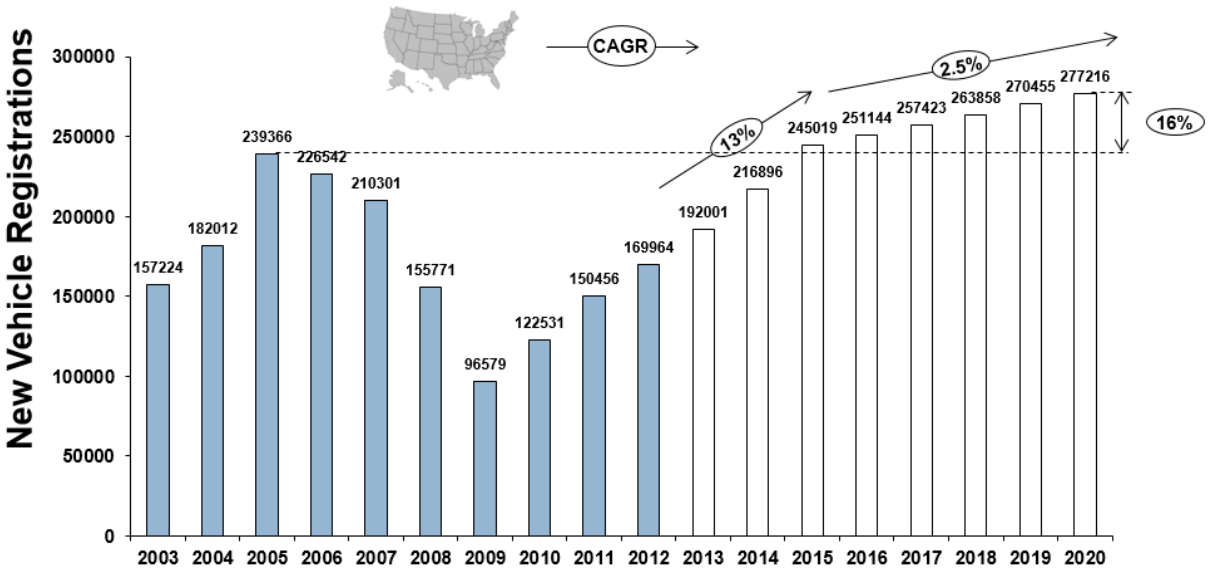


Class 4 to 6 work trucks are not forecasted to reach pre-recession peak volumes even by 2020. Figure 96 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed

United States New Vehicle Registration Forecasts: by Weight Class

An analysis of new vehicle registrations categorized by vocation, weight class, and calendar year was completed. The first part of the study categorized the vehicles by weight class and included all vocations within each class. The second part of the analysis was restricted to the six selected vocations.

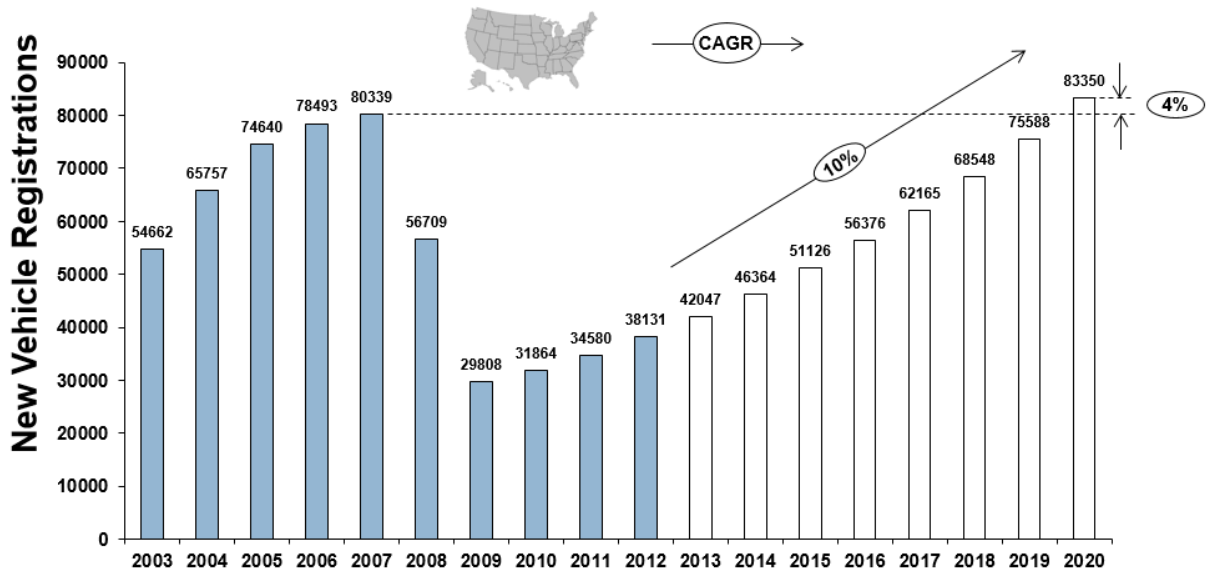
Figure 97: United States Class 3 New Vehicle Registrations by Calendar Year, Entire United States



Note, all vehicle vocations in Figure 97 are included.

Figure 97 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

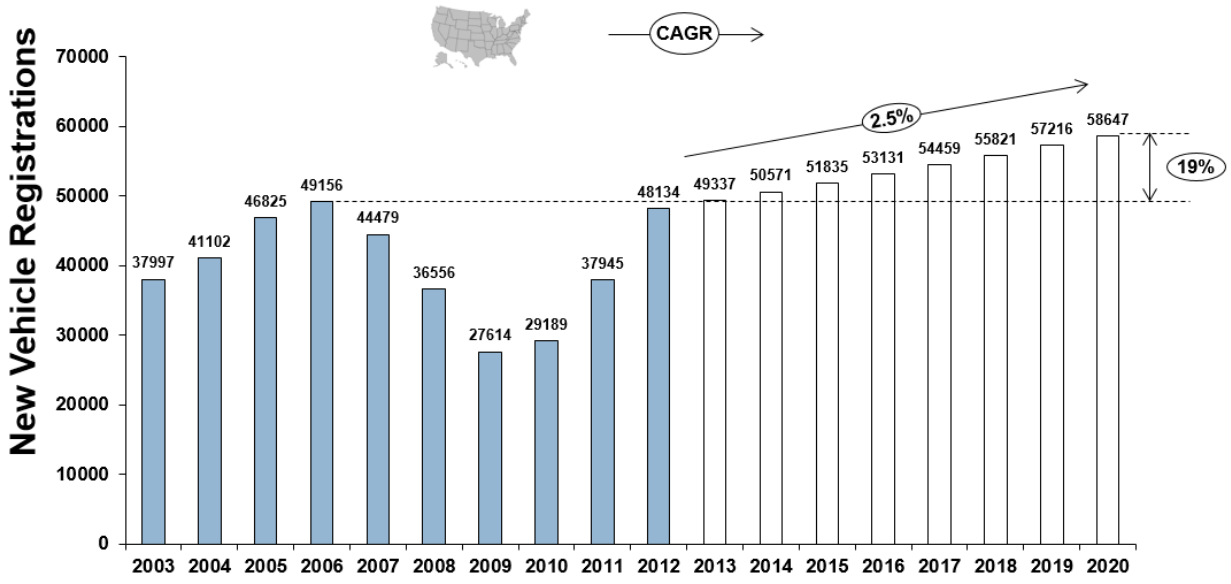
Figure 98: United States Class 4 New Vehicle Registrations by Calendar Year



Note all vehicle vocations in Figure 98 are included.

Class 4 vehicles are not forecasted to reach pre-recession peak volumes until 2020. Figure 98 above assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

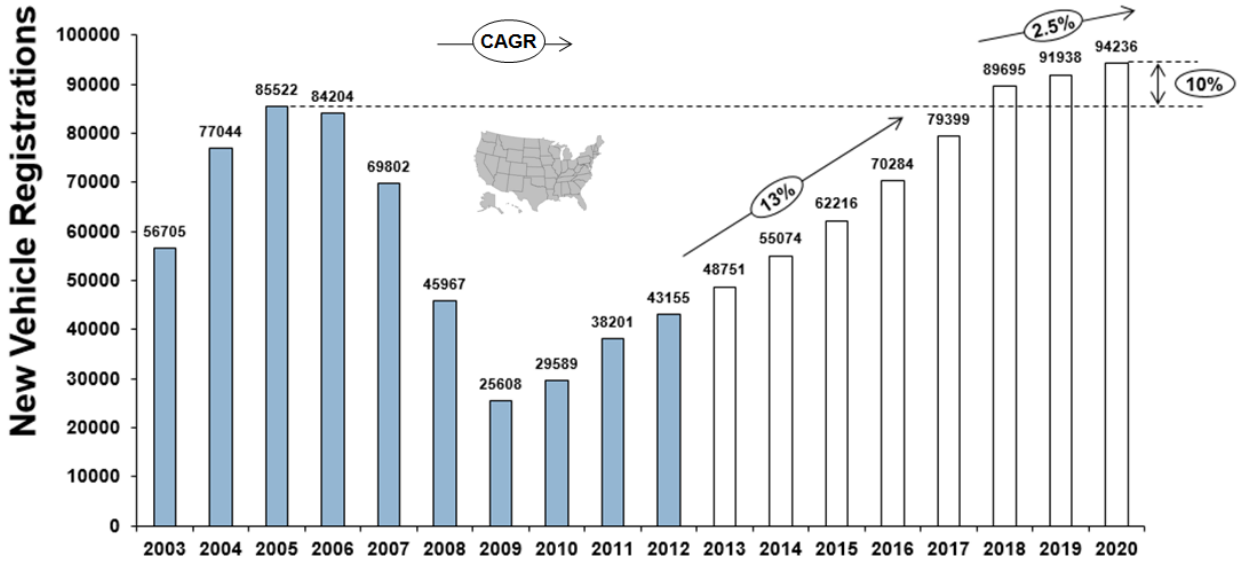
Figure 99: United States Class 5 New Vehicle Registrations by Calendar Year



Class 5 vehicle volumes are already at pre-recession levels and and are expected to experience steady GDP level growth in the future[57]. All vehicle vocations are included.

Figure 99 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Figure 100: United States Class 6 New Vehicle Registrations by Calendar Year

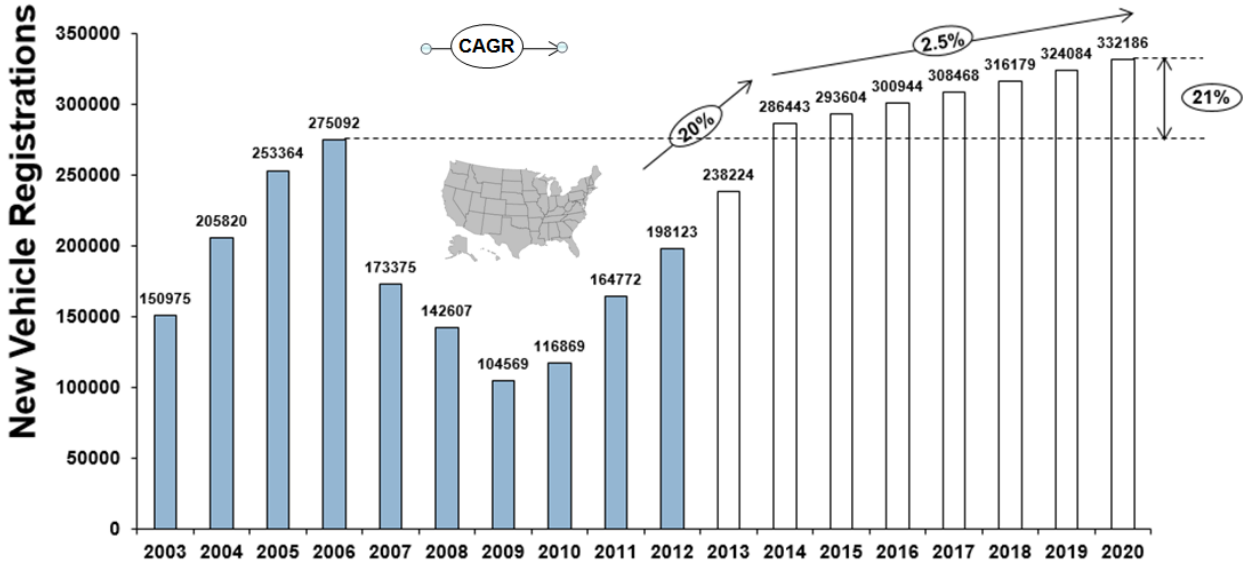


Class 6 vehicles are not forecasted to reach pre-recession peak volumes until 2018[58]. Note, all vehicle vocations are included in Figure 100. This figure assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

[57] Source: R.L. Polk (IHS):

[58] Source: R.L. Polk (IHS):

Figure 101: United States Class 8 New Vehicle Registrations by Calendar Year



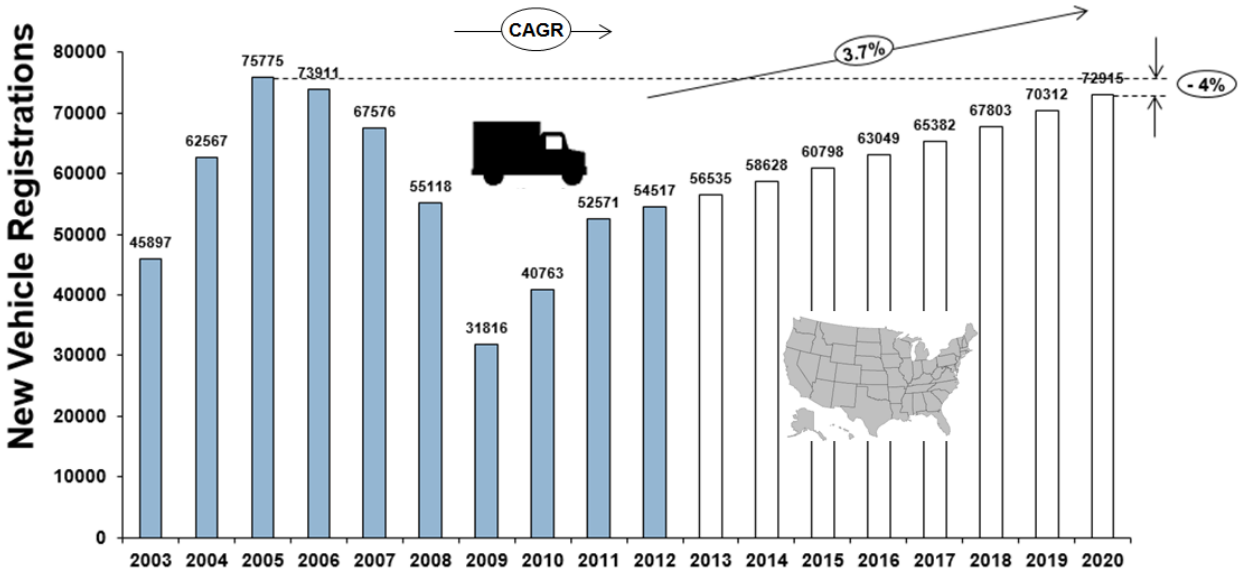
Class 8 vehicles are forecasted to reach pre-recession peak volumes during 2014. All vehicle vocations are included. Figure 101 above assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

United States New Vehicle Registration Forecasts by Vocation

An analysis of new vehicle registrations categorized by vocation was completed as a part of this study.

Class 3 Service Vans (Entire United States)

Figure 102: Class 3 Service Van New Vehicle Registrations by Calendar Year, Entire United States

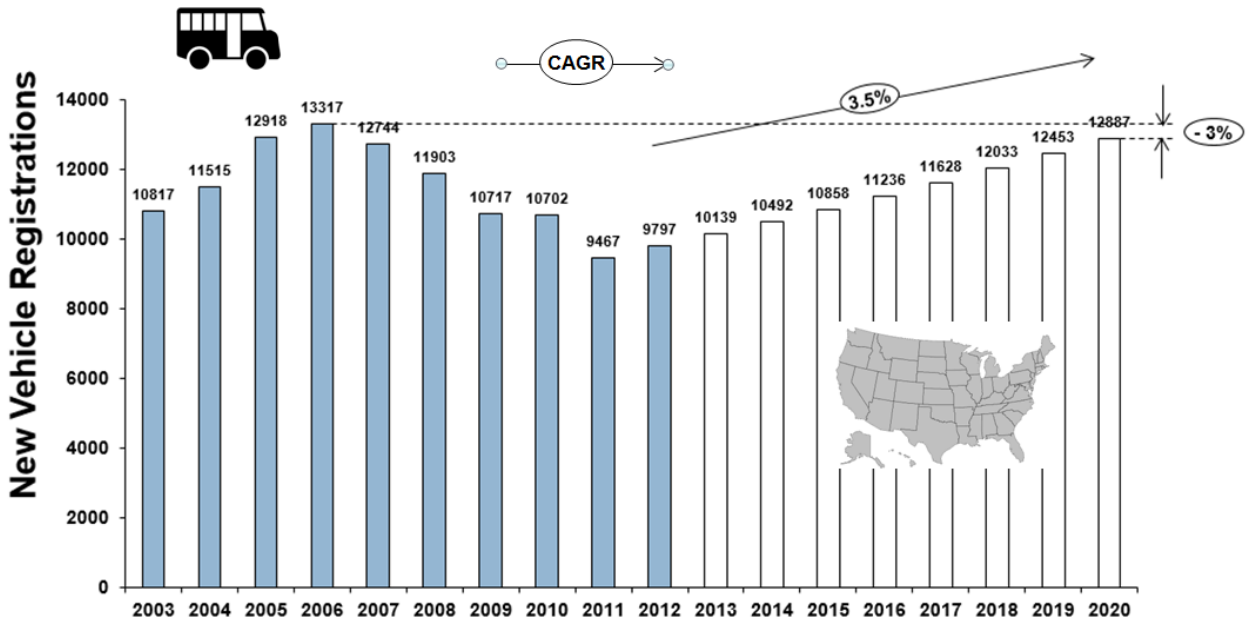


Class 3 service vans are not forecasted to reach pre-recession peak volumes even by 2020.

Figure 102 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 3-6 Shuttle Buses (Entire United States)

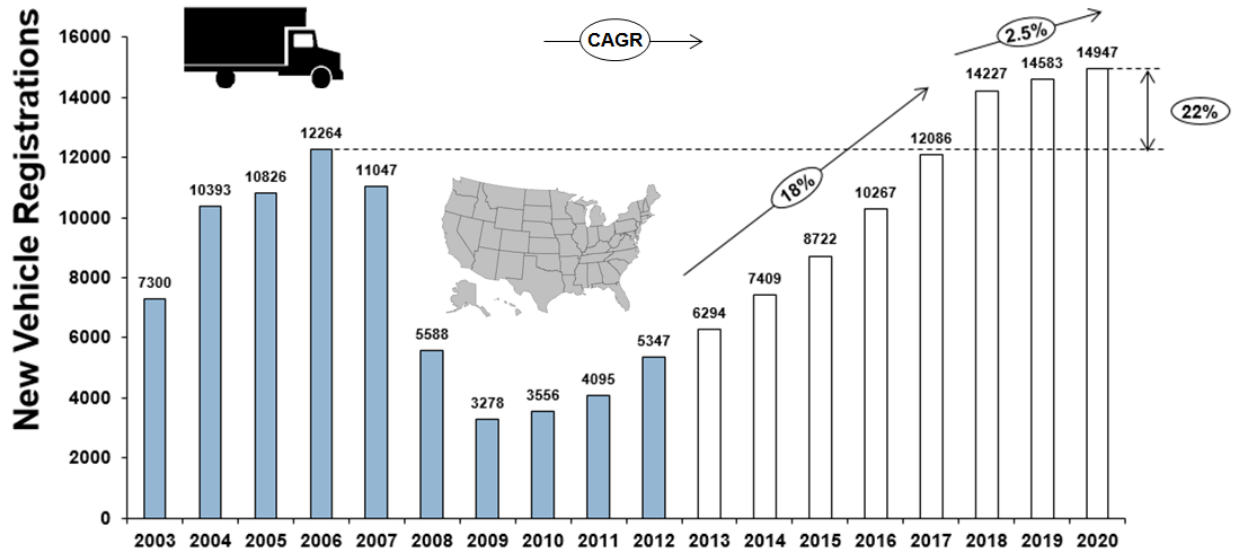
Figure 103: Class 3-6 Shuttle Buses New Vehicle Registrations by Calendar Year, Entire United States



Class 3 – 6 shuttle buses are not forecasted to reach pre-recession peak volumes even by 2020. Figure 103 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 6 Box Trucks (Entire United States)

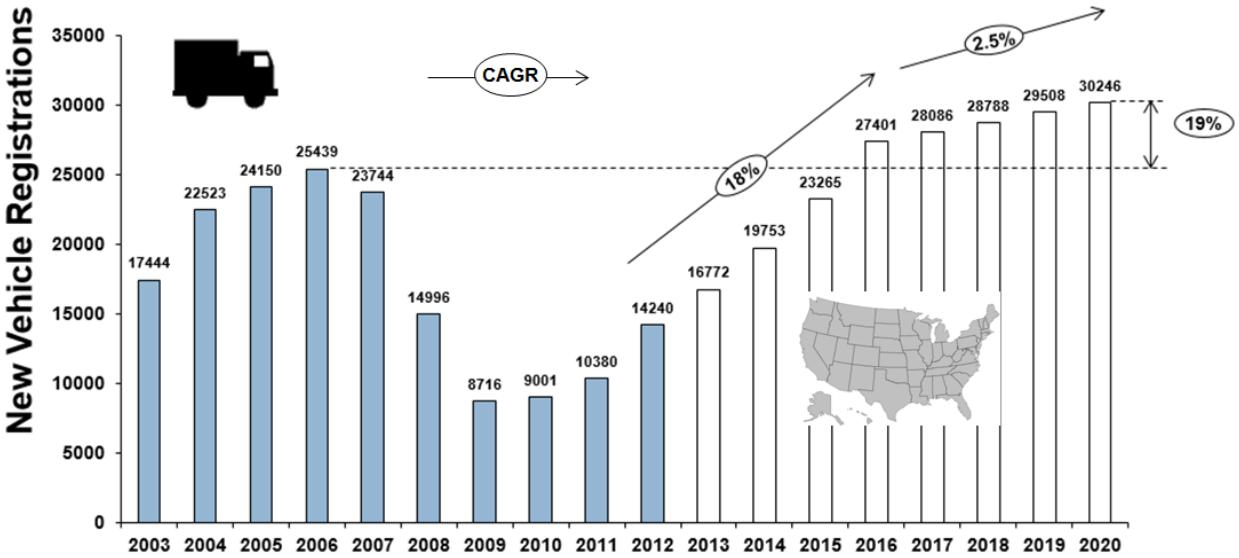
Figure 104: Class 6 Box Trucks: New Vehicle Registrations by Calendar Year, Entire United States



Class 6 box trucks are forecasted to reach pre-recession peak volumes by 2018. Figure 104 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 4-6 Urban Delivery Trucks (Entire United States)

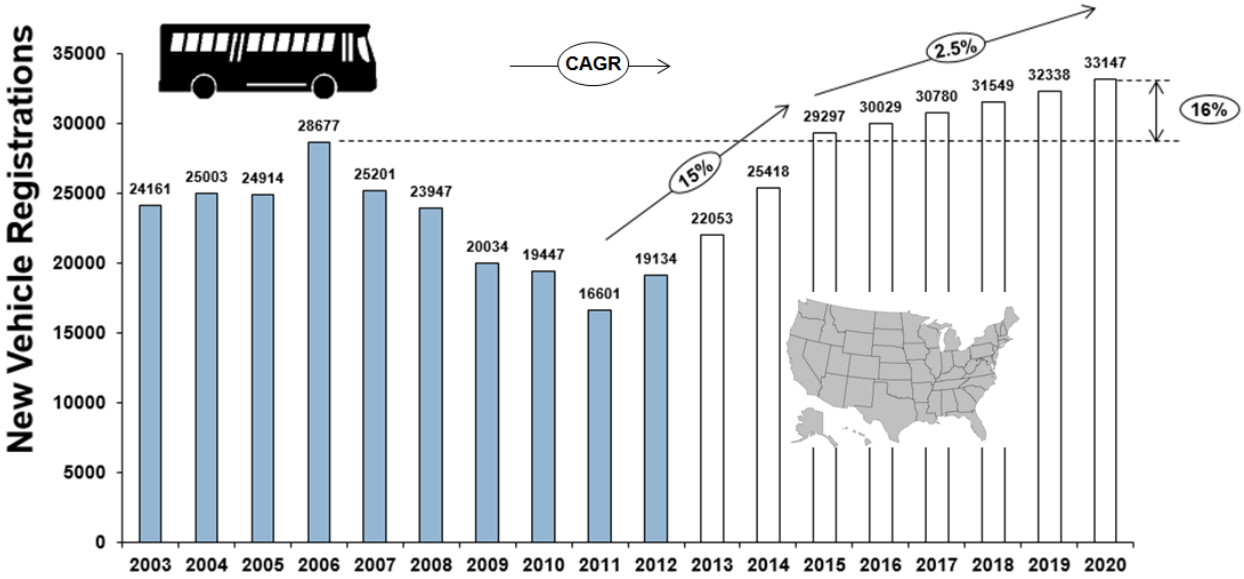
Figure 105: Class 4-6 Urban Delivery Trucks: New Vehicle Registrations by Calendar Year, Entire United States



Class 4 to 6 urban delivery trucks are forecasted to reach pre-recession peak volumes by 2016. Figure 105 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 7-8 Transit Buses, All Buses (Entire United States)

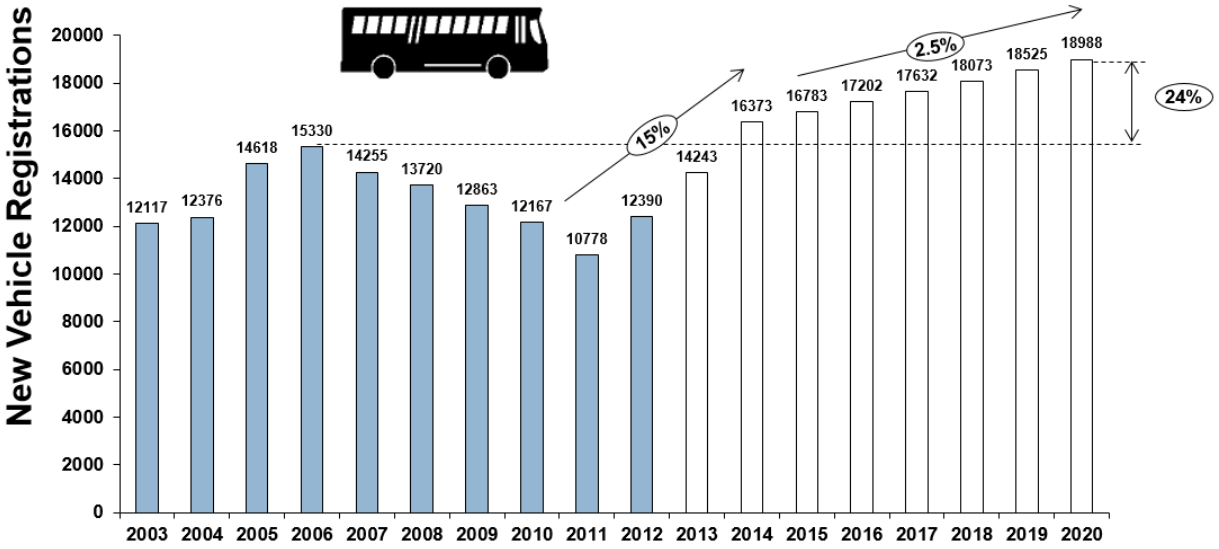
Figure 106: Class 7-8 Transit Buses (all buses): New Vehicle Registrations by Calendar Year, Entire United States



Class 7 to 8 transit buses (total) are forecasted to reach pre-recession peak volumes by 2015. Figure 106 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 7-8 Transit Buses, School Buses Excluded (Entire United States)

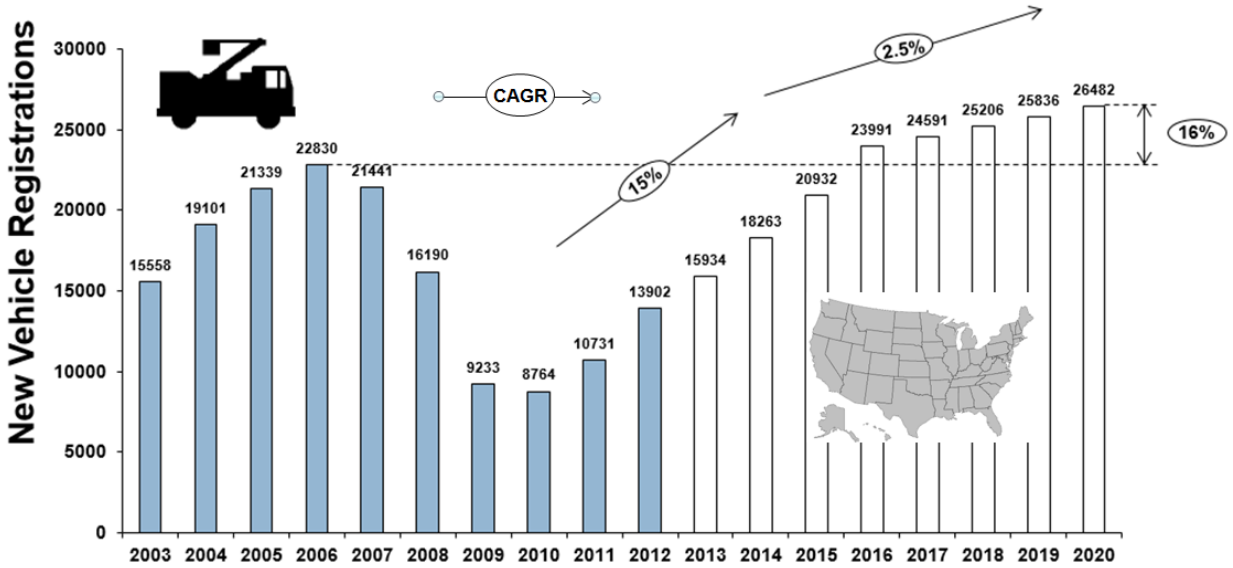
Figure 107: United States Class 7-8 Transit Buses (excludes school buses) New Vehicle Registrations by Calendar Year



Class 7 to 8 transit buses (excluding school buses) are forecasted to reach pre-recession peak volumes by 2014. Figure 107assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

Class 4-6 Work Trucks (Entire United States)

Figure 108: United States Class 4-6 Work Trucks: New Vehicle Registrations by Calendar Year



Class 4 to 6 work trucks are forecasted to reach pre-recession peak volumes by 2016. Figure 108 assumes a faster than GDP growth post recession recovery until the market reaches the pre recession volume, following which a growth correlated to GDP is assumed.

These forecasts were utilized with the adoption rate model to predicte the number of EV, PHEV, and HEV commercial vehicles entering service for each calendar year through 2020. This adoption rate forecast was then coupled with the assessment of vehicle duty cycles and battery first use expectancy to determine the number of second use batteries that will become available during each calendar year through 2025.

1.2.1.13 Battery Pack Specifications for Key Vehicle Segments: Supply-Side Portion of Analysis of Battery Pack Availability

A survey of current production electric-drive vehicles (automobile and commercial vehicles) was completed. The purpose of this survey was to provide input to two key project tasks:

1. The development of standard designs (addressed in Chapter 2)
2. The definition of currently-available battery chemistries, battery system capacities, and manufacturing methods (including form factors) as part of the assessment of applicability of PEV batteries for second use applications.

The battery pack electronic specifications are summarized in Figure 109 through 110. Cell, module and pack specifications (dimensions, weights, cooling systems) are included in Figures 111-112.

Figure 109: Automotive Battery System Specifications

Automobiles

Vehicle	Pack	Battery Chemistry	Cell Supplier	Form Factor		Nominal Voltage (Voc)			Qty		Configuration (#S#P)
				Module	Cell	Pack	Module	Cell	Modules	Cells	
Nissan Leaf, 2012		$LiMn_2O_4$	AESC		Pouch	360.00	7.50	3.75	48	192	Pack - 48S2P Module - 2S2P
Chevy Volt		$LiMn_2O_4$	LG Chem		Pouch	355.20	111.00	3.70	3	288	Pack - 96S3P Module 1 - 30S3P
							88.80				Module 2 - 24S3P
							155.40				Module 3 - 42S3P
Chevy Spark		$LiFePO_4$	A123 Systems		Pouch	364.00	91.00	3.25	4	336	Pack - 112S3P Module - 28S3P

Vehicle OEMs define the effective capacity (maximum available kWh) at which the battery must be replaced. This varies with the vehicle type and duty cycle, but industry trends suggest that OEMS generally indicate that replacement shall occur when either the battery power or energy capacity drops to between 70 percent to 80 percent of its initial (when new) specified value.

Figure 110: Automotive Battery System Specifications

Automobiles

Vehicle	Pack	Pack Energy (kWhr)		Capacity (Ahr)			Energy Density (Wh / kg)			Energy Density (Wh / L)		
		Total	Usable	Pack	Module	Cell	Pack	Module	Cell	Pack	Module	Cell
Nissan Leaf, 2012		24.0	16.0	66.0	66.0	33.0	81.4	131.8	157.2	48.1	199.4	282.2
Chevy Volt		16.0	10.8	45.0	45.0	15.0	83.6	105.8 131.5 75.1	146.4	28.8	125.9 TBC in Task 3 86.9	248.3
Chevy Spark		22.1	17.1	60.6	60.6	20.2	TBC in Task 3	115.7	132.4	TBC in Task 3	TBC in Task 3	249.3

Figure 111: Automotive Battery System Specifications

Automobiles

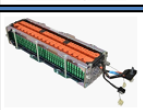
Vehicle	Pack	Battery Chemistry	Cell Supplier	Form Factor		Nominal Voltage (V_{OC})			Qty		Configuration (#S#P)
				Module	Cell	Pack	Module	Cell	Modules	Cells	
Chevy Malibu Eco		$LiMn_2O_4$	Hitachi		Cylindrical	115.20	115.20	3.60	2	32	Pack - 32S1P Module - 16S1P
Toyota Prius Plug-In		$LiNiMnCoO_2$	Panasonic (Sanyo)		Prismatic	207.20	51.8	3.70	4	56	Pack - 56S1P Module - 14S1P
Mitsubishi i-MiEV		$LiNiMnCoO_2$	GS Yuasa		Prismatic	325.60	14.80	3.70	22	88	Pack - 88S1P Module - 4S1P
Ford Fusion Hybrid		$LiNiMnCoO_2$	Panasonic (Sanyo)		Prismatic	281.20	140.60	3.70	38	76	Pack - 76S1P Module - 38S1P

Figure 112: Automotive Battery System Specifications

Automobiles

Vehicle	Pack	Pack Energy (kWhr)		Capacity (Ahr)			Energy Density (Wh / kg)			Energy Density (Wh / L)		
		Total	Usable	Pack	Module	Cell	Pack	Module	Cell	Pack	Module	Cell
Chevy Malibu Eco		0.5	TBC in Task 3	4.4	4.4	4.4	36.2	72.4	60.7	29.6	TBC in Task 3	34.3
Toyota Prius Plug-In		4.4	3.4	21.2	21.2	21.2	57.5	84.2	108.2	35.2	TBC in Task 3	187.3
Mitsubishi i-MiEV		16.0	TBC in Task 3	50.0	50.0	50.0	73.0	94.8	108.8	60.9	185.4	217.6
Ford Fusion Hybrid		1.4	TBC in Task 3	4.4	4.4	4.4	28.4	42.7	62.4	15.8	45.3	122.8

Figure 113: Automotive Battery Packs Specifications (dimensions, cooling systems)

Automobiles

Vehicle	Size (mm)									Weight (kg)			Cooling
	Pack			Module			Cell			Pack	Module	Cell	
	Length	Width	Height	Length	Width	Height	Length	Width	Height				
Nissan Leaf, 2012	1570.5	1188.0	264.9	326.0	224.0	34.0	290.0	216.0	7.0	292.059	3.756	0.787	Passive, conduction
Chevy Volt	1660.0	930.0	360.0	580.0	240.0	285.0	230.0	162.0	6.0	191.112	47.202	0.379	Active, liquid
				TBC in Task 3							37.975		
				840.0							66.476		
Chevy Spark	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	227.0	160.0	7.3	TBC in Task 3	47.680	0.496	Active, liquid
Chevy Malibu Eco	417.0	304.0	135.0	417.0	TBC in Task 3	135.0	92.0	40.0	-	14.000	7.000	0.261	Active, forced air

Figure 114: Automotive Battery Packs Specifications (dimensions, cooling systems)

Automobiles

Vehicle	Size (mm)									Weight (kg)			Cooling
	Pack			Module			Cell			Pack	Module	Cell	
	Length	Width	Height	Length	Width	Height	Length	Width	Height				
Toyota Prius Plug-In	747.0	948.0	176.0	TBC in Task 3	TBC in Task 3	TBC in Task 3	148.0	27.0	105.0	76.448	13.036	0.726	Active, forced air
Mitsubishi i-MiEV	1400.0	735.0	260.0	195.0	178.0	115.0	171.0	43.8	113.5	222.952	7.802	1.700	Active, forced air
Ford Fusion Hybrid	961.0	525.0	155.0	625.0	168.0	130.0	120.0	13.0	85.0	43.609	14.473	0.261	Active, forced air

In addition, a survey of current commercial EVs was completed. Battery pack specifications for these vehicles are summarized in Figure 115 through Figure 118 below.

Figure 115: Commercial Vehicle Battery Specifications Commercial Vehicles

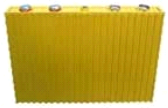
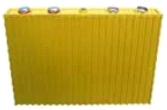
Vehicle	Battery Chemistry	Cell Supplier	Form Factor		Nominal Voltage (V_{DC})			Qty		Configuration (#S#P)
			Module	Cell	Pack	Module	Cell	Modules	Cells	
Smith Newton (Gen 2)	$LiFePO_4$	A123 Systems		Pouch	345.60	86.40	3.20			Module - 25S3P
										Module - 25S3P
										Module - 25S3P
										Module - 25S3P
										Module - 25S3P
Balqon Nautilus XRE30	$LiFePO_4$	Winston Battery		Prismatic	312.00	3.25	3.25	96	96	Pack - 96S1P
Balqon Nautilus MX30	$LiFePO_4$	Winston Battery		Prismatic	540.00	3.25	3.25	166	166	Pack - 166S1P
Balqon Nautilus M100	$LiFePO_4$	Winston Battery		Prismatic	312.00	3.25	3.25	96	96	Pack - 96S1P

Figure 116: Commercial Vehicle Battery Chemistries and Suppliers Commercial Vehicles: Battery Types and Suppliers

Vehicle	Battery Chemistry	Cell Supplier
Smith Newton (Gen 2)	$LiFePO_4$	A123 Systems
Balqon Nautilus XRE30	$LiFePO_4$	Winston Battery
Balqon Nautilus MX30	$LiFePO_4$	Winston Battery
Balqon Nautilus M100	$LiFePO_4$	Winston Battery
Amp Electric Vehicles - E-100 (Workhorse)	$LiFePO_4$	CALB CA180
EVI EVI-MD	$LiFeMgPO_4$	Valence (U27-12XP)
EVI EVI-WI	$LiFeMgPO_4$	Valence (U27-12XP)
Boulder DV500	$LiFePO_4$	TBC in Task 3

Figure 117: Commercial Vehicle Battery Specifications

Commercial Vehicles

Vehicle	Battery Chemistry	Cell Supplier	Form Factor	Nominal Voltage (V_{DC})			Qty		Configuration (#S#P)	Pack Energy (kWhr)		Capacity (Ahr)			Energy Density (Wh / kg)			Energy Density (Wh / L)		
			Cell	Pack	Module	Cell	Modules	Cells		Total	Usable	Pack	Module	Cell	Pack	Module	Cell	Pack	Module	Cell
Balqon Nautilus XRE 30	$LiFePO_4$	Winston Battery	Prismatic	312.00	3.25	3.25	96	96	Pack - 96S1P	215.0	172.0	700.0	700.0	700.0	TBC in Task 3	107.3	107.3	TBC in Task 3	177.0	177.0
Balqon Nautilus MX30	$LiFePO_4$	Winston Battery	Prismatic	540.00	3.25	3.25	166	166	Pack - 166S1P	380.0	304.0	700.0	700.0	700.0	TBC in Task 3	107.3	107.3	TBC in Task 3	177.0	177.0
Balqon Nautilus M 100	$LiFePO_4$	Winston Battery	Prismatic	312.00	3.25	3.25	96	96	Pack - 96S1P	220.0	176.0	1000.0	1000.0	1000.0	TBC in Task 3	79.3	79.3	TBC in Task 3	125.4	125.4
Amp Electric Vehicles - E-100 (Workhorse)	$LiFePO_4$	CALB CA180	Prismatic	547.20	3.20	3.20	171	171	Pack - 171S1P	98.5	78.8	180.0	180.0	180.0	TBC in Task 3	101.1	101.1	TBC in Task 3	161.0	161.0
EVI EVI-MD	$LiFeMgPO_4$	Valence (U27-12XP)	TBC in Task 3	358.40	12.80	3.20	56	224	Pack - 28S2P	99.0	79.2	276.0	138.0	TBC in Task 3	TBC in Task 3	90.6	TBC in Task 3	TBC in Task 3	149.2	TBC in Task 3
EVI EVI-WI	$LiFeMgPO_4$	Valence (U27-12XP)	TBC in Task 3	358.40	12.80	TBC in Task 3	56	TBC in Task 3	Pack - 28S2P	99.0	79.2	276.0	138.0	TBC in Task 3	TBC in Task 3	90.6	TBC in Task 3	TBC in Task 3	149.2	TBC in Task 3
Boulder DV500	$LiFePO_4$	TBC in Task 3	TBC in Task 3	358.40	TBC in Task 3	3.20	TBC in Task 3	112	TBC in Task 3	72.0	57.6	200.9	TBC in Task 3	200.9	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3

Figure 118: Commercial Vehicle Battery Specifications Commercial Vehicles

Vehicle	Size (mm)									Weight (kg)		
	Pack			Module			Cell			Pack	Module	Cell
	Length	Width	Height	Length	Width	Height	Length	Width	Height			
Balqon Nautilus XRE30	TBC in Task 3	TBC in Task 3	TBC in Task 3	627.0	306.0	67.0	627.0	306.0	67.0	TBC in Task 3	21.200	21.200
Balqon Nautilus MX30	TBC in Task 3	TBC in Task 3	TBC in Task 3	627.0	306.0	67.0	627.0	306.0	67.0	TBC in Task 3	21.200	21.200
Balqon Nautilus M100	TBC in Task 3	TBC in Task 3	TBC in Task 3	560.0	356.0	130.0	560.0	356.0	130.0	TBC in Task 3	41.000	41.000
Amp Electric Vehicles - E-100 (Workhorse)	TBC in Task 3	TBC in Task 3	TBC in Task 3	180.0	71.0	280.0	180.0	71.0	280.0	TBC in Task 3	5.700	5.700
EVI EVI-MD	TBC in Task 3	TBC in Task 3	TBC in Task 3	306.0	225.0	172.0	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	19.500	TBC in Task 3
EVI EVI-WI	TBC in Task 3	TBC in Task 3	TBC in Task 3	306.0	225.0	172.0	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	19.500	TBC in Task 3
Boulder DV500	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3	TBC in Task 3

1.2.1.14 Second use Battery Availability through 2025: Supply-Side Portion of Analysis of Battery Pack Availability

Second use Battery Availability Forecasts

The impact of grants and incentives on vehicle total cost of ownership, adoption rates, and second use battery availability (supply) was evaluated for three conditions relative to predicted sales of ECVs, PHECVs, and HECVs for the six selected vocational vehicle categories[59]:

1. Grants and incentives were not included in the total cost of ownership.
2. Currently-available grants and incentives WERE included in the total cost of ownership with the assumption of no restrictions on the number of vehicles eligible for obtaining funds.

[59] Source: Brotherton, T., CALSTART, Clean Commercial Truck Incentives, presented at the NTEA Work Truck Show, 6 March 2013 and Teleconference dated 12 November 2013.

3. Grants and incentives were considered for the first few years during which ECVs, PHECVs, and HECVs were offered for sale based on the following analysis:

    a. Currently-available grants and incentives within the United States have a total award level of approximately $50M per year.

    b. The average value of these incentives is $33,000 per vehicle. Thus, incentive funding is available for approximately 1,500 ECVs, PHECVs, and HECVs, per year.

    c. The number of vehicles receiving funding for Condition 3 is based on the ratio of predicted adoption rates for the No-Incentive Condition 1 analysis.

    d. The largest currently-available grants are 1) California: $14M, 2) New York State + New York City: $15M, and 3) Chicago: $15M.

To calculate the number and capacity of batteries that will become available for second use stationary energy storage applications, the following procedure was followed.

1. The number of vehicles entering service for each of the six vocations and electric drive systems (PEV, PHEV, HEV) was determined using the total cost of ownership and adoption rate models, coupled to new vehicle registration projections.

2. An assessment was made for vehicle attrition rates (number of vehicles that are retired from service due to non-scheduled events, such as accidents, floods, fires, or weather related events.

3. Based on the duty cycle analysis for each vocation and electric drive technology, the time the battery will remain in the vehicle was determined.

4. The number of battery systems and their corresponding capacities (kWh) at the time they are removed from the vehicle was determined for each calendar year through 2025 for each vocation and for each electric drive system type.

The total number of systems from each of the six vocations and electric drive systems are tallied to determine the number of battery systems

Avaliability of commercial electric drive vehicle batteries that become available was calculated for the entire United States, and separately for California-only. The following tables contain summaries of the second use battery availability forecasts.

Second use Availability Forecasts: Entire United States

Condition 1: Grants and Incentives Not included

Vocation: Class 3 Service Vans
Region: Entire United States

Figure 119: Second use Battery Availability Forecasts: Class 3 Service Vans, No Incentives, Entire United States

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)				10.7	Without Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				75	At End of First Life (kw-hr):			60	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	20	450	1,450	3,300	5,300	8,000	10,500	12,000					
Vehicle Attrition (at 5%)	1	23	73	165	265	400	525	600					
Vehicles Available to Supply Second Life Batteries	19	427	1,377	3,135	5,035	7,600	9,975	11,400					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	19	427	1,377	3,135	5,035	7,600	9,975
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	1,140	25,620	82,620	188,100	302,100	456,000	598,500

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)				10.7	Without Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				20	At End of First Life (kw-hr):			16	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	6	20	200	952	2,409	4,500	7,906	10,800					
Vehicle Attrition (at 5%)	-	1	10	48	120	225	395	540					
Vehicles Available to Supply Second Life Batteries	6	19	190	904	2,289	4,275	7,511	10,260					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	6	19	190	904	2,289	4,275	7,511
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	96	304	3,040	14,464	36,624	68,400	120,176

Vocation: Class 6 Box Trucks
Region: Entire United States

Figure 120: Second use Battery Availability Forecasts, Class 6 Box Trucks, No Incentives, Entire United States

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)				>12	Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				120	At End of First Life (kw-hr):			96	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	40	666	981	1,443	2,124	2,795	3,203	4,103					
Vehicle Attrition (at 5%)	2	33	49	72	106	140	160	205					
Vehicles Available to Supply Second Life Batteries	38	633	932	1,371	2,018	2,655	3,043	3,898					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						38	633
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	3,648	60,768

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)				>12	Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				28.4	At End of First Life (kw-hr):			22.7	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	1	2	4	7	13	336	840	1,681					
Vehicle Attrition (at 5%)	-	-	-	-	1	17	42	84					
Vehicles Available to Supply Second Life Batteries	1	2	4	7	12	319	798	1,597					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						1	2
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	23	45

Vocation: Class 4-6 Urban Delivery
Region: Entire United States

Figure 121: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery, No Incentives, Entire United States

Vehicle Vocation: Class 4-6 Urban Delivery	Battery Life Based on Duty Cycle (years)				>12	Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				110	At End of First Life (kw-hr):			88	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	8	400	1,500	2,800	3,948	5,058	6,481	6,643					
Vehicle Attrition (at 5%)	-	20	75	140	197	253	324	332					
Vehicles Available to Supply Second Life Batteries	8	380	1,425	2,660	3,751	4,805	6,157	6,311					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						8	380
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	704	33,440

Vocation: Class 4-6 Work Trucks

Figure 122: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, No Incentives, Entire United States

Vehicle Vocation: Class 4-6 Work Trucks	Battery Life Based on Duty Cycle (years)				10.7	Without Incentives				Vehicle Useful Life (years)			15
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				13	At End of First Life (kw-hr):			22	Replacements per Veh. Life:			1
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	4	512	2,430	4,782	5,596	6,437	7,323	8,248					
Vehicle Attrition (at 5%)	-	26	122	239	280	322	366	412					
Vehicles Available to Supply Second Life Batteries	4	486	2,308	4,543	5,316	6,115	6,957	7,836					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						4	486
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	88	10,692

Vocation: Class 7-8 City Transit Buses
Region: Entire United States

Figure 123: Second use Battery Availability Forecasts, Class 7-8 CityTransit Buses, No Incentives, Entire United States

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	260				At End of First Life (kw-hr):		208		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	36	99	309	619	991	1,588	2,543	3,258					
Vehicle Attrition (at 5%)	2	5	15	31	50	79	127	163					
Vehicles Available to Supply Second Life Batteries	34	94	294	588	941	1,509	2,416	3,095					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						34	94
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	7,072	19,552

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	90				At End of First Life (kw-hr):		72		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	9	49	79	127	203	325	417	534					
Vehicle Attrition (at 5%)	-	2	4	6	10	16	21	27					
Vehicles Available to Supply Second Life Batteries	9	47	75	121	193	309	396	507					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						9	47
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	648	3,384

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: HEV	Average Battery Capacity: New (kw-hr):	11.8				At End of First Life (kw-hr):		9.4		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	14	121	155	198	254	325	417	427					
Vehicle Attrition (at 5%)	1	6	8	10	13	16	21	21					
Vehicles Available to Supply Second Life Batteries	13	115	147	188	241	309	396	406					
Number of Batteries Available for Second Life:	-	-	-	-	-	-			13	115	147	188	241
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	123	1,086	1,388	1,775	2,275

Vocation: Class 3-6 Shuttle Buses
Region: Entire United States

Figure 124: Second use Battery Availability Forecasts, Class 3-6 Shuttle Buses, No Incentives, Entire United States

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years)	10.7				Without Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	105				At End of First Life (kw-hr):		84		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	10	125	350	758	1,226	1,586	2,051	2,653					
Vehicle Attrition (at 5%)	1	6	18	38	61	79	103	133					
Vehicles Available to Supply Second Life Batteries	9	119	332	720	1,165	1,507	1,948	2,520					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	9	119	332	720	1,165	1,507	1,948
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	756	9,996	27,888	60,480	97,860	126,588	163,632

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years)	10.7				Without Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	15				At End of First Life (kw-hr):		12		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	1	3	9	18	44	173	350	453					
Vehicle Attrition (at 5%)	-	-	-	1	2	9	18	23					
Vehicles Available to Supply Second Life Batteries	1	3	9	17	42	164	332	430					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	1	3	9	17	42	164	332
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	12	36	108	204	504	1,968	3,984

Forecast for Condition 1: Grants and Incentives NOT included in total cost of ownership

With no incentives, the cummultive number of batteries originating from the six selected vehicle vocations and projected to become available for the entire United States through 2025 is 21,649. These battery systems are projected to have an energy storage capacity of 2.54 GW-hr, as summarized inFigure 125.

Figure 125 is based on Adoption Rates for ECVs, PHECVs, and HECVs, through 2020 and Six Selected Vehicle Vocations for Entire United States

Figure 125: Without Incentives, Projected Energy Capacity of Second use Batteries from Selected Vocational Vehicles for entire United States is 2.5 GW-hr through 2025

Totals for Six Selected Vocations Power Train Types: EV, PHEV, HEV Without Incentives	+	+	+	+	+	For Entire US							
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	149	2,447	7,467	15,004	22,108	31,123	42,031	50,800					
Vehicle Attrition (at 5%)	7	122	373	750	1,105	1,556	2,102	2,540					
Vehicles Available to Supply Second Life Batteries	142	2,325	7,094	14,254	21,003	29,567	39,929	48,260					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	35	568	1,921	4,891	8,678	13,828	21,649
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	2,004	35,956	113,779	264,334	438,476	666,913	1,016,448
Total Energy Capacity of Second Life Batteries (2019 - 2025):													**2,537,910**

Vehicle Vocation	Power Train Type	Battery Capacity: Originally Installed (kw-hrs)	Battery Capacity: End of First Life (kw-hrs)	Time to Initial Battery Replacement (years)	Vehicle Useful Life (years)	Number of Battery Replacements during Useful Life	Number of Second-Life Batteries/Vehicle	Capacity of Second-Life Batteries (kw-hr)
Service Vans (Class 3, 71 miles/day)	EV	75	71	10.7	6	0	1	60
	PHEV	20	18	10.7	6	0	1	16
Box Truck (Class 6, 80 miles/day)	EV	120	89	>12	12	0	1	96
	PHEV	28.4	25	>12	12	0	1	23
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	71	>12	12	0	1	88
	PHEV	No commercial PHEVs offered for this category						
City Transit Bus (Class 7-8) (120 miles/day)	EV	260	133	>12	12	0	1	208
	HEV	11.8	21	>12	12	0	1	9
	PHEV	90	80	>12	12	0	1	72
Work Trucks (Class 4-6, 43 miles/day)	EV	No commercial EVs offered for this category						
	PHEV	13	11	10.7	15	1	2	22
Shuttle Bus (Class 3-6, 100 miles/day)	EV	105	89	10.7	6	0	1	84
	PHEV	15	13	10.7	6	0	1	12

Condition 2: Unlimited Grants and Incentives Included

Vocation: Class 3 Service Vans
Region: Entire United States

Figure 126: Second use Battery Availability Forecasts, Class 3 Service Vans, Unlimited Incentives, Entire United States

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)	10.7	With Incentives		Vehicle Useful Life (years)	6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	75	At End of First Life (kw-hr):	60	Replacements per Veh. Life:	0

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	20	500	1,500	3,500	5,500	8,747	11,000	12,236					
Vehicle Attrition (at 5%)	1	25	75	175	275	437	550	612					
Vehicles Available to Supply Second Life Batteries	19	475	1,425	3,325	5,225	8,310	10,450	11,624					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	19	475	1,425	3,325	5,225	8,310	10,450
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	1,140	28,500	85,500	199,500	313,500	498,600	627,000

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)	10.7	With Incentives		Vehicle Useful Life (years)	6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	20	At End of First Life (kw-hr):	16	Replacements per Veh. Life:	0

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	21	2,000	6,500	12,000	20,938	30,000	35,000	36,653					
Vehicle Attrition (at 5%)	1	100	325	600	1,047	1,500	1,750	1,833					
Vehicles Available to Supply Second Life Batteries	20	1,900	6,175	11,400	19,891	28,500	33,250	34,820					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	20	1,900	6,175	11,400	19,891	28,500	33,250
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	320	30,400	98,800	182,400	318,256	456,000	532,000

Vocation: Class 6 Box Trucks
Region: Entire United States

Figure 127: Second use Battery Availability Forecasts, Class 6 Box Trucks, Unlimited Incentives, Entire United States

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)	>12	With Incentives		Vehicle Useful Life (years)	12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	120	At End of First Life (kw-hr):	96	Replacements per Veh. Life:	0

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	40	795	2,806	4,129	4,860	7,152	7,331	7,514					
Vehicle Attrition (at 5%)	2	40	140	206	243	358	367	376					
Vehicles Available to Supply Second Life Batteries	38	755	2,666	3,923	4,617	6,794	6,964	7,138					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						38	755
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	3,648	72,480

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)	>12	With Incentives		Vehicle Useful Life (years)	12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	28.4	At End of First Life (kw-hr):	22.7	Replacements per Veh. Life:	0

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	2	508	935	1,376	2,025	2,384	2,444	2,505					
Vehicle Attrition (at 5%)	-	25	47	69	101	119	122	125					
Vehicles Available to Supply Second Life Batteries	2	483	888	1,307	1,924	2,265	2,322	2,380					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						2	483
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	45	10,974

Vocation: Class 4-6 Urban Delivery
Region: Entire United States

Figure 128: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery, Unlimited Incentives, Entire United States

Vehicle Vocation: Class 4-6 Urban Delivery	Battery Life Based on Duty Cycle (years) >12					With Incentives				Vehicle Useful Life (years) 12			
Power Train Type: EV	Average Battery Capacity: New (kw-hr): 110					At End of First Life (kw-hr): 88				Replacements per Veh. Life: 0			
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	100	500	2,495	1,000	16,852	18,511	20,538	22,685					
Vehicle Attrition (at 5%)	5	25	125	50	843	926	1,027	1,134					
Vehicles Available to Supply Second Life Batteries	95	475	2,370	950	16,009	17,585	19,511	21,551					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						95	475
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	8,360	41,800

Vocation: Class 4-6 Work Trucks

Figure 129: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, Unlimited Incentives, Entire United States

Vehicle Vocation: Class 4-6 Work Trucks	Battery Life Based on Duty Cycle (years) 10.7					With Incentives				Vehicle Useful Life (years) 15			
Power Train Type: EV	Average Battery Capacity: New (kw-hr): 13					At End of First Life (kw-hr): 22				Replacements per Veh. Life: 1			
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	4	607	2,722	4,782	5,596	6,437	7,328	8,248					
Vehicle Attrition (at 5%)	-	30	136	239	280	322	366	412					
Vehicles Available to Supply Second Life Batteries	4	577	2,586	4,543	5,316	6,115	6,962	7,836					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						4	577
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	88	12,694

Vocation: Class 7-8 City Transit Buses
Region: Entire United States

Figure 130: Second use Battery Availability Forecasts, Class 7-8 City Transit Buses, Unlimited Incentives, Entire United States

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				With Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	260				At End of First Life (kw-hr):			208	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	40	150	755	1,209	1,936	3,101	3,973	5,091					
Vehicle Attrition (at 5%)	2	8	38	60	97	155	199	255					
Vehicles Available to Supply Second Life Batteries	38	142	717	1,149	1,839	2,946	3,774	4,836					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						38	142
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	7,904	29,536

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				With Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	90				At End of First Life (kw-hr):			72	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	10	40	175	484	620	635	814	1,043					
Vehicle Attrition (at 5%)	1	2	9	24	31	32	41	52					
Vehicles Available to Supply Second Life Batteries	9	38	166	460	589	603	773	991					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						9	38
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	648	2,736

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				With Incentives				Vehicle Useful Life (years)			12
Power Train Type: HEV	Average Battery Capacity: New (kw-hr):	11.8				At End of First Life (kw-hr):			9.4	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	14	75	185	309	425	635	814	1,043					
Vehicle Attrition (at 5%)	1	4	9	15	21	32	41	52					
Vehicles Available to Supply Second Life Batteries	13	71	176	294	404	603	773	991					
Number of Batteries Available for Second Life:	-	-	-	-	-	-			13	71	176	294	404
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	123	670	1,661	2,775	3,814

Vocation: Class 3-6 Shuttle Buses
Region: Entire United States

Figure 131: Second use Battery Availability Forecasts, Class 3-6 Shuttel Buses, Unlimited Incentives, Entire United States

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years)	10.7				With Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	105				At End of First Life (kw-hr):			84	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	10	125	450	771	998	1,290	1,669	2,159					
Vehicle Attrition (at 5%)	1	6	23	39	50	65	83	108					
Vehicles Available to Supply Second Life Batteries	9	119	427	732	948	1,225	1,586	2,051					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	9	119	427	732	948	1,225	1,586
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	756	9,996	35,868	61,488	79,632	102,900	133,224

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years)	10.7				With Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	15				At End of First Life (kw-hr):			12	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	25	458	1,765	3,700	5,845	6,049	6,260	6,478					
Vehicle Attrition (at 5%)	1	23	88	185	292	302	313	324					
Vehicles Available to Supply Second Life Batteries	24	435	1,677	3,515	5,553	5,747	5,947	6,154					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	24	435	1,677	3,515	5,553	5,747	5,947
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	288	5,220	20,124	42,180	66,636	68,964	71,364

Forecast for Condition 2: Grants and Incentives included in total cost of ownership: no limit on number of grants and incentives awarded

With unlimited incentives, the cummultive number of batteries originating from the six selected vehicle vocations and projected to become available for the entire United States through 2025 is 54,107. These battery systems are projected to have an energy storage capacity of 4.27 GW-hr, as summarized inFigure 132.

Figure 132: Projected Energy Capacity of Second use Batteries from Selected Vocational Vehicles

Totals for Six Selected Vocations Power Train Types: EV, PHEV, HEV With Unlimited Incentives	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	286	5,758	20,288	33,260	65,595	84,941	97,171	105,655					
Vehicle Attrition (at 5%)	14	288	1,014	1,663	3,280	4,247	4,859	5,283					
Vehicles Available to Supply Second Life Batteries	272	5,470	19,274	31,597	62,315	80,694	92,312	100,372					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	72	2,929	9,717	19,043	31,793	44,262	54,107
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	2,504	74,116	240,415	486,238	779,685	1,149,933	1,537,622
												Total Energy Capacity of Second Life Batteries (2019 - 2025):	**4,270,513**

Vehicle Vocation	Power Train Type	Battery Capacity: Originally Installed (kw-hrs)	Battery Capacity: End of First Life (kw-hrs)	Time to Initial Battery Replacement (years)	Vehicle Useful Life (years)	Number of Battery Replacements during Useful Life	Number of Second-Life Batteries/Vehicle	Capacity of Second-Life Batteries (kw-hr)
Service Vans (Class 3, 71 miles/day)	EV	75	71	10.7	6	0	1	60
	PHEV	20	18	10.7	6	0	1	16
Box Truck (Class 6, 80 miles/day)	EV	120	89	>12	12	0	1	96
	PHEV	28.4	25	>12	12	0	1	23
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	71	>12	12	0	1	88
	PHEV	No commercial PHEVs offered for this category						
City Transit Bus (Class 7-8) (120 miles/day)	EV	260	133	>12	12	0	1	208
	HEV	11.8	21	>12	12	0	1	9
	PHEV	90	80	>12	12	0	1	72
Work Trucks (Class 4-6, 43 miles/day)	EV	No commercial EVs offered for this category						
	PHEV	13	11	10.7	15	1	2	22
Shuttle Bus (Class 3-6, 100 miles/day)	EV	105	89	10.7	6	0	1	84
	PHEV	15	13	10.7	6	0	1	12

Condition 3: Limited Grants and Incentives Included

The methodology for determining number of awards available for each selected vehicle vocation for each identified year[60] is shown in Figure 133: Determination of Available Grant and Incentive Awards for Six Selected Vocations, Entire United States.

Currently-available grants and incentives within the United States have a total award level of approximately $50M per year. The average value of these incentives is $33,000 per vehicle.

Thus, incentive funding is available for approximately 1,500 ECVs, PHECVs, and HECVs, per year. The number of vehicles receiving funding for Condition 3 is based on the ratio of

[60] Source: Brotherton, T., CALSTART, Clean Commercial Truck Incentives, presented at the NTEA Work Truck Show, 6 March 2013 and Teleconference dated 12 November 2013.

predicted adoption rates for the No-Incentive Condition 1 analysis. The largest currently-available grants are 1) California: $14M, 2) New York State + New York City: $15M, and 3) Chicago: $15M.

Later in chapter four the Energy Stoage Computational Tool (ESCT), a tool to help the user identify and quantify energy storage benefits and costs, is introduced and used for further analysis.

Figure 133: Determination of Available Grant and Incentive Awards for Six Selected Vocations, Entire United States

Determination of Available Awards for Six Selected Vocations	
New Vehicle Registrations (2012): Vocational Vehicles Eligible for Awards (if they meet ECV, PHECV, and HECV criteria)	316,750
New Vehicle Registrations (2012) for Six Vehicle Vocations Chosen for this Study	116,937
Ratio of Six Selected Vocations to Total Vocational Vehicle Registrations	0.3692
Number of grants/awards Available per Year for Six Selected Vocations: (Ratio x Number of Grants/Incentive Awards)	559

Vehicle Vocation	ECV, PHECV, and HECV Sales for 2015	Ratio of Sales for 6 Vocations	Number of Anticipated Awards
Service Vans (Class 3, 71 miles/day)	4,370	0.442	247
Box Truck (Class 6, 80 miles/day)	936	0.095	53
Urban Delivery (Class 4-6, 71 miles/day)	1,425	0.144	80
City Transit Bus (Class 7-8) (120 miles/day)	516	0.052	30
Work Trucks (Class 4-6, 43 miles/day)	2,308	0.233	130
Shuttle Bus (Class 3-6, 100 miles/day)	341	0.034	19
Total or 6 Selected Vocations:	9,896	1.000	559

Vocation: Class 3 Service Vans
Region: Entire United States

Figure 134: Second use Battery Availability Forecasts, Class 3 Service Vans, Limited Incentives, Entire United States

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)				10.7	With Limited Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				75	At End of First Life (kw-hr):			60	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	20	573	1,573	3,423	5,423	8,000	10,500	12,000					
Vehicle Attrition (at 5%)	1	29	79	171	271	400	525	600					
Vehicles Available to Supply Second Life Batteries	19	544	1,494	3,252	5,152	7,600	9,975	11,400					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	19	544	1,494	3,252	5,152	7,600	9,975
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	1,140	32,640	89,640	195,120	309,120	456,000	598,500

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)				10.7	With Limited Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				20	At End of First Life (kw-hr):			16	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	6	78	323	1,075	2,562	4,500	7,906	10,800					
Vehicle Attrition (at 5%)	-	4	16	54	128	225	395	540					
Vehicles Available to Supply Second Life Batteries	6	74	307	1,021	2,434	4,275	7,511	10,260					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	6	74	307	1,021	2,434	4,275	7,511
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	96	1,184	4,912	16,336	38,944	68,400	120,176

Vocation: Class 6 Box Trucks
Region: Entire United States

Figure 135: Second use Battery Availability Forecasts, Class 6 Box Trucks, Limited Incentives, Entire United States

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				120	At End of First Life (kw-hr):			96	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	40	693	1,004	1,466	2,147	2,795	3,203	4,103					
Vehicle Attrition (at 5%)	2	35	50	73	107	140	160	205					
Vehicles Available to Supply Second Life Batteries	38	658	954	1,393	2,040	2,655	3,043	3,898					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						38	658
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	3,648	63,168

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				28.4	At End of First Life (kw-hr):			22.7	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	2	26	29	30	36	336	840	1,681					
Vehicle Attrition (at 5%)	-	1	1	2	2	17	42	84					
Vehicles Available to Supply Second Life Batteries	2	25	28	28	34	319	798	1,597					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						2	25
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	45	568

Vocation: Class 4-6 Urban Delivery
Region: Entire United States

Figure 136: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery Trucks, Limited Incentives, Entire United States

Vehicle Vocation: Class 4-6 Urban Delivery	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				110	At End of First Life (kw-hr):			88	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	88	488	1,580	2,880	3,948	5,058	6,481	6,643					
Vehicle Attrition (at 5%)	4	24	79	144	197	253	324	332					
Vehicles Available to Supply Second Life Batteries	84	464	1,501	2,736	3,751	4,805	6,157	6,311					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						84	464
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	7,392	40,832

Vocation: Class 4-6 Work Trucks

Figure 137: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, Limited Incentives, Entire United States

Vehicle Vocation: Class 4-6 Work Trucks	Battery Life Based on Duty Cycle (years)				10.7	With Limited Incentives				Vehicle Useful Life (years)			15
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				13	At End of First Life (kw-hr):			22	Replacements per Veh. Life:			1
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	4	560	2,560	4,912	5,726	6,437	7,328	8,248					
Vehicle Attrition (at 5%)	-	28	128	246	286	322	366	412					
Vehicles Available to Supply Second Life Batteries	4	532	2,432	4,666	5,440	6,115	6,962	7,836					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						4	532
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	88	11,704

Vocation: Class 7-8 City Transit Buses
Region: Entire United States

Figure 138: Second use Battery Availability Forecasts, Class 7-8 City Transit Buses, Limited Incentives, Entire United States

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years) >12					With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr): 260					At End of First Life (kw-hr): 208				Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	50	109	319	619	991	1,588	2,543	3,258					
Vehicle Attrition (at 5%)	3	5	16	31	50	79	127	163					
Vehicles Available to Supply Second Life Batteries	47	104	303	588	941	1,509	2,416	3,095					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						47	104
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	9,776	21,632

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years) >12					With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr): 90					At End of First Life (kw-hr): 72				Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	10	59	89	137	213	325	417	534					
Vehicle Attrition (at 5%)	1	3	4	7	11	16	21	27					
Vehicles Available to Supply Second Life Batteries	9	56	85	130	202	309	396	507					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						9	56
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	648	4,032

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years) >12					With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: HEV	Average Battery Capacity: New (kw-hr): 11.8					At End of First Life (kw-hr): 9.4				Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	14	131	165	208	264	325	417	427					
Vehicle Attrition (at 5%)	1	7	8	10	13	16	21	21					
Vehicles Available to Supply Second Life Batteries	13	124	157	198	251	309	396	406					
Number of Batteries Available for Second Life:	-	-	-	-	-	-			13	124	157	198	251
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	123	1,171	1,482	1,869	2,369

Vocation: Class 3-6 Shuttle Buses
Region: Entire United States

Figure 139: Second use Battery Availability Forecasts, Class 3-6 Shuttel Buses, Limited Incentives, Entire United States

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years) 10.7					With Limited Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr): 105					At End of First Life (kw-hr): 84				Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	10	135	360	768	1,236	1,586	2,051	2,653					
Vehicle Attrition (at 5%)	1	7	18	38	62	79	103	133					
Vehicles Available to Supply Second Life Batteries	9	128	342	730	1,174	1,507	1,948	2,520					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	9	128	342	730	1,174	1,507	1,948
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	756	10,752	28,728	61,320	98,616	126,588	163,632

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years) 10.7					With Limited Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr): 15					At End of First Life (kw-hr): 12				Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	3	13	19	28	54	173	350	453					
Vehicle Attrition (at 5%)	-	1	1	1	3	9	18	23					
Vehicles Available to Supply Second Life Batteries	3	12	18	27	51	164	332	430					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	3	12	18	27	51	164	332
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	36	144	216	324	612	1,968	3,984

Forecast for Condition 3: Grants and Incentives included in total cost of ownership: WITH LIMIT on number of grants and incentives awarded

With limited incentives, the cummultive number of batteries originating from the six selected vehicle vocations and projected to become available for the entire United States through 2025 is 54,107. These battery systems are projected to have an energy storage capacity of 2.73 GW-hr, as summarized in Figure 140.

Figure 140: With Limited Incentives, Projected Energy Capacity of Second use Batteries from Selected Vocational Vehicles for Entire United States is 2.7 GW-hr through 2025

Totals for Six Selected Vocations Power Train Types: EV, PHEV, HEV With Incentives	+	+	+	+	+	For Entire US							
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	286	5,758	20,288	33,260	65,595	84,941	97,171	105,655					
Vehicle Attrition (at 5%)	14	288	1,014	1,663	3,280	4,247	4,859	5,283					
Vehicles Available to Supply Second Life Batteries	272	5,470	19,274	31,597	62,315	80,694	92,312	100,372					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	72	2,929	9,717	19,043	31,793	44,262	54,107
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	2,504	74,116	240,415	486,238	779,685	1,149,933	1,537,622
												Total Energy Capacity of Second Life Batteries (2019 - 2025):	**2,732,891**

Vehicle Vocation	Power Train Type	Battery Capacity: Originally Installed (kw-hrs)	Battery Capacity: End of First Life (kw-hrs)	Time to Initial Battery Replacement (years)	Vehicle Useful Life (years)	Number of Battery Replacements during Useful Life	Number of Second-Life Batteries/Vehicle	Capacity of Second-Life Batteries (kw-hr)
Service Vans (Class 3, 71 miles/day)	EV	75	71	10.7	6	0	1	60
	PHEV	20	18	10.7	6	0	1	16
Box Truck (Class 6, 80 miles/day)	EV	120	89	>12	12	0	1	96
	PHEV	28.4	25	>12	12	0	1	23
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	71	>12	12	0	1	88
	PHEV	No commercial PHEVs offered for this category						
City Transit Bus (Class 7-8) (120 miles/day)	EV	260	133	>12	12	0	1	208
	HEV	11.8	21	>12	12	0	1	9
	PHEV	90	80	>12	12	0	1	72
Work Trucks (Class 4-6, 43 miles/day)	EV	No commercial EVs offered for this category						
	PHEV	13	11	10.7	15	1	2	22
Shuttle Bus (Class 3-6, 100 miles/day)	EV	105	89	10.7	6	0	1	84
	PHEV	15	13	10.7	6	0	1	12

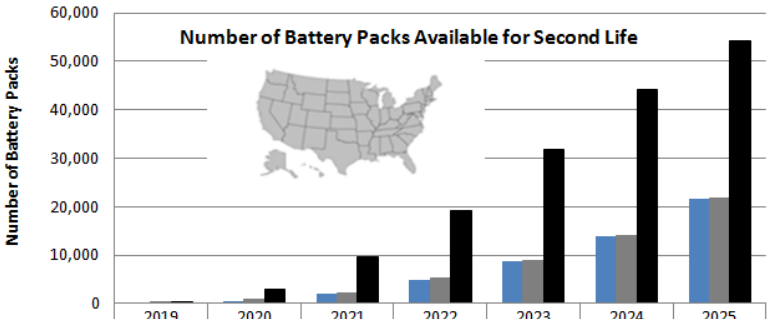
Conclusions that can be drawn from this table include:

1. Second use battery availability is dependent on the status of grant and incentive programs. The incentive funds have a significant impact on vehicle adoption rates.
2. Currently available grant funds have a minor impact on adoption rates due to the limited number of vehicles affected. Note that the "limited-incentives" analysis was based on identified grants and voucher programs for calendar year 2014.
3. Second use battery systems originating from ECVs, PHECVs, and HECVs are expected to become available for second use applications beginning in 2019.

Projections for number of second use battery packs and corresponding energy storage capacity of these packs for the entire United States and originating with the six selected vehicle vocations are summarized in Figure 141 and Figure 142.

Figure 141: Impact of Incentives on Availability of Second use Battery Packs (Number of Batteries), Selected Vocational Vehicles, Entire United States

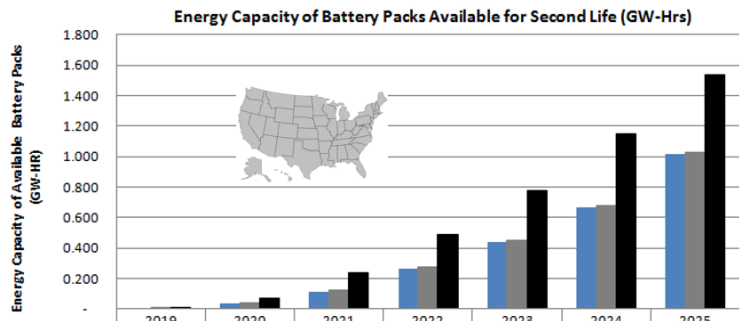
Number of Battery Packs			
Year	Without Incentives	With Limited Incentives	With Unlimited Incentives
2019	35	37	72
2020	568	758	2,929
2021	1,921	2,174	9,717
2022	4,891	5,154	19,043
2023	8,678	8,968	31,793
2024	13,828	13,928	44,262
2025	21,629	21,856	54,107
Totals:	**51,550**	**52,875**	**161,923**



	2019	2020	2021	2022	2023	2024	2025
Without Incentives	35	568	1,921	4,891	8,678	13,828	21,629
With Limited Incentives	37	758	2,174	5,154	8,968	13,928	21,856
With Unlimited Incentives	72	2,929	9,717	19,043	31,793	44,262	54,107

Figure 142: Impact of Incentives on Availability of Second use Battery Packs (Capacity), Selected Vocational Vehicles, Entire United States

Capacity of Battery Packs (GW-Hrs)			
Year	Without Incentives	With Limited Incentives	With Unlimited Incentives
2019	0.002	0.002	0.003
2020	0.036	0.045	0.074
2021	0.114	0.124	0.240
2022	0.264	0.274	0.486
2023	0.438	0.449	0.780
2024	0.667	0.676	1.150
2025	1.016	1.031	1.538
Totals:	**2.538**	**2.600**	**4.271**



	2019	2020	2021	2022	2023	2024	2025
Without Incentives	0.002	0.036	0.114	0.264	0.438	0.667	1.016
With Limited Incentives	0.002	0.045	0.124	0.274	0.449	0.676	1.031
With Unlimited Incentives	0.003	0.074	0.240	0.486	0.780	1.150	1.538

Second use Battery Availability Forecasts: California

Based on the analysis performed for adoption rates and second use battery availability for the entire US, a second study was completed for vehicles registered within the State of California. The impact of grants and incentives on vehicle total cost of ownership, adoption rates, and second use battery availability (supply) was evaluated for two conditions relative to predicted sales of ECVs, PHECVs, and HECVs for the six selected vocational vehicle categories:

1. Grants and incentives were not included in the total cost of ownership
2. Grants and incentives were considered for the first few years during which ECVs, PHECVs, and HECVs were offered for sale based on the following analysis:

Currently-available grants and incentives within the California have a total award level of approximately $14M per year[61].*

The average value of these incentives is $33,000 per vehicle. Thus, incentive funding is available for approximately 425 ECVs, PHECVs, and HECVs, per year.

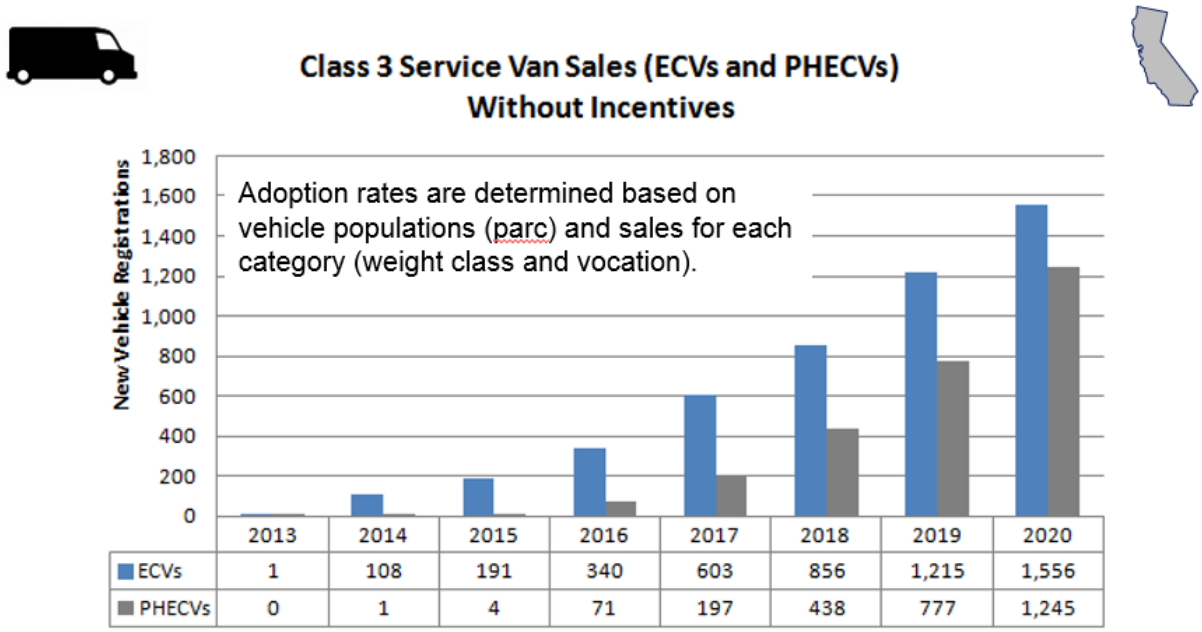
A procedure similar to that used to determine the availability of second use batteries originating with the six selected vocations and electric drive technologies for the entire United States was employed to determine the availability of second use batteries from these same vehicle classifications within California:

1. Complete projections for new vehicle registrations for the six selected vocations through 2025.
2. The number of vehicles entering service for each of the six vocations and electric drive systems (PEV, PHEV, HEV) was determined using the total cost of ownership and adoption rate models, coupled to new vehicle registration projections.
3. An assessment was made for vehicle attrition rates (number of vehicles that are retired from service due to non-scheduled events, such as accidents, floods, fires, or weather related events.
4. Based on the duty cycle analysis for each vocation and electric drive technology, the time the battery will remain in the vehicle was determined.
5. The number of battery systems and their corresponding capacities (kW-hrs) at the time they are removed from the vehicle was determined for each calendar year through 2025 for each vocation and for each electric drive system.

[61] Source: Brotherton, T., CALSTART, Clean Commercial Truck Incentives, presented at the NTEA Work Truck Show, 6 March 2013 and Teleconference dated 12 November 2013.

Condition 1: Grants and Incentives Not Included in Total Cost of Ownership
Class 3 Service Vans for California

Figure 143: Class 3 Service Van Sales (ECV's and PHECVs) without Incentives, California



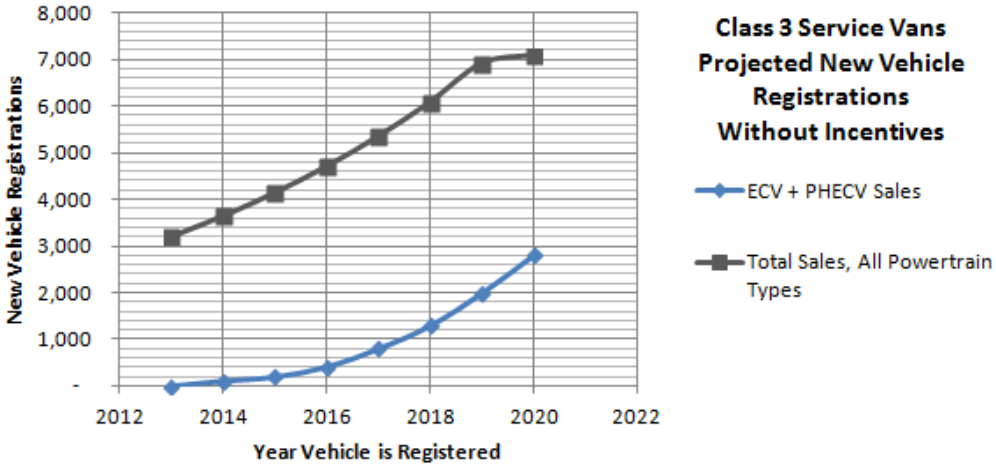
	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	1	108	191	340	603	856	1,215	1,556
PHECVs	0	1	4	71	197	438	777	1,245

Without Incentives, ECV + PHECV Class 3 services vans are projected to attain annual sales within California of 2,800 Units by 2020.

Figure 143 is based on projected new vehicle sales for this class and vocation and the results of Ricardo's Total Cost of Ownership analysis.

Figure 144: Class 3 Service Vans Projected New Vehicle Registrations without Incentives, California

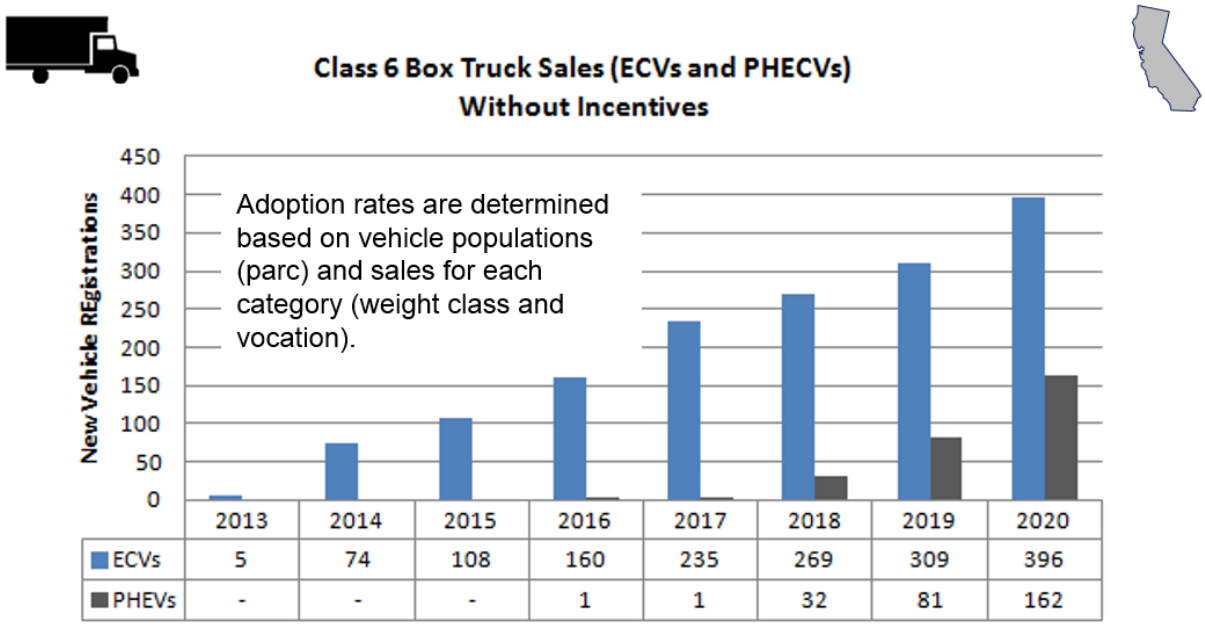
Year	Class 3 Service Van Sales without Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	3,219	1	0	1	0.0%
2014	3,656	108	1	109	3.0%
2015	4,153	191	4	196	4.7%
2016	4,718	340	71	411	8.7%
2017	5,359	603	197	800	14.9%
2018	6,087	856	438	1,294	21.3%
2019	6,914	1,215	777	1,992	28.8%
2020	7,086	1,556	1,245	2,801	39.5%



Without Incentives, ECVs and PHECVs are Projected to Account for 39.5 percent of New Class 3 Service Van Registrations in CA by 2020

Class 6 Box Trucks for California

Figure 145: Class 6 Box Truck Sales (ECV's and PHECVs) without Incentives, California



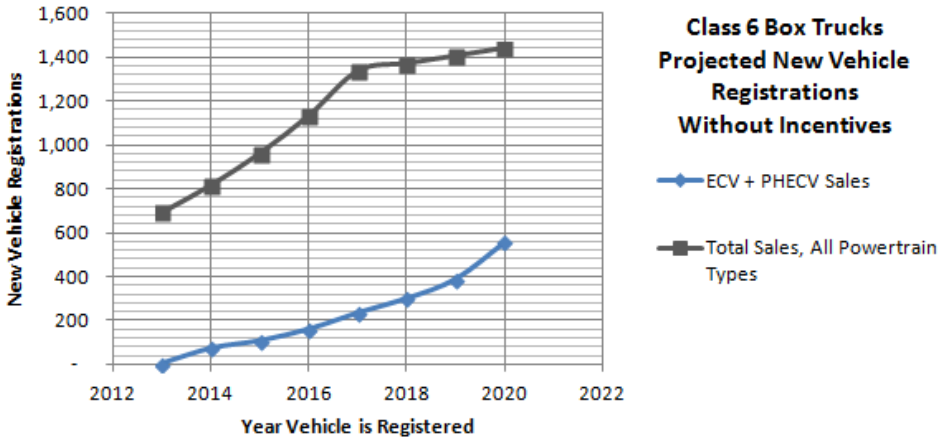
	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	5	74	108	160	235	269	309	396
PHEVs	-	-	-	1	1	32	81	162

Without Incentives, ECV + PHECV Class 6 Box Trucks are Projected to Attain Annual Sales in CA of 558 Units by 2020.

Figure 145 is based on projected new vehicle sales for this class and vocation and the results of Ricardo's Total Cost of Ownership analysis.

Figure 146: Class 6 Box Trucks Projected New Vehicle Registrations without Incentives, California

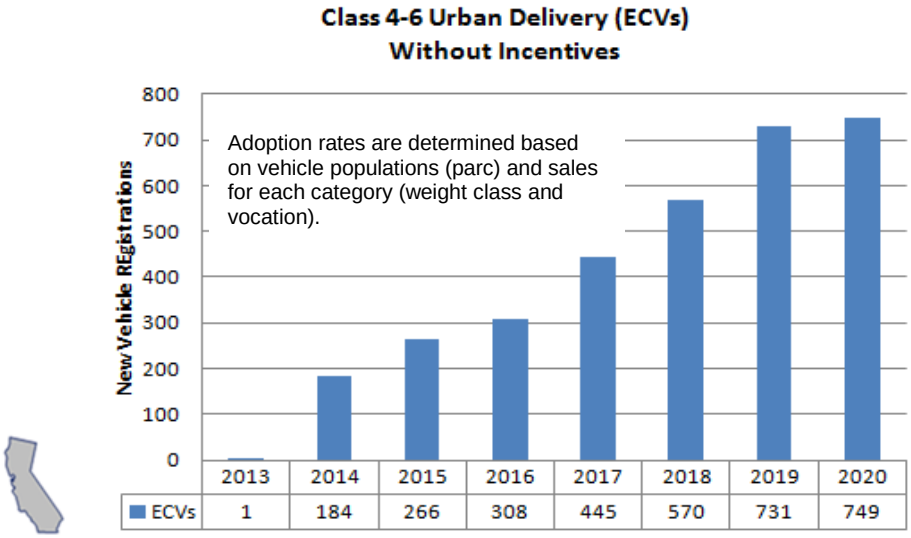
Year	Class 6 Box Truck Sales without Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	695	5	-	5	0.7%
2014	819	74	-	74	9.0%
2015	964	108	-	108	11.2%
2016	1,136	160	1	161	14.2%
2017	1,338	235	1	236	17.6%
2018	1,371	269	32	301	22.0%
2019	1,406	309	81	390	27.7%
2020	1,441	396	162	558	38.7%



Without Incentives, ECVs and PHECVs are Projected to Account for 38.7 percent of New Class 6 Box Trucks Registrations in CA by 2020.

Class 4-6 Urban Delivery Trucks for California

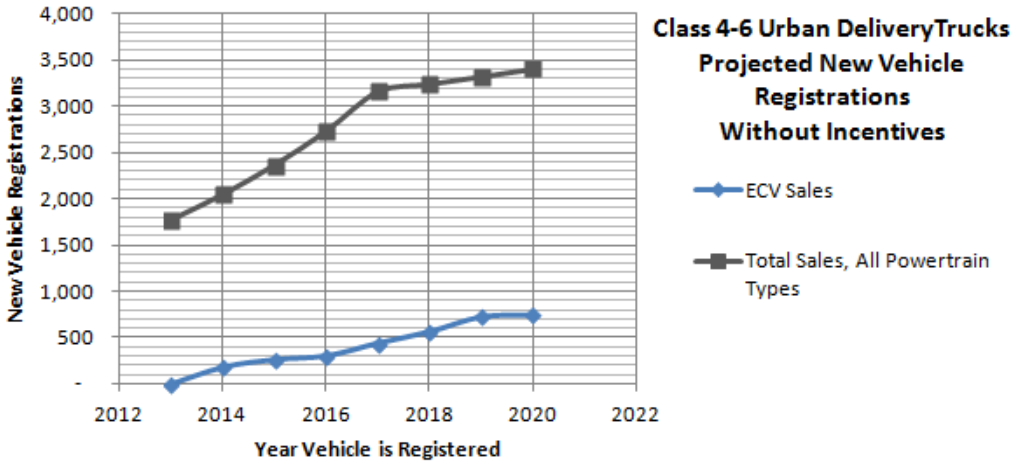
Figure 147: Class Class 4-6 Urban Delivery Truck Sales (ECVs) without Incentives, California



Without incentives, ECV Class 4-6 urban delivery trucks are projected to attain annual sales in CA of 749 Units by 2020.

Figure 148: Class 4-6 Urban Delivery Trucks Projected New Vehicle Registrations without Incentives, California

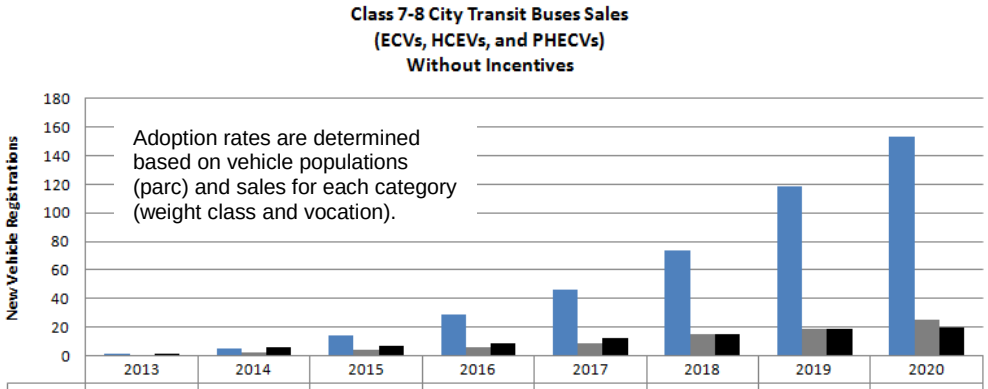
Class 4-6 Urban Delivery Truck Sales without Incentives			
Year	Total, All Powertrain Types	ECV Sales	ECV Sales as % of Total, All Powertrain Types
2013	1,772	1	0.1%
2014	2,049	184	9.0%
2015	2,369	266	11.2%
2016	2,739	308	11.2%
2017	3,167	445	14.1%
2018	3,246	570	17.6%
2019	3,327	731	22.0%
2020	3,410	749	22.0%



Without incentives, ECVs are projected to account for 22 percent of New Class 4-6 Urban Delivery Truck Registrations in CA by 2020.

Class 7-8 City Transit Buses for California

Figure 149: Class 7-8 City Transit Bus Sales (ECVs, HECVs, and PHECVs, does not include school buses) without Incentives, California

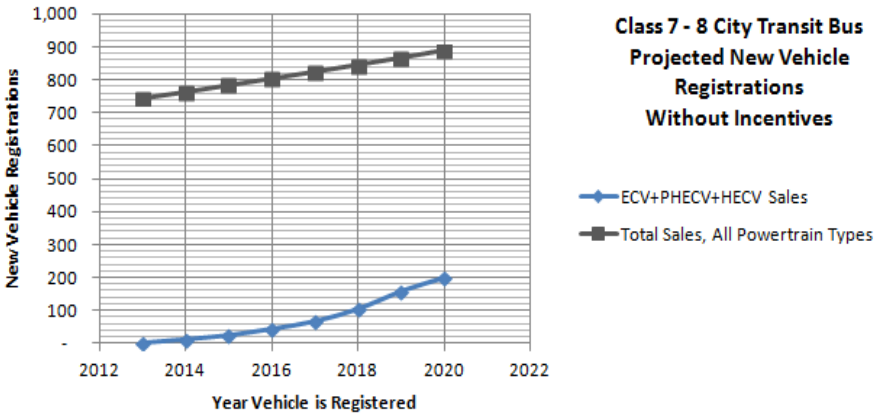


	2013	2014	2015	2016	2017	2018	2019	2020
ECVs	1	5	14	29	46	74	119	153
PHECVs	-	2	4	6	9	15	19	25
HECVs	1	6	7	9	12	15	19	20

Without incentives, ECV + PHECV + HECV Class 7-8 Transit Buses are projected to attain Annual Sales in CA of 198 Units by 2020.

Figure 150: Class 7-8 City Transit Bus Projected New Vehicle Registrations without Incentives, California

Year	Class 7-8 City Transit Bus Sales without Incentives					ECV+PHECV+HECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	HECV Sales	ECV + PHECV + HECV Sales	
2013	746	1	-	1	2	0.3%
2014	765	5	2	6	13	1.7%
2015	785	14	4	7	25	3.2%
2016	805	29	6	9	44	5.5%
2017	825	46	9	12	67	8.1%
2018	846	74	15	15	104	12.3%
2019	867	119	19	19	157	18.1%
2020	889	153	25	20	198	22.3%

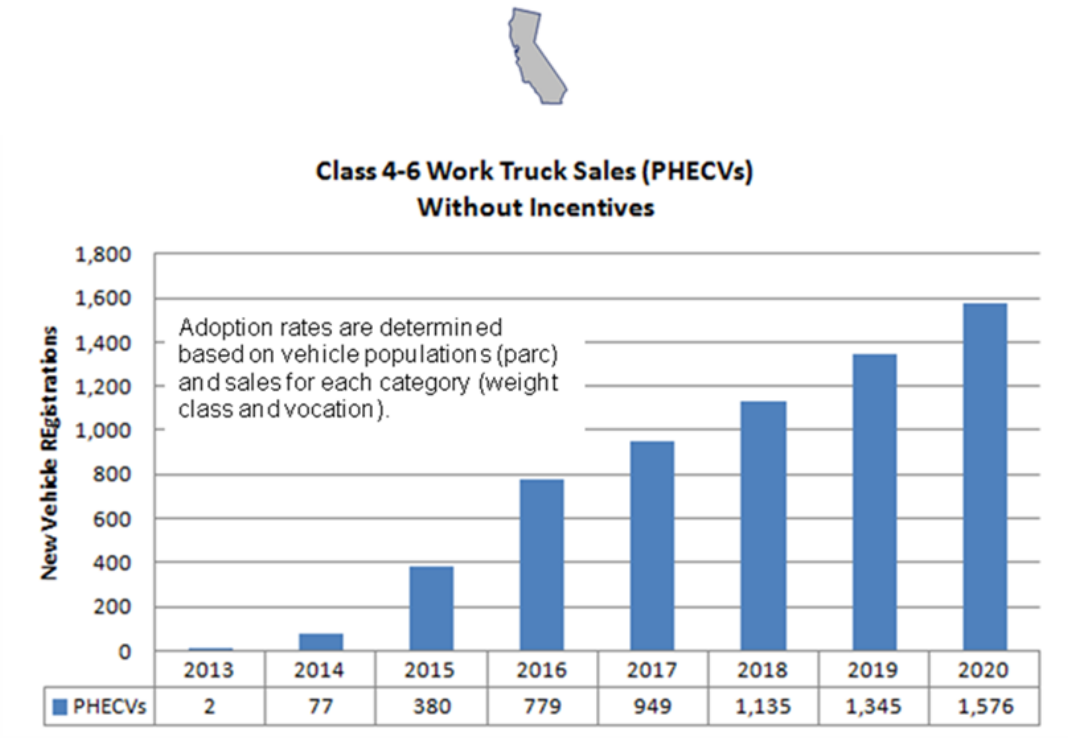


Note, Figure 150 does not include Class 7-8 School Buses.

Without Incentives, ECVs + PHECVs + HECVs are projected to account for 22 percent of New Class 7-8 City Transit Bus Registrations in CA by 2020.

Class 4-6 Work Trucks for California

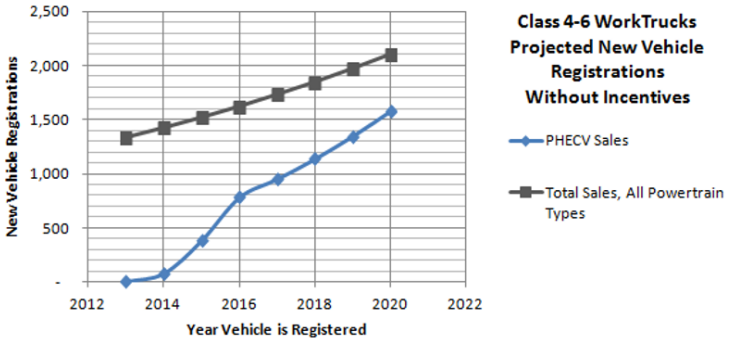
Figure 151: Class 4-6 Work Truck Sales (PHECVs) without Incentives, California



Without Incentives, PHECV Class 4-6 Work Trucks are projected to attain annual sales in CA of 1,576 Units by 2020.

Figure 152: Class 4-6 Work Trucks Projected New Vehicle Registrations without Incentives, California

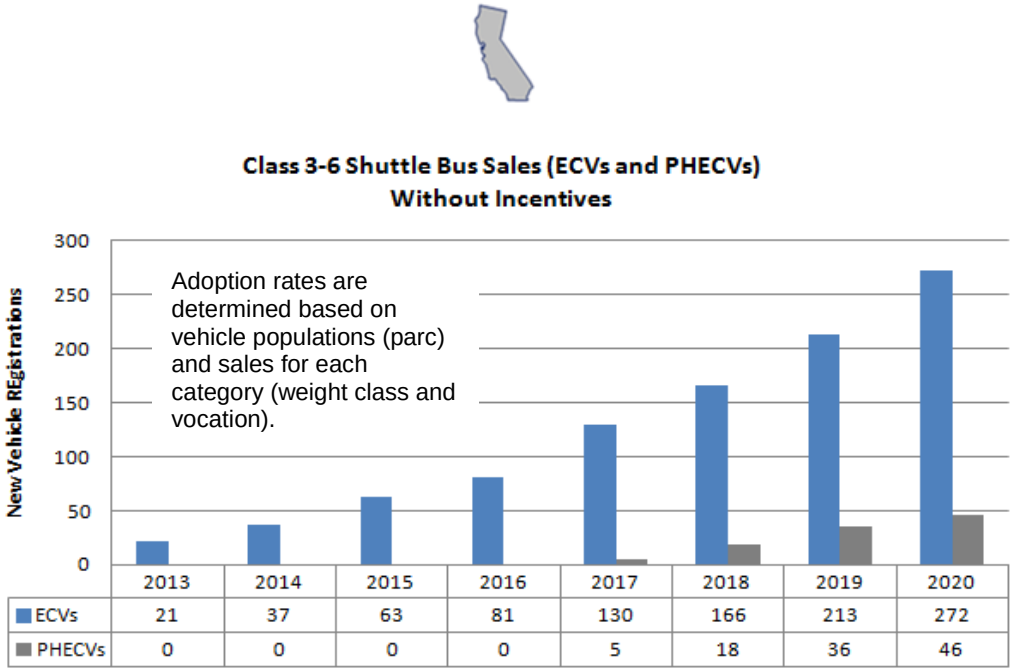
Class 4-6 Work Truck Sales without Incentives			
Year	Total, All Powertrain Types	PHECV Sales	PHECV Sales as % of Total, All Powertrain Types
2013	1,336	2	0.1%
2014	1,425	77	5.4%
2015	1,520	380	25.0%
2016	1,622	779	48.0%
2017	1,731	949	54.8%
2018	1,846	1,135	61.5%
2019	1,970	1,345	68.3%
2020	2,101	1,576	75.0%



Without Incentives, PHECVs are projected to account for 75 percent of New Class 4-6 Work Trucks Registrations in CA by 2020.

Class 3-6 Shuttle Buses for California

Figure 153: Class 3-6 Shuttle Bus Sales (ECVs and PHECVs) without Incentives, California

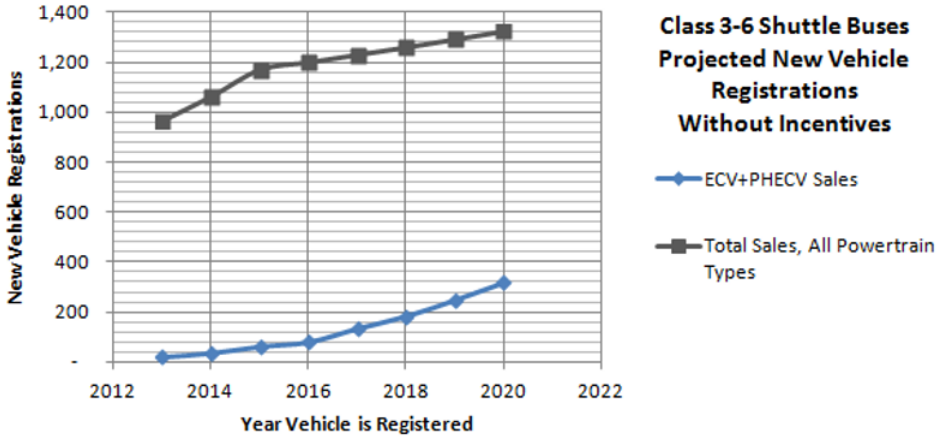


Without Incentives, ECV + PHECV Class 3-6 Shuttle Buses are projected to attain annual sales in CA of 318 Units by 2020.

Figure 154 below shows that without Incentives, ECVs provide an economic advantage over PHEVs for Class 3-6 Shuttle Bus Applications.

Figure 154: Class 3-6 Shuttle Buses Projected New Vehicle Registrations without Incentives, California

Year	Class 3-6 Shuttle Sales without Incentives				ECV + PHECV Sales as % of Total, All Powertrain Types
	Total, All Powertrain Types	ECV Sales	PHECV Sales	ECV + PHECV Sales	
2013	965	21	-	21	2.2%
2014	1,062	37	-	37	3.5%
2015	1,170	63	-	63	5.4%
2016	1,199	81	-	81	6.8%
2017	1,229	130	5	135	11.0%
2018	1,259	166	18	184	14.6%
2019	1,291	213	36	249	19.3%
2020	1,323	272	46	318	24.0%



Without Incentives, ECVs and PHECVs are projected to account for 24 percent of New Class 3-6 Shuttle Bus Registrations in CA by 2020.

Based on these vocational vehicle sales forecasts for California, along with the results of the total cost of ownership and adoption rate models, projections for the number of battery systems becoming available for second use applications within California were generated.

Second use Battery Availability Forecasts for California

Condition 1: California Grants and Incentives NOT included in total cost of ownership

Vocation: Class 3 Service Vans
Region: California

Figure 155: Second use Battery Availability Forecasts, Class 3 Service Vans, No Incentives, California Vehicles

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)				10.7	Without Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				75	At End of First Life (kw-hr):			60	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	1	108	191	340	603	856	1,215	1,556					
Vehicle Attrition (at 5%)	-	5	10	17	30	43	61	78					
Vehicles Available to Supply Second Life Batteries	1	103	181	323	573	813	1,154	1,478					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	1	103	181	323	573	813	1,154
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	60	6,180	10,860	19,380	34,380	48,780	69,240

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)				10.7	Without Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				20	At End of First Life (kw-hr):			16	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	-	1	4	71	197	438	777	1,245					
Vehicle Attrition (at 5%)	-	-	-	4	10	22	39	62					
Vehicles Available to Supply Second Life Batteries	-	1	4	67	187	416	738	1,183					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	-	1	4	67	187	416	738
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	16	64	1,072	2,992	6,656	11,808

Vocation: Class 6 Box Trucks
Region: California

Figure 156: Second use Battery Availability Forecasts, Class 4-6 Box Trucks, No Incentives, California Vehicles

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)				>12	Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				120	At End of First Life (kw-hr):			96	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	5	74	108	160	235	269	309	396					
Vehicle Attrition (at 5%)	-	4	5	8	12	13	15	20					
Vehicles Available to Supply Second Life Batteries	5	70	103	152	223	256	294	376					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						5	70
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	480	6,720

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)				>12	Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				28.4	At End of First Life (kw-hr):			22.7	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	-	0	0	1	1	32	81	162					
Vehicle Attrition (at 5%)	-	-	-	-	-	2	4	8					
Vehicles Available to Supply Second Life Batteries	-	-	-	1	1	30	77	154					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						-	-
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	-	-

Vocation: Class 4-6 Urban Delivery
Region: California

Figure 157: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery Trucks, No Incentives, California Vehicles

Vehicle Vocation: Class 4-6 Urban Delivery	Battery Life Based on Duty Cycle (years)	>12				Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	110				At End of First Life (kw-hr):			88	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	1	184	266	308	445	570	731	749					
Vehicle Attrition (at 5%)	-	9	13	15	22	29	37	37					
Vehicles Available to Supply Second Life Batteries	1	175	253	293	423	541	694	712					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						1	175
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	88	15,400

Vocation: Class 4-6 Work Trucks, Region: California

Figure 158: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, No Incentives, California Vehicles

Vehicle Vocation: Class 4-6 Work Trucks	Battery Life Based on Duty Cycle (years)	10.7				Without Incentives				Vehicle Useful Life (years)			15
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	13				At End of First Life (kw-hr):			22	Replacements per Veh. Life:			1
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	2	77	380	779	949	1,135	1,345	1,576					
Vehicle Attrition (at 5%)	-	4	19	39	47	57	67	79					
Vehicles Available to Supply Second Life Batteries	2	73	361	740	902	1,078	1,278	1,497					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						2	73
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	44	1,606

Vocation: Class 7-8 City Transit Buses
Region: California

Figure 159: Second use Battery Availability Forecasts, Class 3 Service Vans, No Incentives, California Vehicles

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	260				At End of First Life (kw-hr):		208		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	1	5	14	29	46	74	119	153					
Vehicle Attrition (at 5%)	-	-	1	1	2	4	6	8					
Vehicles Available to Supply Second Life Batteries	1	5	13	28	44	70	113	145					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						1	5
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	208	1,040

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	90				At End of First Life (kw-hr):		72		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	-	2	4	6	9	15	19	25					
Vehicle Attrition (at 5%)	-	-	-	-	-	1	1	1					
Vehicles Available to Supply Second Life Batteries	-	2	4	6	9	14	18	24					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						-	2
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	-	-	144

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)	>12				Without Incentives				Vehicle Useful Life (years)			12
Power Train Type: HEV	Average Battery Capacity: New (kw-hr):	11.8				At End of First Life (kw-hr):		9.4		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	1	6	7	9	12	15	19	20					
Vehicle Attrition (at 5%)	-	-	-	-	1	1	1	1					
Vehicles Available to Supply Second Life Batteries	1	6	7	9	11	14	18	19					
Number of Batteries Available for Second Life:	-	-	-	-	-	-			1	6	7	9	11
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	9	57	66	85	104

Vocation: Class 3-6 Shuttle Buses
Region: California

Figure 160: Second use Battery Availability Forecasts, Class 3-6 Shuttle Buses, No Incentives, California Vehicles

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years)	10.7				Without Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):	105				At End of First Life (kw-hr):		84		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	21	37	63	81	130	166	213	272					
Vehicle Attrition (at 5%)	1	2	3	4	7	8	11	14					
Vehicles Available to Supply Second Life Batteries	20	35	60	77	123	158	202	258					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	20	35	60	77	123	158	202
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	1,680	2,940	5,040	6,468	10,332	13,272	16,968

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years)	10.7				Without Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):	15				At End of First Life (kw-hr):		12		Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	-	0	0	0	5	18	36	46					
Vehicle Attrition (at 5%)	-	-	-	-	-	1	2	2					
Vehicles Available to Supply Second Life Batteries	-	-	-	-	5	17	34	44					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	-	-	-	-	5	17	34
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	-	-	-	-	60	204	408

With no incentives, the cummultive number of batteries originating from the six selected vehicle vocations and projected to become available within California through 2025 is 2,464.

These battery systems are projected to have an energy storage capacity of 0.29 GW-hr, as summarized in Figure 161.

Figure 161: Without Incentives, Projected Energy Capacity of Second use Batteries from Selected Vocational Vehicles is 294 MW-hr through 2025

Totals for Six Selected Vocations Power Train Types: EV, PHEV, HEV Without Incentives	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	32	494	1,037	1,784	2,632	3,588	4,864	6,200					
Vehicle Attrition (at 5%)	2	25	52	89	132	179	243	310					
Vehicles Available to Supply Second Life Batteries	30	469	985	1,695	2,500	3,409	4,621	5,890					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	21	139	246	473	895	1,422	2,464
Capacity of Batteries Available for Second Life (kw-hr):	-	-	-	-	-	-	1,740	9,136	15,973	26,977	47,830	69,817	123,438
Total Energy Capacity of Second Life Batteries (2019 - 2025):													**294,911**

Vehicle Vocation	Power Train Type	Battery Capacity: Originally Installed (kw-hrs)	Battery Capacity: End of First Life (kw-hrs)	Time to Initial Battery Replacement (years)	Vehicle Useful Life (years)	Number of Battery Replacements during Useful Life	Number of Second-Life Batteries/Vehicle	Capacity of Second-Life Batteries (kw-hr)
Service Vans (Class 3, 71 miles/day)	EV	75	71	10.7	6	0	1	60
	PHEV	20	18	10.7	6	0	1	16
Box Truck (Class 6, 80 miles/day)	EV	120	89	>12	12	0	1	96
	PHEV	28.4	25	>12	12	0	1	23
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	71	>12	12	0	1	88
	PHEV	No commercial PHEVs offered for this category						
City Transit Bus (Class 7-8) (120 miles/day)	EV	260	133	>12	12	0	1	208
	HEV	11.8	21	>12	12	0	1	9
	PHEV	90	80	>12	12	0	1	72
Work Trucks (Class 4-6, 43 miles/day)	EV	No commercial EVs offered for this category						
	PHEV	13	11	10.7	15	1	2	22
Shuttle Bus (Class 3-6, 100 miles/day)	EV	105	89	10.7	6	0	1	84
	PHEV	15	13	10.7	6	0	1	12

Condition 2: Grants and Incentives included in total cost of ownership for limited number of vehicles based on limited funds available within California

The methodology for determining number of awards available for each selected vehicle vocation for each identified year is shown in Figure 162.

Currently-available grants and incentives within California have a total award level of approximately $14M per year[62]. The average value of these incentives is $33,000 per vehicle. Thus, incentive funding is available for approximately 425 ECVs, PHECVs, and HECVs, per year. The number of vehicles receiving funding for Condition 3 is based on the ratio of predicted adoption rates for the No-Incentive Condition 1 analysis.

Below is the distribution of identified grants/incentive awards to six selected vocations based on NO Incentive Adoption Rates.

[62] Source: Brotherton, T., CALSTART, Clean Commercial Truck Incentives, presented at the NTEA Work Truck Show, 6 March 2013 and Teleconference dated 12 November 2013.

Figure 162: Determination of Available Grant and Incentive Awards for Six Selected Vocations, California

Determination of Available Awards for Six Selected Vocations	
New California Vehicle Registrations (2012): Vocational Vehicles Eligible for Awards (if they meet ECV, PHECV, and HECV criteria)	22,244
New California Vehicle Registrations (2012) for Six Vehicle Vocations Chosen for this Study	8,342
Ratio of Six Selected Vocations to Total Vocational Vehicle Registrations	0.375
Number of grants/awards Available per Year for Six Selected Vocations: (Ratio x Number of Grants/Incentive Awards)	159

Vehicle Vocation	ECV, PHECV, and HECV CA Sales for 2015	Ratio of Sales for 6 Vocations	Number of Anticipated Awards
Service Vans (Class 3, 71 miles/day)	195	0.188	29
Box Truck (Class 6, 80 miles/day)	108	0.104	17
Urban Delivery (Class 4-6, 71 miles/day)	266	0.257	40
City Transit Bus (Class 7-8) (120 miles/day)	25	0.024	6
Work Trucks (Class 4-6, 43 miles/day)	380	0.366	57
Shuttle Bus (Class 3-6, 100 miles/day)	63	0.061	10
Total or 6 Selected Vocations:	1,037	1.000	159

Condition 2: Grants and Incentives included in total cost of ownership for limited number of vehicles based on limited funds available.

Vocation: Class 3 Service Vans
Region: California

Figure 163: Second use Battery Availability Forecasts, Class 3 Service Vans, Limited Incentives, California Vehicles

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)				10.7	With Limited Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				75	At End of First Life (kw-hr):			60	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	1	124	205	356	619	872	1,215	1,556					
Vehicle Attrition (at 5%)	-	6	10	18	31	44	61	78					
Vehicles Available to Supply Second Life Batteries	1	118	195	338	588	828	1,154	1,478					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	1	118	195	338	588	828	1,154
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	60	7,080	11,700	20,280	35,280	49,680	69,240

Vehicle Vocation: Class 3 Service Vans	Battery Life Based on Duty Cycle (years)				10.7	With Limited Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				20	At End of First Life (kw-hr):			16	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	-	4	17	84	197	451	777	1,245					
Vehicle Attrition (at 5%)	-	-	1	4	10	23	39	62					
Vehicles Available to Supply Second Life Batteries	-	4	16	80	187	428	738	1,183					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	-	4	16	80	187	428	738
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	64	256	1,280	2,992	6,848	11,808

Vocation: Class 6 Box Trucks
Region: California

Figure 164: Second use Battery Availability Forecasts, Class 6 Box Trucks, Limited Incentives, California Vehicles

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				120	At End of First Life (kw-hr):			96	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	5	86	120	172	247	281	309	396					
Vehicle Attrition (at 5%)	-	4	6	9	12	14	15	20					
Vehicles Available to Supply Second Life Batteries	5	82	114	163	235	267	294	376					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						5	82
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	480	7,872

Vehicle Vocation: Class 6 Box Trucks	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				28.4	At End of First Life (kw-hr):			22.7	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	-	1	1	6	6	37	81	162					
Vehicle Attrition (at 5%)	-	-	-	-	-	2	4	8					
Vehicles Available to Supply Second Life Batteries	-	1	1	6	6	35	77	154					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						-	1
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	-	23

Vocation: Class 4-6 Urban Delivery
Region: California

Figure 165: Second use Battery Availability Forecasts, Class 4-6 Urban Delivery Trucks, Limited Incentives, California Vehicles

Vehicle Vocation: Class 4-6 Urban Delivery	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				110	At End of First Life (kw-hr):			88	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	6	224	306	348	485	610	731	749					
Vehicle Attrition (at 5%)	-	11	15	17	24	31	37	37					
Vehicles Available to Supply Second Life Batteries	6	213	291	331	461	579	694	712					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						6	213
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	528	18,744

Vocation: Class 4-6 Work Trucks

Figure 166: Second use Battery Availability Forecasts, Class 4-6 Work Trucks, Limited Incentives, California Vehicles

Vehicle Vocation: Class 4-6 Work Trucks	Battery Life Based on Duty Cycle (years)				10.7	With Limited Incentives				Vehicle Useful Life (years)			15
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				13	At End of First Life (kw-hr):			22	Replacements per Veh. Life:			1
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	3	134	437	836	1,006	1,192	1,345	1,576					
Vehicle Attrition (at 5%)	-	7	22	42	50	60	67	79					
Vehicles Available to Supply Second Life Batteries	3	127	415	794	956	1,132	1,278	1,497					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						3	127
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	66	2,794

Vocation: Class 7-8 City Transit Buses
Region: California

Figure 167: Second use Battery Availability Forecasts, Class 7-8 City Transit Buses, Limited Incentives, California Vehicles

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				260	At End of First Life (kw-hr):			208	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	3	7	16	31	48	76	119	153					
Vehicle Attrition (at 5%)	-	-	1	2	2	4	6	8					
Vehicles Available to Supply Second Life Batteries	3	7	15	29	46	72	113	145					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						3	7
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	624	1,456

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				90	At End of First Life (kw-hr):			72	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	2	4	6	8	11	17	19	27					
Vehicle Attrition (at 5%)	-	-	-	-	1	1	1	1					
Vehicles Available to Supply Second Life Batteries	2	4	6	8	10	16	18	26					
Number of Batteries Available for Second Life:	-	-	-	-	-	-						2	4
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	-	-	-	144	288

Vehicle Vocation: Class 7-8 City Transit Buses	Battery Life Based on Duty Cycle (years)				>12	With Limited Incentives				Vehicle Useful Life (years)			12
Power Train Type: HEV	Average Battery Capacity: New (kw-hr):				11.8	At End of First Life (kw-hr):			9.4	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	3	8	9	11	14	17	19	20					
Vehicle Attrition (at 5%)	-	-	-	1	1	1	1	1					
Vehicles Available to Supply Second Life Batteries	3	8	9	10	13	16	18	19					
Number of Batteries Available for Second Life:	-	-	-	-	-	-			3	8	9	10	13
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	-	28	76	85	94	123

Vocation: Class 3-6 Shuttle Buses
Region: California

Figure 168: Second use Battery Availability Forecasts, Class 3-6 Shuttle Buses, Limited Incentives, California Vehicles

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years)				10.7	With Limited Incentives				Vehicle Useful Life (years)			6
Power Train Type: EV	Average Battery Capacity: New (kw-hr):				105	At End of First Life (kw-hr):			84	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	28	44	70	88	137	173	213	272					
Vehicle Attrition (at 5%)	1	2	4	4	7	9	11	14					
Vehicles Available to Supply Second Life Batteries	27	42	66	84	130	164	202	258					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	27	42	66	84	130	164	202
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	2,268	3,528	5,544	7,056	10,920	13,776	16,968

Vehicle Vocation: Class 3-6 Shuttle Buses	Battery Life Based on Duty Cycle (years)				10.7	With Limited Incentives				Vehicle Useful Life (years)			6
Power Train Type: PHEV	Average Battery Capacity: New (kw-hr):				15	At End of First Life (kw-hr):			12	Replacements per Veh. Life:			0
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	-	1	4	4	8	21	36	46					
Vehicle Attrition (at 5%)	-	-	-	-	-	1	2	2					
Vehicles Available to Supply Second Life Batteries	-	1	4	4	8	20	34	44					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	-	1	4	4	8	20	34
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	-	12	48	48	96	240	408

With limited incentives, the cumulative number of batteries originating from the six selected vehicle vocations and projected to become available within California through 2025 is 2,575. These battery systems are projected to have an energy storage capacity of 0.13 GW-hr, as summarized in Figure 169.

Figure 169: With Limited Incentives, Projected Energy Capacity of Second use Batteries from Selected California Vocational Vehicles is 310 MW-hr through 2025

Totals for Six Selected Vocations Power Train Types: EV, PHEV, HEV With Limited Incentives	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Number of Vehicles Entering Service	51	637	1,191	1,944	2,778	3,747	4,864	6,202					
Vehicle Attrition (at 5%)	3	32	60	97	139	187	243	310					
Vehicles Available to Supply Second Life Batteries	48	605	1,131	1,847	2,639	3,560	4,621	5,892					
Number of Batteries Available for Second Life:	-	-	-	-	-	-	28	165	284	514	922	1,469	2,575
Capacity of Batteries Available for Second Life (kw-hr)	-	-	-	-	-	-	2,328	10,684	17,576	28,740	49,373	72,480	129,723
Total Energy Capacity of Second Life Batteries (2019 - 2025):													**310,905**

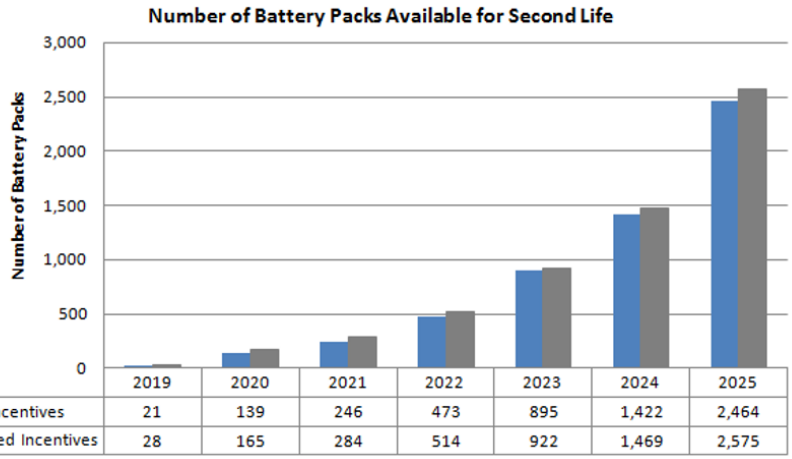
Vehicle Vocation	Power Train Type	Battery Capacity: Originally Installed (kw-hrs)	Battery Capacity: End of First Life (kw-hrs)	Time to Initial Battery Replacement (years)	Vehicle Useful Life (years)	Number of Battery Replacements during Useful Life	Number of Second-Life Batteries/Vehicle	Capacity of Second-Life Batteries (kw-hr)
Service Vans (Class 3, 71 miles/day)	EV	75	71	10.7	6	0	1	60
	PHEV	20	18	10.7	6	0	1	16
Box Truck (Class 6, 80 miles/day)	EV	120	89	>12	12	0	1	96
	PHEV	28.4	25	>12	12	0	1	23
Urban Delivery (Class 4-6, 71 miles/day)	EV	110	71	>12	12	0	1	88
	PHEV	No commercial PHEVs offered for this category						
City Transit Bus (Class 7-8) (120 miles/day)	EV	260	133	>12	12	0	1	208
	HEV	11.8	21	>12	12	0	1	9
	PHEV	90	80	>12	12	0	1	72
Work Trucks (Class 4-6, 43 miles/day)	EV	No commercial EVs offered for this category						
	PHEV	13	11	10.7	15	1	2	22
Shuttle Bus (Class 3-6, 100 miles/day)	EV	105	89	10.7	6	0	1	84
	PHEV	15	13	10.7	6	0	1	12

Battery packs from California ECVs, PHECVs, and HECVs are expected to become available for second use applications beginning in 2019. The cumulative number of battery systems expected to become available prior to 2025 from the six selected vehicle vocational categories is between 5,660 and 5,957 (depending upon available grant and incentive funding).

Limited incentives are based on identified grants and voucher programs for calendar year 2014.

Figure 170: Number of Battery Packs Available for Second use, Originating with Six Vehicle Vocations, Limited Incentives, California

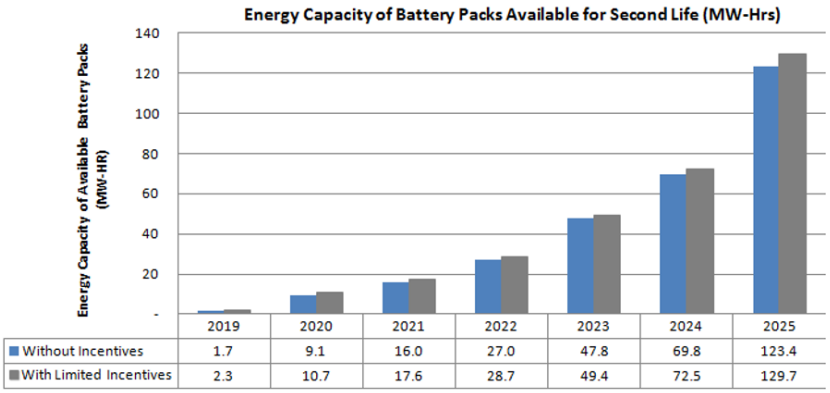
Number of Battery Packs		
Year	Without Incentives	With Limited Incentives
2019	21	28
2020	139	165
2021	246	284
2022	473	514
2023	895	922
2024	1,422	1,469
2025	2,464	2,575
Totals:	**5,660**	**5,957**



Based on identified grant and incentive programs, the cumulative energy capacity of available second use battery packs becoming available in California and originating with the six selected vehicle vocations, is expected to be between 295 and 311 MWh by 2025. The results of this analysis are summarized in Figure 171. Limited incentives are based on identified grants and voucher programs for calendar year 2014.

Figure 171: Energy Storage Capacity of Battery Packs Available for Second use, Originating with Six Vehicle Vocations, Limited Incentives, California

Capacity of Battery Packs (MW-Hrs)		
Year	Without Incentives	With Limited Incentives
2019	1.7	2.3
2020	9.1	10.7
2021	16.0	17.6
2022	27.0	28.7
2023	47.8	49.4
2024	69.8	72.5
2025	123.4	129.7
Totals:	**294.9**	**310.9**



1.2.2 Demand Side Analysis: Forecast of Utility Grid Need for Lithium-Ion Battery Energy Storage Through 2025

The first step in forecasting the future Li-ion battery stationary energy storage market from the demand-side involved conducting a literature search and review of consulting firm and research institution publications and governmental procurement targets. Previous consulting and research firms used their own methodologies to predict future utility grid demand. Because of the rise in renewable energy on the electrical utility grid and a trend toward more sustainable energy sources, state governments have issued energy storage procurement targets. These procurement targets will encourage and/or mandate utility companies to procure energy storage, thus driving their demand. This would be a case where regulatory bodies and policy drive the market, instead of the economics behind the commodity driving the market.

Resources consulted to forecast utility grid demand included the following.

- California Public Utilities Commission (CPUC)[63]
- KEMA Inc.(aka DNV GL)[64]
- Lux Research Inc.[65]
- Navignant Consulting Inc. (AKA Pike Research)[66,67]

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[63] California Public Utilities Commission (CPUC). Procurement Targets. 03 September 2013.
[64] KEMA, Inc. Market Evaluation for Energy Storage in the US. KEMA recently changed to DNV GL.
[65] Lux Research, Inc. Grid Storage Under the Microscope. Using Local Knowledge to Forecast Global Demand.
[66] Navigant Consulting Inc. (AKA Pike Research). Energy Storage on the Grid.
[67] http://www.navigantresearch.com/tag/market-forecasts

- Sandia National Laboratories (SNL)[68]

The numbers provided by the resources consulted varied by the following characteristics:

- geographical scope,
- time range,
- grid applications,
- units (i.e. energy versus power),
- energy storage technologies, and
- market factors.

Each study was standardized to the same geographical scope, time range, grid applications, units, energy storage technologies, and market factors. The paragraphs below describe how each standardization effort took place.

In regards to geographical scope, the resources provided either utility grid demand forecast numbers for California only, the United States, the Americas, or the entire world. All resources were standardized around a national (i.e United States) scope using peak load growth proportional relationships. California energy storage demand predications had to be scale up to a United States scale and global energy storage demand predications had to be scaled down to a United States scale. Peak load growth on the electrical utility grid for each year between 2010 and 2025 was used as an indicator of energy storage adoption. It was assumed that when load on the electrical utility grid increases, there will be a direct proportional increase in energy storage because of such factors as increasing renewable energy and a need for grid infrastructure upgrades which can be mitigated with battery energy storage.

The following equations were used to standardize each publication and governmental procurement estimate by geographical scope.

[68] Eyer, Jim and Garth Corey. Sandia National Laboratories. Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide. A Study for the DOE Energy Storage Systems Program. February 2010.

Figure 172: Equations to standardize each publication and governmental procurement estimate by geographical scope

$$Peak\ Load\ Growth\ Ratio(PLGR1) = \frac{(Total\ US\ Peak\ Load\ Growth)}{(Total\ California\ Peak\ Load\ Growth)}$$

$$Peak\ Load\ Growth\ Ratio\ (PLGR2) = \frac{(Total\ US\ Peak\ Load\ Growth)}{(Total\ North\ America\ Peak\ Load\ Growth)}$$

$$Peak\ Load\ Growth\ Ratio\ (PLGR3) = \frac{(Total\ US\ Peak\ Load\ Growth)}{(Total\ Global\ Peak\ Load\ Growth)}$$

For Example:

$$Energy\ Storage\ Amount\ (US) = Energy\ Storage\ Amount\ (California) * PLGR1$$

$$Energy\ Storage\ Amount\ (US) = Energy\ Storage\ Amount(North\ America) * PLGR2$$

$$Energy\ Storage\ Amount\ (US) = Energy\ Storage\ Amount\ (Global) * PLGR3$$

Most of the resources surveyed provided their projections in terms of power units (kW) instead of energy units (kWh). This is typical of the utility industry because they have historically viewed generation in terms of power units (kW, MW, or GW). Standard fossil-fueled power plants can run indefinitely given a continuous supply of fuel. On the other hand, batteries have a limited supply of energy and are more often understood in terms of kWh, MWh, or GWh. When given instantaneous load numbers, time durations for a specific application were used to convert projection numbers from units of power to units of energy. The conversion from power units and energy units had to occur per application. Additionally, each source dataset was scaled so that only applications that were utility-scale were considered. When time durations per application were not specified in the resource, an estimated time range was made based on any narrative provided in the resource and/or outside knowledge of grid applications. The following equation was used for conversion between power and energy units.

Figure 173: Discharge Durations by Application

$$Energy\ (GWh) = \frac{Power\ (MW) * Discharge\ Duration\ (hours)}{1000}$$

Furthermore, each resource provided total utility grid demand numbers for a varying number of energy storage technologies. The projections provided in this report focus only on Lithium-ion battery energy storage. Therefore, each of the projections given by each resource needed to be scaled to represent only Lithium-ion battery technology. In order to scale the projections of each consulting firm and research institution resource, the market breakout of demand by technology given in that resource was used. The procurement target resource did not provide a breakout of utility grid demand of energy storage by technology. For the CPUC resource,the researchersassumed only Li-ion batteries would be used to reach the target. When breakouts by technology were not provided by year, the percentages of energy storage demand by

technology were assumed to be constant over the time span of demand numbers given by the resource.

Lastly, each resource provided projections out to varying future dates. In this report,the researchersproject the utility grid Li-ion energy storage demand through 2025. Therefore,the researchersextended the projections of each resource using linear fits.

1.2.2.1 Results

The standardized projection data from each resource now represented the United States utility grid's Lithium-ion battery energy storage demand through 2025.[69] The data for each year is the cumulative demand up to that year, not the additional demand added in that year.

Figure 174: Original dates through which each resource's projections are made

Resource	Original Date Through Which Projections Are Made
California Public Utilities Commission (CPUC)	2020
California Energy Storage Alliance (CESA)	2020
KEMA Inc.	2017
Lux Research Inc.	2017
Navignant Consulting Inc. (AKA Pike Research)	2022
Sandia National Laboratories (SNL)	2020

It is important though to understand the value of each resource's projections in terms of market factors as shown in Figure 175. Most of the resources provide what is termed *market estimates*. *Market estimates* are projections based on a consideration of energy storage cost. They are a subset of the *maximum market potential*. The *maximum market potential* is a subset of the *technical market potential* and is based on a consideration of utility and government regulations. The *technical market potential* is the maximum electrical demand reduced by limitations of technology to meet that demand. Lastly, *market proposals* are procurement goals or requirements established by industry regulating bodies or organizations. Governmental regulations or policies inform the market. A summary of the market factors impacting each resource are listed in the results section. Figure 176 showcases the original dataset for each resource and what that dataset was scaled to and the order of scaling. A results summary is provided in Figure 177, Figure 178,

[69] Sandia's dataset represents energy storage demand for all technologies because a market breakout by technology was not provided in the resource.

Figure 179, Figure 180, Figure 181 provide graphic representation of the results. It is estimated that utility demand for Li-ion battery energy storage in 2025 will be 200 MWh to 4.2 GWh.

Figure 175: Projection values based on market factors shown pictorially as subsets

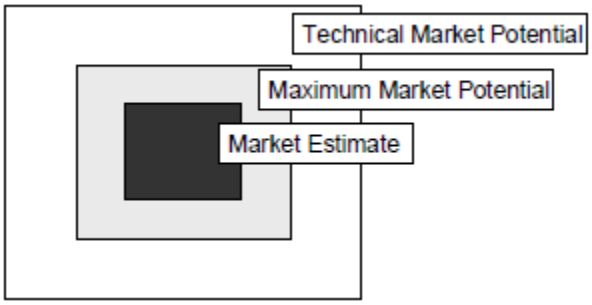


Figure 176: Original and Scaled Data Characteristics

Resource	Scope	Original Data	Scaled To	Scaling Order from Original Data	Notes
CPUC	Geographical Scope	California	U.S.	Original - > Application -> Units -> Geographical -> Projection Extension	We assumed that the CPUC procurement targets reflected all of California, even though it only applies to the investor-owned utilities in California.
	Time Range	2014, 2016, 2018, 2020	2014-2025		A linear fit was used to project the scaled data out to 2025.
	Grid Applications	Transmission, Distribution, Customer	Transmission, Distribution		
	Units	Power (MW)	GWh		
	Technologies	Includes All Energy Storage Technologies Except Pumped Hydro, Compressed Air Energy Storage (CAES), and Lead Acid Batteries.	N/a		We assumed that Li-ion batteries would be the only technology used to meet the CPUC procurement targets.
	Market Factors	Market Proposal	N/a		
KEMA	Geographical Scope	U.S.	N/a	Original -> Units -> Technology -> Application -> Projection Extension	
	Time Range	2012, 2017	2012-2025		The original 2012 data are current estimates and not projections. The original 2017 data are projections under the case that there are no tax credits after 2012. Also, a linear fit was used to project the scaled data out to 2025.
	Grid Applications	Ancillary Services, Community Energy Storage (CES), Transmission Services, Renewable Energy Integration, Other Distributed Storage	N/a		
	Units	Power (MW)	GWh		The time duration ranges assumed for each application to convert from power units to energy units were estimated by an energy storage expert.
	Technologies	Pumped Hydro, Thermal, CAES, Li-ion, Lead Acid, Nickel, Sodium, and Flow Batteries, Flywheels, and Fuel Cells	Li-Ion Batteries		
	Market Factors	Market Estimate	N/a		
Lux	Geographical Scope	Global	U.S.	Original -> Geographical -> Technology -> Application -> Projection Extension	Lux's 'global' estimate includes the energy storage demand potential in 44 countries, including the 50 U.S. states.
	Time Range	2012, 2017	2012-2025		A linear fit was used to project the scaled data out to 2025.
	Grid Applications	Renewable Energy Shifting, Renewable Energy Integration, Ancillary Services, Residential, Commercial	Renewable Energy Shifting, Renewable Energy Integration, and Ancillary Services		The breakout of the energy storage demand potential by application is given for 2017 only. The 2017 breakout is applied to 2012 data.
	Units	Energy (GWh)	N/a		
	Technologies	Li-ion, Vanadium Redox, Sodium Sulfur, Sodium Nickel Chloride, and Zinc Bromine Flow Batteries and Flywheels	Li-Ion Batteries		We assume that each technology is used evenly between the all the applications assumed.
	Market Factors	Market Estimate	N/a		
Navigant	Geographical Scope	North America	U.S.	Original -> Geographical -> Units -> Technology -> Projection Extension	
	Time Range	2012-2022	2012-2025		A linear fit using the scaled data from 2021 and 2022 only was used to project the dataset out to 2025.
	Grid Applications	Grid Asset Optimization, Arbitrage, Renewables Integration for Wind, Renewables Integration for Solar, Transmission and Distribution (T&D) Deferral	N/a		
	Units	Power (MW)	GWh		A single time duration range for the entire set of utility applications was estimated by an energy storage expert because a breakout of the market per application was not given in these Navigant sources.
	Technologies	Compressed Air Energy Storage (CAES), New Pumped Storage, Sodium Sulfur, Advanced Lead Acid, Flow, and Li-ion Batteries	Li-Ion Batteries		We assumed the breakout of technology at the end of 2011 was the same between 2012 and 2025.
	Market Factors	Market Estimate	N/a		
Sandia	Geographical Scope	U.S.	N/a	Original -> Units -> Application -> Projection Extension	
	Time Range	2020	2020-2025		We used peak load growth ratios for 2020-2024 to project the scaled data out to 2025.
	Grid Applications	Electric Enery Time-Scale	N/a		
	Units	Power (MW)	GWh		The time duration ranges were given by the Sandia source.
	Technologies	Electrochemical Batteries (including Lead Acid, Nickel-Cadmium, Li-ion, Sodium-Sulfur, Zinc-Bromine, Vanadium-Redox, Nickel-Metal Hydride, etc.), Flow Batteries, Capacitors, Compressed Air Energy Storage (CAES), Flywheels, Pumped Hydro, Superconducting Magnetic Energy Storage (SMES), Thermal	N/a		We did not scale this dataset to Li-ion battery technology only.
	Market Factors	Maximum Market Potential	N/a		

Figure 177: Results Summary of Utility Li-ion Battery Energy Storage Demand Projection

Overview of U.S. Utility Lithium-Ion Battery Energy Storage Demand Estimates through 2025 (GWh)															
Source	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**Estimation Scale**
CPUC (Min.)	#N/A	#N/A	4.5	4.0	6.0	6.5	7.8	9.1	10.4	11.6	12.9	14.2	15.4	16.7	Market Proposal
CPUC (Max.)	#N/A	#N/A	9.0	8.0	12.0	13.1	15.6	18.2	20.7	23.3	25.8	28.3	30.9	33.4	Market Proposal
KEMA (Min.)	0.1	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.6	1.7	Market Estimate
KEMA (Max.)	0.3	0.5	0.7	1.0	1.2	1.5	1.7	1.9	2.2	2.4	2.6	2.9	3.1	3.3	Market Estimate
Lux	0.2	0.5	0.8	1.1	1.4	1.8	2.1	2.4	2.7	3.0	3.3	3.6	3.9	4.2	Market Estimate
Navigant (Min.)	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	Market Estimate
Navigant (Max.)	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	Market Estimate
Sandia (Min.)	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	525.8	535.5	545.1	554.9	564.9	575.1	Maximum Market Potential
Sandia (Max.)	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1130.4	1150.3	1171.0	1192.1	1213.6	1235.4	Maximum Market Potential

Figure 178: United States Utility Energy Storage Demand (All Technologies) Through 2020 with CSE Projections to 2025 (Maximum Market Potentials

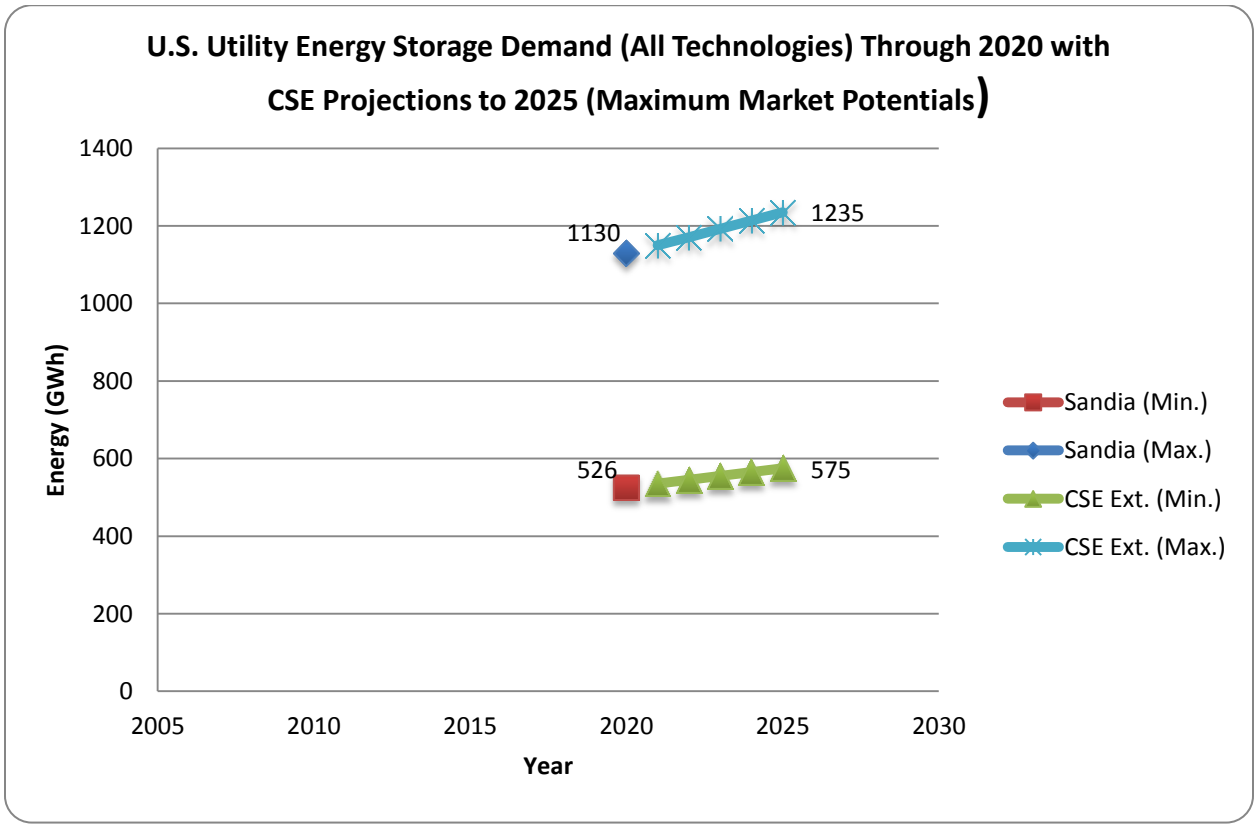


Figure 179: United States Li-Ion Energy Storage Demand Forecast Projections to 2025 (Market Proposals Only)

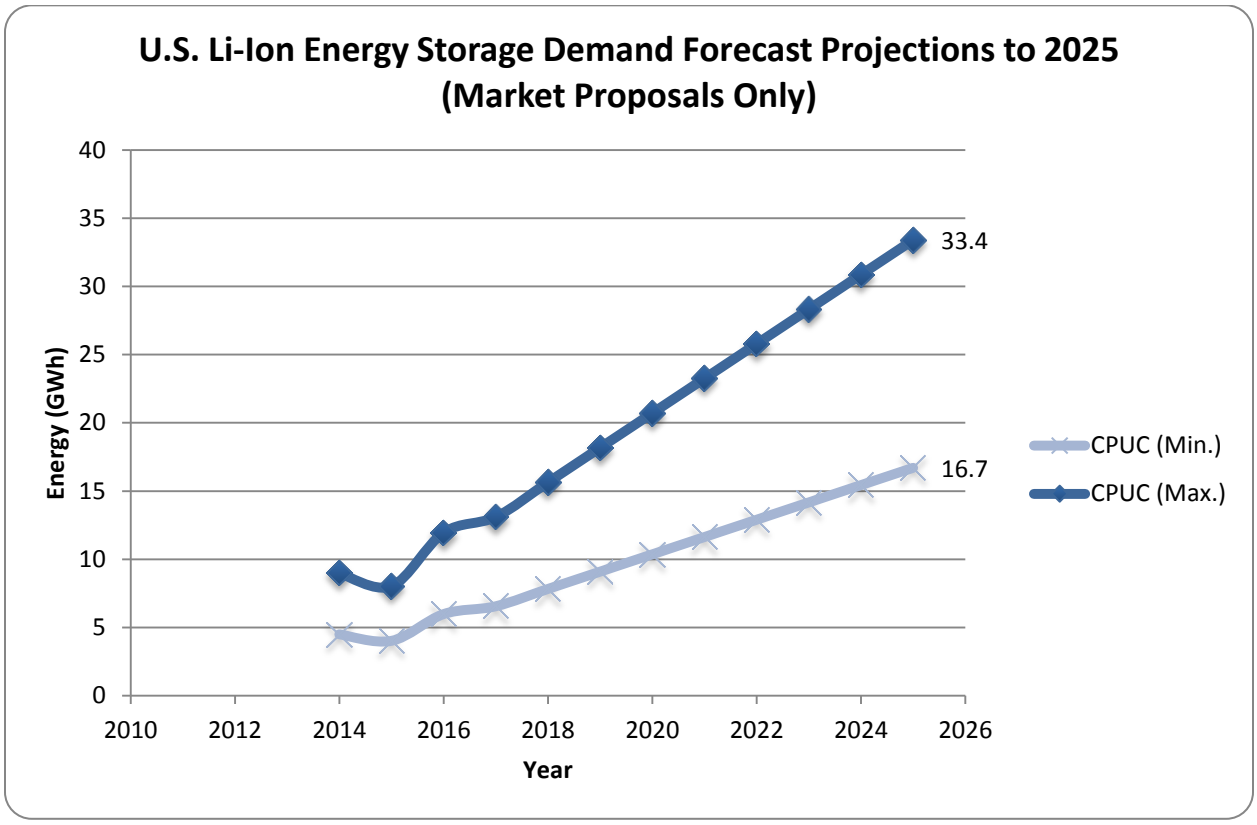


Figure 180: Overall United States Li-Ion Energy Storage Demand Forecast Projections to 2025 (All Projections)

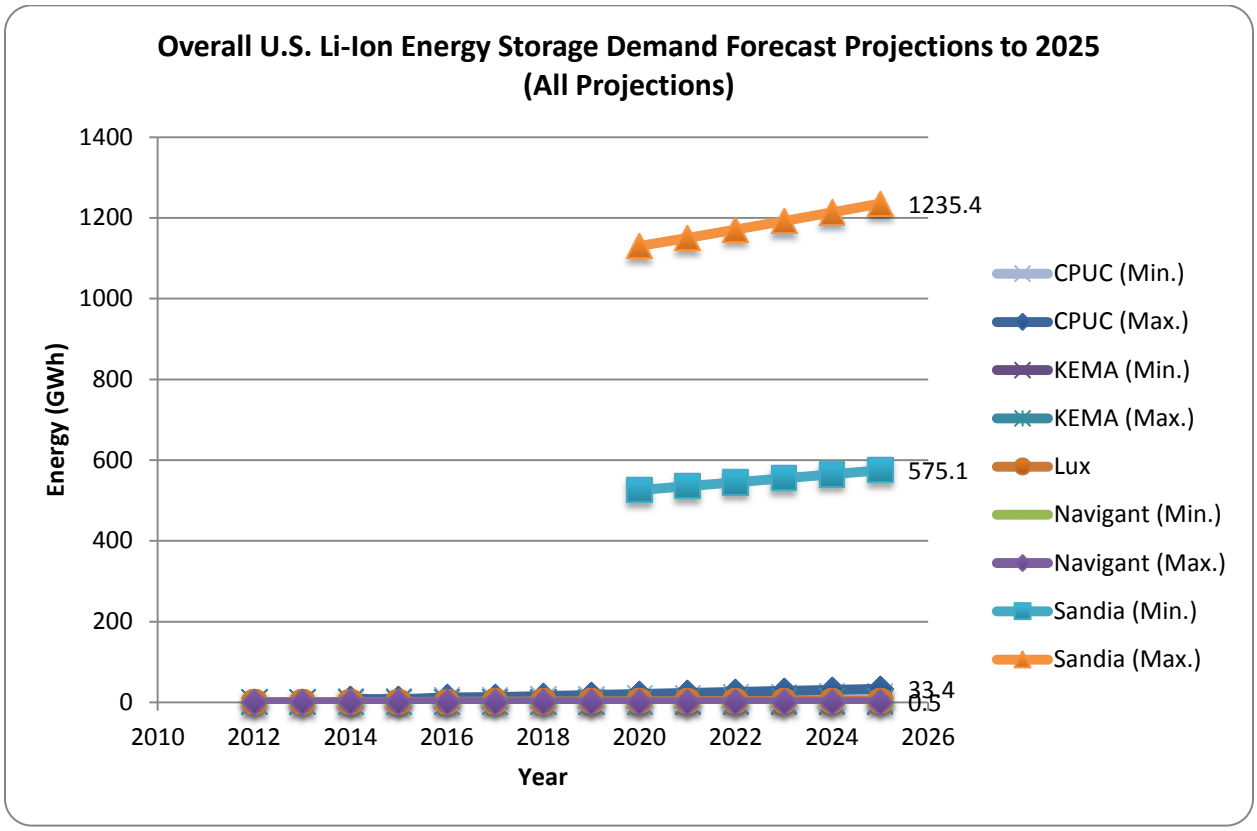
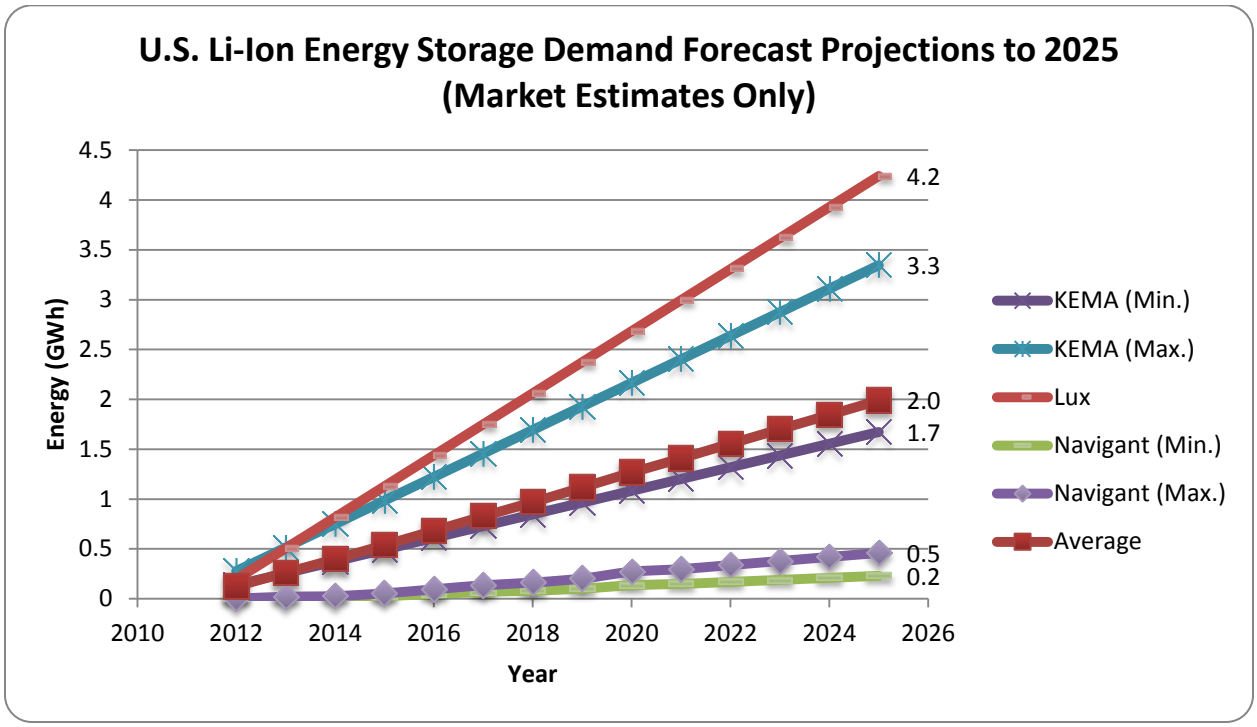


Figure 181: United States Li-Ion Energy Storage Demand Forecast Projections to 2025 (Market Estimates Only)



1.2.3 Chapter 1 Summary and Conclusions

1.2.3.1 Supply Side Analysis Summary

To determine the number and capacity of battery systems originating with electric-drive commercial vehicles and becoming available for second use stationary energy storage applications, the following approach was taken. Adoption rates were calculated for selected vocations (chosen based on favorable total cost of ownership) both with and without government incentives and grants.

1. Using a Total Cost of Ownership model, determine the payback period associated with the incremental cost of the electric or hybrid drive components compared to baseline costs associated with conventional diesel or gasoline powertrains.

2. The adoption rate for the ECV, PHECV, or HECV is determined based on the payback period.

3. For example if the incremental cost of an advanced technology system is less than three years, it is a candidate for adoption by a majority of new vehicle purchasers. Other categories include early adopters (payback periods >8 years) and late adopters (payback periods between 3 and 8 years).

4. Apply the adoption rate to projected new vehicle registrations (based on historical new vehicle registration data) to determine the number of ECV, PHECV, and HECV purchases for each selected vocation through 2020. Predictions for new vehicle registrations through 2022 were developed for each of the selected vehicle vocations

based on historical registration data for the time period 2003-2012 and expected economic drivers.

5. Based on duty cycle, battery capacity degradation, and expected vehicle life, determine the number of second use batteries to become available, the capacity of the batteries as they enter second use, and the year the batteries become available for second use for each selected vehicle vocation.

6. Determine the total number of batteries and total second use energy capacity (kw-hrs) of the batteries expected to become available prior to 2025.

Research was completed regarding currently-available and approved government grants and incentives for purchase of ECVs, PHECVs, and HECVs. For 2014, the cumulative value of these awards is approximately $50M. Based on an average award of $33,000 per vehicle, the awards would support the purchase of approximately 1,500 vehicles. For 2014, the cumulative value of these awards for California is approximately $14M. Based on an average award of $33,000 per vehicle, the awards would support the purchase of approximately 425 vehicles.

Commercial vehicles were key focus of study because owners of these vehicles are key early adopters of PEV and HEV technologies, the construction of commercial vehicles facilitates implementation of standardized battery packs, battery packs associated with commercial vehicles are expected to have capacities (kW-hrs) larger than those for passenger cars, and the increased residual value of battery packs for ECVs, HECVs, and PECVs reduces payback periods and provides cost justification for incorporating electric drive technologies.

Significant numbers of battery packs from ECVs, PHECVs, and HECVs are expected to become available for second use applications within California and the remaining United States states beginning in 2019. Current incentive programs provide limited funds and thus impact less than 1 percent of projected California sales and ½ percent of projected United States sales of ECVs, PHECVs, and HECVs, for identified vocational vehicles through 2025.

The cumulative number of second use battery packs for the entire US, originating with the six selected vehicle vocations, is expected to be greater than 50,000 by 2025, with the average energy capacity per pack equal to 52 kWh. The cumulative number of second use battery packs available within California is expected to be approximately 6,000 by 2025, with the average energy capacity per pack equal to 50 kWh.

Cumulative Energy Capacity of available second use battery packs for the entire United States is expected to be between 2.5 and 4.3 GWh by 2025. Cumulative Energy Capacity of available second use battery packs becoming available in California is expected to be between 295 and 311 MW-Hrs by 2025.

1.2.3.2 Demand Side Analysis Summary

A market analysis of utility demand for Li-Ion energy storage in the United States included the following information sources: industry publications, technical journals, interviews with industry stakeholders, procurement target proposals, and company reports. Data found in texts by the CPUC (California Public Utilities Commission), CESA (California Energy Storage

Alliance), KEMA Inc., Lux Research Inc., Navigant Consulting Inc., Pike Research, and Sandia National Laboratory (SNL) were normalized to United States geospatial boundaries using Peak Load Growth proportional relationships. Once normalized, the data was converted to energy units (GWh) and narrowed to utility-scale applications and Li-Ion battery energy storage. The various identified approaches projected data to different future dates: 1) CPUC to 2020; 2) CESA to 2020; 3) KEMA, Inc. to 2017; 4) Lux Research, Inc. to 2017; 5) Navigant Consulting (Pike Research), Inc. to 2022; and 6) Sandia National Laboratory to 2020. For the current study the market analysis employed single order exponential regressions to project Li-Ion utility energy storage demand through 2025 from the given data.

The predictions for stationary litihium ion energy storage capacity demands through 2025, originating with Sandia National Laboratory (based on Maximum Market Potentials approach) were noted to be significantly larger than those originating with other researchers. This is thought to be related the the larger number of energy storage applications considered by SNL[70].

Sandia's NL Maximum Market Potentials were employed as the basis for the demand projections developed during the current study. The CPUC and CESA market forecasts were also higher than the average estimates, based on the assumption of strong grant and incentive programs for the adoption of utility-scale energy storage. The projections for the current study were based on exponential growth patterns and are in line with identified government mandates for utilities to adopt energy storage.

The results of the demand analysis are summarized in the figure below.

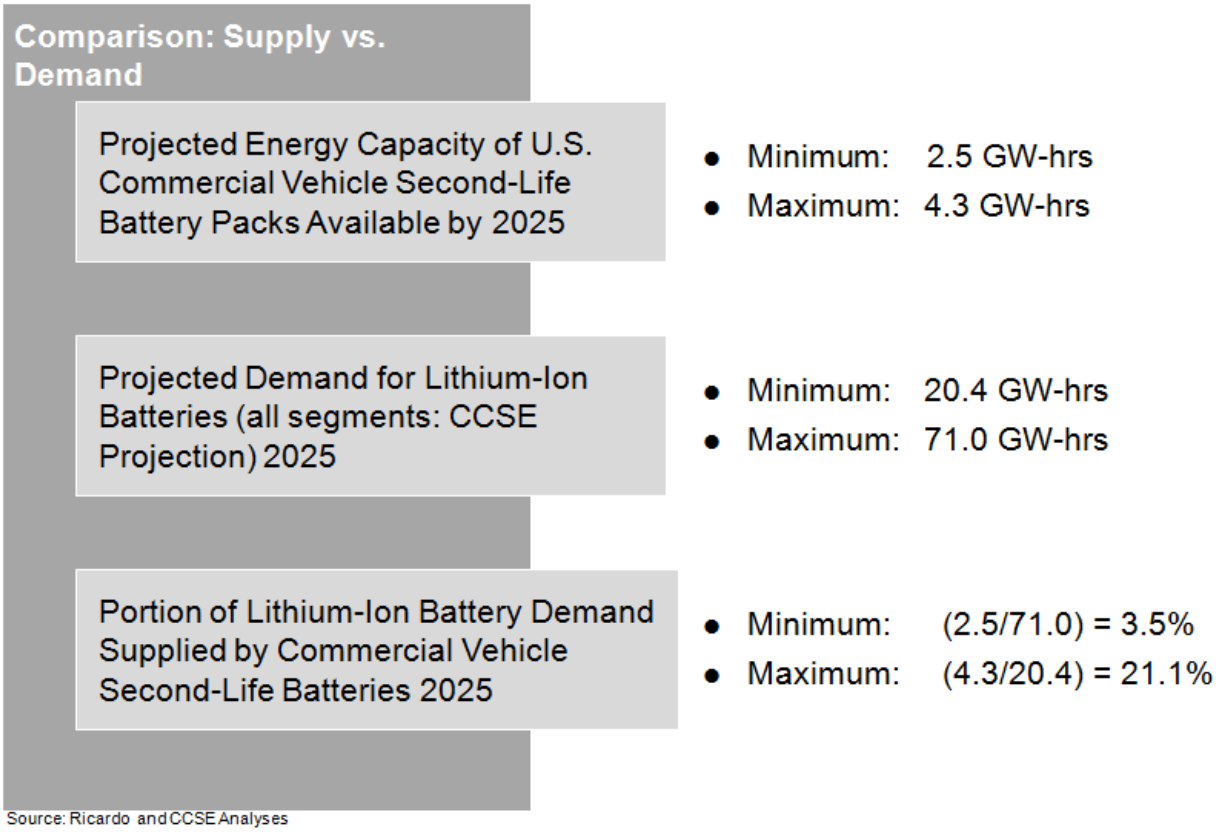
[70] Eyer, James M., Joseph J. Iannucci, and Garth P. Corey. Sandia National Laboratories. Sandia Report: Energy Storage Benefits and MarketAnalysis Handbook. A Study for the DOE Energy Storage Systems Program. December 2004.

Figure 182: Summary of Lithium-Ion Energy Storage Systems Demand through 2025

Summary of U.S. Li-Ion Energy Storage Demand Forecast Projections to 2025						
Sources	2015 (GWh)	2017 (GWh)	2020 (GWh)	2022 (GWh)	2025 (GWh)	Estimation Scale
CPUC (Min)	0.98	1.5	2.9	3.3	4.3	Market Proposal
CPUC (Max)	3.05	4.5	8.9	10.2	13.2	Market Proposal
CESA (Min)	5.00	20.6	43.9	59.4	82.7	Market Proposal
CESA (Max)	32.60	74.0	136.1	177.5	239.6	Market Proposal
KEMA (Min. No Incentive)	0.32	0.5	0.8	1.1	1.8	Market Estimate
KEMA(Max. No Incentive)	0.90	1.3	2.2	3.2	5.6	Market Estimate
Kema(Min. With Incentive)	0.60	1.3	4.0	8.5	26.4	Market Estimate
Kema (Max. With Incentive)	1.59	3.4	10.4	22.0	67.6	Market Estimate
Lux	0.93	2.0	9.8	27.1	124.8	Market Estimate
Navigant (Min)	0.60	1.7	4.6	8.5	33.0	Market Estimate
Navigant (Max)	1.57	4.5	11.9	22.1	86.1	Market Estimate
Sandia (Min)	146	204	292	424	688	Maximum Market Potential
Sandia (Max)	290	406	580	844	1368	Maximum Market Potential

It is projected that second use lithium-ion battery systems have the potential to supply between 3.5 percent and 21.1 percent of the stationary lithium-ion energy storage demand by the utility industry through 2025.

Figure 183: Comparison of Projected Second use Lithium-Ion Battery Systems Originating with Commercial Vehicles to Stationary Energy Storage Systems Demand through 2025



1.3 Chapter 1 References

Supply-Side Portion of Analysis of Battery Pack Availability

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CHAPTER 2:
Barriers Analysis: Industry Reluctance

Goal

The goals of the Barriers Analysis task were to identify technical and commercial barriers to standardized designs of modules and battery systems, to identify approaches to overcominging identified barriers, to conduct interviews with key industry stakeholders to obtain their opinions regarding standardized designs, to develop standard design concepts for electric commercial vehicles (including concept standardized design guidelines), and to evaluate alternative technical approaches to integration of modules/ battery systems into second use, energy storage systems.

2.1 Executive Summary

Technical and commercial barriers to standardized battery modules and systems were identified for both the supply (first use automotive) and demand (second use energy storage) applications.

Resources employed in the study include a literature review and interviews with industry stakeholders. The interviews included representatives of vehicle OEMs, battery suppliers, researchers, standards organizations and regulators.

The results of the Barriers Analysis were employed during the Design and Analysis for Standard Modules (Chapter 3) along with battery performance requirements, to design and analyze standard modules for both first and second use applications.

2.1.1 Identification of Key Barriers to Module/Battery System Standardizaton

Key barriers to standardization were identified and divided into two categories: 1) Technical and 2) Commercial for both Vehicle OEMs and Battery Suppliers.

Identified technical barriers for the supply side (first use vehicle application) include 1) packaging location and space requirements, 2) electrical, electronic, thermal, and communications protocols for each application, 3) durability, 4) charge acceptance, 5) safety, 6) integration with second use requirements, and 7) recycling requirements.

Key commercial barriers include 1) impacts of perceived safety issues, 2) predictable and sustainable supply of cells, modules, and packs, 3) uncertainty in costs, 4) remanufacturing issues (standard vs. non-standard, and comparisons to bespoke battery packs), 5) industry resistance to change and risk, 6) unclear maintenance requirements, variation in system longevity, 7) electrical & electrochemical compatibility, 8) Intellectual Property and competitive position issues, and 9) overall cost.

Advantages and disadvantages were identified for the various technical approaches to integrating current design, non-standardized battery systems into second use stationary energy storage applications (demand side). A key disadvantage was the additional cost associated with

the non-standardized designs, which must be modified for each application and thus cannot take advantages of the cost reductions associated with large scale production volumes. There are also non-recurring labor and design costs associated with this approach.

Other technical approaches to integrating PEV battery systems into second use, stationary energy storage applications were identified and include:

1. Non-standard use of separate DC-DC converter for each system
2. Options to preserve systems intact after removal from vehicle
3. Combining like systems (e.g. from same model vehicle) into second use systems.
4. Adaption/replacement of BMS for modules that are reconfigured into second use systems
5. Develop partnerships between battery and vehicle OEMs to allow reconfigurable BMS to be employed during both first and second use applications
6. Employing standardized end-of-first use testing and validation programs, to allow for the selection of systems for second use based on key performance paramenters.
7. Developing systems that enable extension of vehicle-to-grid (V2G) interfaces into second use applications.
8. Develop customized (one-off) systems based on characteristics of available battery systems for second use applications.

2.1.2 Approaches to Overcoming Identified Barriers

Key approaches to overcoming identified supply-side barriers, identified or developed during the current study, include:

- Continuing with development of electric vehicle battery standards such as those now published by ISO/IEC and GM.
- Improved education regarding industry requirements for both first and second use applications.
- Promotion of cost savings and performance improvements resulting from standardization.
- Establishment of acceptable module specifications to facilitate a "building block" approach to both vehicle and energy storage applications.
- Development of cells and modules that are compatible with a wide range of battery chemistries and performance specifications (voltage, watt-hours, resistance).
- Development of thermal management systems compatible with multiple vehicle applications as well as energy storage environments.

- Development of expanded communications and battery management systems containing options to facilitate a range of vehicle and energy storage applications.
- Development of modules that facilitate repurposing of remanufacturing processes for second use stationary energy storage.

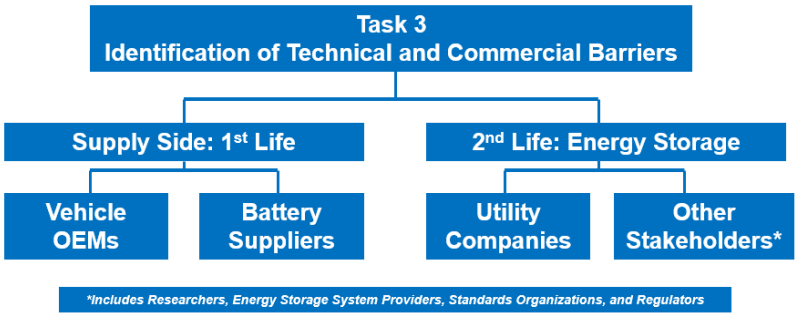
The study also produced recommendations for facilitating integration of used electric vehicle battery systems into stationary storage (demand side) applications and to reduce the cost of this transition. These included:

1. Create a standard location for the placement of variables in CANbus packets
2. Design the safety system to be internally integrated. Battery manufacturer are to provide documented guidance on the operational parameters of the battery system for the second use operator
3. Institute industry-wide standard testing protocols to check state of battery health at end of first use, with conditionals for different cell types and manufacturers
4. Establish standard module voltages and communication ports and protocols

2.2 Barriers Analysis: Industry Reluctance Overview

Technical and commercial barriers to standardized battery modules and packs were identified for the first use supply side (vehicle OEMs, battery suppliers). This included categorization of industry apprehension or reticence. In addition, technical and commercial barriers to the use of non-standard battery packs were examined from the second use energy storage perspective. A schematic of this process is shown in Figure 184. Note that Chapter 2 covers activities related to Task 3 of the project statement of work.

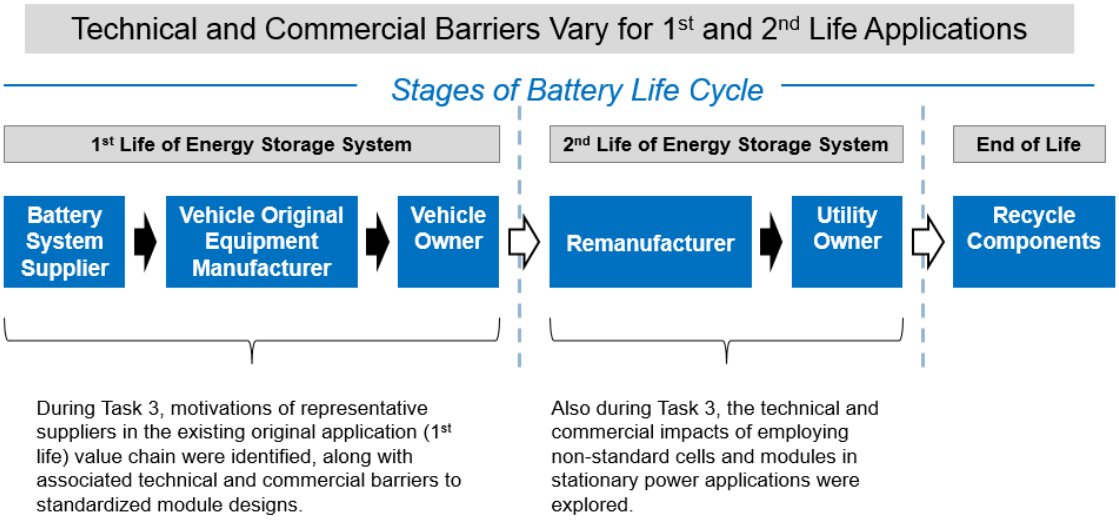
Figure 184: Identification of Technical and Commercial Barriers



The relationship of the Barriers Analysis tasks to the evaluation of battery system cycle life is illustrated in Figure 185. Industry interviews with vehicle manufacturers and battery system suppliers were conducted to identify key drivers for current battery system designs and to obtain opinions regarding technical and commercial barriers to incorporating standard designs as well as recommendations for approaches to implementing standard designs and how these

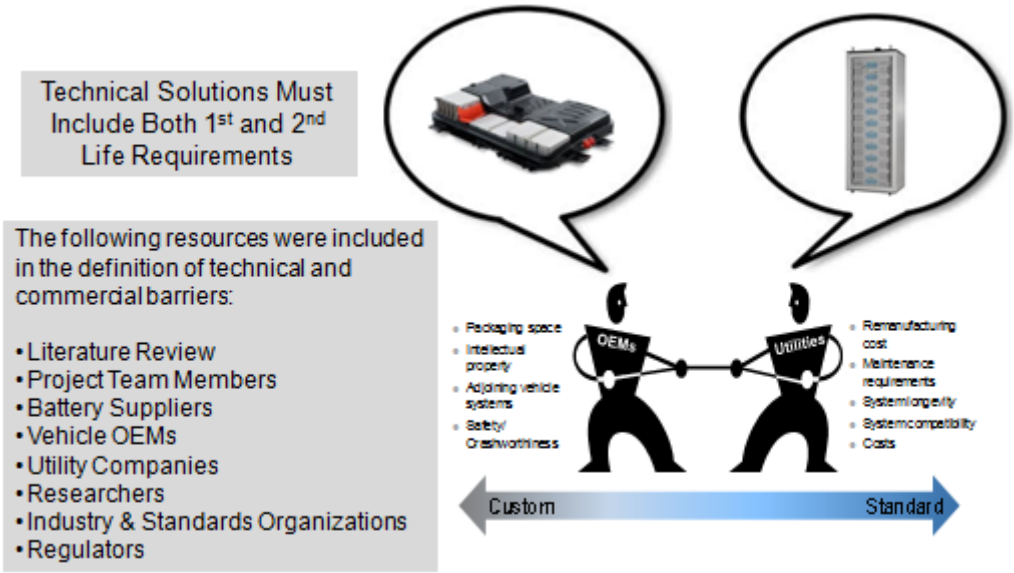
designs might impact first and second use stakeholders from both technical and commercial perspectives. A similar approach (i.e. literature search and industry interviews) was employed to assess the impact of standardized designs on second use stationary energy storage applications.

Figure 185: Stages of Battery Life Cycle



Other resources evaluated during these analyses are listed in Figure 186 and include researchers at national laboratories, industry standards organizations, and government representatives.

Figure 186: Identified Barriers Prompt Technical Solutions



Barriers with a high degree of technical impact were identified. These were later used to develop and evaluate technical solutions during the Design and Analysis for Standard Modules. In other words, the information gathered during the Barriers Analysis served as input to the design process.

Key topics for the barriers analysis included

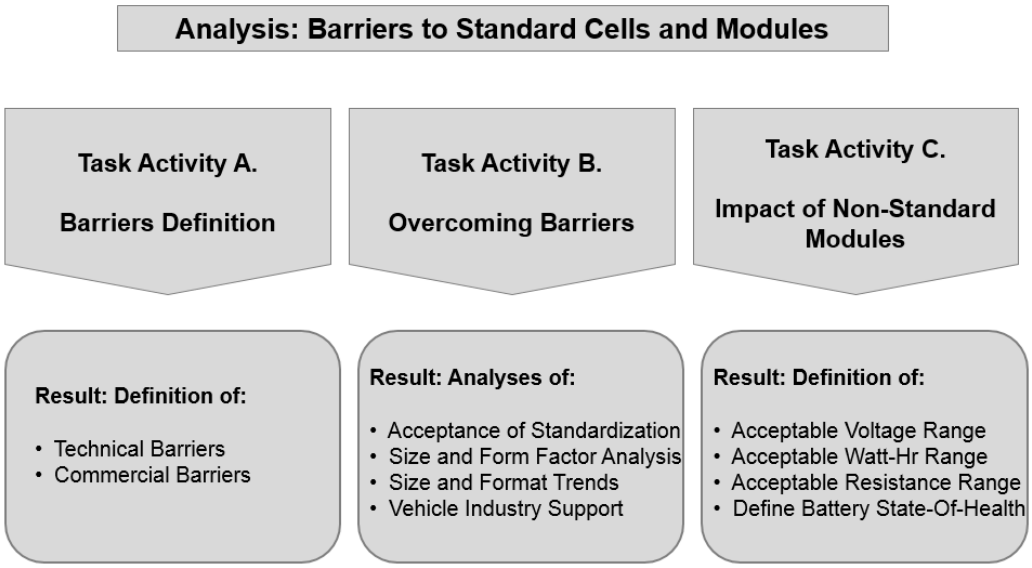
1. acceptance of cell/module standardization
2. battery company cell/module size and form factor analysis
3. cell/module size trends converging/diverging on format
4. industry movement for standard cells
5. impact of non-common battery specifications (voltage, watt-hrs)

Key topics for the design study included:

1. design options for standard modules for each application
2. implications for electrical, mechanical, thermal and controls
3. determination of cost benefits for vehicle OEMs for primary life
4. evaluation of potential pathways for implementing PEV battery pack standards.

For the three primary activities of the Barriers Analysis (barriers definition, paths to overcoming barriers, and impact of non-standard modules and systems), the results for each activity are shown in Figure 187.

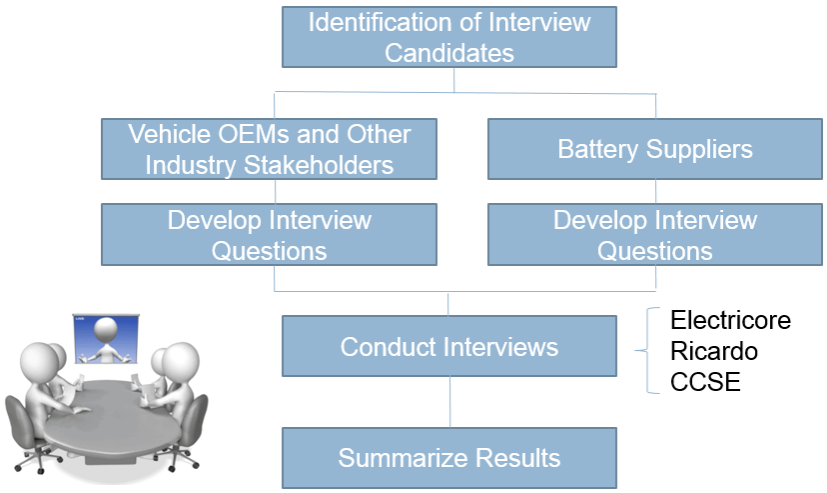
Figure 187: Analysis: Barriers to Supply-Side Standard Cells and Modules



2.3 Supply Side Industry Interviews

Interviews with industry stakeholders, including vehicle OEMs and battery suppliers, were completed to identify and describe technical and commercial barriers to standard modules and battery systems and to obtain opinions regarding alternative technical approaches to the integration of modules/battery systems without standardization. The industry interview process is shown in Figure 188.

Figure 188: Approach to Interview Process



Interviews were conducted with ten (10) industry stakeholders to define technical and commercial barriers to first use (vehicle) battery standardization efforts. Participants were provided the option of remaining anonymous. All but two of the participants elected to remain anonymous so they could provide candid, unbiased responses to the interview questions. A list of industry interview participants is shown in the table of Figure 189.

Figure 189: Industry Interviews: Participant Titles and Organizations

Interview	Organization	Participant	Interview	Organization	Participant
1	National Laboratory	Senior Engineer	6	Vehicle OEM	Science Officer
2	Industry Organization	Managing Director	7	Utility Research Organization	Fleet Engineer
3	Battery Manufacturer	Director, New Technologies	8	Vehicle OEM	CEO
4	Vehicle OEM	Manager, Technology Strategy	9	National Laboratory	Manager
5	University Research Center	Director	10	Vehicle OEM	Engineering Manager

Topic categories for questions included vehicle and battery specifications, identification of technical and commercial barriers, approaches to overcoming barriers, and impact of non-common voltage and watt-hour range. These and topics for specific questions are shown in Figure 190.

Figure 190: Topic Categories and Questions

Topic Categories	Topics for Specific Questions
Vehicle and Battery Specifications	• Vehicle Drive System • Battery System • Factors Influencing Design
Identification of Technical Barriers	• Safety and Crashworthiness • Maintenance Requirements • Component Compatibility
Identification of Commercial Barriers	• Entity Responsible for Battery Second Life • Costs (initial, residual) • Market Forecasts
Approaches to Overcoming Barriers	• Acceptance of Standardization of Cells/Modules • Cell/Module Size/Form Factor Recommendations • Industry Movement toward Standard Cells
Impact of Non-Common Voltage and Watt-Hour Range	• Is a Range of Voltages and Watt-Hours Acceptable? • Predictions for Resistance Range • Impact on State of Battery Health

A structured interview process was employed to obtain consistent, repeatable results. This process has been effectively utilized during prior research projects.

Representatives of Electricore, San Diego Gas & Electric, Ricardo, and the Center for Sustainable Energy participated in preparing presentation materials for the interviews, identifying and contacting industry stakeholders, conducting the interviews, and evaluating the results. This process is illustrated in Figure 191.

Figure 191: The Interview Process

Separate questions were prepared for each stakeholder interview based on the key topics, experience, and target information associated with each participant. It is noted that not all interview participants provided answers to all of the questions posed due to lack of available information, or election to not provide information considered to be proprietary. Example interview forms for vehicle OEMs and battery suppliers.used during this study are displayed in Figure 192 and Figure 193 below.

Figure 192: Interview Form: Vehicle OEMs

Vehicle OEMs Interview Form
CEC PIR-12-005

Interviewer:
Interviewee:
Date:

Question	Answer
1. Would you like to remain anonymous?	
2. What is the drive system for this vehicle (BEV, PHEV, HEV)?	
3. What are your current production plans for electric and hybrid electric vehicles?	
• Vocations	
• Class	
• Planned introduction dates	
4. Please provide the following battery specifications:	
• Battery pack total and useable energy (kW-hr)	
• Battery Pack Capacity (Ahr)	
• Battery Cell Configuration (series parallel arrangement of cells/modules)	
• Space/packaging constraints	
• Battery minimum, nominal and maximum Voltage	
• Cell and Battery Supplier	
• Cell Chemistries	
• Cell Form factors	
• Adjoining vehicle systems, including communication protocols	
• Distributed or Centralized Battery Management System (remote cell temperature and voltage monitoring with master controller or one controller)	
• Battery Warranty (terms, restrictions), Battery Capacity at EOL	
• Battery total energy throughput at EOL	
• Battery maximum SOC swing and DOD	
• Structural configuration (number of modules, configuration of modules, one-size or multiple sizes, integration of thermal management system in modules)	

• Was the battery system developed in-house, co-developed, or purchased as a standard product?	
5. Have you encountered any intellectual property issues regarding the batteries and/or electric drive components?	
6. What have you done to address safety and crashworthiness (including structural elements)? Have you prepared training materials for first responders?	
7. Questions related to battery life strategy:	
• Who is responsible for the batteries at the end of the vehicle life (customer, OEM)?	
• What is the expectation for the batteries at the end of its life in the vehicle; will the batteries be returned to the dealership/OEM, go to a recycler, be remanufactured, or be sold/acquired/sent to a third party?	
• What are the processes and costs associated with these transactions?	
8. What are the recommended battery and drive system maintenance requirements? Who performs these services (dealership/third party/owner)? What are the required training and qualifications needed to perform these tasks? How do these issues affect the battery design architecture?	
9. What is the anticipated drive system longevity (not including battery)?	
10. Have you encountered any intellectual property issues regarding the batteries and/or electric drive components?	
11. What have you done to address safety and crashworthiness (including structural elements)? Have you prepared training materials for first responders?	
12. Have you encountered any system component compatibility issues, for example communications, electrical (voltage, current, isolation)? If so please provide details.	
13. What is the incremental cost of the batteries and electric drive	

system relative to the corresponding ICE (diesel or gasoline) vehicle? This will be used to assess the life cycle costs to the vehicle owner.	
14. Have you prepared any forecasts for the market growth of this vehicle through 2025? If so, are you willing to share this information? (This will be compared to Ricardo's adoption rate predictions developed during Task 2).	
15. What do you see as the primary commercial and technical barriers to module standardization?	
16. Do you have opinions regarding the following topics:	
• Acceptance of cell/module standardization	
• Battery company cell/module size and form factor analysis	
• Cell/module size trends converging/diverging on format	
• Industry movement for standard cells	
17. What do you see as the impact of non-common voltages and watt-hours for standard modules including:	
18. Can a range of module voltage & watt-hrs be acceptable?	
• If so, what would you predict for the voltage and watt-hour range?	
• What is your prediction for resistance range?	
• How do these non-common voltages and watt-hours have on the state of battery health?	

Figure 193: Interview Form: Battery Suppliers

Battery/Cell Manufacturers and Suppliers Form
CEC PIR-12-005

Interviewer:
Interviewee:
Date:

Question	Answer
1. Would you like to remain anonymous?	
2. Please provide specifications for the battery cells, modules, and pack:	
• Battery/cell total and useable energy (kW-hr)	
• Battery/cell capacity (Ahr)	
• Battery Cell Configuration (series parallel arrangement of cells/modules)	
• Space/packaging constraints	
• Battery/cell minimum, nominal and maximum Voltage	
• Cell chemistries	
• Cell Form factors	
• Distributed or Centralized Battery Management System (remote cell temperature and voltage monitoring with master controller or one controller) Battery Warranty Battery Capacity at EOL	
• Battery total energy throughput at EOL	
• Participation of OEM in development process	
3. Battery maximum SOC swing and DOD: Have you encountered any intellectual property issues regarding the batteries and/or electric drive components? Are you willing to share BMS protocols?	
4. Have you encountered any cell and module manufacturing infrastructure constraints (e.g. electrical issues, transportation requirements)?	
5. Will the vehicle batteries be remanufactured at the end of their first application? If so, what at the costs associated with remanufacturing?	
6. What are the recommended battery maintenance requirements?	

Battery/Cell Manufacturers and Suppliers Form
CEC PIR-12-005

7. What are the current and projected battery costs ($/kw-hr)?	
8. Have you prepared any forecasts for the market growth of this battery through 2025? If so, are you willing to share this information?	
9. What are your opinions regarding convergence or divergence of modules and cells?	
10. What do you see as the primary commercial and technical barriers to module standardization?	
11. Do you have opinions regarding potential mitigation approaches with focus on:	
• Acceptance of cell/module standardization	
• Battery company cell/module size and form factor analysis	
• Cell/module size trends converging/diverging on format	
• Industry movement for standard cells	
12. What do you see as the impact of non-common voltages and watt-hours for standard modules including:	
• Can a range of module voltage & watt-hrs be acceptable?	
• If so, what would you predict for the voltage and watt-hour range?	
• What is your prediction for resistance range?	
• How do these non-common voltages and watt-hours have on the state of battery health?	

2.4 Supply Side Barriers

2.4.1 Technical and Commercial Barriers: Results of Interviews and Literature Review

The results of the technical and commercial barriers identification task has been divided into four categories: vehicle OEM input on technical barriers, vehicle OEM input on commercial barriers, battery supplier input on technical barriers, and battery input on commercial barriers. These are summarized in the tables of Figure 194 through Figure 197.

2.4.1.1 Vehicle OEMs Input: Technical Barriers

Figure 194: Vehicle OEMs Input: Technical Barriers

Identified Barrier	Comments
1. Mechanical Integrity	BEVs require extensive testing programs, including crash testing and lifecycle analyses. These can be prohibitively expensive and time consuming and thus foster reluctance to modify designs or add features.
2. Battery protection	Protection (moisture, shock, particulate fouling, vibration, penetration) acceptable to OEMs and utilities must be incorporated at cell or module level while maintaining low cost.
3. CANbus limitations	Communications standards are continually evolving and vary between OEMs, which poses a challenge to standardize for both OEM and utility applications.
4. Additional considerations	Standardization must address internal contactors and fusing, which vary between OEM and energy storage applications.
5. Non-standard BMS reporting	Prefer standardized parameters for reporting battery health (SOC, SOH, temperature, etc.)
6. Reduction in commercial vehicle utility	Standardized batteries and associated power electronics can negatively impact storage space (e.g. utility service vehicles) Limited battery choices; difficulty in matching battery to vehicles with variable duty cycle.
7. Inconsistent safety requirements	Challenges related to varying crashworthiness requirements. Need consistent specifications for system shut-down and isolation requirements in event of an accident. Require definition of uniform “shut off” switch specifications for first responders.
8. Issues related to multiple battery pack locations	Requires development of interface between BMS and thermal management systems for multiple packs located at various sites on

Identified Barrier	Comments
(particularly related to commercial trucks).	the vehicle. -Requires development of standardized connectors for multiple packs.
9. Internal resistance	Standardization should not impact internal resistance which is to be as low as possible to reduce heating and improve efficiency.
10. Battery quality assurance	Battery quality assurance requirements are still developing across the industry.
11. Definition of battery state of health (SOH)	There is no industry standard or consensus on what parameters should be use to determine SOH.

2.4.1.2 Vehicle OEMs Input: Commercial Barriers

Figure 195: Vehicle OEMs Input: Commercial Barriers

Identified Barrier	Comments
1. Issues related to batteries at end of initial application (first use)	Responsibility options for batteries at end of first use: – OEM – Vehicle Owner – Battery Manufacturer – Options for disposition of end of first use: – Return to dealership/OEM – Sent to recycler – Remanufactured – Sold/Acquired by third party
2. Warranties	– Warranties do not extend to second use applications. – Some warranties limited (i.e. one year) due to extreme duty cycles (e.g. utility service vehicles).
3. Intellectual property issues	Battery manufacturers are reluctant to share detailed specifications for batteries, limiting progress on standardization efforts.
4. Product Liability	– If vehicle OEMs develop their own BMS, they must assume responsibility for the battery pack (even if manufactured by others).

Identified Barrier	Comments
	– Warranties and liability paths/cascades vary from OEM to OEM. – Unclear definition of interfaces between various battery and battery management system components.
5. Standardization and other battery design preferences	– Redundant safety systems result in higher battery costs. – Reducing battery size will improve safety by allowing batteries to be isolated from vehicle crush zones. – Improving accessibility for replacing damaged modules. – Vehicle size limited by battery performance.
6. Decision tools	Lack of credible information regarding technologies and costs.
7. Quality assurance	Cell prices are high due to high rejection rates at the manufacturers. Improved quality assurance is required.
8. Opportunities to Lower Cost	– Reducing battery costs is key to improve adoption rates. – Low sales volumes of electric vehicles impact production volume cost reductions. – Other interviewees suggested the need for more EV and sustainable infrastructure financing options. – Public-Private finance coordination
9. Incentives	Limited number of incentives impact sales of commercial electric vehicles, which, in turn, decreases OEM revenues and funding available for development of standardized modules
10. Lack of availability	Limited availability and high prices of commercial electric vehicles results in lower sales and decreased revenues for standardization efforts.
11. Education	Particularly related to total cost of ownership and which vocations are appropriate for CEVs.

2.4.1.3 Battery Supplier Input: Technical Barriers

Figure 196: Battery Suppliers Input: Technical Barriers

Identified Barrier	Comments
1. Sharing of BMS Protocols	Having access to original BMS protocols would facilitate

Identified Barrier	Comments
	implementation of second use applications.
2. Issues related to multiple battery chemistries	– Cell characteristics vary; requiring multiple inverters for second use applications. This increases system costs. – Systems must be coordinated to ensure maximum battery life (related to SOC management).
3. Remanufacturing requirements	To facilitate second use applications, remanufacturing requirements are to be minimized.
4. Communication protocols	– Standard communication protocols from the automotive sector are contemplated to serve adequately at the module and system control levels for second use applications. – Interfaces with energy storage communication systems requires development
5. Thermal management	Variations in thermal management systems may limit applications to utility-scale energy storage second use applications
6. Additional integration requirements	– Energy storage systems will have to accommodate various battery voltages and energy capacities. – Integration with energy storage networked control systems. – Development of management system at module level will facilitate standardization.
7. Battery package space	Automotive requirements dictate battery geometry, which results in divergence of cell and module designs.
8. Safety	– Development of standard battery deactivation for first responders (fuse plug to isolate cells). – Test methods remain to be developed for molded casing heating assessments, open circuit voltage, internal short circuits, and insulation resistance. – Standardized risk assessment tools require additional development along with definition of standardized safety tests. – Several vehicle OEMs expressed concern regarding battery protection for commercial vehicles (exposure for outside rail mounting, vibration and shock protection).
9. Charge acceptance	Improvements required in charge acceptance to improve regenerative braking efficiency.
10. Durability	Impact of deep discharge events on battery life.

Identified Barrier	Comments
11. Climate related battery degradation	A concern for locations experiencing very hot or very cold ambient temperatures.

2.4.1.4 Battery Supplier Input: Commercial Barriers

Figure 197: Battery Suppliers Input: Commercial Barriers

Identified Barrier	Comments
1. Cost	– Including features to support second use applications will increase battery costs. – Incentives for standardization are required. – Low cost replaceable batteries vs. higher-cost long life (10-year) designs.
2. Convergence	– Currently, there is wide divergence among manufacturers regarding cell chemistries and formats. Some vehicle OEMs employ "off-the shelf" packs; others develop their own. – Divergence of chemistries and formats will limit industry innovation.
3. Industry resistance	IP and varying auto industry requirements are hindering standardization.
4. Safety	A battery safety roadmap is required, including a definition of roles for all stakeholders, from battery manufacturers to vehicle OEMs. Standardize safety procedures will impact design and integration tasks.
5.Lack of access to capital	Fleet budgets are limited, reducing the options for purchasing higher-cost electric vehicles.
6. Supply of battery components and materials	Concern expressed regarding security of long-term supply.
7. Maintenance	The expressed goal is to develop a battery that requires no maintenance during the first use and only one remanufacturing preceding the second use.
8. Production security, international economics	Currently, Japan and South Korea produce approximately 80% of the world's advanced lithium-ion batteries.

The following key categories for technical barriers are based on literature research and industry interviews. The objective of this activity was to identify technical and commercial obstructions to implementing standard battery systems designs for commercial and passenger vehicles. These identified barriers relate to both first and second use applications.

- Communications networks, protocols and connectors
- Thermal management – air or liquid cooling and active or passive
- Module form factor
- Voltage, current and temperature monitoring
- Options for defective cells (replacement, options at end of rirst life)
- Lack of common battery management system (BMS) standards and methods
- Module mounting

The following key categories for commercial barriers were determined from the literature research and industry interviews:

- Predictable supply of second use batteries
- Uncertainty in cost of second use batteries
    - Repurposing of standardized designs vs. non-standardized designs
    - Comparison to bespoke stationary energy storage battery systems
- Industry resistance to change and risk
- Unclear maintenance requirements
- Variation in system longevity
- Electrical and electrochemical compatibility
- Intellectual property (IP) and competitive position issues

2.4.2 Overcoming Identified Supply-Side Barriers to Standardization

The following approaches to overcoming barriers related to module and battery system design standardization were identified and addressed:

- Acceptance of cell/module standardization by vehicle OEMs and battery system suppliers. A survey of progress-to-date was completed. Key findings from the survey include:
    - Passenger cars have begun to use a semi-standard cell size dependent on battery pack package location within the vehicle.
    - Passenger cars may accept a standard module size if it lowers development and production cost.

    - As described below, commercial trucks already have a standard package location supporting a standard size module.
- Battery company cell size analysis: A survey was initiated regarding specifications of currently-available and pending products and the results are reported in this chapter.
- Cell size trends (converging or diverging on format) and industry movement for standard cell and module designs: history of standardization efforts. Results of the literature search and industry interviews indicate:
    - Prior efforts initiated by the Society of Automotive Engineers (SAE) Committee on Battery Standardization met with significant resistance and were abandoned.
    - Only two vehicle battery standards are currently in effect:
        - The German Association of the Automobile Industry (Verband der Automobilindustrie, VDA) created a standard cell size standard (now International Organization for Standardization/International Electrotechnical Commission Passenger Car (ISO/IEC PAS) Standard 61850, November 2012)
        - General Motors Corporation created standards for pouch cells associated with vehicle tunnel battery system packages supported by LG Chem and A123 (now GM General Requirements GR-3150, December 2013)

The following parameters were investigated to identify the range of variations in current battery system module designs. This effort was related to the determination of current, non-standard modules on second use applications. Key parameters include:

- Suitability of a range of module specifications for
    - vehicle applications.
    - utility second use applications.
- Voltage range.
- Watt-hour range.
- Resistance range.
- State of battery health.
- Variation in original certification protocols, for example, those developed by Underwriters Laboratories (UL)

Second use batteries will have varying degrees of internal resistance and state of health (SOH). SOH is generally assigned a value between 0 percent and 100 percent and is based on the battery performance at time of delivery from the manufacturer. Some typical SOH parameters include internal resistance / impedance / conductance, capacity, voltage, ability to accept a charge, and number of charge–discharge cycles the battery has undergone. These variations in

state of health will present challenges in configuring modules into second use battery systems. Other impacts of variations in internal resistance and capacity include:

- Internal resistance and thus power capabilities will occur at the cell and module level.
- The cell resistance determines its remaining capacity and power performance in a second use application and is the constraining variable.
- The lowest performing cell will limit the performance of a series string within an Energy Storage System (ESS).

Vehicle OEMs must optimize ESS packaging within the vehicle in order to meet duty cycle and weight targets. The goal is to obtain more energy and power at lower weight. This demand is forcing automakers to develop unique battery systems, often with custom sized cells, modules and packs. The different types of vehicles: micro hybrid, mild hybrid, full hybrid, series hybrid (including range extender) and full EV have differing energy storage system requirements. The micro to mild hybrids are trending towards more power versus more energy. For series hybrids and full EVs, the trend is towards more energy versus power to maximize the vehicles range. As a result the industry has a wide range of cells formats and dimensions. The differing vehicle requirements promote variations in module and battery system designs.

2.4.2.1 Battery System Key Technical Barriers

The most demanding challenge faced by vehicle OEMs regarding on-board battery systems is related to packaging location and space requirements. Other challenges include electrical, electronic, thermal, communications, and application requirements. These systems must be compatible with the vehicle design as illustrated inFigure 198.

Figure 198: Examples of Unique Automotive Battery System Designs

Form Factor

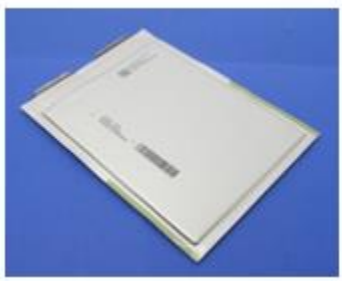
Automotive vehicles employ energy storage systems constructed of modules containing individual cells arranged within a battery system, or pack. Module and battery system form factors (shape and dimensions) are driven by the vehicle's unique packaging requirements. It is not expected that major automakers will standardize battery pack form factors during the near future because of the individual vehicle (platform/model) requirements. The variation in battery system designs, including electrical and mechanical interfaces, make second use use technically challenging, because the module form factor is highly affected by the cell design. Modules are designed to support the mechanical and electrical requirements of the cells. Variations in the cell type as well as other vehicle and automaker requirements have steered the creation of varying module form factors.

As noted earlier, commercial vehicles were selected for analysis during the current study because they generally have more space available to accommodate energy storage systems are thus candidates for standardized designs incorporating common form factors as well as electrical and mechanical components.

The form factor of cells was one of the first battery system parameters to attain some level of standardiztion. As noted above, standards for cells have been developed, although not widely

adopted, that can serve as a basis for standardized modules. General Motors created a standard size pouch cell to support packaging within the tunnel of passenger vehicles. The GM pouce cell and VDA prismatic cell are shown in Figure 199.

Figure 199: GM Pouch Cell and German VDA Prismatic Cell



Multiple cell form factors have also resulted in variations of module sizes and shapes. Obtaining form factor commonality will be required if battery system standardization is to be achieved.

Figure 200: Variations in Automotive Battery Systems Designs

Voltages

Design requirements associated with automotive system power electronics have resulted in two battery system voltage ranges. PHEVs and BEVs use battery packs with an operating voltage range of 250V to 400V. HEVs use battery packs with an operating voltage range of 150V to 350V.

However, the voltage of the modules within the battery systems has not been commonized. Module voltages depend on the number of cells or groups of cells and their arrangement within the system. The number of cells or cell groups within a module is determined by the available package space.

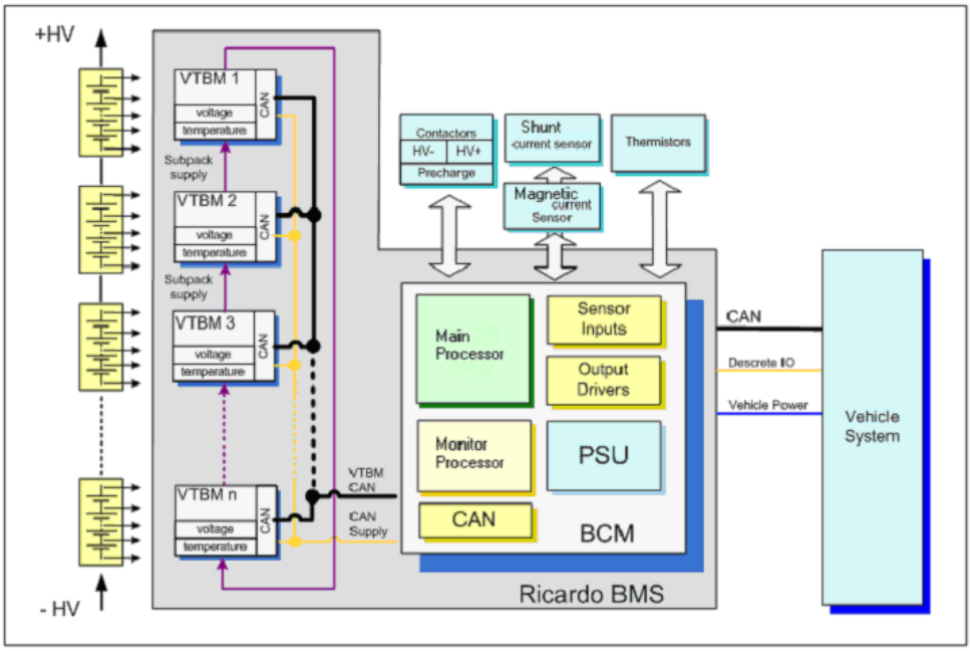
Battery Management Systems

The second use applications of an automotive battery will require a Battery Management System (BMS). The BMS is an electronic system that monitors and controls the state of the battery by measuring or calculating parameters including:

- Voltage: battery system total voltage and the voltage of the individual cells
- Temperature: battery system cooling system temperature and the temperatures of cells
- Current: current into and out of the battery system
- State-of-Charge: charge level of the battery is calculated
- State-of-Health: calculated overall condition of the battery system
- Insulation Resistance: resistance between high voltage and vehicle chassis

The BMS, in an automotive application, reports the monitored data to the vehicle over the vehicle controller area network (CAN). BMS functions are common among automotive battery packs and are driven by the operational safety requirements of the lithium-ion chemistry.

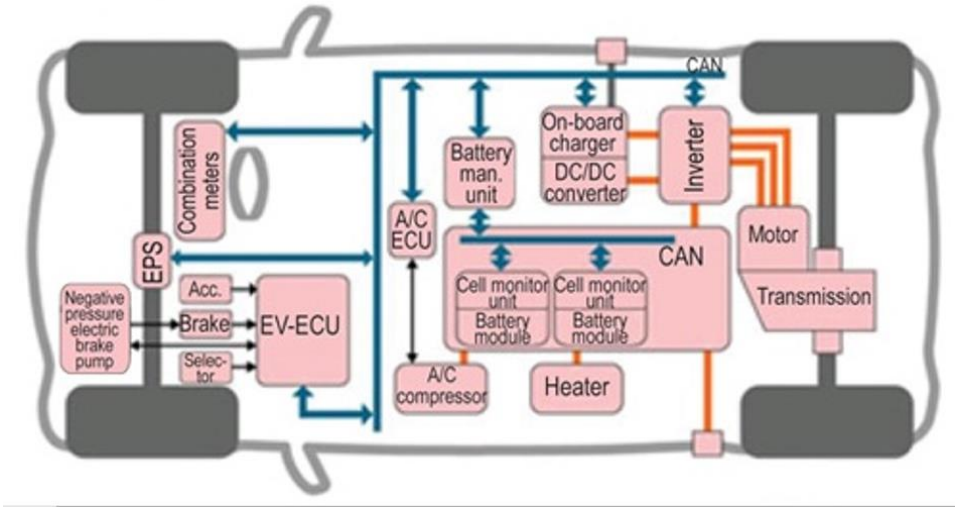
Figure 201: Example Battery Management System (BMS)



There are two BMS architectures in use by major automakers.

- Centralized architecture: One electronic control unit which includes all sensing processing circuitry. This approach is utilized in the Nissan Leaf, Toyota Prius Plug-In, and Ford's Fusion and C-Max Energi. This architecture is limited by the number of available inputs.
- Distributed architecture: Multiple electronic controls units with sensing and processing distributed between multiple units. This approach is utilized in the Chevy Volt, Spark, and Mitsubishi i-MiEV. The system includes serial communication, typically CAN, to share data between control units.

Figure 202: Example Electric-Drive Automotive Electronics and Control Systems



Automakers have not yet standardized the messaging and data protocols for BMS operation, both internal and external to the battery system, even though it is expected that such standardization will result in improved safety and operation. There are no indications that major United States automakers are moving toward standardizing messaging. Automotive battery systems communicate internally and with other vehicle systems using the Controller Area Network (CAN). A typical electronics and control system schematic is shown in Figure 202.

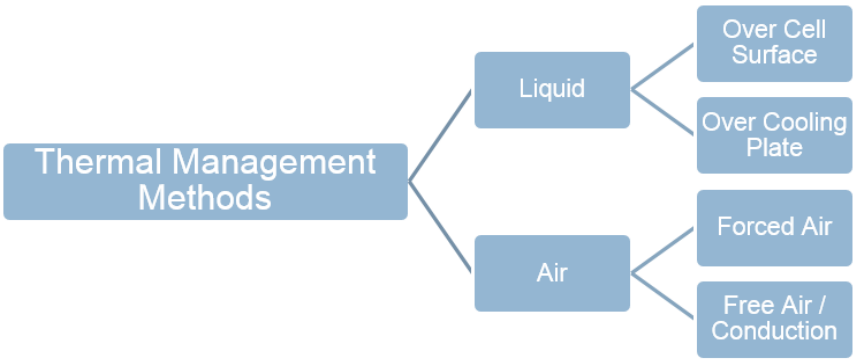
It may not be necessary for vehicle OEMs to adopt standardized battery communication to accommodate second use applications. Creation and adoption of a standard messaging could be used with a new or reprogrammed second use BMS. Research is underway at several organizations, including the National Renewable Energy Laboratory, on the topic of cell designs that allow ready reconfiguration into a range of module and battery system configurations.

Vehicle OEMs have developed unique algorithms for managing batteries within their vehicles. Significant time and money has been invested developing these algorithms. The algorithms are considered intellectual property and are closely guarded. The use of the BMS with the proprietary OEM controller software will require the release of certain details of these algorithms which the OEMs may be reluctant to provide. Because the BMS is directly related to safe operation of a battery system, automakers may have a liability concern regarding release of the BMS for second use applications.

Battery Systems Cooling

The second use use of an automotive Li-Ion battery system will likely require a thermal management system which maintains the cell temperature within the desired range. High (>~40°C) or low (<~0°C) cell temperatures typically limit battery charge and discharge current and thus impact battery life and safety.

Figure 203: Battery Thermal Management Methods



The selection by vehicle OEMs of a battery thermal management system is a trade-off between packaging, performance, cost, and weight constraints. Widely different approaches have been taken. Some standardization has been occurring across vehicles manufactured by specific OEMs, but not generally across the industry. Industry interviews suggest such industrywide standardization is not currently a key area of focus.

Plug-In Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV) from major automakers use liquid and air cooling.

- Liquid-Cooled
    - Chevy Volt PHEV
    - Chevy Spark
    - Tesla Model S
    - BMW i3
- Air-Cooled
    - Ford Fusion PHEV – forced air
    - Ford C-Max Energi – forced air
    - Toyota Prius – forced air
    - Mitsubishi i-MiEV – forced air
    - Nissan Leaf – convection

Figure 204: Example Battery Pack Cooling Systems (Air and Liquid Cooling)

Cell Failure at End of Life

Batteries at the end of first use (at the time they are removed from the vehicle) may have defective cells, which would limit performance of the module. Not all modules have been developed to support the replacement of defective cells. The replacement of defective cells within a module can be a labor-intensive process. An industry standard method to screen for defective cells within modules has not been developed, but would be required. The business case of when to replace defective cells versus scrapping a module will also need to be understood.

Automotive Battery Systems and Packaging

Unlike commercial vehicles, light-duty passenger cars have very unique packaging requirements that vary from model to model. The locations within the vehicle that can accommodate the battery system are limited and include.

- Locations exterior to the passenger compartment
    - Vehicle tunnel area from the engine to the rear passenger seat: This approach is utilized in the Chevy Volt and includes a T-shaped architecture.

Chevy Volt
Tunnel/Rear seat

- Vehicle floor area typically requires a low profile battery system such as those developed for the Nissan Leaf and BMW i3.

Nissan Leaf
Under floor

- In front and behind the rear axle such as the system developed for the Chevy Spark architecture.

- Locations interior to the passenger compartment
  - Trunk or under rear seat area such as systems employed in the Ford Fusion and Toyota Prius.

Prius Hybrid
Trunk

Ford Fusion Hybrid
Trunk

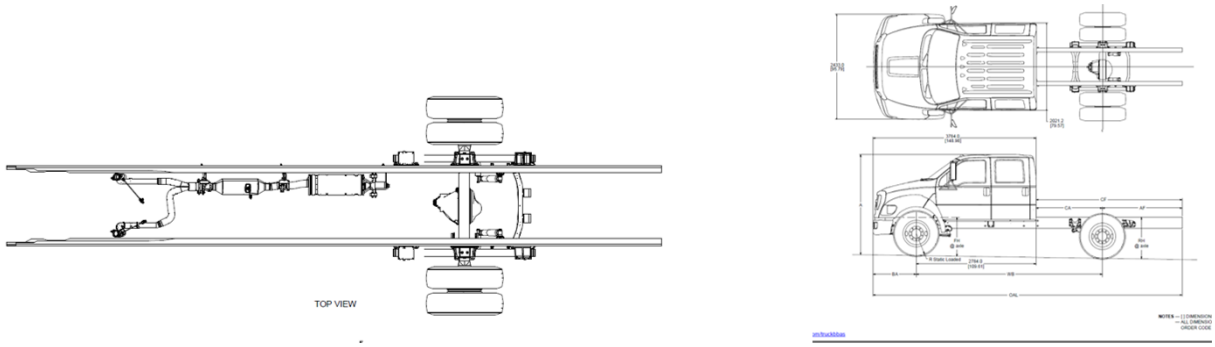
Thus, the passenger car OEMs will likely not lead the charge for standardizing battery systems; however, if the packaging barriers are overcome, it is expected that standardization will lead to lower costs for vehicle battery systems (see Chapter 4: Value Analysis).

Commercial Vehicle Segment

Commercial vehicles have very common architectures and similar space dimensions for packaging energy storage systems. Most commercial vehicles include a frame design and the area outside the frame rails are prime areas for locating battery systems. The area inside the frame rails is generally occupied by the gas tanks, exhaust and drivetrain systems, making it difficult to accommodate a battery system in that location.

Commercial trucks offer the opportunity to utilize standardized battery systems designs and were thus selected for development of two concepts.

Figure 205: Typical Frame Design for Commercial Truck



Standard Design Concepts for Electric Commercial Vehicles

A detailed description of the standardized commercial truck battery/module designs is included in Chapter 3. An abbreviated description is provided here to illustrate how standardized designs can be accommodated by these vehicles types.

Design guidelines were based on industry interviews, literature search, and the barriers analysis. These included strategies, and associated compromises, from both the automotive (first use) and stationary energy storage (second use) industries.

Two designs were generated, one based on the prismatic pouch cell type, such as those manufactured for General Motors by LG Chem and A123 Systems, and another based on a prismatic can concept, such as those specified for several PHEV vehicles with cell size specified by ISO/IEC PAS Standard 61850_2012. The energy storage capacity of the packs was based on the vehicle duty cycle analysis of vocational vehicles presented in Chapter 1. It was found during the duty cycle analysis that energy storage capacity requirements could be divided into 25 kW-hr increments and thus battery systems with this capacity rating could be combined to accommodate the full range of vocational vehicles included in the current study. The two standardized designs are shown in Figure 206 and Figure 207.

Figure 206: Concept Standarized Battery System Design: Prismatic Pouch

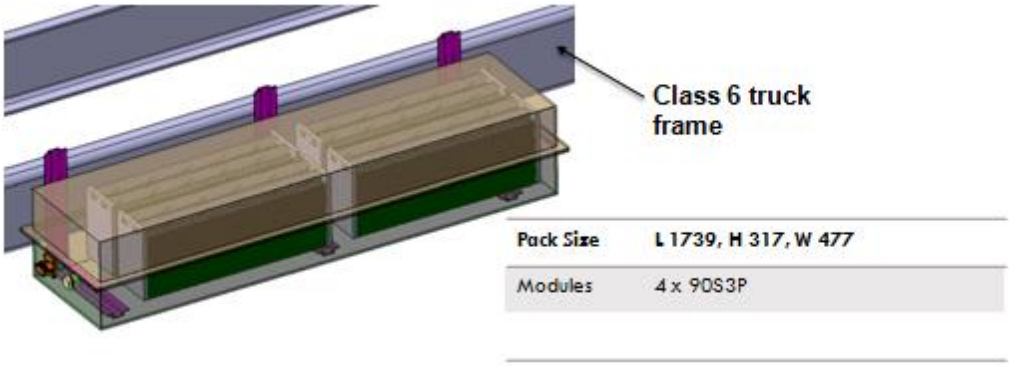
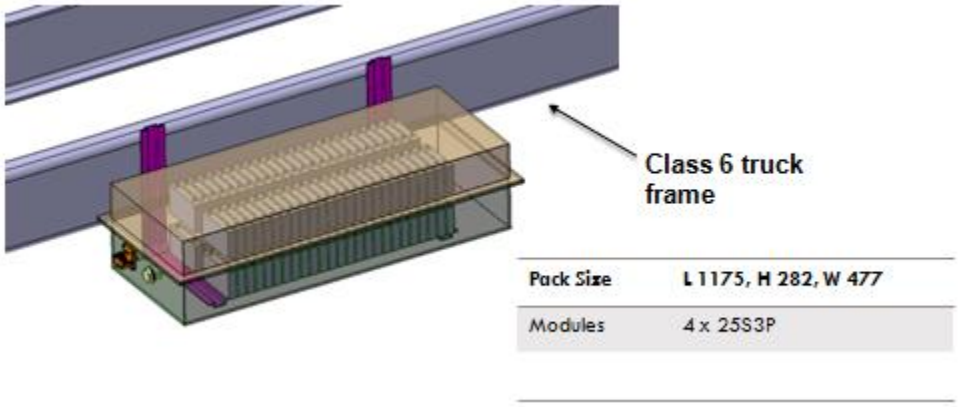


Figure 207: Concept Standardized Battery System Design, Prismatic Can



Concept Standardized Battery System Design Guidelines

This two concept battery system designs are targeted for electric drive, commercial vocational vehicles. It is noted that these battery system designs are at a concept stage. Design constraints have been kept to a minimum to prevent eliminating design ideas.

Battery system requirements are:

- Pack energy storage capacity of 25 kWh.
    - Selected based on known commercial vehicle drive cycles requiring 25kWhr, 50 kWh, 75 kWh, and up to 350 kW-hr in 25 kW-hr increments.
    - Utilize a 25 kWh modular system design with 5 kW-hr modules
- Cell Type

- GM Pouch Cell as manufactured by A123 Systems and LG Chem.(these cells are produced in high volumes
- PHEV 2 Prismatic Can: this is the only currently released cell that meets ISO/IEC PAS Standard 61850:2012

- Pack Size: constrained to fit on the outside of a commercial vehicle frame rail between the cab and rear wheels. Space claim based on vehicle outfitter manual.

2.5 Demand Side Barriers

2.5.1 Suitability of Range of Voltages and Watt-Hours for Utility Second use Applications

The second use battery market can be facilitated through informed first use battery design. Repurposing costs to prepare used electric vehicle batteries for second use use can be reduced if the electrical and physical requirements of batteries in second use applications (stationary storage) are understood during the first use design process. If first use modules are designed to meet second use needs, they will be easier to integrate into stationary storage systems.

To get an overview of the voltage and energy (watt-hour) requirements of second use applicatons, a market survey of existing energy storage systems was conducted. Because this project is focused on *modules* as the system building block for both first and second use of the battery, the prevailing nominal voltage and energy provided by the modules making up the commercial storage systems are also surveyed. Systems by such companies as A123 Systems, Altairnano, Boston Power and more were reviewed.

Below are figures showcasing the results of surveying these modules for voltage and energy capacities. The average nominal DC voltage of the modules in the existing stationary storage systems was 20.2 VDC. The modules' voltage range was between 2.3 and 48.3 VDC. The majority of modules had voltages in increments of 12 VDC. The average watt-hour range for modules surveyed was 0.75 kWh. The modules' watt-hour range was between 0.06 and 2.85 kWh. This observation was used to guide the first use electric vehicle battery standard designs herein.

Figure 208: Voltage Range (According to Existing Industry Modules)

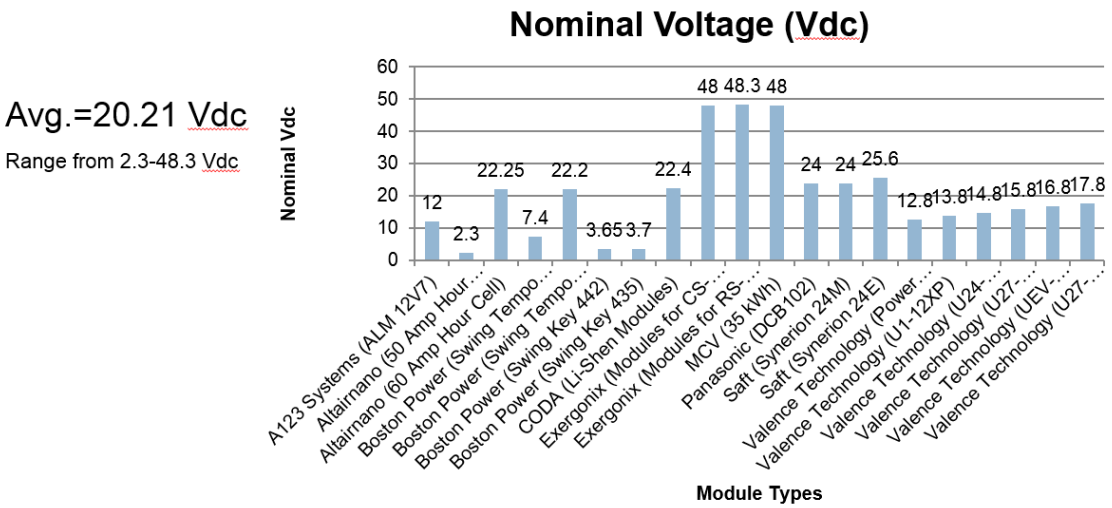
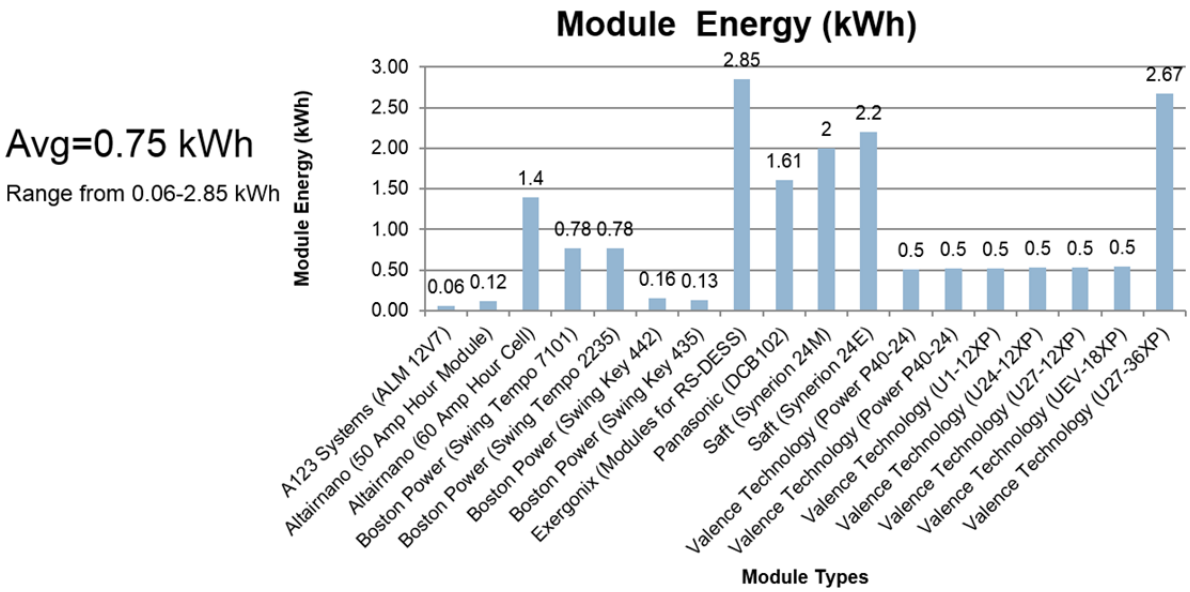


Figure 209: Watt-hour Range (According to Existing Industry Modules)



2.5.2 Resistance Range and State of Battery Health

Propulsion batteries retired from an electric vehicle will vary in cell resistance and state of health. In this next section,the researchersconsider the impact of a varying range of resistances and states of health on the use of batteries in second use applications. To answer this question, primary and secondary research was conducted.

Acceptable resistance ranges and battery states of health for utilizing a used EV battery in a second use application depend on the following three variables: (1) utility grid application, (2) customer load, and (3) battery chemistry.

Utility grid applications vary in intensity of power rates and the frequency at which the power rate changes. Because of this, acceptable resistances of batteries leaving EVs will vary depending on the requirements of the utility grid applications. Used EV batteries with higher resistance will be less desirable for utility grid applications that may require frequent deep discharges, or fast response characteristics. Moreover, lower power applications, such as peak shaving and regulation, will allow a wider resistance range than high demand, fast response applications. Similarly, consumer load will drive acceptable resistance ranges of second use systems. If the consumer load is relatively stable on a day-to-day basis, a battery with higher cell resistance may be acceptable because its operation is more or less predictable. The battery can be appropriately rated without inaccurate expectations by the customer. Defining an acceptable resistance range is highly dependent on the intended applications for battery usage in its second use.

2.5.3 Alternative Approaches to Integration without Standardization

To understand the impact of standardization to the used electric vehicle battery and energy storage market, it is critical to evaluate alternative approaches to integrating used EV batteries into stationary energy storage systems without standardization. Evaluating these alternative technical approaches is also important in the sense that lessons learned by those having to integrate used electric vehicle batteries into stationary storage systems could help inform the design concepts for standardization.

A number of research and small-scale commercial projects have demonstrated the use of used electric vehicle battery systems for stationary energy storage. Six of these proof-of-concept projects have been identified. Feedback from key contacts at companies participating in these projects was solicited when possible. Of particular interest to the current project was the use of non-standardized electric vehicle batteries, with regards to the challenges, additional costs (engineering design, labor, and integration), maintenance requirements, and safety concerns. The following is a list of the seven proof-of-concept projects.

1. Partnerships between SDG&E, UCSD, CCSE and AeroVironment (2011-2014)
2. Partnership between BMW, Princeton Power, EVGrid, and CCSE (2013)
3. Prototype designed by Manitoba HVDC Research Centre (2013-2014)
4. Partnership between Sandia National Labs, General Motors (GM) and ABB (2010, 2013)
5. Partnership between NEC, Nissan and Sumitomo (2009) presently referred to as 4R
6. Partnership between Duke Energy and Itochu (2010)
7. Paternership between University of Delaware and NRG Energy Inc. (2013).

The BMW system is described in Chapter 3. For more information on the basics of each partnership/project see the Chapter 2 Appendix.

2.6 Demand Side Industry Interviews

The projects thatthe researcherswere able to obtain more information on were projects (1) through (3). Key contacts involved in the projects were interviewed. The sponsoring organizations and interviewees were allowed to remain anonymous. The information gathered in these interviews is summarized below in Figure 210. Figure 211 provides the overall structure of the interviews conducted and the questions posed to participants.

2.7 Demand Side Evaluation of Alternative Approaches

Figure 210: Summary of alternative technical approaches to integration without standardization interview responses

Evaluation of Alternative Approaches	Pros	Cons
1. Separate DC-DC convertor used for each battery pack.	-Non-common voltages, internal resistances, communication protocols of BMS, and a lack of standardization are no longer an issue. -If battery packs need to be replaced, the DC-DC converter is still useable. -Only one DC-AC converter needed. -Each battery pack can be operated on a different duty cycle simultaneously.	-Loss in roundtrip efficiency -More costly -Additional power electronics
2. Battery packs are kept intact after vehicle life.	-BMS does not have to be reconstructed -Less additional costs needed due to a reduction in repurposing and repackaging of the pack	-Bad cells or modules cannot be replaced.
3. Battery packs from the same model vehicle are combined into a single system.	-Non-common voltages are no longer an issue.	-Limits flexibility of second use market. -Weakest battery pack limits the ability to use system fully. -Lower-voltage packs may degrade faster.
4. New BMS system is designed if packs are combined or disassembled and reassembled.	-Multiple packs can operate as a single larger storage system.	-Additional software and hardware development.

Evaluation of Alternative Approaches	Pros	Cons
5. Battery and/or OEM manufacturers are partners on the project.	-BMS infrastructure does not have to be redesigned.	-Non-disclosure agreements are required. -Additional costs to gain intellectual property rights.
6. Battery packs are tested for state of health after first use, prior to entering second use.	-Allows for the selection of packs for second use based on internal resistance and capacity loss.	-Additional labor required. -Requires knowledge of operational limits and access to testing equipment.
7. Employ use of battery pack for grid services while vehicle is still on the road (vehicle-to-grid approach).	-Eliminates the need for separate siting and permitting measures to ensure safety because battery pack is not removed from the vehicle. -Reduces integration time and effort because external power electronics and an off-board BMS infrastructure are not needed.	-EVSE equipment must be able to handle bi-directional load flow.
8. One-off design system	-Flexible platform for duty cycle control and operation.	-Additional costs -Potential for unreliability. -Upgrades to one-off systems are not beneficial to future market products.

Figure 211: Structure and list of questions for alternative technical approaches to integration without standardization interviews

Structure of Interview Questions:
The impacts of a lack of standardization
1. Technical approaches to integration without standardization. Provide actual examples.
2. What were the challenges to reconfiguring these battery packs for a second use? In particular, • Additional costs associated with remanufacturing, labor, power conditioning equipment, maintenance • Intellectual property issues • Infrastructure constraints (electrical issues, transportation requirements)
3. What are the potential impacts of non-common voltages, watt-hours, resistances, and states of health on operating stationary energy storage systems? In particular, • Additional maintenance requirements • Accelerated degradation of battery states of health • Safety concerns
Opinions on standardization
4. What are your opinions regarding convergence or divergence of modules and cells?
5. What do you see as the primary commercial and technical barriers to module standardization?
6. Do you have opinions regarding potential mitigation approaches with focus on: • Acceptance of cell/module standardization • Battery company cell/module size and form factor analysis • Cell/module size trends converging/diverging on format • Industry movement for standard cells

2.8 Chapter 2 Barriers Analysis Summary and Conclusions

Technical and commercial barriers to standardized battery modules and packs were identified for both supply (first use automotive applications) and demand (second use energy storage applications).

Resources employed in the study included a literature review and interviews with industry stakeholders. Stakeholders included representatives of vehicle OEMs, battery suppliers, researchers, as well as standards organizations and regulators.

The results of the Barriers Analysis were employed during the Design and Analysis for Standard Modules (see Chapter 3), along with battery performance requirements, to design and analyze standard modules for both first second use applications.

Supply Side: The project team identified key supply-side technical barriers divided into two categories: technical and commercial for both vehicle OEMs and battery suppliers. Identified barriers include:

1. Packaging location and space requirements.
2. Electrical, electronic, thermal, and communications protocols for each application.
3. Durability.
4. Charge acceptance.
5. Safety.
6. Integration with second use requirements.
7. Remanufacturing requirements.

Key commercial barriers include:

1. Impacts of perceived safety issues.
2. Predictable and sustainable supply of cells, modules, and packs.
3. Uncertainty in costs.
4. Remanufacturing issues (standard vs. non-standard, and comparisons to bespoke battery packs).
5. Industry resistance to change and risk.
6. Unclear maintenance requirements, variation in system longevity.
7. Electrical & electrochemical compatibility.
8. IP and competitive position issues.
9. Cost

Key approaches to overcoming these barriers include:

1. Continuing with development of electric vehicle battery standards such as those now published by ISO/IEC and GM.
2. Improved education regarding industry requirements for both first and second use applications.
3. Promotion of cost savings and performance improvements resulting from standardization.

4. Development of cells and modules that are compatible with a wide range of battery chemistries and performance specifications (voltage, watt-hours, resistance).
5. Establishment of acceptable module specifications to facilitate "building block" approach to both vehicle and energy storage applications.
6. Development of thermal management systems that are compatible with multiple vehicle applications as well as energy storage environments.
7. Development of expanded communications and battery management systems containing options to facilitate a range of vehicle and energy storage applications.
8. Development of modules that facilitate remanufacturing processes for stationary energy storage.

Demand Side: Based on industry interviews, advantages and disadvantages were identified for the various technical approaches to integrating current design, non-standardized battery systems into second use stationary energy storage applications. A key disadvantage was the additional cost associated with the non-standardized designs, which must be modified for each application and thus cannot take advantages of the cost reductions associated with large scale production volumes. There are also non-recurring labor and design costs for this approach.

Other technical approaches to integrating PEV battery systems into second use, stationary energy storage applications include:

1. Use of separate DC-DC converter for each battery system
2. Keep battery systems intact after removal from vehicle
3. Combine like battery systems (from same model vehicle) into second use systems.
4. Develop new BMS for modules that are reassembled into second use systems
5. Develop partnerships between battery and vehicle OEMs to allow reconfigurable BMS to be employed during both first and second use applications
6. Employ rigorous end-of-first use testing and upgrade program, to allow for the selection of systems for second use based on key performance paramenters.
7. Develop systems that will allow extension of vehicle-to-grid interfaces into second use.
8. Develop customized (one-off) systems based on characteristics of available battery systems for second use applications.

The study also produced recommendations for facilitating integration of used electric vehicle battery systems into stationary storage applications and to reduce the cost of this transition. These included:

1. Create a standard location for the placement of variables in CANbus packets

2. Design the safety system to be internally integrated. Battery manufacturer to provide documented guidance on the operational parameters of the battery system for the second use operator
3. Have industry-wide standard testing protocols to check state of battery health at end of first use, with conditionals for different cell types and manufacturers
4. Establish standard module voltages and communication ports and protocols

2.9 Chapter 2 References

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CHAPTER 3: Design Concepts: Standards Design

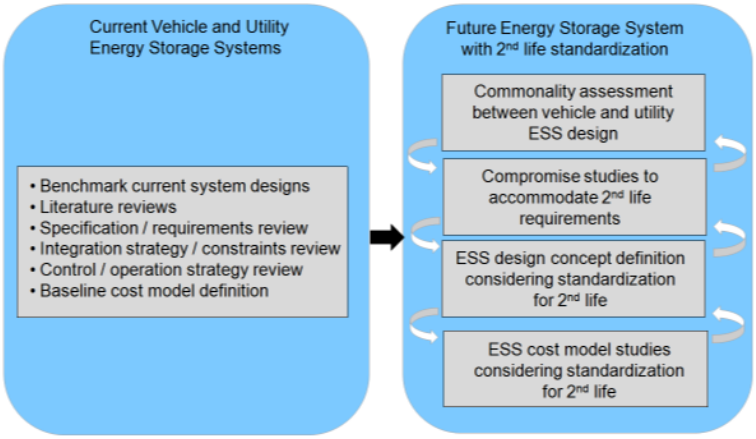
Goal

The goals of the Design Concepts: Standards Design, were to conduct design and analysis of standard lithium ion modules and battery systems, to demonstrate a second use battery energy storage system, and to perform a cost/ benefit analysis of standardization impacts on first use battery systems.

3.1 Executive Summary

The Design Concepts: Standards Design portion of the project included development of standardized design concepts for lithium-ion battery systems, evaluation of currently available lithium-ion battery system specifications and communication protocols, determination of the cost impact of standardization on the price of batteries delivered to vehicle OEMs, design and demonstration of a second use battery energy storage system, and the evaluation of pathways for implementing PEV battery pack standards.

Figure 212: Design Concepts Approach



The baseline standardized module and pack designs were based on identification of critical performance requirements, evaluation of available design options, and definition of design compromises based on input from industry stakeholders.

In keeping with the application focus of the current study, two standard battery pack designs were developed for commercial vocational vehicles. The packs were based on the following design parameters:

1) Module energy of 5kWhr: Supports 25 kWhr battery system energy increments and allows reasonable series and parallel cell configuration within module

2) Cell types: GM standard pouch cell (A123 and LG Chem cells) and VDA PHEV2 prismatic cell

3) Module dimension: Keep to minimum to maintain energy density

   Driven largely by cell configuration

The standardized battery pack communication systems and BMS interfaces were also defined.

A market research study was completed for commercially available energy storage modules of varying specifications, including size, voltages, and energy capacities. The market research was conducted to give an overview on the specifications of many different existing energy storage modules (totaling 20+ from 9 different companies). The research included tabulation of specifications and identification of trends and patterns of available energy storage modules to facilitate development of the standardized EV battery modules.

A cost/benefit analysis was completed based on a value chain assessment of the battery life cycle beginning with the battery manufacturing process, the first use vehicle application, and the transfer from vehicle to stationary energy storage application.

The impact of standardization on EV OEM module and battery price (delivered price to vehicle OEM) was determined using a lithium-ion manufacturing cost model. Individual component costs were defined as a function of the delivered battery price to the vehicle manufacturer. During Task 5 (Chapter 4), the impact of standardization on battery price for second use applications was quantified, along with the value derived from the individual players in the supply chain.

The battery manufacturing cost model included both unit (module/battery) costs as well as system (thermal and battery management systems, cables, connectors, and housing) costs to determine the sales price to the vehicle OEM.

Each cost component was evaluated to determine the impact of standardization. This included assessments of variable costs, fixed expenses, profit warranty, pack integration, and addition of thermal and battery management systems.

Materials and purchased items were found to range from 45 percent to 76 percent of the delivered battery price, depending upon battery chemistry and topology. It was determined that standardization could reduce these costs between 3 percent and 12 percent of the delivered battery price.

Direct labor represents between 0.4 percent and 7 percent of the delivered battery price, again depending upon battery chemistry and topology. Standardization can reduce direct labor costs between 0.4 percent and 1 percent of the delivered battery price.

Other cost components, such as GSA, R&D, overhead, depreciation, and warranty are projected to be impacted by standardization within the range of 0.4 percent to 1.6 percent.

Addition of thermal management systems and pack integration adds between 20 percent and 29 percent to the delivered battery price. Standardization can reduce these between 2.5 percent and 5.75 percent of the delivered battery price.

Standardization thus has the potential to reduce the delivered battery price to the vehicle OEM by 3 percent to 15 percent.

BMW led the development of a grid-tied stationary energy storage system located at the University of California San Diego which integrates six used MINI E high-voltage Li-Ion battery packs. The system architecture was dictated by the goals of design for commercialization and reuse of vehicle components. The system safety concept relies on each battery to be self-protecting, reducing the need for higher level safety measures and enabling a standard interface to any proprietary vehicle BMS design. The introduction of the "Super BMS" system between the vehicle BMS's and the site controller and inverter is another key to enabling communication interface standardization.

Potential pathways to implementing PEV battery pack standards were identified and included:

1. Participation in standards committees for OEM and stationary battery industry organizations, such as SAE, ISO/IEC, IEEE, and IEC.
2. Improved education regarding industry requirements for both first and second use applications.
3. Preparing and presenting technical papers containing results of battery standardization analyses.
4. Promotion of cost savings, savings, and performance improvements resulting from standardization.
5. Development of cells and modules compatible with a wide range of battery chemistries and performance specifications (voltage, watt-hours, resistance).
6. Identification of acceptable module specifications to facilitate "building block" approach to both vehicle and energy storage applications and preparation of "draft" specifications for delivery to standards organizations.
7. Development of expanded communications and battery management systems containing option to facilitate a range of vehicle and energy storage applications.
8. Development of modules that facilitate remanufacturing processes for stationary energy storage and remain compatible for EV use.

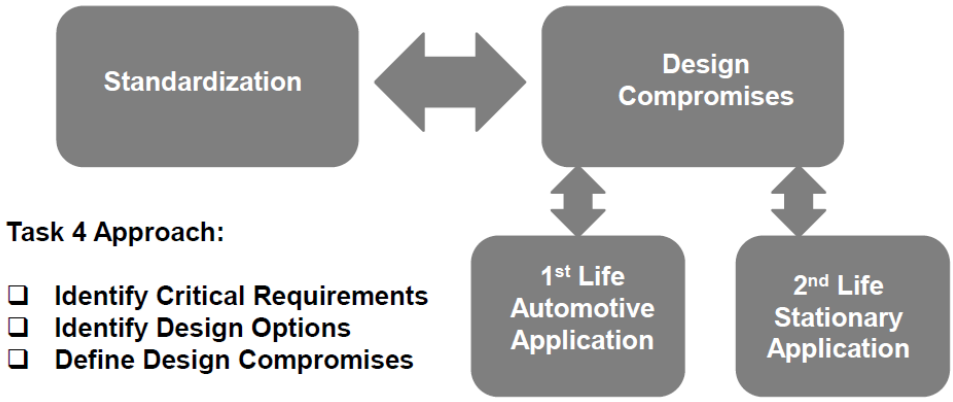
3.2 Introduction to Design Concepts: Standardized Design Scope of Work

During the Market Analysis economics study, six categories of vocational vehicles were identified as sources for standardized second use batteries based on a number of factors, including favorable cost of ownership and compatibility with battery systems appropriate for stationary energy storage applications. Also during the Market Analysis, it was demonstrated that a significant number of commercial vehicle batteries will become available for second use applications starting in 2019. During the Barriers Analysis, design guidelines for standardized batteries for commercial electric-drive vehicles were developed. During the Design Concepts

phase, these guidelines and specifications were employed to develop design concepts for standardized battery modules and systems and to subject these designs to a cost/benefit analysis.

The first key activity for the Design Concepts study was to conduct an analysis of design requirements for standardized modules and battery systems and to develop two concept designs for application to commercial vocational vehicles. This process is illustrated inFigure 213.

Figure 213: Design Process



A second, related activity was to develop benchmarks of current lithium ion system designs and map current communication protocols. The specifications tables from the benchmark exercise provided guidance for the concept design process as well as insight regarding the range of differences in current specifications as a gauge for assessing the standardization challenge. The communications protocol survey was used as input assessing second use BMS requirements, including interface with the smart grid.

To assess the economic viability of standardized modules and battery systems, a cost/benefit analysis was performed for first use batteries. This included an evaluation of potential cost reduction methods to reduce the price of battery systems delivered to the vehicle OEMs.

To demonstrate design for second use and recycling, BMW teamed with UC San Diego to develop the largest battery second use (B2L) application in North America. This grid-tied stationary energy storage system uses 6 high-voltage lithium ion battery packs from earlier BMW MINI E Field Trials.

The final activity of the Design Concepts includes the evaluation of potential pathways for implementing PEV battery pack standards, an extension of the barriers-to-standardization work which began during the Barriers Analysis.

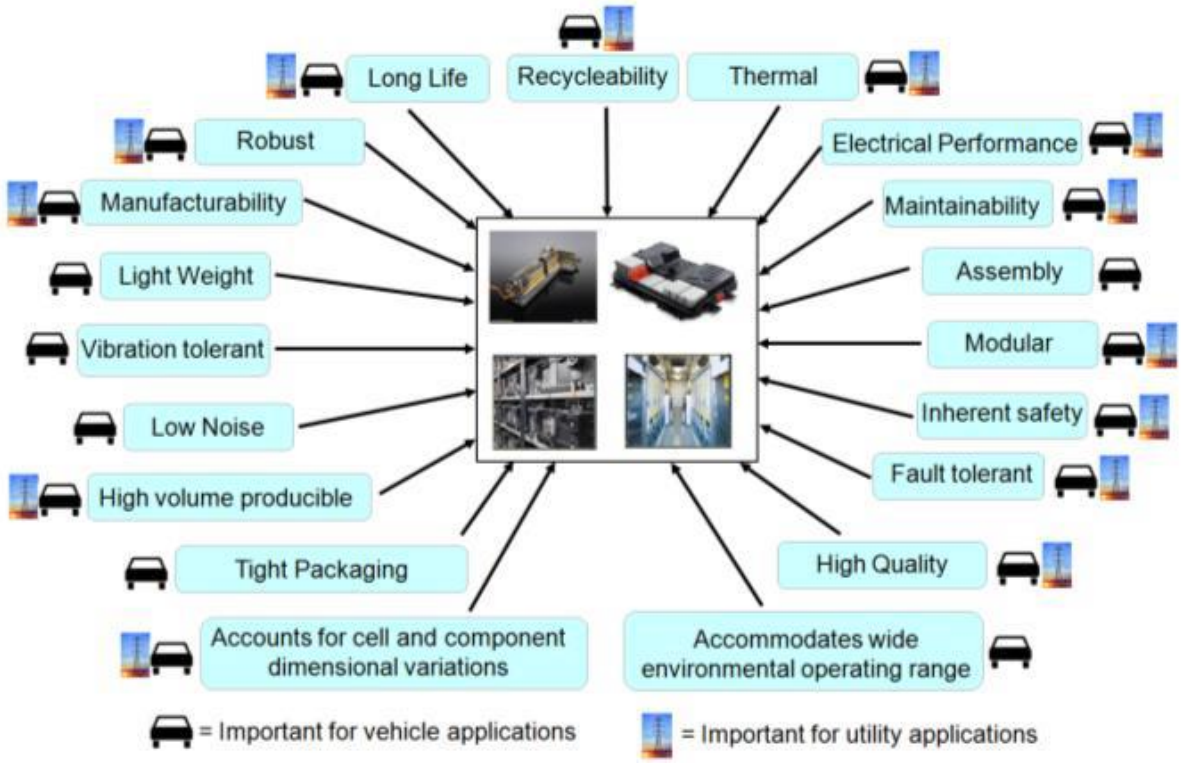
3.3 Development of Standardized Lithium-Ion Module Design Concepts

Accommodating second use standards within an energy storage system (ESS) can significantly impact overall ESS design strategy. Challenges include difficulty of integration within the application and associated costs, including those associated with development, capital requirements and maintenance. As noted in Figure 214, a variety of design options exists and must be evaluated to ensure compliance with operational and economic constraints for both first and second use applications.

Figure 214: Conduct Design and Analysis for Standard Modules

Although the automotive and utility stationary energy storage system environments are very different, the design drivers for both applications are similar. Priorities had to be assigned to the various design drivers. These drivers are illustrated in Figure 215.

Figure 215: Energy Storage System Design Priorities by Application



A subset of the automotive storage system attributes was defined for utility applications including:

- Form Factor (shape and dimensions)
- Electrical Interfaces
- Communications Interface and Protocol
- Housing and hold-down systems, including mounting locations
- Environmental controls (e.g. temperature, humidity)
- Safety systems (e.g. fire suppression)
- Noise suppression
- Transportation to site (e.g. shock loads, temperature

In addition, the target first use concept designs addressed potential second use standardization efforts. The design process included:

- An iterative approach to evaluating design options, including discussions with industry stakeholders and literature review.

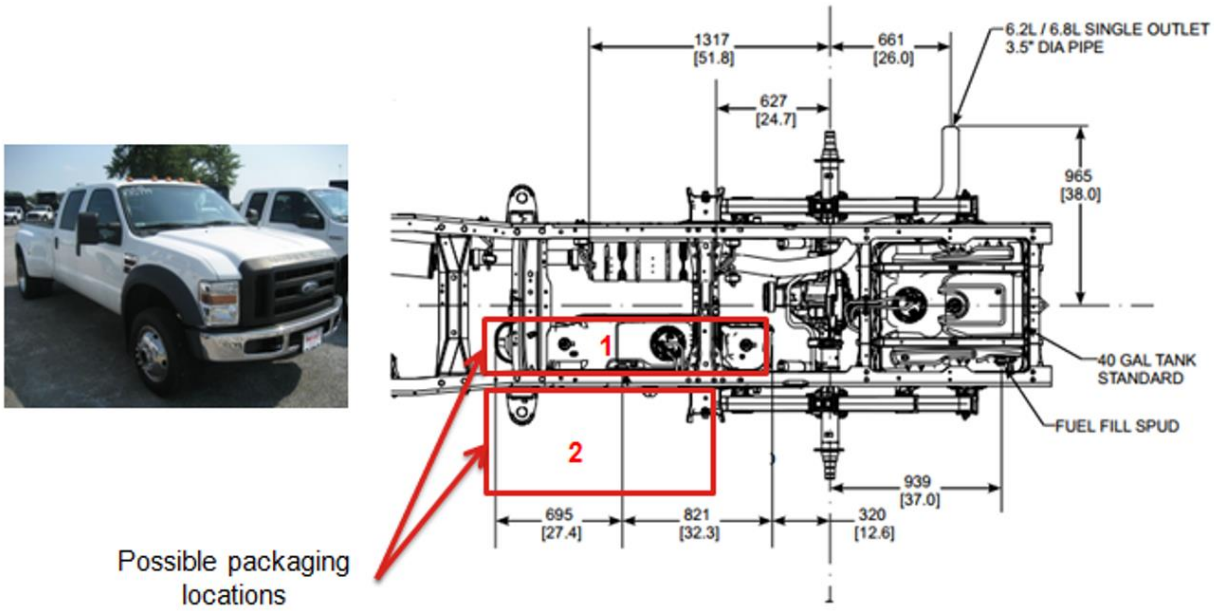
- Preparation of design constraints and design targets: balance priorities and needs between the vehicle and stationary storage applications.
- Identify common and unique features of each application.
- Conduct high-level strategy sessions to balance priorities between first use automotive applications and second use stationary energy storage applications.
- Leverage stakeholder experience; obtain stakeholder input to ensure viability of concepts under development and select reasonable and credible pathways to implementation.

3.3.1 Standardized Module and Battery System Requirements

Two conceptual, standardized lithium ion battery system designs, for application to commercial vocational vehicles were developed for this analysis. Battery system requirements were initially kept to a minimum to prevent elimination of candidate technologies. Based on the Barriers Analysis reviewed in Chapter 2, the following design requirements were selected.

- Battery system energy storage capacity of 25 kWh. This capacity requirement was chosen based on known commercial vocational vehicle drive cycles: as noted in Chapter 2, the energy required for these drive cycles can be categorized in increments of 25 kWh. Thus, baseline 25 kWh systems can be combined to provide the required energy for all of the duty cycles associated with the selected vocational vehicles.
- Cell Type and Size: the following cell types were chosen because they allows reasonable series and parallel cell configurations within each module
    - GM Pouch Cell (A123 and LG Chem Cells): it is noted that these cells are produced in large volumes and thus have favorable pricing.
    - PHEV 2 Prismatic can: this is the only currently-released industry standardized cell (based on standard of ISO/IEC PAS 61850:2012)
- Battery System Size: configured to fit on outside of commercial vehicle frame rail between cab and rear wheels. The space claim is based on vehicle outfitter manual. Possible packaging locations are illustrated in Figure 216.
- Module Dimensions: high energy density cells were chosen to minimize module dimensions and maintain energy density.

Figure 216: Packaging Options for a Class 4 Truck



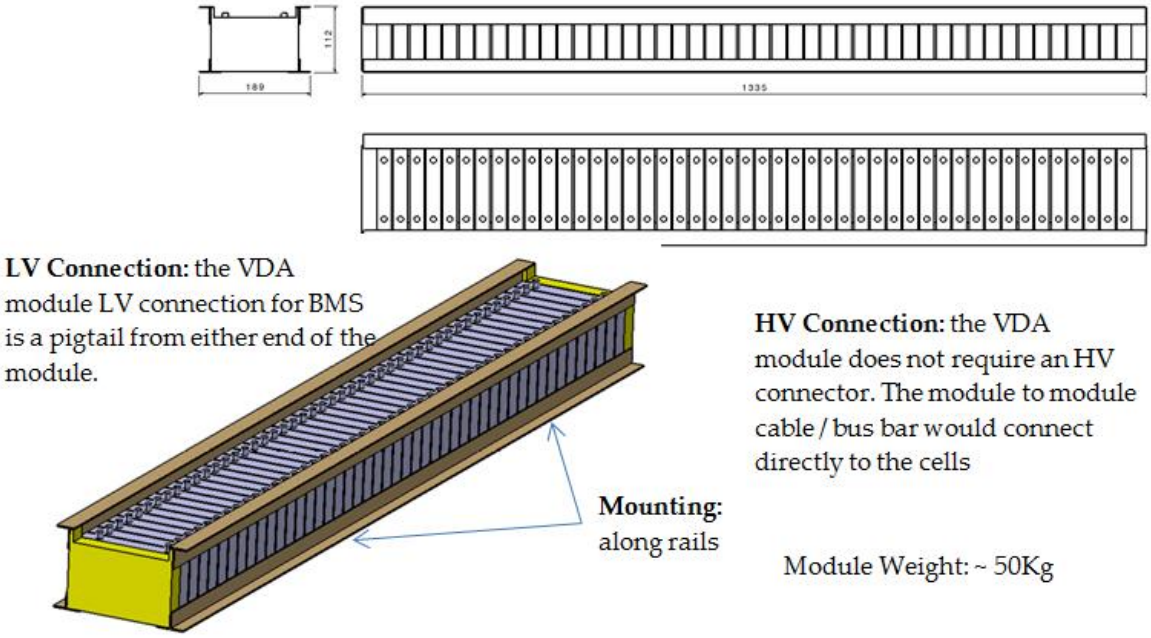
The following cell configurations were determined for a 5 kWh module:

- A123 (20Ahr cell) 5kWh module configuration is a 25S3P
- LG Chem (15Ahr cell) 5 kWh module configuration is 30S3P
- VDA PHEV 2 (30Ahr cell) 5 kWh module configuration is 23S2P

The module and battery system configurations for the two standardized designs are shown in Figures 200 through 203. The modules are designed to both General Motors (GM) and Verband der Automobilindustrie (VDA) PHEV2 standard dimensions. Note that LV refers to the low voltage module connection and HV refers to the module high voltage connection.

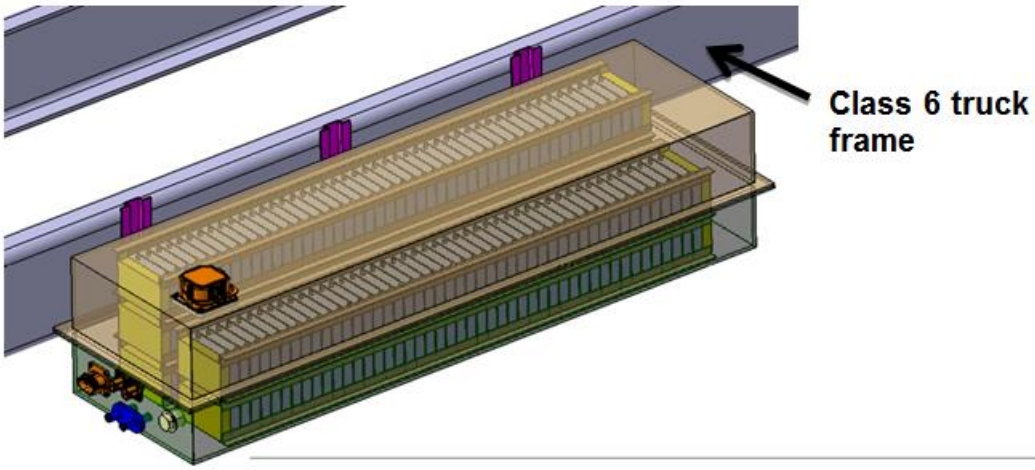
VDA PHEV2 5 kWh 23S2P Standard Module

Figure 217: VDA PHEV2 5 kWh 23S2P Standard Module Design Concept



VDA PHEV2 25 kWh Battery Pack

Figure 218: VDA PHEV2 25 kWh 23S2P Battery System Design Concept



Pack Size	L 1540, H 352, W 477
Modules	5 x 23S2P
Estimated weight	330 Kg

GM Pouch Cell, A123, 5 kWh Standard Module

Figure 219: GM Pouch Cell, A123, 5 kWh Standard Module Design Concept

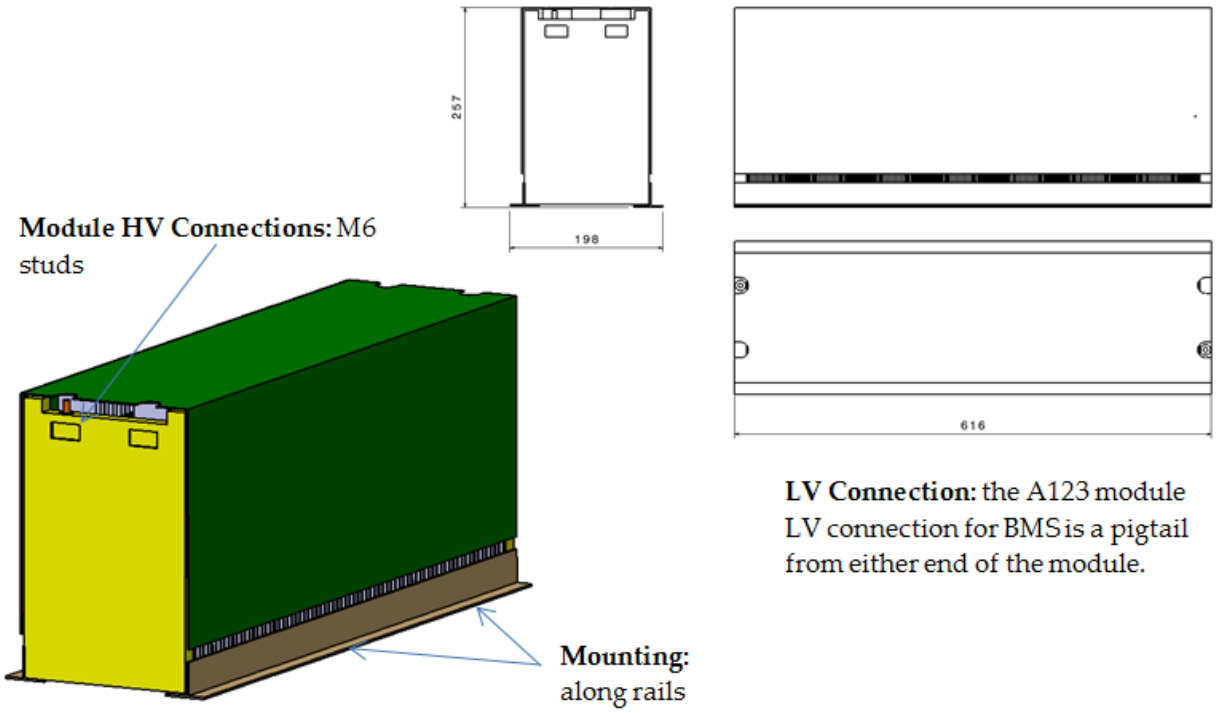
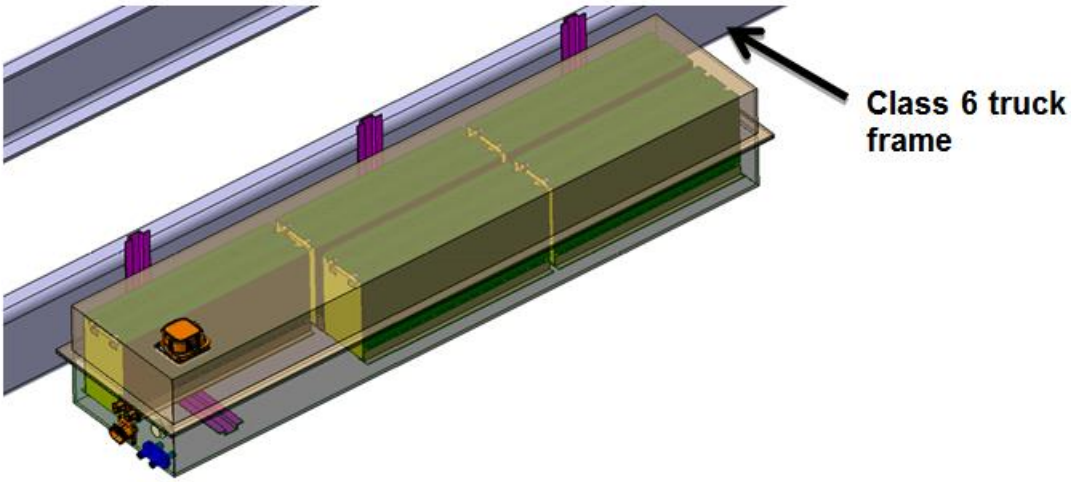


Figure 220: GM Pouch Cell (A123) 25 kWh Battery Pack Design Concept



Pack Size	L 2000, H 317, W 477
Modules	5 x 25S3P
Estimated weight	235 Kg

3.3.2 Module BMS Interface - Digital

The BMS requires voltage and temperature signals (either digital or analog) from the module. A digital interface requires an electronic control unit on the module. Examples of modules employing digital communications are shown inFigure 221.

- Chevy Volt, Chevy Spark and Mitsubishi i-Miev employ digital communication with the BMS.
- Voltage and temperature information are communicated to master BMS controller using CAN.

Figure 221: Examples of Battery Systems with Modules that Employ Digital BMS Interface

The following signals are required for a digital module BMS interface as shown in Figure 222.

Figure 222: Digital Module BMS Interface: Required Signals

Signal	Description
CAN Low	CAN communication negative
CAN High	CAN communication positive
ECU Power	Power for module ECU
ECU Ground	Ground for module ECU
Safety Signal	Redundant analog safety signal, typically included in automotive BMS systems

3.3.3 Module BMS Interface – Analog

An analog interface requires a wiring connection to a centralized BMS:

- Ford Fusion HEV/PHEV, Ford C-MAX HEV/PHEV, Toyota Prius HEV/PHEV and Nissan Leaf employ analog communication with the BMS.

- Voltage connections are required for each cell group.
- Sensors can be configured to record temperatures at each individual cell or for each packaged group of prismatic cells. Temperature measurements are required as part ot the state-of-charge calculation within the BMS. The temperature sensors can identify failed cells and provide input for the BMS safety and life-extension logic.

Figure 223: Examples of Battery Systems with Modules that Employ Analog BMS Interface

The following signals are required for an analog module BMS interface shown in Figure 224.

Figure 224: Analog Module BMS Interface: Required Signals

Signal	Description	Circuit Quantity		
		A123 25S3P	LG Chem 30S3P	VDA 23S2P
Voltage	Pair of circuit connected across each cell group providing voltage measurement	26	31	24
Temperature	Module temperature sensors, assumed 2-4 per module	4-8	4-8	4-8

3.4 Benchmark Current Designs and Map Current Communications Protocols

To understand the stationary storage market, over twenty existing commercially available energy storage modules manufactured by nine different companies were surveyed. These systems varied in size, voltages, and energy capacities. The market research was conducted to

give an overview on the specifications of many different existing energy storage modules. Graphical interpretation of these varying specifications exposes trends and patterns of existing energy storage modules to benchmark the designs of the standardized first use EV battery modules.

Limitations on the ability to design a battery pack and specify electrical parameters for the second use purpose may impact how the secondary stationary storage system is configured in one-off projects. Therefore, the second use stationary storage system may be configured in such a way that is optimal to the first use vehicle design of the packs and less optimal to the grid requirements in second use. If second use requirements are considered in first vehicle life design, the stationary storage system might not only be easier to configure and less costly, but also perform more optimally for its specific purpose, i.e. grid energy storage applications.

3.4.1 Battery System Specifications

The following is a complete list of battery characteristics identified with units indicated in parenthesis. Stationary storage specifications listed in the list and datasets that follow apply to the module level, unless otherwise specified.

- Cell Form Factor
- Battery Chemistry
- Nominal Voltage (Vdc)
- Maximum Continuous Charge & Discharge Current (A)
- Number of Cells
- Cell Configuration (#S #P)
- Energy (kWh)
- Power (kW)
- Capacity (Ah)
- Length (mm) x Width (mm) x Height (mm)
- Volume (cm3)
- Weight (kg)
- Energy Density Gravimetric, a.k.a. Specific Energy (Wh/kg)
- Energy Density Volumetric (kWh/m3)
- Voltage Specific Density (kV/ m3¬)
- Voltage Density (V/kg)
- Charge & Discharge Impedence (mOhms)

- DC Internal Resistance (mOhms)
- Minimum & Maximum Optimal Operating Temperature (degC)
- Minimum & Maximum Operating Temperature (degC)
- Cooling Requirements (A stands for Active and P stands for Passive)
- Communication Systems (Serial Data Interfaces & Protocols)
- Safety

Highlighted in the following figures are graphical summaries of some of the battery characteristics collected.

Benchmark Current Designs and Map Current Communications Protocols

Figure 225: Benchmark Current Designs and Map Current Communications Protocols: Nominal Voltage

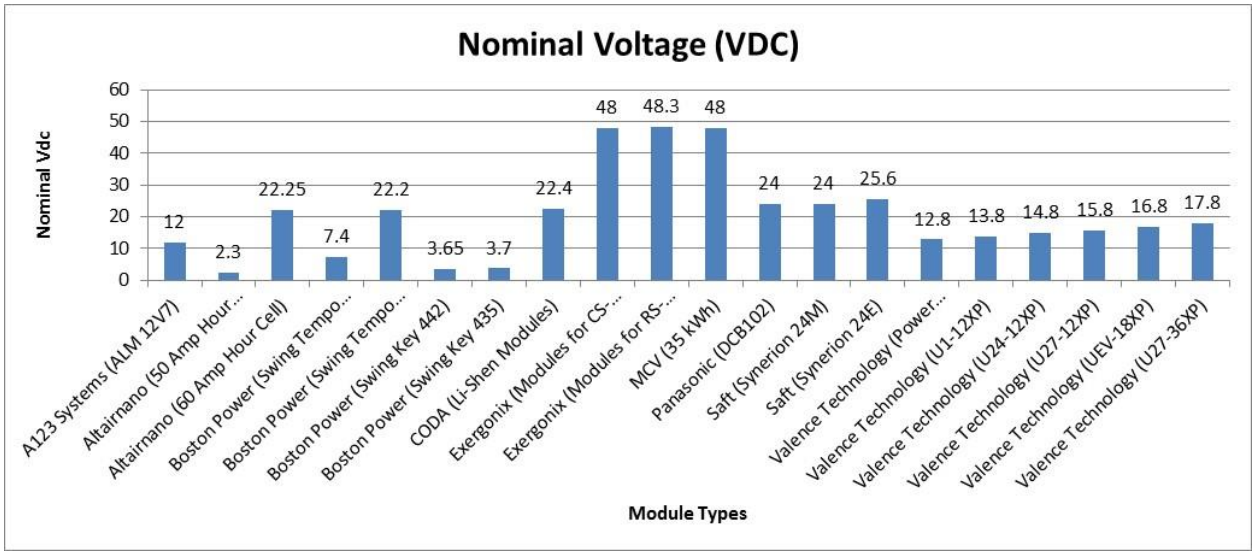


Figure 226: Benchmark Current Designs and Map Current Communications Protocols: Module Energy

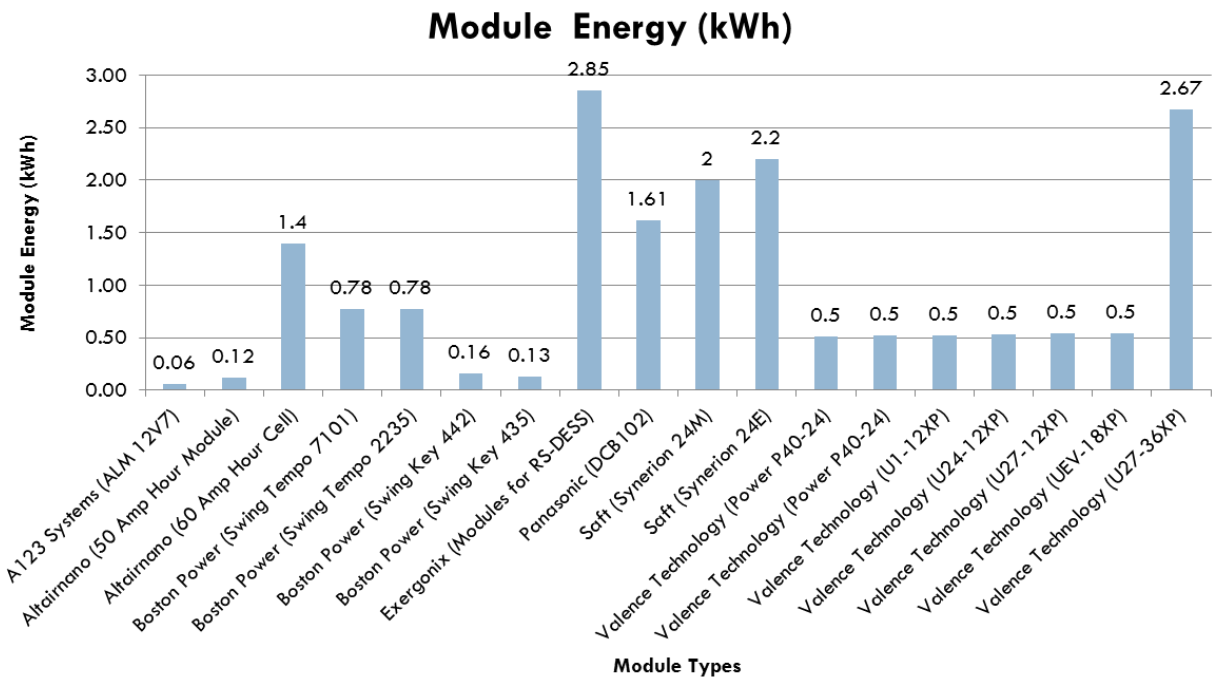


Figure 227: Benchmark Current Designs and Map Current Communications Protocols: Capacity (Ah)

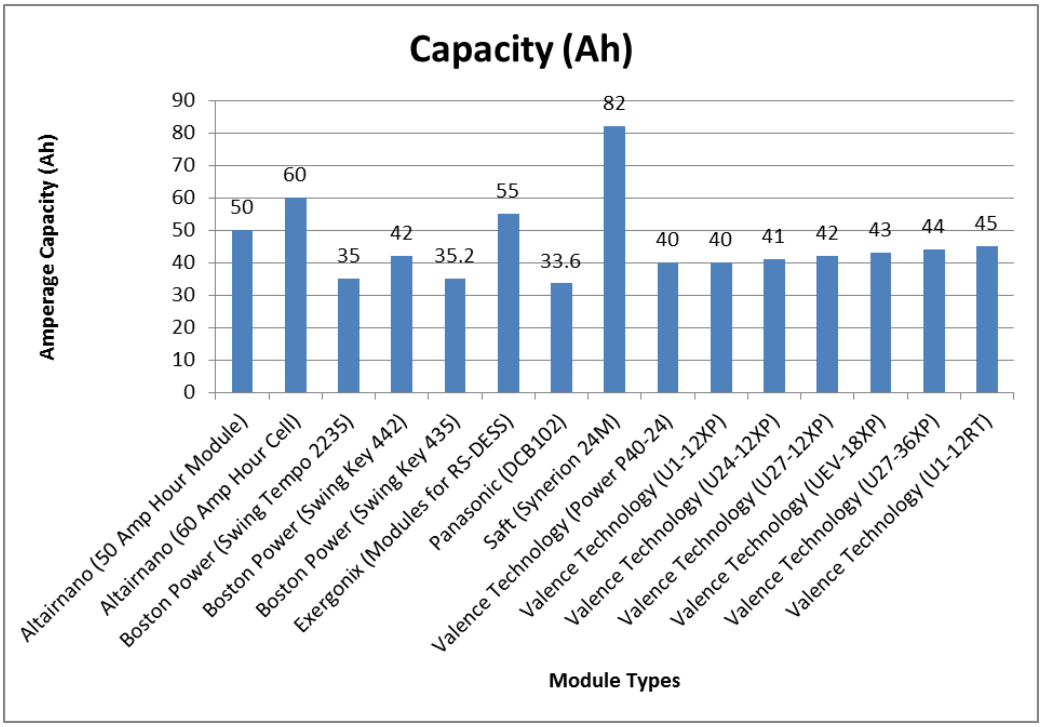


Figure 228: Benchmark Current Designs and Map Current Communications Protocols: Continuous Charge Current (A)

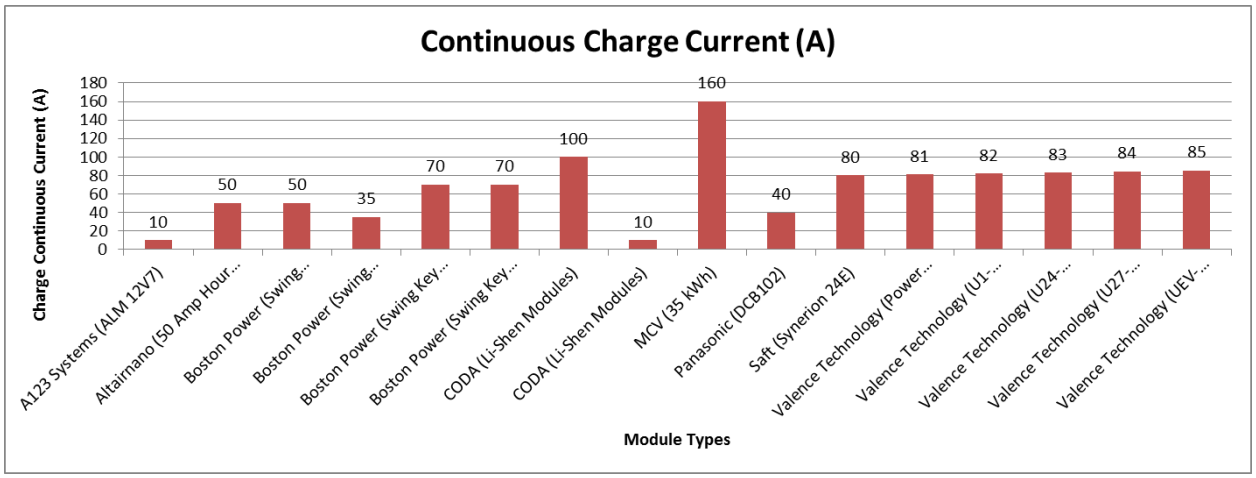


Figure 229: Benchmark Current Designs and Map Current Communications Protocols: Continuous Discharge Current (A)

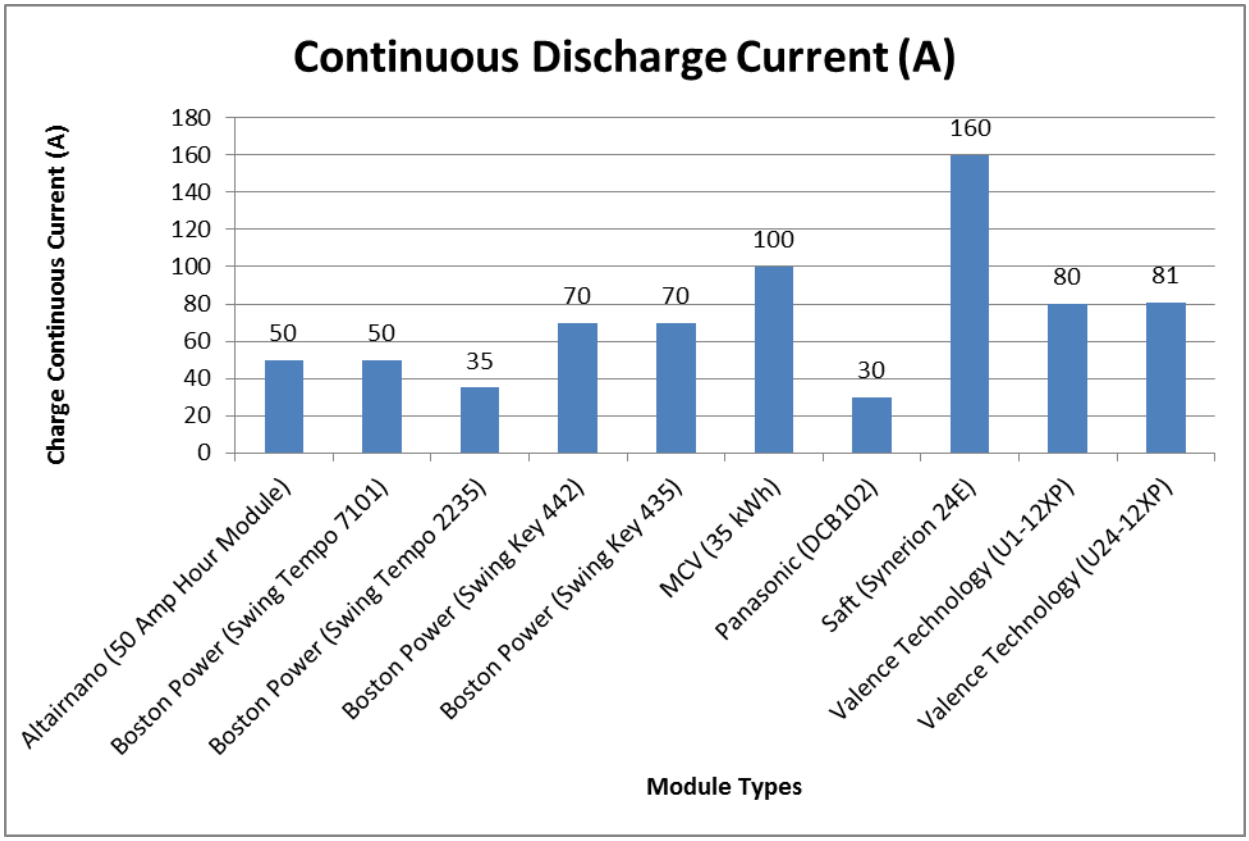


Figure 230: Benchmark Current Designs and Map Current Communications Protocols: Length

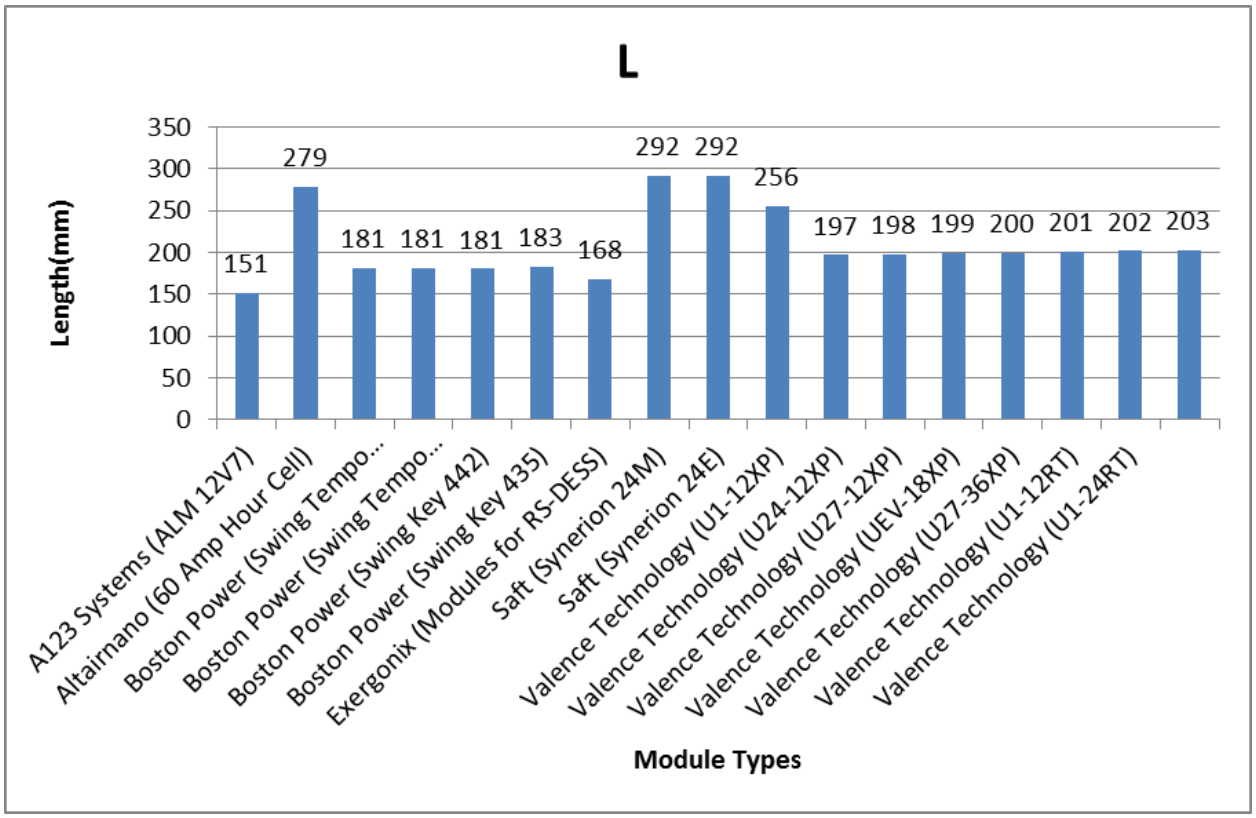


Figure 231: Benchmark Current Designs and Map Current Communications Protocols: Height

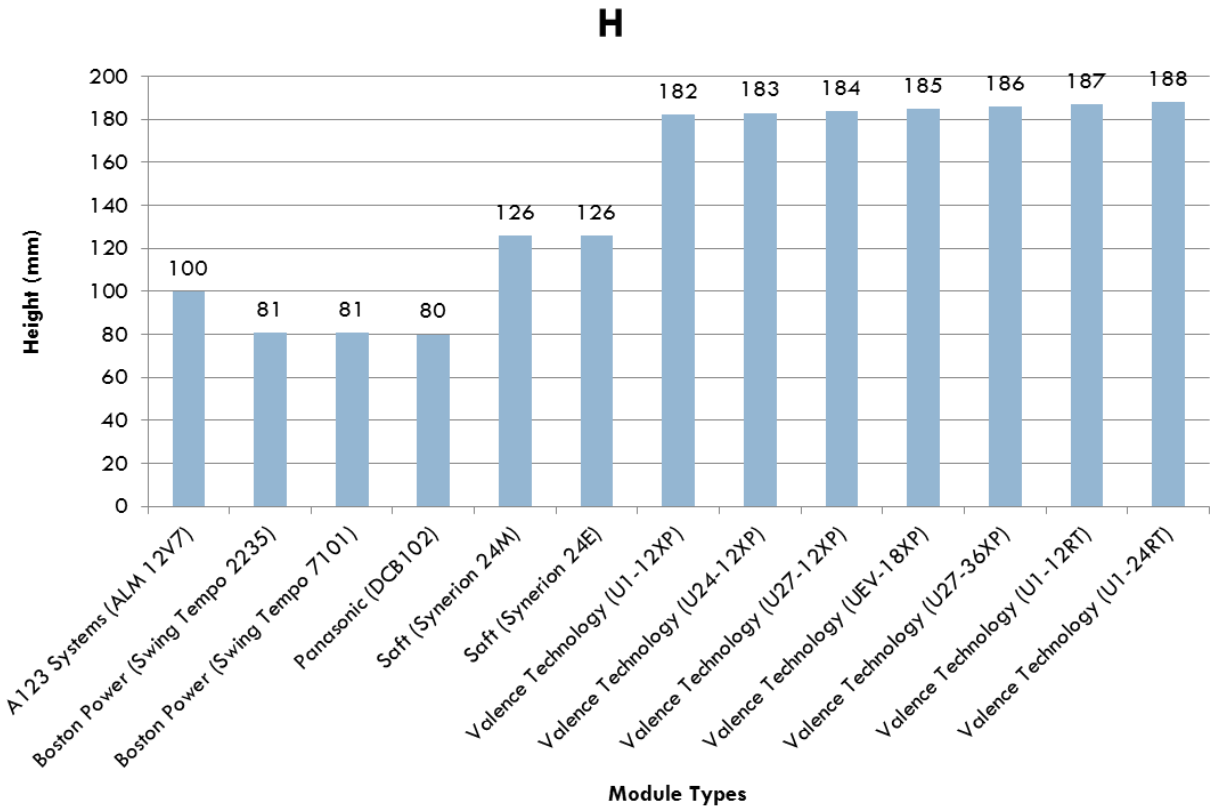


Figure 232: Benchmark Current Designs and Map Current Communications Protocols: Width

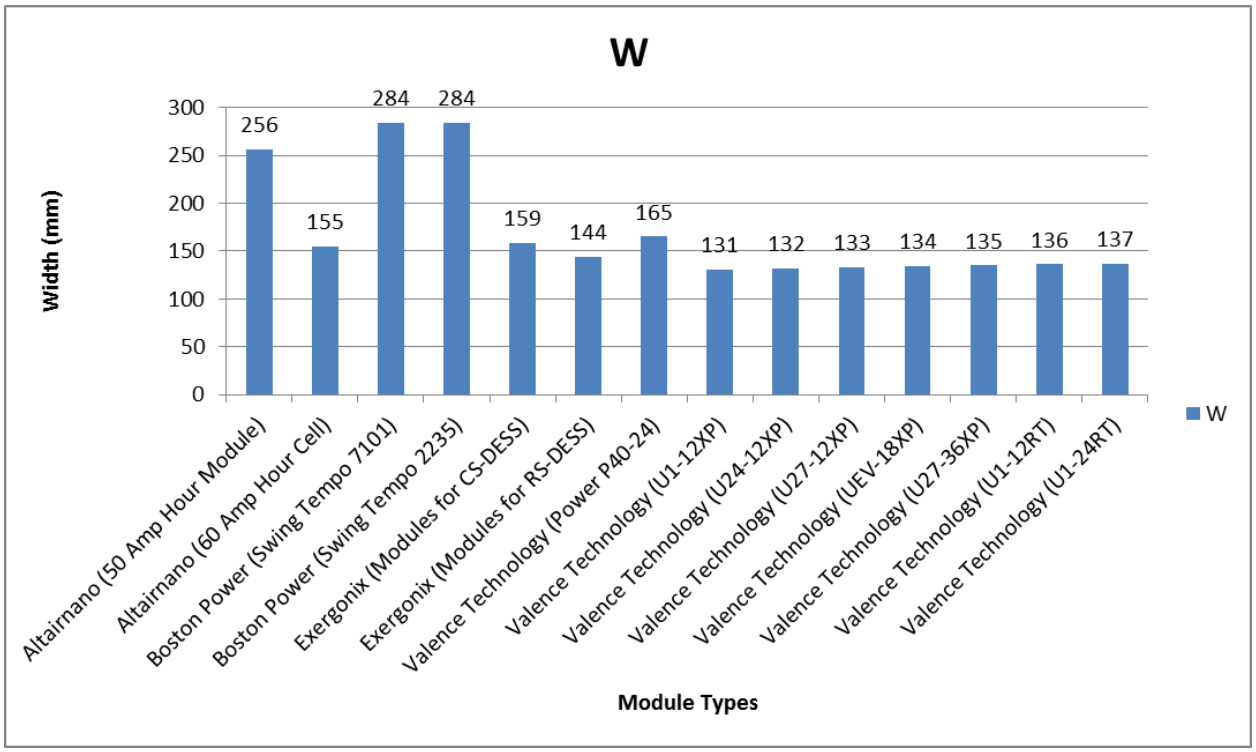


Figure 233: Benchmark Current Designs and Map Current Communications Protocols: Volume

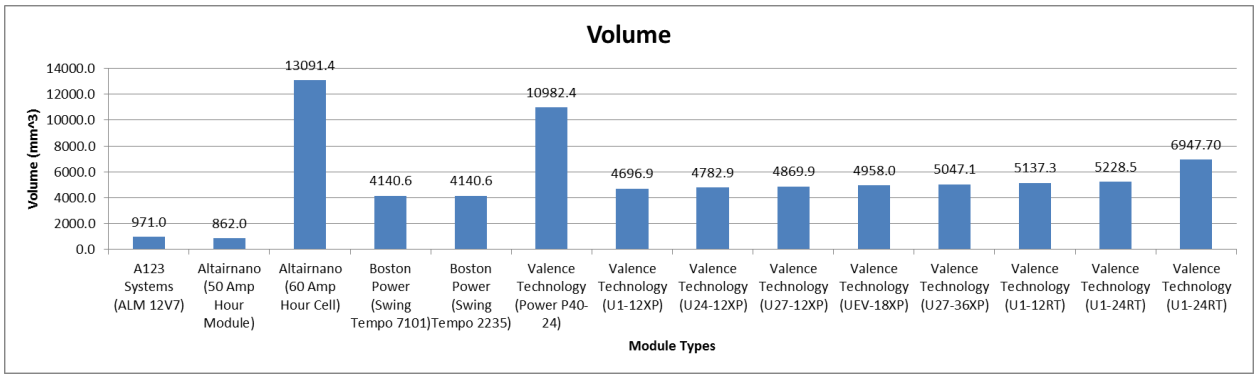


Figure 234: Benchmark Current Designs and Map Current Communications Protocols: Weight

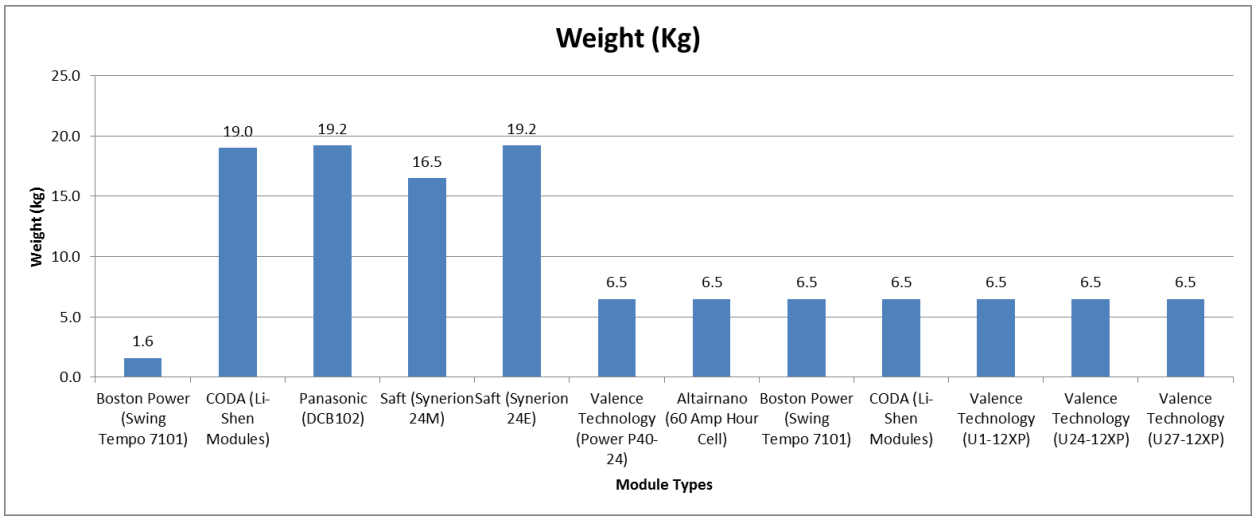


Figure 235: Benchmark Current Designs and Map Current Communications Protocols: Energy Density Gravimetric (Wh/kg)

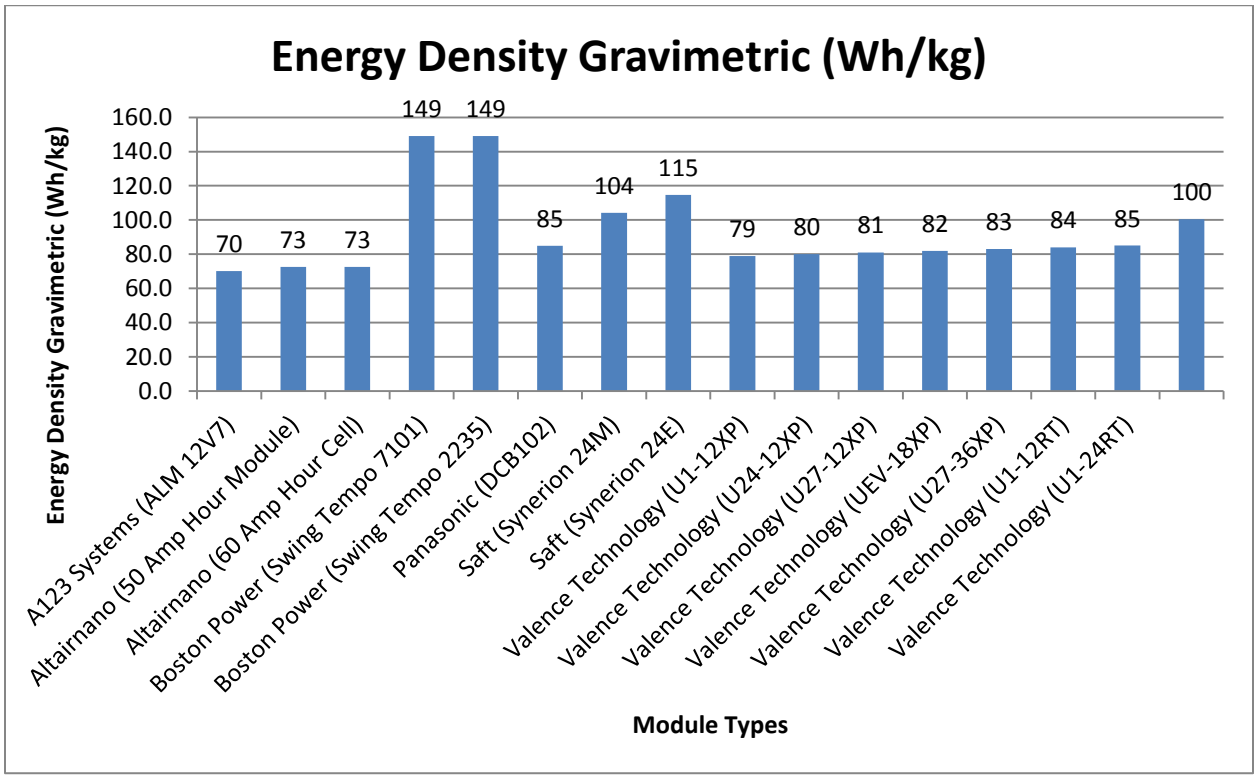


Figure 236: Benchmark Current Designs and Map Current Communications Protocols: Energy Density Volumetric (kWh/m^3)

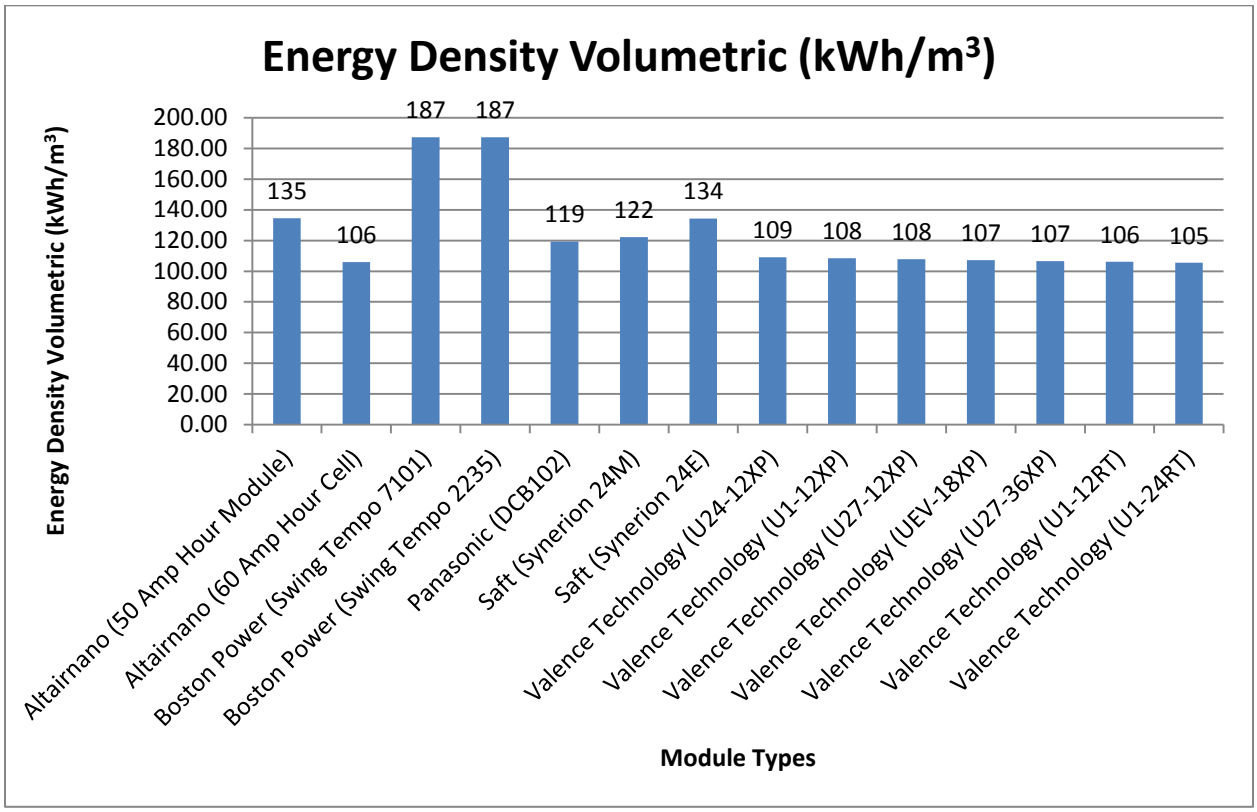


Figure 237: Benchmark Current Designs and Map Current Communications Protocols:Min Optimal Operating Temp (Celsius)

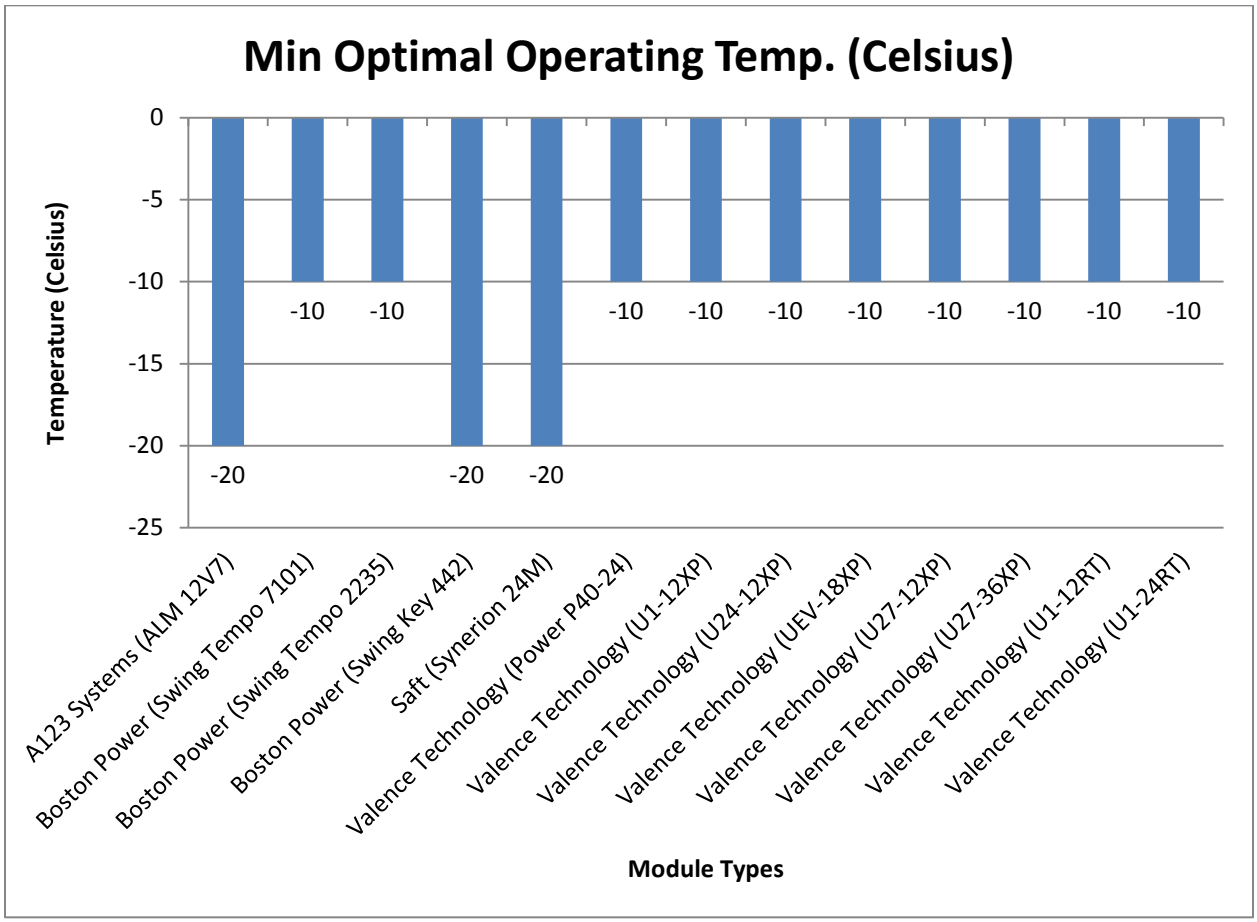


Figure 238: Benchmark Current Designs and Map Current Communications Protocols: Max Optimal Operating Temp (Celsius)

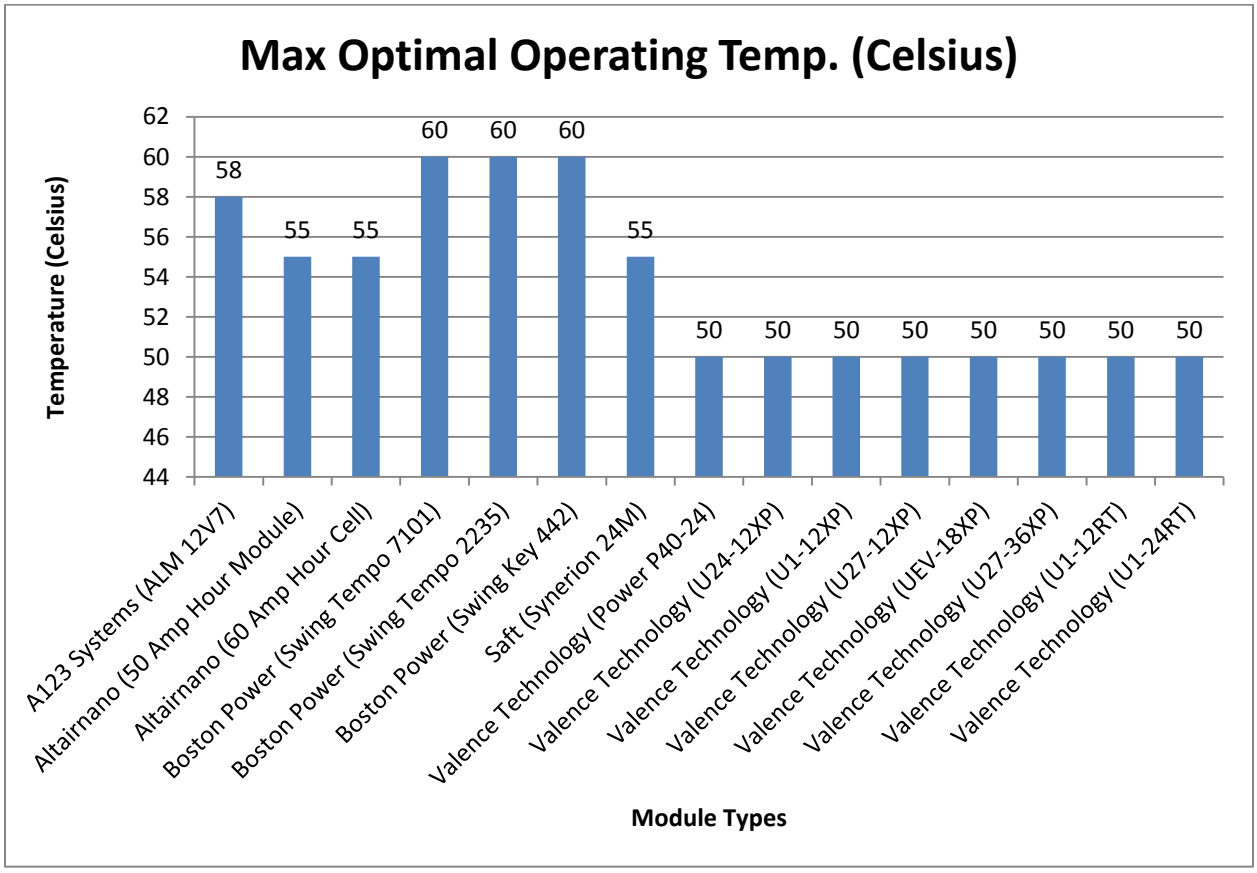


Figure 239: Benchmark Current Designs and Map Current Communications Protocols: Minimum Operating Temp (Celsius)

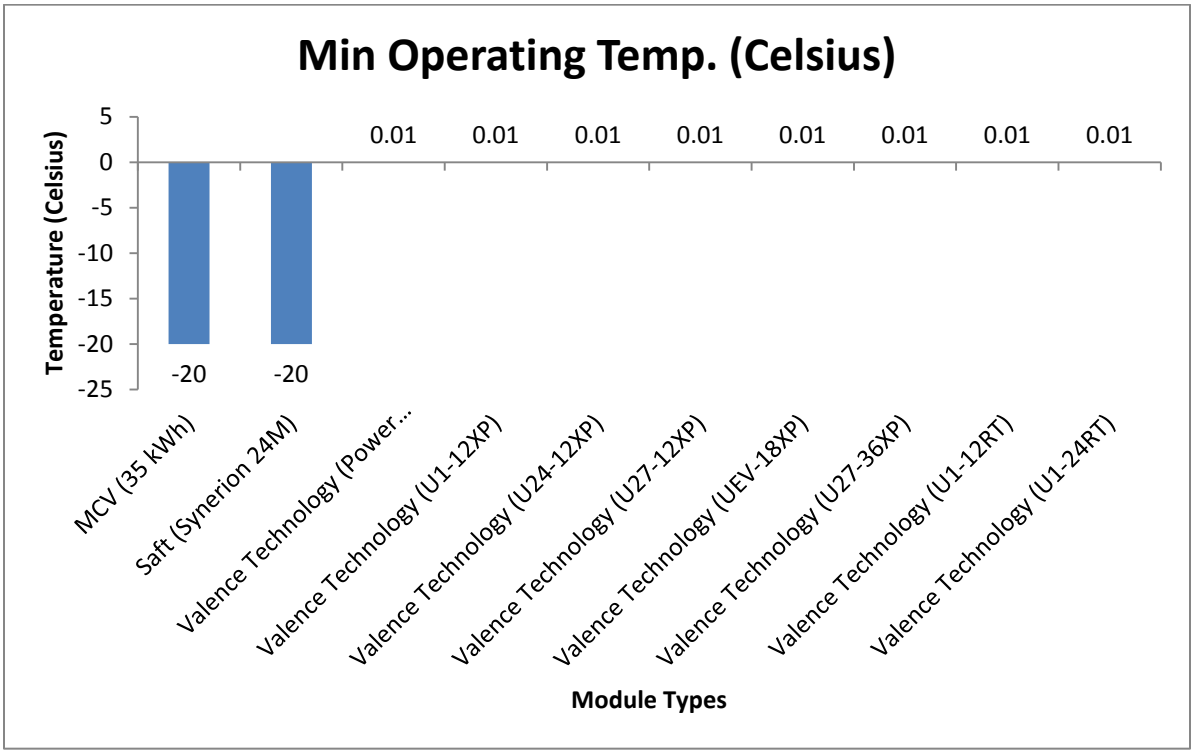
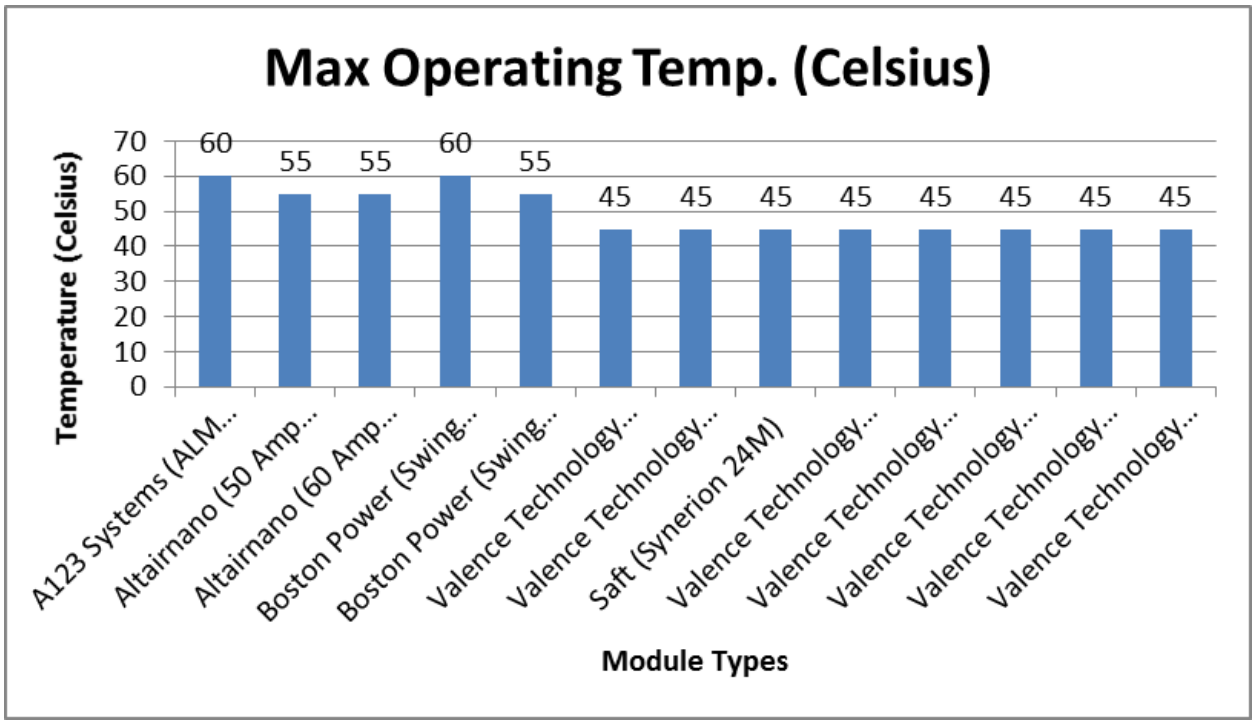


Figure 240: Benchmark Current Designs and Map Current Communications Protocols: Max Operating Temp (Celsius)



3.4.2 Communications and Serial Data Interfaces

The following figure lists the communication serial data interfaces for each stationary storage module. Empty cells indicate that the information was either not publically available orthe researcherswere unable to obtain the information from the battery or system manufacturer.

Figure 241: Communication Serial Data Interfaces for Stationary Storage Modules

Company	Equipment Model	Communication Interfaces
A123 Systems (ALM 12V7)	ALM 12V7	DNP 3.0, IEC61850, Modbus TCP, SNMP, and IEEE C37.118
Altairnano (50 Amp Hour Module)	50 Amp Hour Battery Module	
Altairnano (60 Amp Hour Cell)	60 Amp Hour Battery Module	
Boston Power (Swing Tempo 7101)	Swing Tempo 7101	CAN 2.0b
Boston Power (Swing Tempo 2235)	Swing Tempo 2235	CAN 2.0b
Boston Power (Swing Key 442)	Swing Key 442	CAN 2.0b
Boston Power (Swing Key 435)	Swing Key 435	CAN 2.0b
CODA (Li-Shen Modules)	Li Shen Modules(Made from Li Shen Cells)	Isolated D89 CAN, CAN/ RS485
Exergonix (Modules for CS-DESS)	Modules for CS-DESS	CANbus, USB, Ethernet
Exergonix (Modules for RS-DESS)	Modules for RS-DESS	CANbus, USB, Ethernet
MCV (35 kWh)	35kWh	CAN (Including J-1939),RS232, RS485
Panasonic (DCB102)	DCB102	
Saft (Synerion 24M)	Synerion 24M	UN Transportion, UL 1642
Saft (Synerion 24E)	Synerion 24E	UN Transportion, UL 1642
Valence Technology (Power P40-24)	Power P40-24	Rs485
Valence Technology (U1-12XP)	U1-12XP	Rs485
Valence Technology (U24-12XP)	U24-12XP	Rs485
Valence Technology (U27-12XP)	U27-12XP	Rs485
Valence Technology (UEV-18XP)	U1EV-18XP	Rs485
Valence Technology (U27-36XP)	U27-36XP	Rs485
Valence Technology (U1-12RT)	U1-12RT	Rs485
Valence Technology (U1-24RT)	U1-24RT	Rs485

3.4.3 Module Specification Summary

The following figure summarizes all the module specifications. Again, empty cells indicate that the information was either not publically available orthe researcherswere unable to obtain the information from the battery or system manufacturer.

Figure 242: Benchmark Current Designs and Map Current Communications Protocols:Battery System Specifications

Company	Equipment Model	Form Factor	Battery Chemistry	Nominal Voltage (VDC)	Current (A)		Qty	Configuration of Cells	Module Energy (kWh)	Module Power (kW)	Capacity (Ah)	Module Size (mm)			Volume (cm^3)	Weight (Kg)	Specific Energy (Wh/kg)	Energy Density (kWh/M^3)	Voltage Density (kV/M^3)	Specific Voltage (V/kg)	Impedence		Resistance	Thermal Characteristics				Cooling Requirements	Communication
		Cell		Module	Charging	Discharging	Cells	(# S # P)				L	W	H		Module					Charge Impedence (mOhms)	Discharge Impedence (mOhms)	DC Internal Resistance (mOhms)	Min Optimal Operating Temp. (C)	Max Optimal Operating Temp. (C)	Min Operating Temp. (C)	Max Operating Temp. (C)		
A123 Systems (ALM 12V7)	ALM 12V7	Prismatic	Lithium Ion Nanophosphate	12	10	10	0	0	0.06	0	0	151	65	99.7	971	0.855	70.175	61.79	12.36	14.035	0	0	0	-20	58	-40	60		DNP3.0, IEC61850, Modbus TCP, SNMP, IEEE C37.118
Altairnano (50 Amp Hour Module)	50 Amp Hour Battery Module		Nano Lithium Titanate	2.3	50	50	0	0	0.116	1.25	50	13	256	259	862	1.6	72.5	134.6	2.668	1.4375	0.55 (Internal Impedence at 10 sec DC)	0.55 (Internal Impedence at 10 sec DC)	0	-40	55	-40	55		
Altairnano (60 Amp Hour Cell)	60 Amp Hour Battery Module		Nano Lithium Titanate	22.25	360	360	0	0	1.4	0	60	279	155	303.4	13091	1.6	72.5	106	1.7	0.812	4 (Internal Impedence (10 sec DC 50% SOC at 25 Celsius)	3.8 (Internal Impedence (10 sec DC 50% SOC at 25 Celsius)	0	-40	55	-40	55		
Boston Power (Swing Tempo 7101)	Swing Tempo 7101	Prismatic	Lithium-Ion	7.4	50	50	0	0	0.775	0	101	181	284	80.64	4141	5.2	149.04	187.2	1.787	1.4231	0	0	0	-10	60	-40	60		
Boston Power (Swing Tempo 2235)	Swing Tempo 2235	Prismatic	Lithium-Ion	22.2	35	35	24	6S5P	0.775	0	35	181	284	80.64	4141	5.2	149.04	187.2	5.361	4.2692	0	0	0	-10	60	-40	70		
Boston Power (Swing Key 442)	Swing Key 442	Prismatic	Lithium-Ion	3.65	70	70	8	1S8P	0.155	0	42	181	39	70	495.7	0.905	171.27	312.7	7.364	4.0331	2.65 (1kHz)	2.65 (1kHz)	0	-20	60	-40	70		
Boston Power (Swing Key 435)	Swing Key 435	Prismatic	Lithium-Ion	3.7	70	70	8	1S8P	0.13	0	35.2	183	39	70	499.6	0.905	143.65	260.2	7.406	0	3 (1kHz)	3 (1kHz)	0	0	0	0	0		
CODA (Li-Shen Modules)	Li Shen Modules(Made from Li Shen Cells)	Prismatic	Lithium Iron Phosphate	22.4	0	0	49	7S7P	0	0	112	0	0	0	0	0	0	0	0	0	0	0	0	0.01	45	0	0		Isolated DB9 CAN, RS485

Figure 243: Benchmark Current Designs and Map Current Communications Protocols: Battery Specifications (cont.)

Company	Equipment Model	Form Factor	Battery Chemistry	Nominal Voltage (VDC)	Current (A)		Qty	Configuration of Cells	Module Energy (kWh)	Module Power (kW)	Capacity (Ah)	Module Size (mm)			Volume (cm^3)	Weight (Kg)	Specific Energy (Wh/kg)	Energy Density (kWh/M^3)	Voltage Density (kV/M^3)	Specific Voltage (V/kg)	Impedence		Resistance	Thermal Characteristics				Cooling Requirements	Communication
		Cell		Module	Charging	Discharging	Cells	(# S # P)				L	W	H		Module					Charge Impedence (mOhms)	Discharge Impedence (mOhms)	DC Internal Resistance (mOhms)	Min Optimal Operating Temp. (C)	Max Optimal Operating Temp. (C)	Min Operating Temp. (C)	Max Operating Temp. (C)		
Exergonix (Modules for CS-DESS)	Modules for CS-DESS		Lithium Nickel Magnesium Cobalt	48	0	0	0	0	0	0	0	432	159	323.9	22199	0	0	0	2.162	0	0	0	0	0	0	0	0		USB, Ethernet
Exergonix (Modules for RS-DESS)	Modules for RS-DESS		Lithium Nickel Magnesium Cobalt	48.3	0	0	280	14S2P	2.85	0	55	168	144	24	580.6	0	0	0	0	0	0	0	0	0	0	0	0		USB, Ethernet
MCV (35 kWh)	35kWh		Lithium Iron Phosphate	360	100	100	112	0	35	40	100	0	0	0	0	0	0	0	0	0	0	0	0	0.01	70	-20	70	Forced Convection	CAN (Including J-1939),RS232, RS485, CANOpen 2.0, Encryted 3G/4G Modem, LAN/WAN Connection
Panasonic (DCB102)	DCB102		Lithium Ion	48	10	30	0	13S24P	1.613	0	33.6	438	386	80	13525	19	84.895	119.3	3.549	2.5263	0	0	0	0	0	0	0		
Saft (Synerion 24M)	Synerion 24M		Lithium Nickel-Cobalt-	24	200	200	24	7S2P	2	15	82	292	445	126	16372	19.2	104.17	122.2	1.466	1.25	0	0	0	-20	55	-20	55	Forced Convection	UN Transport ion, UL
Saft (Synerion 24E)	Synerion 24E		Lithium Nickel-Cobalt-Aluminium	24	160	160	0	0	2.2	15	90	292	445	126	16372	19.2	114.58	134.4	1.466	1.25	0	0	0	0	0	0	0	Forced Convection	UN Transport ion, UL 1642
Valence Technology (Power P40-24)	Power P40-24		Lithium Iron Magnesium Phosphate	25.6	40	240	0	0	0	0	40	256	165	260	10982	16.5	0	0	2.331	1.5515	0	0	0	-10	50	0.01	45		RS485
Valence Technology (U1-12XP)	U1-12XP	Rectangular Prism	Lithium Iron Magnesium Phosphate	12.8	80	80	0	0	0.5124	0	40	197	131	182	4697	6.4863	79	109.1	2.725	1.9734	0	0	15	-10	50	0.01	45		RS485

Figure 244: Benchmark Current Designs and Map Current Communications Protocols: Battery Specifications (cont.)

Company	Equipment Model	Form Factor	Battery Chemistry	Nominal Voltage (VDC)	Current (A)		Qty	Configuration of Cells	Module Energy (kWh)	Module Power (kW)	Capacity (Ah)	Module Size (mm)			Volume (cm^3)	Weight (Kg)	Specific Energy (Wh/kg)	Energy Density (kWh/M^3)	Voltage Density (kV/M^3)	Specific Voltage (V/kg)	Impedence		Resistance	Thermal Characteristics				Cooling Requirements	Communication
		Cell		Module	Charging	Discharging	Cells	(# S # P)				L	W	H		Module					Charge Impedence (mOhms)	Discharge Impedence (mOhms)	DC Internal Resistance (mOhms)	Min Optimal Operating Temp. (C)	Max Optimal Operating Temp. (C)	Min Operating Temp. (C)	Max Operating Temp. (C)		
Valence Technology (U24-12XP)	U24-12XP	Rectangular Prism	Lithium Iron Magnesium Phosphate	13.8	81	81	1	1	0.5189	1	41	198	132	183	4783	6.4863	80	108.5	2.885	2.1275	0	0	6	-10	50	0.01	45		RS485
Valence Technology (U27-12XP)	U27-12XP	Rectangular Prism	Lithium Iron Magnesium Phosphate	14.8	82	82	2	2	0.5254	2	42	199	133	184	4870	6.4863	81	107.9	3.039	2.2817	0	0	5	-10	50	0.01	45		RS485
Valence Technology (UEV-18XP)	U1EV-18XP	Rectangular Prism	Lithium Iron Magnesium Phosphate	15.8	83	83	3	3	0.5319	3	43	200	134	185	4958	6.4863	82	107.3	3.187	2.4359	0	0	10	-10	50	0.01	45		RS485
Valence Technology (U27-36XP)	U27-36XP	Rectangular Prism	Lithium Iron Magnesium Phosphate	16.8	84	84	4	4	0.5384	4	44	201	135	186	5047	6.4863	83	106.7	3.329	2.5901	0	0	25	-10	50	0.01	45		RS485
Valence Technology (U1-12RT)	U1-12RT	Rectangular Prism	Lithium Iron Magnesium Phosphate	17.8	85	85	5	5	0.5449	5	45	202	136	187	5137	6.4863	84	106.1	3.465	2.7442	0	0	0	-10	50	0.01	45		RS485
Valence Technology (U1-24RT)	U1-24RT	Rectangular Prism	Lithium Iron Magnesium	18.8	86	86	6	6	0.5513	6	46	203	137	188	5228	6.4863	85	105.4	3.596	2.8984	0	0	43	-10	50	0.01	45		RS485

The following figure shows an image of each module that was surveyed.

Figure 245: Benchmark Current Designs and Map Current Communications Protocols: Image of Modules

A123 Systems (ALM 12V7)		Boston Power (Swing Key 435)		Valence Technology (U27-12XP)	
Altairnano (50 Amp Hour Module)		Saft (Synerion 24M)		Valence Technology (UEV-18XP)	
Altairnano (60 Amp Hour Cell)		Saft (Synerion 24E)		Valence Technology (U27-36XP)	
Boston Power (Swing Tempo 7101)		Valence Technology (Power P40-24)		Valence Technology (U1-12RT)	
Boston Power (Swing Tempo 2235)		Valence Technology (U1-12XP)		Valence Technology (U1-24RT)	
Boston Power (Swing Key 442)		Valence Technology (U24-12XP)			

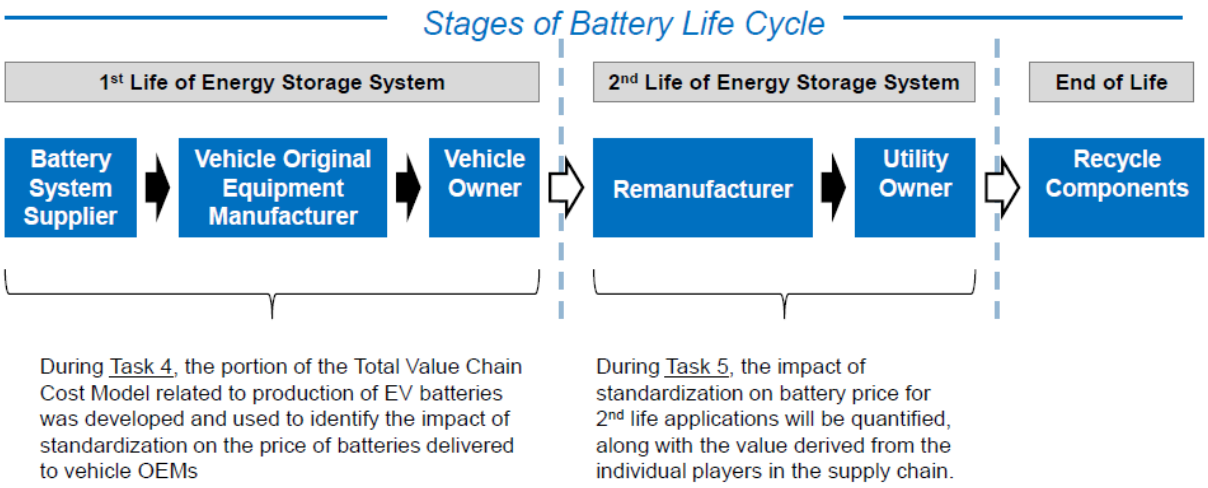
3.5 Cost/Benefit Analysis of Standardization Impacts on First use Li-Ion Battery System

3.5.1 Cost/Benefit Analysis of Standardization Value Chain Analysis

A cost/benefit analysis was completed based on a value chain assessment of the battery life cycle beginning with the battery manufacturing process, the first use vehicle application, and the transfer from vehicle to stationary energy storage application.

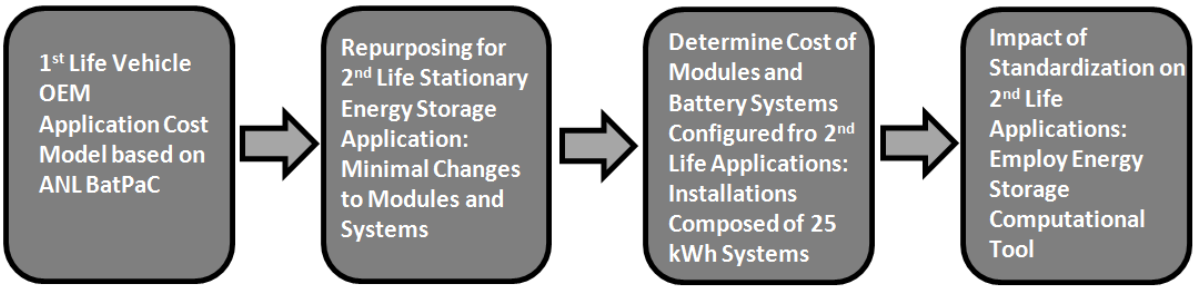
During Design Concepts: Standards Design, the portion of the total value chain cost model related to production of EV batteries was developed and used to identify the impact of standardization on the price of batteries delivered to vehicle OEMs. During the Value Analysis, the impact of standardization on battery price for second use applications was quantified, along with the value derived from the individual players in the supply chain. The relationship of these tasks to the stages of a battery life cycle is shown in Figure 246.

Figure 246: Relationships of Design Concepts and Value Analysis to Battery Life Cycle



The approach for determining impact of standardization on the value chain is shown in Figure 247. It includes determination of the impact on price of modules and battery systems delivered vehicle OEMs as well as evaluation of modifications and costs required to prepare modules and battery systems for second use stationary energy storage applications.

Figure 247: Procedure for Determining the Impact of Standardization on the Value Chain



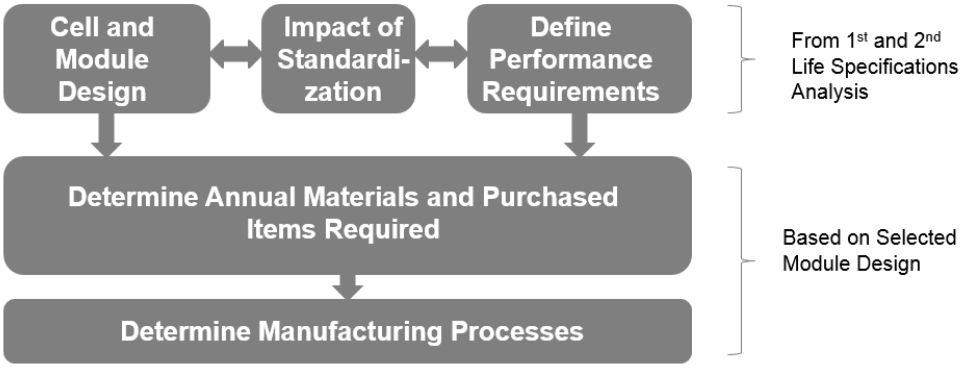
The impact of standardization on EV OEM module and battery costs was determined using a lithium-ion manufacturing cost and economics model. Individual component costs were defined as a function of the delivered battery price to the vehicle manufacturer.

The battery manufacturing cost and economics model included both unit (module/battery) costs as well as system (thermal and battery management systems, cables, connectors, and housing) costs to determine the sales price to the vehicle OEM.

This lithium-ion battery manufacturing cost and economics model was based on work performed at Argonne National Laboratory (Report ANL-12/55: *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric Drive Vehicles*: See Reference 2). The model requires cell

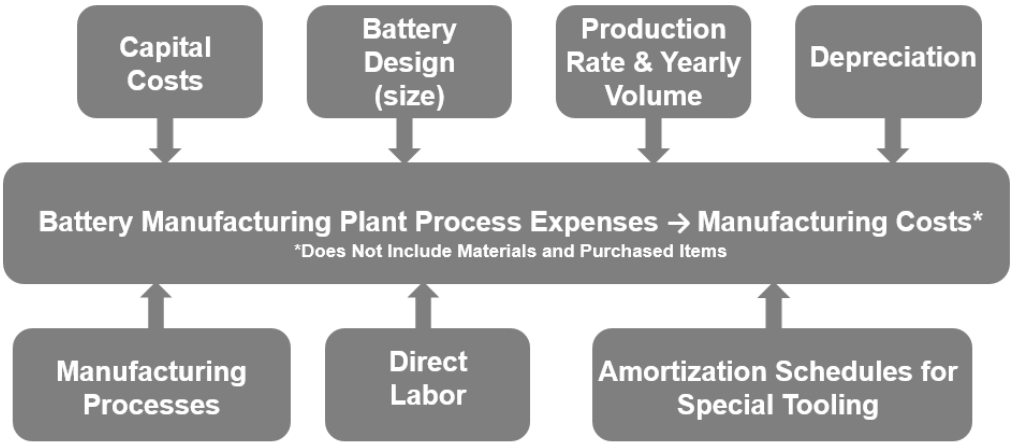
and module design specifications and performance requirements as input. The input values were modified to account for the impact of standardization. An example of the impact of standardization on model input variables might be the specification of a standardized electrode geometry which would lead to higher production volumes and lower costs. As shown in Figure 248, an intermediate result of the analysis is 1) a determination of annual materials and purchased items required and 2) a determination of the required manufacturing processes.

Figure 248: Inputs to Lithium-Ion Battery Manufacturing Cost Model



The battery manufacturing process inputs shown in Figure 249 are included in the calculation of manufacturing costs.

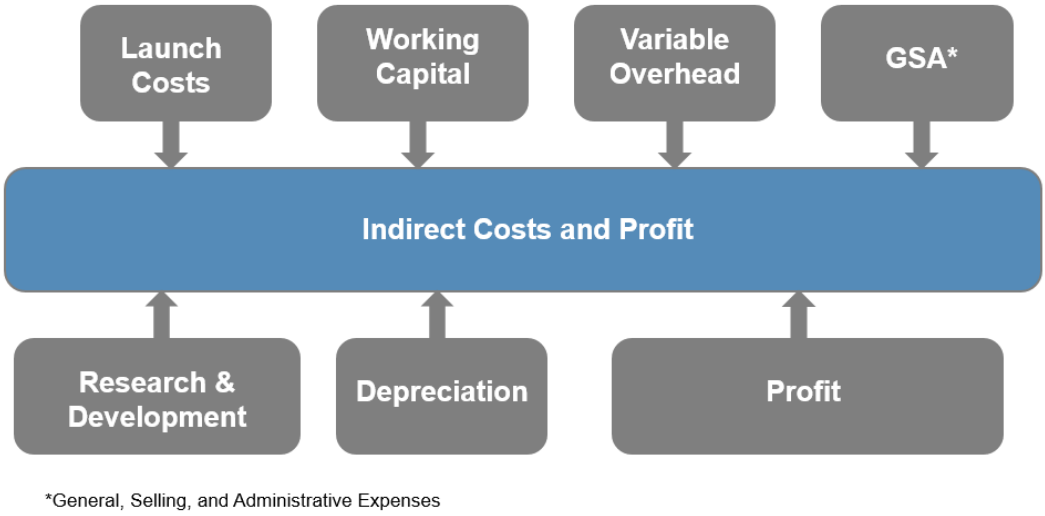
Figure 249: Inputs to Manufacturing Plant Process Expense Portion of Model



The manufacturing cost categories are based on Argonne's concept of a lithium-ion battery manufacturing plant producing 100,000 packs/year during 2020.

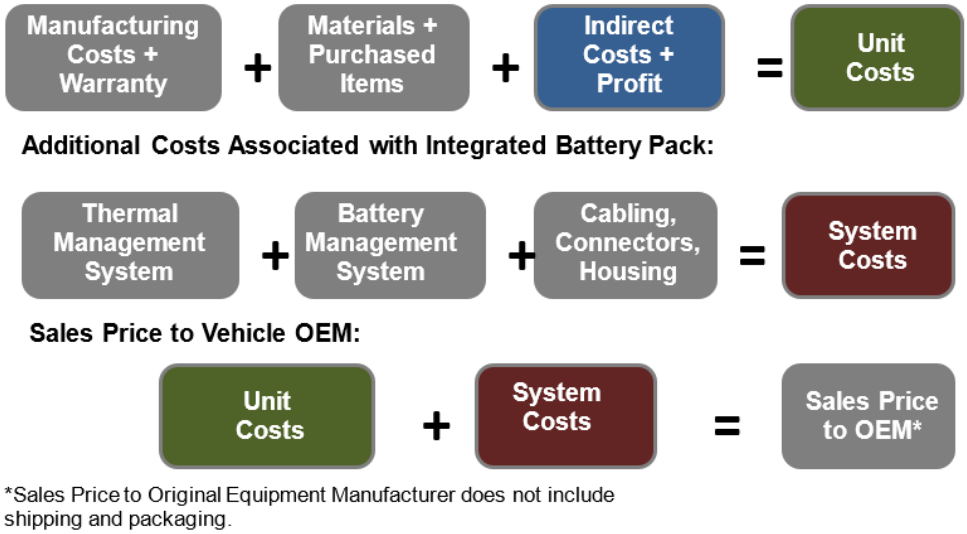
Additional cost inputs for the manufacturing facility cost model are shown in Figure 250. These inputs are used to calculate indirect costs and profit.

Figure 250: Additional Cost Inputs Related to Manufacturing Facility Operations



The relationships shown in Figure 251 were then used to calculate unit costs, systems costs and the battery system sales price to the manufacturer. Unit costs include manufacturing costs, warranty, materials and purchased items, and indirect costs and profit.

Figure 251: Determination of Unit Costs, System Costs, and Sales Price to Vehicle OEM



Battery system costs include the thermal management system and battery management system as well as cabling, connectors, and housing. The sum of the unit costs and system costs determine the sales price of the battery system. Note that indirect costs and profit are included in the unit costs.

A determination was made regarding the impact of standardization on the various manufacturing cost model inputs. These inputs were divided into the following categories:

1. Manufacturing costs (e.g. materials)
2. Manufacturing rate (e.g production volume, plant operating hours)
3. Manufacturing investment costs (e.g. building, land)
4. Unit costs (e.g. labor, GSA, depreciation)
5. Profit and warranty
6. Battery System Integration Costs (e.g. controls, disconnects)
7. Thermal control system costs
8. Battery assembly costs

Specific inputs in each category, units, and indications regarding variables impacted by standardization are displayed in the figures below.

Figure 252: Unit Cell Manufacturing Cost Input Variables

Manufacturing Costs			Impacted by Standardization
Category	Variable	Units	
Unit Cell Materials	Positive Electrode	$/kg	
	Negative Electrode	$/kg	
	Positive Current Collector	$/m²	✔
	Negative Current Collector	$/m²	✔
	Separators	$/m²	✔
	Electrolyte	$/L	
Unit Cell Hardware Costs	Positive Terminal	$/kg	
	Negative Terminal	$/kg	
	Cell Container	$/kg	✔
	Heat Conductor or Thermal Enclosure	$/kg	✔

Figure 253: Purchased Materials Manufacturing Cost Input Variables

Manufacturing Costs			Impacted by Standardization
Category	Variable	Units	
Module Purchased Materials Costs	State of Charge Regulator and Safety Monitors	$/cell	✓
	Module Terminals	$/kg	
	Balance of Module Materials	$/kg	✓
Battery Purchased Materials Costs	Module Inter-Connectors & Signal Wiring	$/kg	✓
	Module Compression Straps and Steel Plates	$/kg	✓
	Battery Terminals	$/Battery	
	Bus Bar for Packs	$/each	✓
	Battery Jacket	$/kg	✓

Figure 254: Manufacturing Rate Input Variables

Manufacturing Rate Variables		Impacted by Standardization
Category	Units	
Production Volume	Batteries/year	✓
Plant Operation	Days/year	✓
Plant Operation	Shifts/day	✓
Number of 8-hour shifts per year	Shifts/year	✓
Plant Energy Use	kW-hr/year	✓
Production Rate: number of acceptable cells	Cells/year	✓
Production Rate: number of cells adjusted for yield	Cells/year	✓

Figure 255: Manufacturing Rate Input Variables

Manufacturing Rate Variables		Impacted by Standardization
Category	Units	
Electrode Materials	m^2/year	✔
Positive Active Material	kg/year	✔
Negative Active Material	kg/year	✔
Positive Binder Solvent Evaporated	kg/year	✔
Negative Binder Solvent Evaporated	kg/year	✔
Dry Room, Enclosed Operating Area	m^2	✔

Figure 256: Manufacturing Investment Costs

Manufacturing Investment Costs		Impacted by Standardization
Category	Units	
Building, Land, and Utilities	$/$m^2$	✔
Launch Cost Rates		
% of Direct Annual Materials and Purchased Items Costs	%	✔
% of Direct Labor + Variable Overhead	%	✔
Working Capital (% of Annual Variable Costs)	%	✔

Figure 257: Battery System Unit Costs

Unit Cost of Battery Pack			Impacted by Standardization
Category		Units	
Variable Costs	Direct Labor	$/hr	✔
	Variable Overhead Rate	% of Direct Labor	✔
		% of Depreciation	✔
Fixed Expenses	General, Sales, Administration	% of Direct Labor	✔
		% of Variable Overhead	✔
		% of Depreciation	✔
	Research & Development	% of Depreciation	✔
	Depreciation	% of Capital Equipment	✔
		% of Building Investment	✔

Figure 258: Profit and Warranty Costs

Profit and Warranty		Impacted by Standardization
Category	Units	
Profit after Taxes	% of Investment	✔
Warranty Cost	% Added to Sales Price	✔

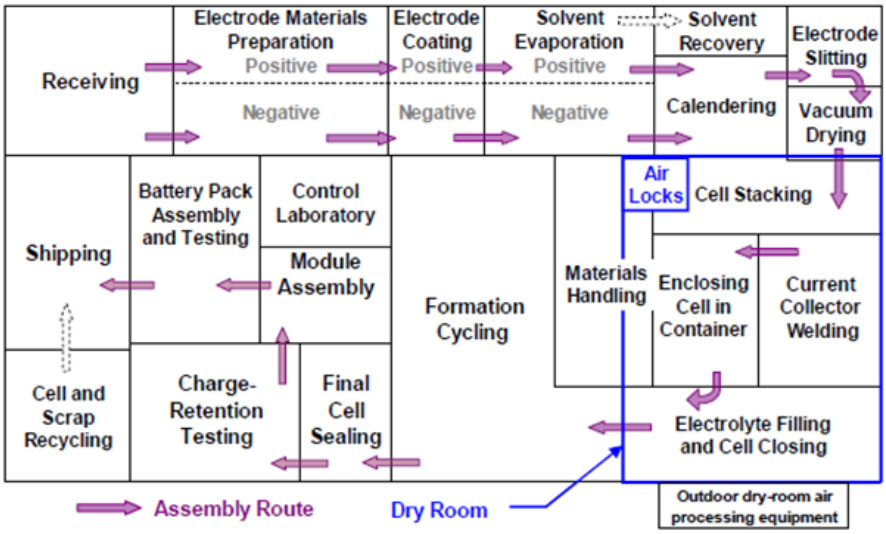
Figure 259: Battery Pack Integration System Costs

Battery Pack Integration System Costs		Impacted by Standardization
Category	Units	
Current and Voltage Sensing	$/Pack	✔
Module Controls	$/Module	✔
Auto. Battery Disconnect	$/Pack	✔
Manual Disconnect	$/Pack	✔
Additional Costs for Parallel Modules and Packs	$/String	✔

Figure 260: Thermal Control System Costs

Thermal Control Systems Costs		Impacted by Standardization
Category	Units	
Baseline Thermal System	$/Pack	✔
Additions to AC System	$/kW	✔
Heating System	$/ kW/Pack	✔
Additional for Multiple packs	$/Additional Pack	✔

Figure 261: Baseline Li-Ion Battery Manufacturing Plant Diagram



- 100,000 packs/year
- NCA-Gr Chemistry*
- 50 kW Power
- 40 Ahr Capacity
- 60 Cells/Battery
- 300 Days/Year
- 8 hr Shifts

Baseline Lithium-Ion Battery Manufacturing Plant Diagram:
From Argonne National Laboratory (Reference 2).

*nickel cobalt aluminum oxide graphite chemistry

Figure 262: Impact of Standardization on Battery Assembly Costs

Battery Assembly Costs Assembly Operations Categories Variables Defined for Each Category: Direct Labor, Capital Equipment Costs, Plant Area		Impacted by Standardization
Receiving		✔
Electrode Processing	Materials Preparation	✔
	Electrode Coating	✔
	Solvent Recovery	✔
	Calendaring	✔

Figure 263: Impact of Standardization on Battery Assembly Costs

Battery Assembly Costs Assembly Operations Categories Variables Defined for Each Category: Direct Labor, Capital Equipment Costs, Plant Area	Impacted by Standardization
Formation Cycling	✔
Final Cell Sealing	✔
Charge-Retention Testing	✔
Module Assembly	✔
Battery Pack Assembly and Testing	✔
Rejected Cell and Scrap Recycle	✔
Shipping (Includes Packaging)	✔

Detailed results of the battery manufacturing cost analysis are presented in Figure 264. Key cost elements are summarized inFigure 265. It can be seen that materials + purchased items are the largest cost components and represent between 45 percent (29 percent + 16 percent) and 76 percent (52 percent +24 percent) of the price of the battery as delivered to the vehicle OEM.

Battery system integration and addition of a thermal management sytem adds between 20 percent and 29 percent to the price of the delivered battery system.

Figure 264: Summary of Lithium Ion Battery System Manufacturing Costs (as percent of price to vehicle OEM)

Cost Breakdown Overview: Range of Costs Associated with Current Lithium-Ion Battery Designs	
Category	**Cost Range (% of Price to OEM)**
Materials	29% to 52%
Purchased Items	16% to 24%
Direct Labor	4% to 7%
Variable Overhead	4% to 5%
General, Sales, Administration	4% to 6%
Research & Development	4% to 5%
Depreciation	4% to 13%
Profit	4% to 5%
Warranty (for Battery Packs)	5% to 6%

Figure 265: First use Cost Breakdown Detail: Cost Components as a Percentage of Price to Vehicle OEM

Cost Components as a Percentage of Price to OEM for Battery Pack			% of Price to OEM	
Category	**Subcategory**	**Cost Component**	**High**	**Low**
Variable Costs	*Materials and Purchased Items*	Cell Materials	52.00%	29.00%
		Cell Purchased Items	3.69%	2.46%
		Module Materials and Purchased Items	13.57%	9.04%
		Pack Materials and Purchased Items	6.74%	4.50%
		Total Materials and Purchased Items:	76.00%	45.00%
	Direct Labor	Electrode Processing	2.11%	1.20%
		Cell Assembly	1.69%	0.96%
		Formation Cycling, Testing, and Sealing	1.09%	0.62%
		Module Assembly	0.50%	0.29%
		Battery Assembly	0.50%	0.29%
		Cell Materials Rejection, Recycling	0.25%	0.14%
		Module Materials Rejection, Recycling	0.20%	0.11%
		Receiving and Shipping	0.39%	0.22%
		Control Laboratory Tasks	0.28%	0.16%
		Total Direct Labor:	7.01%	3.99%
	Variable Overhead		5.00%	4.00%
		Total Variable Costs:	88.01%	52.99%
Fixed Expenses	*General, Sales, Administration*		6.00%	4.00%
	Research & Development		5.00%	4.00%
	Depreciation		13.00%	4.00%
		Total Fixed Expenses:	24.00%	12.00%
Profits After Taxes:			5.00%	4.00%
Warranty (includes battery packs only):			6.00%	5.00%
Price to OEM for Battery Pack:			100.00%	
Pack Integration (BMS, Connectors) $/pack:			22.00%	15.00%
Addition of Themal Management System:			7.00%	5.00%
		Total Cost to OEM for Complete System:	129%	120%

The manufacturing cost model was used to determine the impact of standardization on the price of the first use battery system. The study was based on parametric evaluations of the model inputs. This included, for example, variations in materials prices originating with higher production volumes associated with standardized designs. It is interesting to note that some of the simulations resulted in increases in some costs due to constraints posed by standardization. An example is research and development costs, which in one case were seen to increase relative to those for the non-standardized design due to projected increases in research costs associated with generating designs that meet the additional constraints. As might be expected from the manufacturing cost study, the largest potential savings associated with standardized battery systems is expected to occur in the areas of cell materials and purchased items, with projected saving ranging from 3 percent 1to 12 percent of the delivered battery price.

The impact of standardization displayed as a percentage of the price of the battery pack to the OEM is shown in Figure 266.

Figure 266: Cost Impact of Standardization on Selected Categories

Overview: Cost Impact of Standardization on Selected Categories		
Key Cost Categories	**Cost Range Of Current Systems (% of Price to OEM)**	**Range of Potential Cost Savings Due to Standardization (% of Price to OEM)**
Materials	29% to 52%	2% to 10%
Purchased Items	16% to 24%	1% to 2%
Depreciation	4% to 13%	0.4% to 1.3%
Direct Labor	4% to 7%	0.4% to 1%

Figure 267: Impact of Standardization on First use Cells, Modules, and Packs

Cost Components as a Percentage of Price to OEM for Battery Pack			Impact of Standardization[1]	
Category	**Subcategory**	**Cost Component**	**High**	**Low**
Variable Costs	*Materials and Purchased Items*	Cell Materials	8.21%	2.05%
		Cell Purchased Items	0.58%	0.15%
		Module Materials and Purchased Items	2.14%	0.54%
		Pack Materials and Purchased Items	1.06%	0.27%
		Total Materials and Purchased Items:	12.00%	3.00%
	Direct Labor	Electrode Processing	0.30%	0.12%
		Cell Assembly	0.24%	0.10%
		Formation Cycling, Testing, and Sealing	0.16%	0.06%
		Module Assembly	0.07%	0.03%
		Battery Assembly	0.07%	0.03%
		Cell Materials Rejection, Recycling	0.04%	0.01%
		Module Materials Rejection, Recycling	0.03%	0.01%
		Receiving and Shipping	0.06%	0.02%
		Control Laboratory Tasks	0.04%	0.02%
		Total Direct Labor:	1.00%	0.40%
	Variable Overhead		0.50%	0.00%
		Total Variable Costs:	13.50%	3.40%
Fixed Expenses	*General, Sales, Administration*		0.00%	0.00%
	Research & Development		0.50%	-0.25%
	Depreciation		1.30%	0.40%
		Total Fixed Expenses:	1.25%	0.15%
Profits After Taxes:			0.50%	0.30%
Warranty (includes battery packs only):			0.40%	-0.50%
Impact on Price to OEM for Battery Pack:			15.15%	3.05%
Pack Integration (BMS, Connectors) $/pack:			5.00%	2.00%
Addition of Themal Management System:			0.75%	0.50%
		Impact on Total Cost to OEM for Complete System:	20.90%	5.55%

[1]Positive entries indicate a reduction in the cost component; negative entries represent an increase.

During the Value Analysis (Chapter 4), the value chain analysis was continued and included results of the first use lithium-ion manufacturing cost model. Also during the Value Analysis, industry stakeholders were interviewed to obtain comments and validation of the model inputs.

3.6 Design for Second use and Recycling: Demonstration of Second use Battery Energy Storage System

The BMW Battery Second use project at UC San Diego is the largest B2L application in North America. The grid-tied stationary energy storage system uses 6 high-voltage lithium ion battery packs from the BMW MINI E Field Trial, which lasted from 2008-2010. The final system design is driven by maximizing reuse of vehicle components and by the commercialization potential of the stationary storage system.

By the end of 2013, BMW, along with its partners, had accomplished the following:

- Completed design and development of the grid-tied energy storage system.
- Developed inverter software simulation to start communication chain to BMS and Battery.
- Initiated real-time testing for battery system, BMS, and super BMS components.
- Integrated the Battery/BMS/super BMS and Battery second use stationary storage container at the UC San Diego micro-grid.

In 2014, BMW and its partners continued the development of the system:

- Established software communication from BMS 1-6 through super BMS, site controller, and Paladin energy management system to the UCSD PI server.
- Final system commissioning and validation of system level functionality (in process, as of the date of this report).

3.6.1 BMS Architecture Overview

The goal of the BMW B2L UC San Diego Project was to re-utilize as much functionality and as many components as possible from the vehicle in a stationary application. Since the battery management system was originally designed for a vehicle application, some system functionality had to be changed or adapted.

The control architecture for both a stationary and vehicle application defines how the BMS is implemented. This includes the level at which functionality of the BMS is implemented and communication requirements between system layers. The control architecture will depend on the physical system architecture and performance requirements of the application.

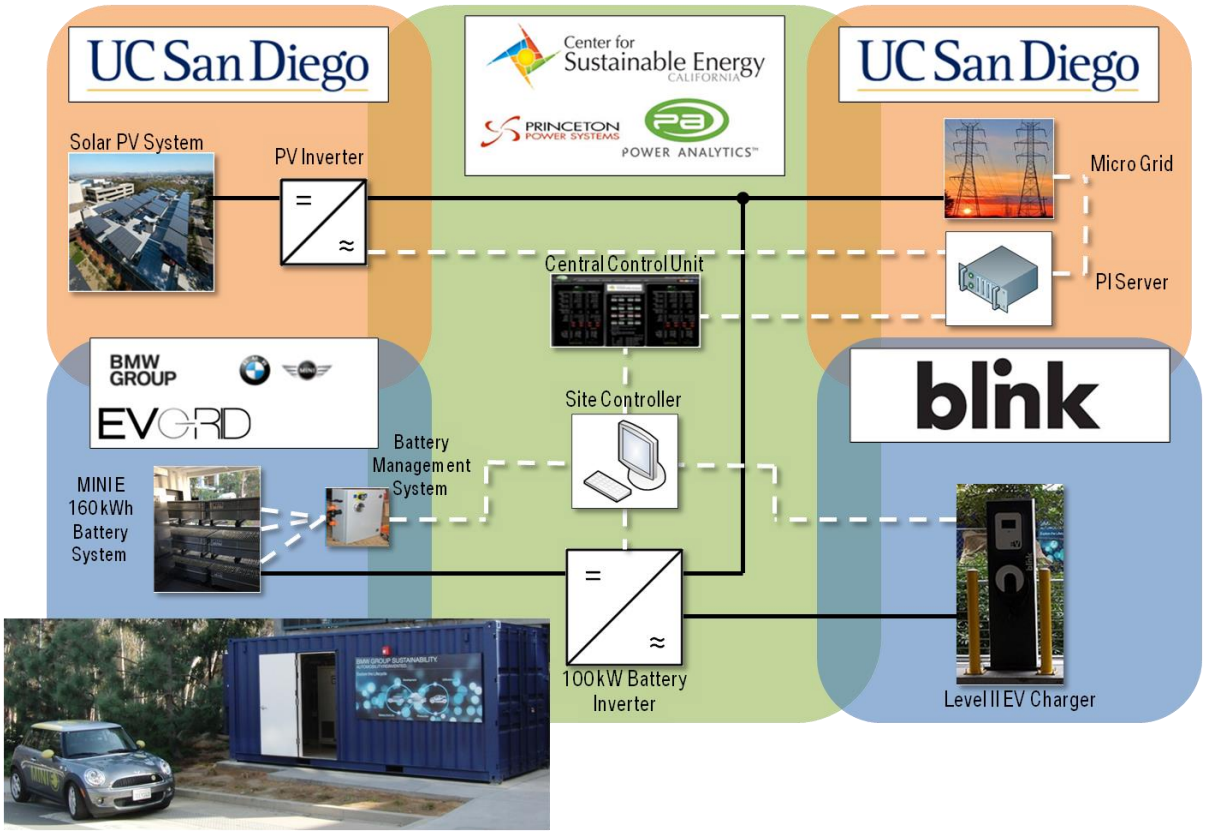
The control architecture for a vehicle system consists of two or three nested layers, which mimic the physical architecture of the system. The lower cell and module layers are responsible for the monitoring functions, while the higher level pack layer is responsible for the communication and control functions. The functionality of cell level balancing and voltage monitoring is incorporated on the module level. Between layers is determined by the pack architecture and

reliability requirements. As discussed in the previous chapter, the control architecture will differ among battery systems and is often proprietary knowledge of the OEM[71].

3.6.2 BMW UC San Diego B2L System Overview

Figure 268 provides an overview of the key components and partners in the BMW UC San Diego Battery Second use System. The battery system is housed in a 20ft storage container. It uses a 100 kW 4 port GTIB 480-100 inverter from Princeton Power Systems. The storage capacity of 6 full MINI E battery packs is 160 kWh. The battery management system (BMS), and "Super BMS" were designed by EV Grid. The system integrates with existing photovoltaic panels and inverters located at UC San Diego as well providing battery backup to a Level II EV charging station.

Figure 268: BMW UC San Diego B2L Project System Overview



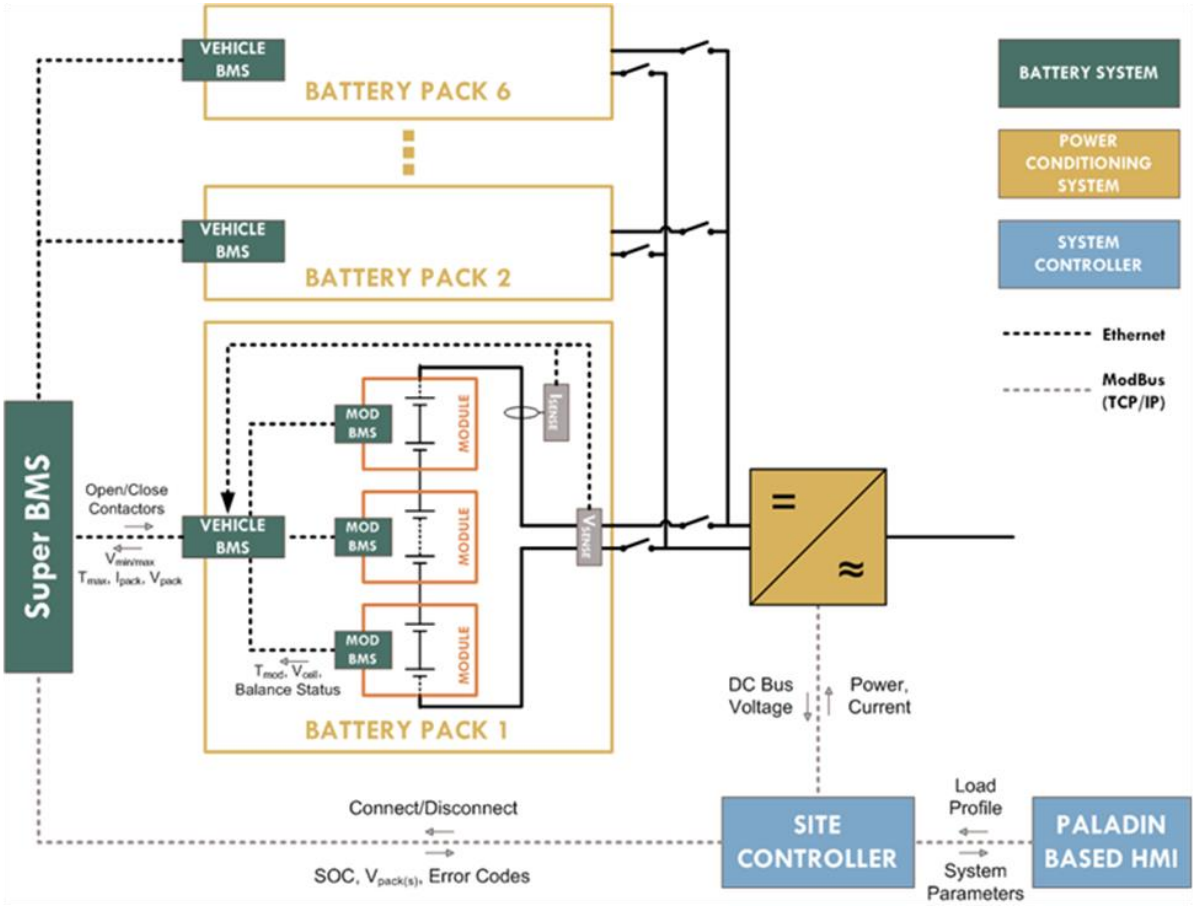
The BMW UC San Diego B2L Project has several research goals. The one most applicable to this report was to develop controls and software interfaces for a second use vehicle battery management system (BMS) and BMS definition for various stationary storage applications. Further research topics include evaluating performance of battery, BMS, balancing algorithms

[71] Bowler, M. Battery Second Use: A Framework for Evaluating the Combination of Two Value Chains. Clemson University, ProQuest, UMI Dissertations Publishing, 2014

and thermal management of system for different load profiles, and quantifying any performance difference between new and old batteries.

The B2L system contains three (3) major subsystems: battery system, power conditioning system, and system controller. The battery system consists of the MINI E packs (cells, module and pack level BMS) and the Super BMS (sBMS). The power conditioning system is the 4 port GTIB 480-100 PPS inverter. The system controller is made up of the site controller provided by PPS and the Paladin Energy Software based HMI developed by Power Analytics. The interactions between these major subsystems and the overall functional architecture are illustrated in Figure 269.

Figure 269: BMW UC San Diego B2L Project Functional Architecture



For the BMW UC San Diego B2L project, battery modules, module and pack level BMS, and pack current and voltage sensors were used from the MINI E vehicles. Hardware modifications consisted of repackaging battery modules into boxes, incorporation of high voltage interlocks, and the addition of an isolation detector.

In a vehicle the purpose of the battery management system is not only to ensure the safe operating conditions of the battery system and overall vehicle performance, but is also an

integrated part of the entire vehicle safety system. As a result there are numerous safety and functionality checks that are required both internal and external to the battery system. When repurposing the battery system, changes to the software of the battery management system are required to allow the system to function.

In order to use the vehicle battery in a stationary system, the source code of the BMS was adapted as follows:

1. Start up and initialization algorithms had to be adapted to enable the use of the pack independent of the other vehicle systems.
2. Methods for sending and receiving data between the vehicle system and external system were developed (sBMS).
3. New balancing algorithms for maintaining a consistent SOC throughout the individual packs had to be developed due to the new electrical operating requirements.

A key component in successfully reusing each vehicle BMS for stationary storage applications was the development of the "super BMS." The sBMS is the interface between the vehicle battery systems and the site controller. As shown in the previous figure, the sBMS collects and communicates individual pack data to the system controller using a single interface. The sBMS also coordinates connection and disconnection of batteries to the power control system (PPS Inverter). In an emergency condition, the sBMS can also isolate a pack from the system.

3.6.3 Communications Protocols

As indicated in the previous figure, communication between sBMS, inverter, site controller, and energy management system uses the ModBus standard. Communication protocols between sBMS and BMS are exclusive to EVGrid design. In the course of this project several communication protocols by ISO/IEC and SAE were identified. The ISO/IEC and SAE organizations have harmonized vehicle to grid communication interface major documents and functions. However, these standards are in progress and currently at draft level. Communication standards relevant to vehicle-grid communication are summarized in Figure 270 below.

Figure 270: Communication Standards Relevant to Vehicle Grid Communication

ISO/IEC	SAE	Description
15118-1	J2836	Cases (establishes requirements)
15118-2	J2847	Messages, diagrams, etc. (derived from the use case requirements)
15118-3	J2931	Communication Requirements & Protocol
15118-4/5	J2953	Interoperability

3.6.4 Project Implications for B2L Standardization

One key difference between the BMW UC San Diego B2L project and the other tasks in this report is that rather than identifying specific design requirements for implementing a standardized battery module, this system started with proprietary vehicle hardware and developed an design that could maximize reuse of the existing safety design while also creating a common communication and control interface. As a result of the research project, several conclusions were found with implications to standardization in battery design for second use applications. First and foremost, functional safety measures must be implemented on every system level, and coordinated between system levels. The BMW B2L system safety concept is based on the fact that the battery system has the ability to protect itself without relying on a system controller or sBMS. Each battery in the BMW design has the ability to isolate itself from the system.

The additional system level of the the sBMS allows for the development of a standardized communication interface between the vehicle system, which uses automotive protocols, and a standard stationary system interface. In this case the communication protocol used was ModBus. Looking to the future of B2L system developments, the automotive side of this interface will likely be unique to each OEM's battery system. This system should maximize reuse of functionality already within the vehicle system (e.g. balancing algorithms and system status communication). Any architecture based on integration of batteries at the module level (rather than battery pack level) will have additional requirements for this system level.

3.7 Evaluation of Pathways for Implementing PEV Battery Pack Standards

Barriers to implementation of standard modules and batteries were identified during the Barriers Analysis portion of the project. Potential pathways to implementing PEV battery pack standards include:

1) Participation in standards committees for OEM and stationary battery industry organizations, such as SAE, ISO/IEC, IEEE, and IEC.

2) Improved education regarding industry requirements for both first and second use applications. Prepare and present technical papers containing results of battery standardization analyses.

3) Promotion of cost savings, savings, and performance improvements resulting from standardization

4) Development of cells and modules that are compatible with a wide range of battery chemistries and performance specifications (voltage, watt-hours, resistance)

5) Identification of acceptable module specifications to facilitate "building block" approach to both vehicle and energy storage applications and preparation of "Draft" specifications for delivery to standards organizations

6) Development of expanded communications and battery management systems containing options to facilitate a range of vehicle and energy storage applications

7) Development of modules that facilitate remanufacturing processes for stationary energy storage and remain compatible for EV use.

3.8 Chapter 3 Summary and Conclusions

The Design Concepts portion of the study included development of standardized design concepts for lithium-ion battery systems, evaluation of currently available lithium-ion battery system specifications and communication protocols, determination of the cost impact of standardization on the price of batteries delivered to vehicle OEMs, design and demonstration of a second use battery energy storage system, and the evaluation of pathways for implementing PEV battery pack standards.

In keeping with the application focus of the current study, two standard battery pack designs were developed for commercial vocational vehicles. The packs were based on the following design parameters:

1. Module energy of 5kWhr: Supports 25 kWhr battery pack energy increments and allows reasonable series and parallel cell configuration in module
2. Cell types: GM standard pouch cell (A123 and LG Chem cells) and VDA PHEV2 prismatic cell
3. Module dimension: Keep to minimum to maintain energy density driven largely by cell configuration

The standardized battery pack communication systems and BMS interfaces were also defined.

A market research study was completed for commercially available energy storage modules of varying size, voltages, energy capacities and etc. The market research was conducted to give an overview on the specifications of many different existing energy storage modules (totaling 20+ from 9 different companies). The research included tabulation of specifications and identification of trends and patterns of available energy storage modules to facilitate development of the standardized EV battery modules.

A cost/benefit analysis was completed based on a value chain assessment of the battery life cycle beginning with the battery manufacturing process, the first use vehicle application, and the transfer from vehicle to stationary energy storage application.

The impact of standardization on EV OEM module and battery price (delivered price to vehicle OEM) was determined using a lithium-ion manufacturing cost model. Individual component costs were defined as a function of the delivered battery price to the vehicle manufacturer. During Task 5, the impact of standardization on battery price for second use applications was quantified, along with the value derived from the individual players in the supply chain.

The battery manufacturing cost model included both unit (module/battery) costs as well as system (thermal and battery management systems, cables, connectors, and housing) costs to determine the sales price to the vehicle OEM.

Each cost component was evaluated to determine the impact of standardization. This included assessments of variable costs, fixed expenses, profit warranty, pack integration, and addition of thermal and battery management systems.

Materials and purchased items were found to range from 45 percent to 76 percent of the delivered battery price, depending upon battery chemistry and topology. It was determined that standardization could reduce these costs between 3 percent and 12 percent of the delivered battery price.

Direct labor represents between 0.4 percent and 7 percent of the delivered battery price, again depending upon battery chemistry and topology. Standardization can reduce direct labor costs between 0.4 percent and 1 percent of the delivered battery price.

Other cost components, such as GSA, R&D, overhead, depreciation, and warranty are projected to be impacted by standardization within the range of 0.4 percent to 1.6 percent.

Addition of thermal management systems and pack integration adds between 20 percent and 29 percent to the delivered battery price. Standardization can reduce these between 2.5 percent and 5.75 percent of the delivered battery price.

Standardization thus has the potential to reduce the delivered battery price to the vehicle OEM by 3 percent to 15 percent.

BMW led the development of a grid-tied stationary energy storage system located at the University of California San Diego which integrates six used MINI E high-voltage Li-Ion battery packs. The system architecture was dictated by the goals of design for commercialization and reuse of vehicle components. The system safety concept relies on each battery to be self-protecting, reducing the need for higher level safety measures and enabling a standard interface to any proprietary vehicle BMS design. The introduction of the "Super BMS" system between the vehicle BMS's and the site controller and inverter is another key to enabling communication interface standardization.

Based on a literature search and interviews with industry stakeholders, potential pathways to implementing PEV battery pack standards were identified and included:

1. Participation in standards committees for OEM and stationary battery industry organizations, such as SAE, ISO/IEC, IEEE, and IEC.
2. Improved education regarding industry requirements for both first second use applications.
3. Preparing and presenting technical papers containing results of battery standardization analyses.

4. Promotion of cost savings, savings, and performance improvements resulting from standardization.
5. Development of cells and modules that are compatible with a wide range of battery chemistries and performance specifications (voltage, watt-hours, resistance).
6. Identification of acceptable module specifications to facilitate "building block" approach to both vehicle and energy storage applications and preparation of "Draft" specifications for delivery to standards organizations.
7. Development of expanded communications and battery management systems containing option to facilitate a range of vehicle and energy storage applications.
8. Development of modules that facilitate remanufacturing processes for stationary energy storage and remain compatible for EV use.

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28. Sinsley, L., "California Energy Commission Joins U.S. Department of Energy to Dedicate EnerVault's Long-Duration Energy Storage System", California Energy Commission, News Release, May 22, 2014.

29. Lippert, M., "Balancing Renewables with Li-Ion Energy Storage", Power, May 2014, Pages 34-37.

30. Patel, S., "The Big Picture: Storage Snapshot, Breakdown by Storage Technology", Power, May 2014, Page 12.

CHAPTER 4: Value Analysis: Financial Benefit

The primary goal of the value analysis was to determine the financial benefit of standard modules and packs in second use and to estimate life cycle cost impacts from standardizing battery pack parameters, design, and components. The task also included an assessment of pathways to implementing standardized module and pack designs.

4.1 Executive Summary

The value analysis study included four primary sub-tasks:

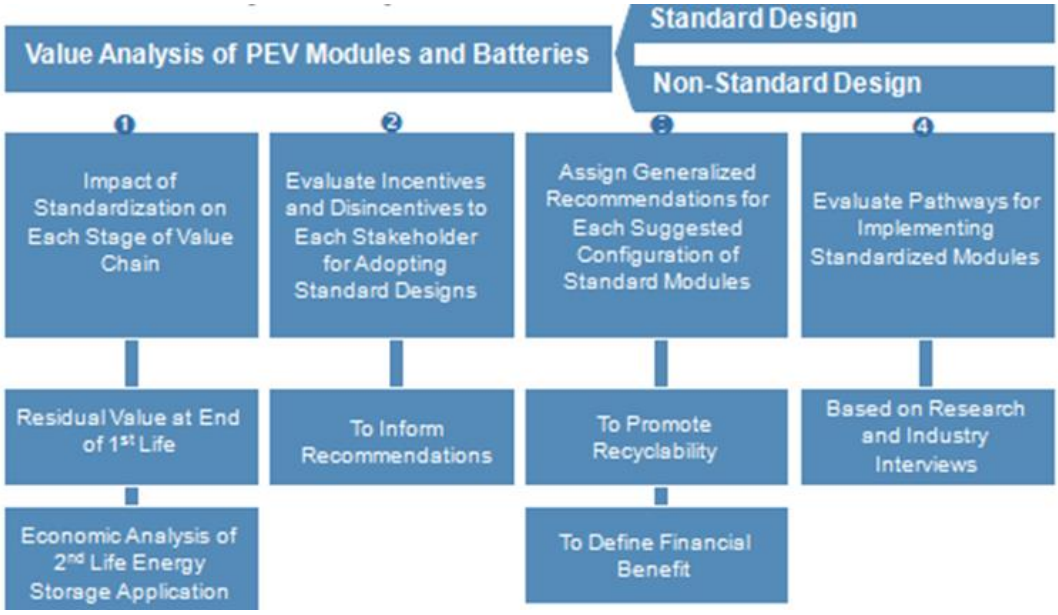
1) Determine the impact of standardization on each stage of the value chain, including research on the residual value of battery systems at the end of first use and an economic analysis of second use stationary energy storage applications.

2) Evaluate incentives and disincentives to each stakeholder for adopting standard designs; the purpose of this sub-task was to inform recommendations for standardization.

3) Assign generalized recommendations for each suggested configuration of standardized modules to promote recyclability and define financial benefits.

4) Evaluate pathways for implementing standardized modules based on research and industry interviews as shown in Figure 271.

Figure 271: Four Key Sub-Tasks of the Value Analysis



Additional interviews were conducted with industry stakeholders (vehicle original equipment manufacturers, battery manufacturers, national laboratories, and battery recyclers) to obtain comments on the impact of standardization from both commercial and technical perspectives,

as well as views regarding the impact of standardization on residual value of first use battery systems, and definition of incentives and disincentives to standardization.

It is projected that significant cost reductions due to module and battery design standardization will not occur until production volumes exceed 100,000 units per year, at which time price reductions on the order of 10 percent to 15 percent are expected relative to current first use battery system prices. It is noted that continuing improvements in lithium-ion chemistries for the electric vehicle market are likely to reduce prices to below $300/kWh by 2020, assuming large-volume production facilities are put in place.

It is the opinion of the industry experts interviewed during this portion of the study that standardization will lead to improved battery safety through the implementation of improved separators, coatings, thermal management systems, and housing designs.

Industry stakeholders are recommending that a family of up to four design standards be implemented to account for differences in applications, chemistries, and performance specifications. Currently, economic and technical considerations dictate that assembled second use modules and packs will contain like cells. As standard designs become available, this assumption can be relaxed.

The residual value of lithium-ion batteries at the end of their first use was determined using a variety of methods, including: (1) scrap materials prices; (2) battery recycle values; (3) results of research conducted by the national laboratories; (4) vehicle battery pack trade-in values; and (5) second use value based on economics of second use grid energy storage applications. The resulting values ranged from -$30/kWh (battery owner must pay to have battery recycled) to +$150/kWh (based on high value second use application).

The suitability of the standardized module/battery system configurations for different grid applications was assessed and compared to the suitability of the current non-standardized PEV system architectures. An energy storage economics model was utilized to determine the dollarized benefit of selected grid/storage scenarios for both non-standardized and standardized battery system designs. It was determined that, in general, all applications show potential for net benefit results if battery modules are standardized. Key grid applications that will benefit from battery energy storage include electric service reliability, renewable time shift, and power quality. The maximum economically feasible installed battery costs range from $183/kWh to over $1,000/kWh.

A list of incentives and disincentives for implementing standardized battery designs for electric-drive commercial vehicles was assembled. Many of the stakeholders expressed concern regarding possible negative impacts on battery development if design standards are imposed too early in the maturation of the industry.

Organizations such as Society of Automotive Engineers (SAE), Federal Motor Vehicle Safety Standards (FMVSS), National Highway Traffic Safety Administration (NHTSA), UNMTC (UNECE), FreedomCAR, and the International Organzation for Standardization (ISO), have already put in place many components and testing standards for rechargeable energy storage

systems, but have not yet addressed design standards. It is recommended that these organizations be approached regarding support for design standards aimed at commercial vehicle modules and packs.

Standardized modules will facilitate recycling because (1) there will be fewer module types and chemistries; (2) construction will favor disassembly; (3) components may be labeled with bar codes to enable identification and machine sorting; and (4) future packs are anticipated to have a larger energy capacity and available in larger volumes, thus promoting recycling operations.

Commercial vehicles have been identified as primary candidates for standardized module/pack designs because of the favorable economics associated with electric drive systems, the packaging options available for implementing standardized packs, and the projected supply of second use batteries originating from these vehicles.

As described in Chapter 3, example module and pack designs have been developed based on energy capacity increments of 25 kW-hrs that meet the identified duty cycles. These are intended to establish a basis for developing a family of module and pack design standards applicable to the commercial vehicle industry. It is projected that three to four sets of designs standards can eventually be developed for various electric drive vehicle categories (design standards for hybrid electric vehicles (HEVs) are expected to be different than those for battery electric vehicles (BEVs), for example). It is recommended that the design standards include sections on accommodations of repurposing and second use applications and recycling.

It is recommended that initial module and pack design standardization activity be focused on commercial vehicle applications. Module production volumes for application to commercial vehicles are projected to exceed 100,000 units during 2018. Significant cost reductions associated with large volumes and standardized designs occur at this production level. Thus, design activity associated with standard modules and packs aimed at the commercial vehicle market should begin during 2015.

Pathways to implementing standardized modules and battery systems, in addition to those defined in Chapter 3, were identified and include:

- Identifying commercial and technical advantages of standard designs for all portions of the module/pack life cycle.
- Including monetary incentives for implementing standardized battery designs as part of government-funded battery-electric vehicle adoption rate programs (based on clear benefits to entire value chain).
- Improving supply chain reliability. The supply chain has been erratic in recent years as a result of changes in ownership and strategy. To effectively implement design standards, an improvement in supply chain coordination and cooperation will be required.

4.1.1 Sub-Task 1: Impact of Standardization on Each Stage of Value Chain

For this portion of Task 5, a value analysis of module battery systems (from first use vehicle application through second use stationary energy storage, and finally, recycling) was

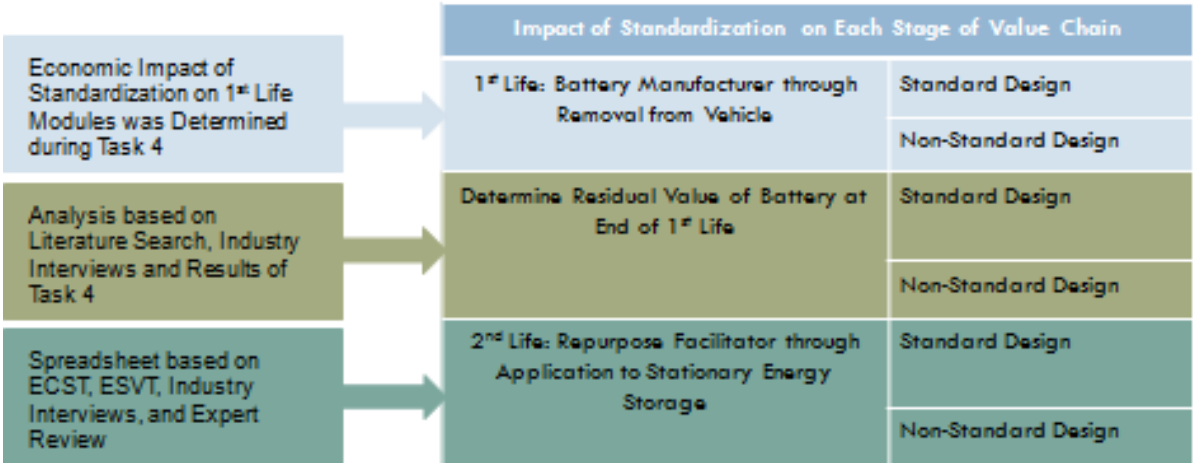
completed. The analysis included battery systems in both the current state (with custom system designs for each vehicle) and in a projected future state (with standardized battery system designs).

The impact of standardization on each stage of the value chain included:

- Effect on battery price and battery residual value at end of first use
- Effect on the value derived from the individual players in the supply chain including:
    - Cell and system manufacturers
    - Vehicle OEMs
    - Vehicle end users
    - Repurpose facilitators
    - Second use energy storage system owners (utilities)

The approach employed during Sub-Task 1 is illustrated in Figure 272. The economic impact of standardization on first use modules and battery systems was defined in Chapter 3. An additional analysis was conducted based on a literature search and industry interviews to determine the residual value of lithium-ion battery systems at the end of their first use. The residual value was one of the inputs to the second use energy storage value analysis.

Figure 272: Key Activities Associated with Sub-Task 1: Impact of Standardization on Each Stage of Value Chain

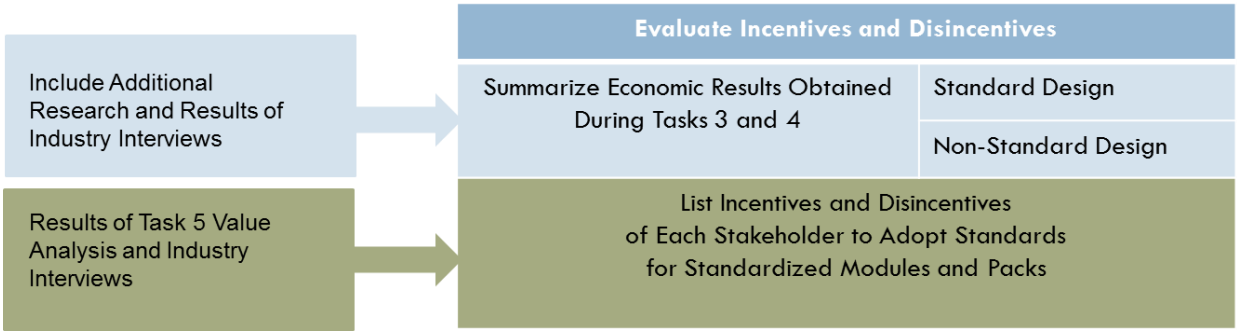


4.1.2 Sub-Task 2: Evaluation of Incentives and Disincentives to Each Stakeholder for Adopting Standardized Designs

The reasearchers listed incentives and disincentives of each stakeholder to adopt standards for standardized modules and packs using the impact analysis on each stakeholder defined during Chapter 2, combined with the cost analysis from Chapter 3, and the additional holistic value stream analysis from Chapter 4. This analysis was used to inform recommendations for pack standard development and implementation. The approach employed during Sub-Task 2 is

illustrated in Figure 273. An additional literature search coupled with interviews of industry stakeholders was used to enhance and summarize the economic results developed earlier in the study and described in Chapter 2 and Chapter 3.

Figure 273: Key Activities Associated with Sub-Task 2: Evaluation of Incentives and Disincentives to Each Stakeholder for Adopting Standardized Module and Battery System Designs

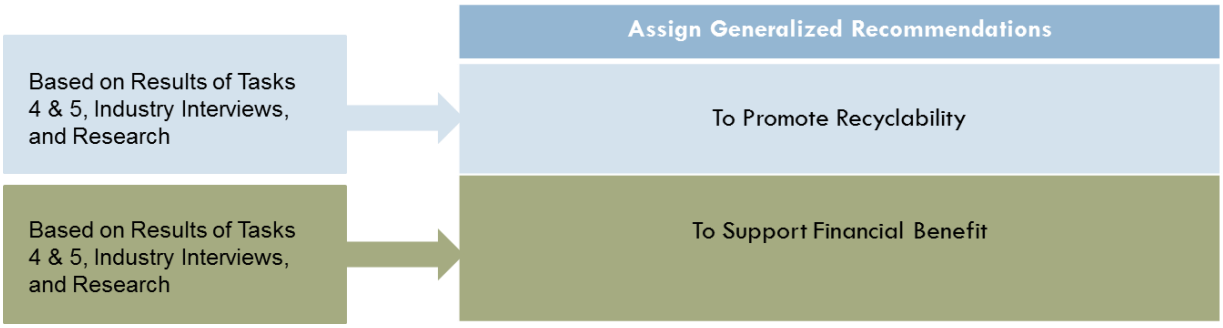


4.1.3 Sub-Task 3: Assign Generalized Recommendations for Each Suggested Configuration of Standardized Modules

During Sub-Task 3, the authors determined generalized recommendations for each suggested configuration of standardized modules to promote recyclability and to define financial benefits. The approach employed during Sub-Task 2 is illustrated in Figure 274.

Again, industry interviews and research conducted during Chapter 3 were employed as the basis for recommendations to promote battery system recyclability and to define financial benefits associated with standardization.

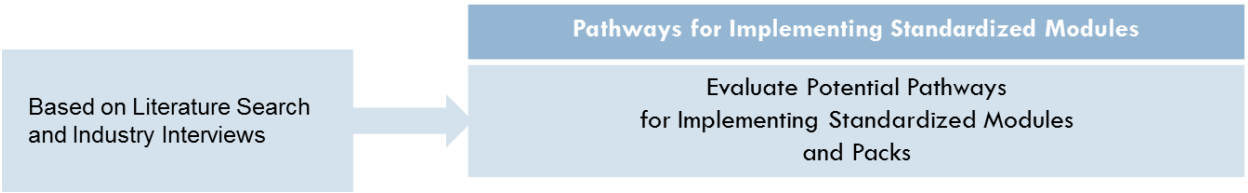
Figure 274: Key Activities Associated with Sub-Task 3: Assignment of Generalized Recommendations for Each Suggested Configuration of Second Use Standardized Modules and Battery Systems



4.1.4 Sub-Task 4: Evaluating Pathways for Implementing Standardized Modules

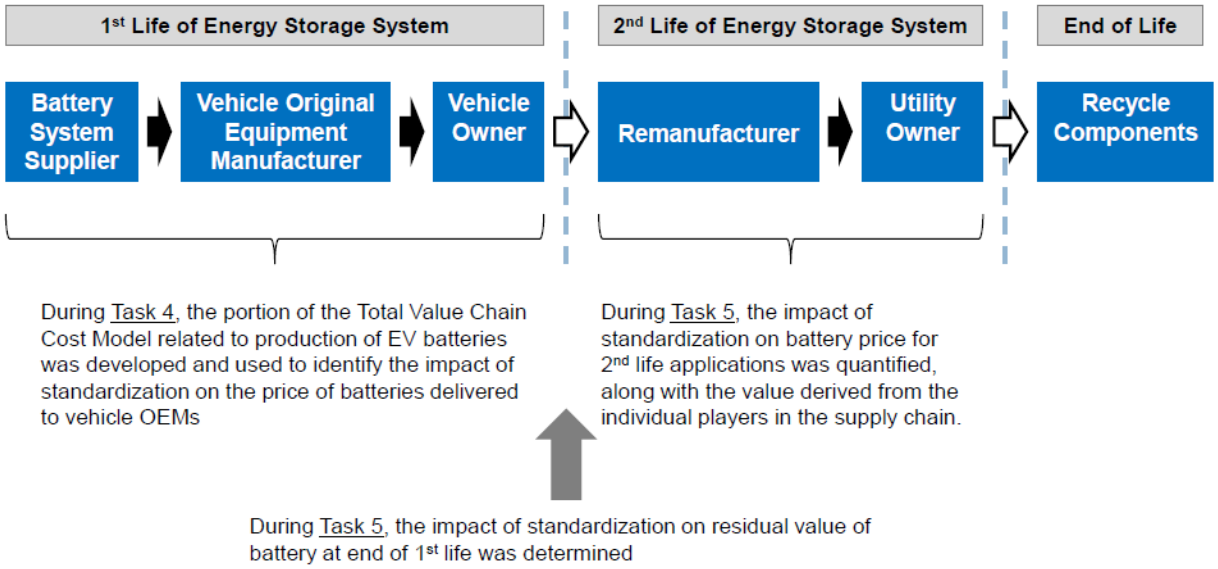
The potential pathways for implementing standardized battery modules defined during Chapter 2 were expanded to include recommendations obtained during additional interviews with industry stakeholders. Key activities associated with Sub-Task 4 are shown in Figure 275.

Figure 275: Key Activities Associated with Sub-Task 4: Evaluation of Pathways for Implementing Standardized Modules and Battery Systems



The relationship of Chapter 4 to the stages of the battery life cycle is illustrated in Figure 276.

Figure 276: Relationship of Task 5 to Stages of the Battery Value Chain



Chapter 4 sub-tasks were distributed among the research participants based on capabilities and experience as illustrated in Figure 277.

Figure 277: Resource Utilization: Assignment of Sub-Tasks

4.2 Sub-Task 1: Impact of Standardization on Each Stage of Value Chain: Economic Benefits, Standardized Compared to Non-Standardized Modules and Battery Systems

4.2.1 Industry Interviews: Overview

Interviews were conducted with nine organizations relative to the impact of standardization on first and second use battery applications. Interview questions relate to the four sub-tasks of the Chapter 4 research.

Figure 278: Types of Organizations Included in Task 5 Industry Interviews

Type of Organization	Number of Organizations in this Category
Vehicle OEMs	3
Battery Manufacturers	2
National Laboratories	2
Battery Recyclers	2

The topic categories for interviews with industry stakeholders and their relationship to the four Chapter 4 sub-tasks are shown in the table of Figure 279.

Figure 279: Relationship of Interview Questions to Task 5 Sub-Tasks

Interview Question	Sub-Task 1:	Sub-Task 2:	Sub-Task 3:	Sub-Task 4:
1. Cost and Performance Impacts of Standardization	✓		✓	
A. Range of impacts on cell and module cost elements	✓		✓	
B. Impacts on battery safety	✓		✓	
2. Battery and Module Price Projections	✓			
3. Value Impact of Standardization on Industry Stakeholders	✓			
A. Impact on supply chain stakeholders	✓			
B. Factors impacting 1st life residual value	✓			
C. Impact on 1st life residual value	✓			
4. Non-Cost Impacts of Standardization on Industry Stakeholders		✓		
A. Incentives for adopting standardized designs		✓		
B. Disincentives for adopting standardized designs		✓		
5. Design for Recyclability			✓	
6. Pathways for Implementing Standards				✓

Sub-Task 1: Impact of Standardization on Each Stage of Value Chain
Sub-Task 2: Evaluate Incentives and Disincentives to Each Stakeholder for Adopting Standard Designs
Sub-Task 3: Assign Generalized Recommendations for Each Suggested Configuration of Standard Modules
Sub-Task 4: Evaluate Pathways for Implementing Standardized Modules

The results, categorized by these topic categories, are presented below. The questions below relate specifically to Sub-Task 1: Impact of Standardization on Each Stage of the Value Chain.

4.2.2 Industry Interviews: Cost and Performance Impacts of Standardization and Battery Safety

1. ***Question: What range of cost impacts would you expect on cell and module cost elements if standardization is implemented?***

Projected production volumes (through 2020) of commercial electric vehicle battery packs are too low to support significant cost reductions due to implementation of standard designs (reference 36).

While technology developments have been promising, unanswered questions remain on the issue of cost. No significant cost improvements relative to energy storage are anticipated in the near term. The situation is not helped by the wide range of powertrain variants, from low voltage mild hybrids and battery electric vehicles, complex packaging challenges and differing requirements in energy density and power density. The current approach to mass customization is unlikely to yield the savings the industry needs; this will only come about through some level of standardization either at the pack level or most probably at the cell level (reference 46).

It is possible that negative residual values of modules at the end of their first use would provide an economic advantage to second use applications. If the battery owner must pay to have the modules recycled or processed for disposal, then it is conceivable that the owner would be willing to pay to transfer ownership at no cost to the second use repurposer (references 45, 47).

Argonne National Laboratory has been investigating the impacts of standardization on the first use costs of batteries. This includes producing different battery types within the same manufacturing facility. The study indicates it is difficult to obtain significant cost reductions until production levels reach 100,000 batteries per year. One option is to standardize the size of electrodes, while allowing variations in thickness, chemistry, and coatings (all on the same processing line); this has the potential to reduce module costs on the order of 15 percent (reference 36).

Battery manufacturers (reference 47, 49) predict standardization will increase first use battery costs for the near future due to the additional development costs associated with meeting the new standards, and current low-volume production levels. Once standardization is widely implemented, production volumes will result in reduced first use costs.

A 10 percent to 15 percent reduction in first use battery costs is possible through standardized design (reference 52).

Commercial vehicles are a good choice for implementing standardized designs because of the relaxed battery system packaging constraints (references 48 and 52).

2. ***Question: What impacts would cell and module standardization have on battery safety?***

Safety standards and regulations (including test procedures) should be tied to battery chemistry since not all lithium-ion chemistries and module designs react in the same way to failure modes. Standardization of designs should include safety as a key factor (reference 47).

Use of improved separators and coatings could be included in the standardized design specification to improve safety (references 24, 36, 47).

Vehicle crash performance relative to battery systems is a key design parameter. Standardized designs must include rigorous failure mode analysis (reference 52).

Standardized modules and battery system designs can more rigorously address the main failure modes for lithium-ion cell, module, and battery systemss as well as factors that influence the effect of failures (reference 50):

i. Non-Energetic Failures (loss of capacity, internal impedance increase, electrolyte leakage)

ii. Energetic Failures (thermal runaway: self-heating due to exothermic chemical reaction)

3. ***Question: Would incorporating features to facilitate second use, stationary applications have negative impacts on first use performance or cost?***

It is likely that adding features to facilitate second use applications will be favorable for both first use and second use costs. It will depend upon the level of added first use costs, of course, but by extracting additional services and revenue from the battery in a post-vehicle application, the total lifetime value of the battery is increased, thereby decreasing the overall cost of energy-storage solutions for both primary and secondary customers (references 33, 40, 47).

4.2.3 Industry Interviews: Value Impact of Standardization on Industry Stakeholders

1. ***Question: What are your opinions regarding value derived by individual players in the supply chain if standardization is implemented?***

Responses to this question are categorized by the industry of the respondent:

A. Cell and module manufacturers

- It is possible that standardization could allow a wider degree of future integration (for both first and second use applications) if a number of design standards could be developed, for example these standards could be based upon 4 types of cells, 4 types of modules, and 4 types of packs, all designed for a particular catergory of vehicle application (e.g. under floor or within body area, BEV application, PHEV application, or HEV application) (reference 36).

B. Battery manufacturers

- It is unlikely that one standard would be appropriate for the entire vehicle market (light duty to heavy duty). However, some components, for example electrodes, might be compatible across a wide range of cell types. Economies of scale for electrodes begin at production rates exceeding 25,000,000 m^2/year (reference 36).

C. Vehicle OEMs

- Manufacturers of MD and HD commercial vehicles can emphasize lower cost of ownership due to higher residual value of first use battery and reduced cost of replacement battery (reference 48).

D. Vehicle owners

- Vehicle owners would benefit primarily from a financial standpoint; standard battery designs are expected to increase production volumes for these designs, resulting in lower prices. In addition, the standardized designs will reduce the cost of repurposing the batteries for second use stationary energy storage applications, thus increasing their first use residual value (references 40, 42, 45, 47).
- Once the battery industry matures and standard module designs are the norm, replacement costs are expected to decrease as batteries approach commodity status (reference 51). However, this assumes a corresponding drop in the cost of associated systems, such as battery management systems and thermal management systems.

E. Battery/module repurposing for second use

- There is little correlation between residual value at the end of first use and original module/pack cost. Residual value is determined by the second use market or recycle value (references 36, 45).
- Repurposing costs range from $18/kw-hr to $150/kW-hr depending upon the module chemistry, form factor, and compatibility with other modules being integrated into the second use pack (references 36, 40).

F. Recyclers

- Currently, the recycle value of lithium-ion batteries is directly related to the content of nickel, cobalt, and copper and the ease by which these materials can be extracted (reference 45).
- Recycling of lithium-ion battery materials potentially reduces the material production energy by as much as 50 percent (reference 19).

4.2.4 Impact of Standardization on Module and Battery System First Use Price Projections

4.2.4.1 Industry Interviews: Module and Battery System Price Projections

1. ***Question: What are your projections for lithium-ion battery cell, module, and pack prices ($/kWh) through 2025 and 2050?***

Battery prices are related to application. First use prices of HEV batteries are expected to remain in the range of $500-$600/kWh. BEV batteries will likely approach $200/kWh (reference 36).

Lithium-Ion batteries are expected to remain above $300/kWh until large scale manufacturing facilties are put in place (reference 47).

4.2.5 Research Results: Assessment of Battery Prices at Start of First Use Application

The current price for Tesla Model S battery packs is on the order of $200/kWh. It is projected that it will decrease to $120/kWh by 2020 (references 3, 10). The new Tesla battery factory ("Gigafactory") is projected to produce lithium-ion batteries priced at $200/kWh or less (reference 5). A Tesla battery replacement option is now available for purchase at a cost of $10,000 for the 60 kWh battery ($166/kWh) and $12,000 for the 85 kWh battery ($141/kWh). Chevy Volt replacement batteries are currently $2,300 each (16 kWh capacity), or $144/kWh (reference 4).

The electric utility industry has witnessed prices of battery energy storage systems decrease by 50 percent over the last three years (reference 25). Lithium-ion battery prices are expected to drop 75 percent by 2020; Tesla's planned "Gigafactory" is expected to have a favorable impact on battery system prices (reference 20). Lithium-ion battery prices must decrease by 32 percent from today's levels in order to be competitive as grid-connected energy storage systems (reference 20).

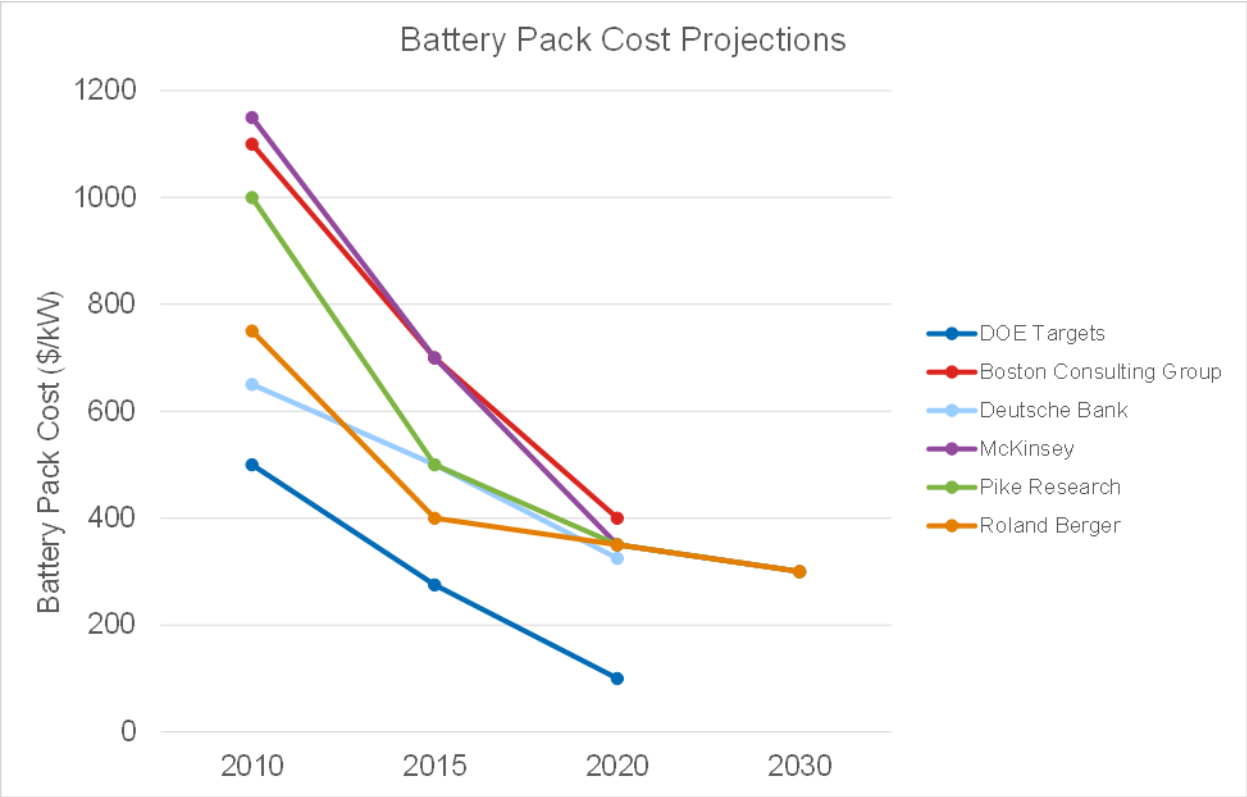
Ricardo's summary of lithium-ion battery price projections is included in Chapter 1. This study indicated that under business as usual conditions (for example, no basic changes in energy storage technologies), lithium-ion battery systems should achieve price levels of less than $300/kWh by 2020.[72] LG Chem predicts Li-ion battery costs will decrease by a factor of two prior to 2020[73]. A study conducted by Deutsche Bank predicts that lithium-ion battery systems prices will drop below $200/kWh by 2020.[74] The results of a recent survey completed by the National Renewable Energy Laboratory are shown in Figure 280. Steep declines in battery prices are forecast over the next several years primarily due to improved, volume production methods.

[72] Sources: References 3, 4, 10, and 24-31

[73] Automotive News, 17 September 2013

[74] Reference: Electric Vehicle Initiative: Global EV Outlook, April 2013
Source: IEA, U.S. DOE, Deutsche Bank)

Figure 280: Multiple Battery Pack Cost Projections[75]

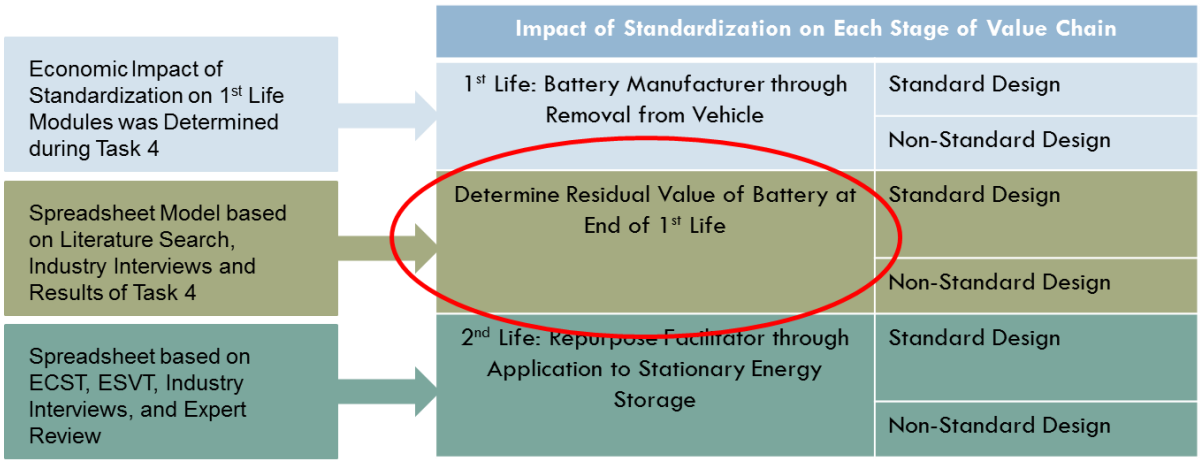


4.2.6 Determination of Residual Value of Battery Systems at End of First Use

A key input to the second use economic analysis is the value of lithium ion battery systems at the time they are removed from their initial first use vehicle application. The residual value of lithium-ion batteries at the end of their first use was determined using a variety of methods, including: 1) scrap materials prices, 2) battery recycle values, 3) results of research conducted that the national laboratories, 4) vehicle battery pack trade-in values, and 5) evaluation of second use value based on economics of second use grid energy storage applications. As shown in Figure 281, determination of the residual value of first use battery systems is one of the key tasks in Sub-Task 1: Impact of Standardization on Each Stage of the Value Chain.

[75] *Reference:* Neubauer, J.S., *et. Al.*, SAE International Paper 2012-01-0349, "A Techno-Economic Analysis of PEV Battery Second Use: Repurposed-Battery Selling Price a*nd Commercial and Industrial End-user Value*, 04/16/2012.

Figure 281: Determine Residual Value of Battery at End of First Use



For the current study, it is assumed the battery system reaches end of first use when its energy storage capacity reaches 80 percent of its original value. This will vary based on duty cycle requirements and a variety of other factors (see Figure 283).

Additionally, it is assumed the battery system reaches the end of second use when its energy storage capacity reaches 40 percent of its original value (note that older batteries have increased impedance and associated heat generation; this increases thermal cooling system loads).

4.2.6.1 Industry Interviews: Residual Value at End of First use

1. ***Question: What is your opinion regarding the impact of standardization on the residual values of first use batteries?***

Standardization would improve residual value at end of first use because it would increase the number of economically viable second use applications. It is difficult to integrate stationary storage systems containing different electrical characteristics and chemistries. The second use market will be the key factor in determining the residual value of first use batteries (references 36, 40, 47)

It is likely standardization must occur at the cell level in order to allow reassembly into new modules for second use applications. In addition, the cells to be repurposed should be at the same level of health (faulty cells to be identified and replaced). Currently, second use applications are restricted to using batteries of the same type, for example from the same manufacturer and vehicle type (reference 36).

There is a wide range of residual values for end-of-first-life batteries. This is due to: (1) impacts of battery chemistry, some have better second use characteristics than others, for example, slope of loss-of-capacity-with-time curve; (2) number of "appropriate" applications for each module/pack: Battery manufacturers have identified many customers that have applications for which packs with 60 percent to 80 percent of the original energy capacity are acceptable; and (3) value of recycled materials (reference 47).

The scrap value of lithium-ion batteries varies from negative (battery owner must pay to have battery recycled) to highly positive (if key materials are easy to extract at low cost). (reference 47). Some European manufacturers have been charging between $5 and $7/kg to recycle used lithium ion batteries (internal Ricardo research).

Larger capacity, repurposed vehicle battery systems may be an option for use in other vehicles with lower-energy duty cycles, but an analysis would have to be performed regarding the penalty of carrying the additional weight (due to lower specific energy of the repurposed battery system) (reference 47).

Based on the results of industry interviews, it is assumed that for the near future, assembled second use modules and battery systems will contain like cells. As standard designs become available, this assumption can be relaxed. Current, non-standard designs would require development of battery management systems, thermal systems, and packaging systems capable of accommodating varying chemistries, voltages, form factors, etc. (references 45, 47, 49).

One indicator of battery residual value at end of first use is the depreciated value of the electric vehicle (which includes the battery pack). The following table (based on reference 16) shows the residual value of light duty electric vehicles at the end of the 5th year of ownership:

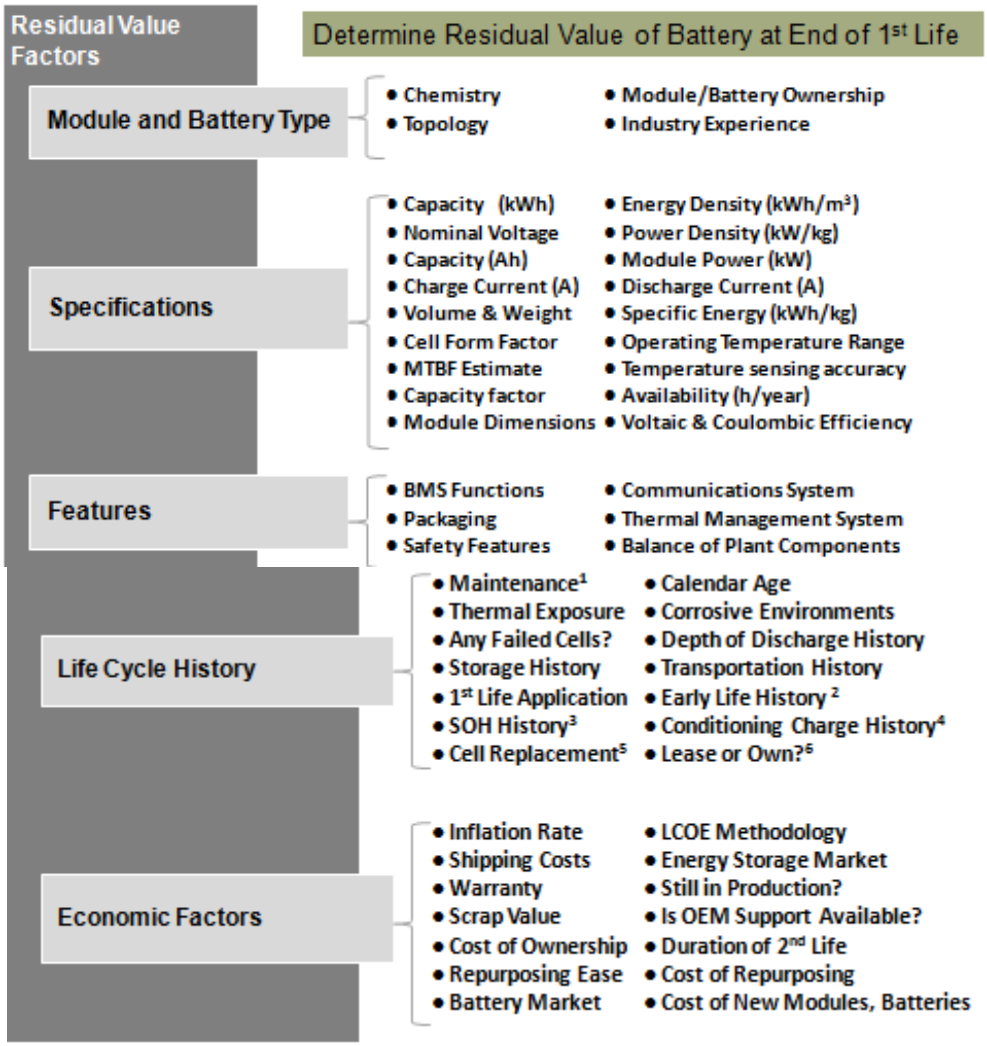
Figure 282: Residual Values of Light Duty Electric Vehicles after 5 Years

Make & Model	Vehicle Original Price	Vehicle Value at End of 5th Year	Residual Value (% of Original Price)	Battery Size
Chevrolet Spark	$28,305	$8,000	28%	21 kWh
Ford Focus Electric	$36,000	$7,200	20%	23 kWh
Nissan Leaf	$35,700	$5,355	15%	24 kWh

4.2.6.2 Factors Impacting Residual Value of Battery Systems at End of First use

A variety of factors influence the value of the battery at the end of its first use. These can be divided into five primary categories: (1) module and battery type; (2) battery system specifications; (3) battery system features; (4) life cycle history; and (5) economic factors. Specific parameters included in each of these categories are shown in Figure 283.

Figure 283: Residual Value Factors[76]



4.2.6.3 Residual Value Research Results

The results of the lithium-ion battery system first use residual battery analysis are shown in the table of Figure 284. Information sources for this research included scrap materials purchasers, battery recyclers, research organizations, vehicle OEMs, and an evaluation of the economics of second use stationary energy storage applications (that is, the value of second use battery systems to energy storage system operators).

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[76] [1]First Life Maintenance (scheduled, use-based, or condition-based), [2]Usage when initially placed in service (degradation due to idle time), [3]State of Health History: How closely was battery monitored?, [4]Conditioning charge cycles can restore battery capacity, [5]Were failed cells replaced regularly and with compatible cells, [6]Modules/packs may be designed for lease period.

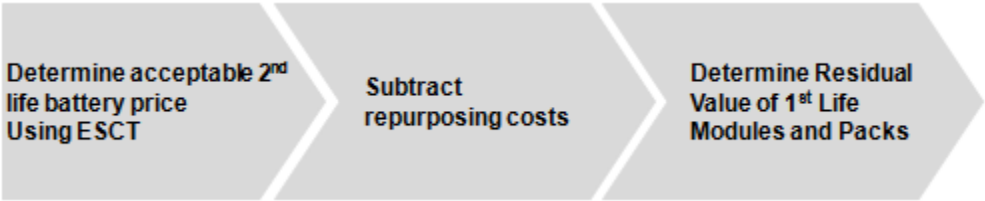
Figure 284: Residual Value Research Results

Information Source	Reference	Residual Value ($/kWh)		Comments
		Low*	High	
Scrap Materials Purchaser (2014)	43	$29	$47	Scrap Value: $1.70/lb, (Specific Energy) range: 17.0-27.5 lb/kWh
Battery Recycler: (value highly dependent on battery type) (2014)	45	$(30)	$30	Range = -10% to +10% of new battery price (assumed to be $300/kWh)
NREL: End of 1st Life Battery, Repurposing cost not included (2014)	37	$20	$103	Highly dependent upon second life application
Sandia National Laboratories (2002)	38	n/a	$82	Based on buy-down offered by vehicle manufacturer
Fraunhofer Institute (2011)	41	n/a	$40	Based on integrating used battery packs into microgrids
Trade-in value when Purchasing Replacement Battery Pack (2014)	42	n/a	$42	Nissan Leaf (24 kWh pack: trade-in value =$1000)
Based on Economically-Favorable 2nd Life Grid Applications	This Report	$35	$150	Based on ESCT Analysis and 50% Used Product Discount Factor
*negative entries indicate owner must pay to have battery recycled				

It is noted that the economics associated with the second use stationary energy storage application can determine the price of acceptable batteries to be repurposed, and hence the corresponding residual value of the first use batteries. The approach employed to calculate the impact of second use applications on first use residual value is shown in Figure 285 and includes the following tasks:

- Conduct parametric study of the second use energy storage market: identify applications for which the economics model indicates a favorable return on investment.
- For each second use energy storage application exhibiting favorable economics, determine the acceptable module/battery price (price of modules ready for assembly into second use packs).
- Subtract repurposing costs (reference 40) to determine the residual value of the battery at the end of first use. This is the battery price that corresponds to a favorable return on investment for the identified application.

Figure 285: Method for Calculating First Use Residual Value Based on Second Use Application

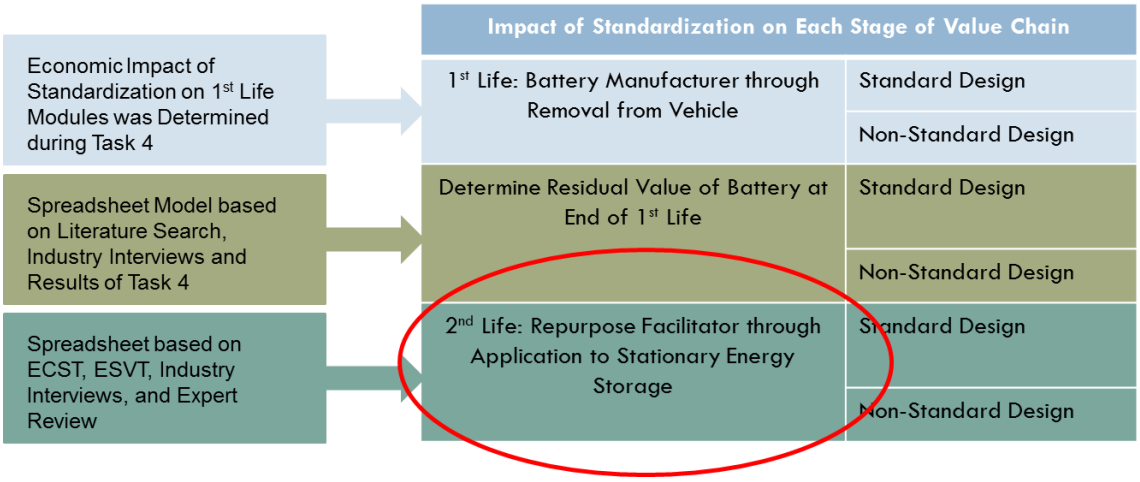


For example, the range of battery cost benefits for energy storage applications related to electric service reliability can range from $183/kWh to $300/kWh, depending upon the storage system size (25 kWh to 1000 kWh). Thus, after subtracting the repurposing cost ($18 to $32/kWh, references 40 and 42), these applications would have favorable lifetime benefits even if the first use residual values were in the range of $151/kWh to $282/kWh. Ifthe researcherslimit the first use residual value to a "used product discount factor" equal to 50 percent of a new battery price, the residual value range would vary from $75/kWh to $150/kWh (corresponding to new battery prices of $150/kWh to $300/kWh), well within the acceptable range for electric service reliability applications.

4.2.7 Value Analysis: Second Use Module and Battery Systems

The value analysis of second use modules and battery systems is part of Chapter 4, Sub-Task 1: Impact of Standardization on Each Stage of the Value Chain, as shown in Figure 286.

Figure 286: Relationship of Second Use Value Analysis to Sub-Task 1: Impact of Standardization on Each Stage of Value Chain



The utility industry has addressed the application of second use BEV batteries for stationary energy storage applications as summarized in the figure below (reference 33):

Figure 287: Applications for Second Use Batteries

Application	Use of 2nd Life Batteries	Comments
Transmission	Not Recommended	Key issue is long-term reliability
Distribution	Marginal	Again, long-term reliability is a concern
Customer	Primary Application	Focus is on behind-the-meter applications (decentralized energy management)

Primary application for second use BEV batteries is in distributed generation and customer (residential, commercial, industrial) locations. Applications include (reference 34):

1. ***Generation level:*** arbitrage, capacity firming, curtailment reductions
2. ***Transmission level:*** frequency and voltage control, investment deferral, curtailment reduction, black starting
3. ***Distribution level:*** voltage control, capacity support, curtailment reduction
4. ***Customer level:*** peak shaving, time of use cost management, off-grid supply load leveling, frequency control

As part of the final value stream analysis, the following were investigated:

- Suitability of the standardized system configurations for different grid applications as compared to the suitability of the current non—standardized PEV system architectures:
    - Ease of installation and use of the standardized system configuration second use utility applications
    - Standard housing requirements
    - Standardized connectors and locations
    - Standardized BMS and communication protocols (especially ISO 15118)
- Reliability and risk impact of standardized module configurations
- Impact of standardized pack configurations on first and second use maintenance costs

4.2.7.1 Determining Dollarized Benefit of Standard versus Non-Standard Modules in Secondary Use

The goal of this section was to compare the dollarized benefit, difference between deploying an energy storage solution in comparison to not deploying an energy storage solution.The researchers investigated using standard and non-standard modules in secondary life energy storage solution deployment effects and in particular the following aspects of secondary life: (1)

suitability for different grid applications, (2) ease of installation, (3) reliability and risk reduction, and (4) maintenance cost savings. Two different approaches were taken to evaluate these four secondary life aspects. One approach (Method A) involved using an economic benefit model developed by Navigant Consulting known as the Energy Storage Computational Tool (ESCT). This approach was used to determine the dollarized benefit of the standard module versus non-standard module's (1) suitability for different grid applications.

The second approach (Method B) involved consultation with a second-life EV battery expert. In this approach the lifecycle processes from the battery's end-of-vehicle stage through secondary life to disposal stage were assessed. The figure below summarizes the approach used to determine the dollarized benefit of standard versus non-standard batteries with respect to each secondary use aspect.

Lastly, it should be noted that there are no commercial-scale used battery storage system manufacturers and therefore the researchers could not explicitly identify a dollarized benefit for a standard battery's suitability for different grid applications. Instead, the researchers identified the necessary impact of standardization in order to make different grid applications profitable (that is, positive net benefit). Additionally, the researchers could only qualitatively estimate the impact of standardization on battery modules for the remaining three secondary life aspects: ease of installation, reliability and risk reduction, and maintenance cost savings.

Figure 288: Methods Used for each Benefit[77]

Benefit	Method Used
• **Suitability for different grid applications**	A
• **Ease of installation**	B
• **Reliability and risk reduction**	B
• **Maintenance cost savings**	B

4.2.7.2 Suitability for Different Grid Applications

The Energy Storage Computational Tool (ESCT) was used to determine the dollarized benefit of a non-standard battery module's suitability for different grid applications. Secondly, ESCT was used to determine a battery price threshold at which standardization would result in profitable grid applications.

To get started, the project team researched the usability and functionality of the ESCT. The ESCT allowed for operator configuration and input. Operator inputs include costs, system size, location, market, owner, and application(s). Providing inputs and running the model produces the net benefit for said system.

Costs are variable between non-standard and standard battery modules. Figure 289 provides a summary table of the cost inputs impacted by standardization.[78]The researchers can look to

[77] U.S. Department of Energy. Energy Storage Computational Tool (ESCT). https://www.smartgrid.gov/recovery_act/publications/analytical_tools

Method B to better understand how these costs differ. With non-standard battery modules the researchers can look to currently deployed stationary storage systems as a proxy to estimate cost inputs, but because there are no current stationary storage systems deployed that use standardized batteries the researchers cannot estimate those cost inputs. This led the team to begin its review with determining the dollarized benefit of a non-standard module's suitability for different grid applications.

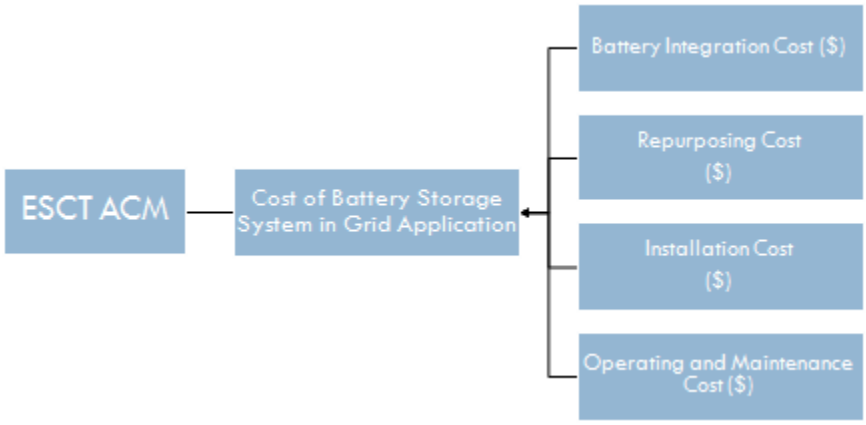
Figure 289: Impact of Standardization on Input Costs

Impact of Standardization: Is it a fixed or variable cost between a non-standard and standard used battery?		
Battery Integration Costs		
	Battery	Fixed
	Power Conditioning System	Variable
	Engineering Commissioning	Variable
Repurposing Costs		Variable
Installation Costs		
	Equipment Purchases	Variable
	Engineering	Variable
	Environmental	Variable
	Construction	Variable
	Information Technology	Variable
	Miscellaneous	Fixed
	Services	Fixed
	Internal Labor	Variable
Incentive Costs (i.e. Tax Credits and/or Cap & Trade Benefits)		Fixed
Financing and Insurance Costs		Fixed
Operating and Maintenance Costs		Variable

[78] Conversations with John Holmes, Sr. Technology Development Advisor, et al.

The first step involved collecting the cost inputs. The cost input could be broken down into four categories: (1) battery integration costs, (2) repurposing costs, (3) installation costs, and (4) operating and maintenance costs. Figure 290 illustrates this breakdown.

Figure 290: Top Level ESCT ACM Cost Inputs



These cost inputs were used in an ESCT module--that is, the Asset Characterization Module (ACM) shown in the Chapter 4 Appendix. There were three modules in the ESCT—Asset Characterization Module, Data Input Module (DIM), and Computational Module (CM). The ACM collects cost inputs related to the battery system, the DIM collects benefits related to utilizing the battery system for a specific application, and the CM integrates the costs and benefits from the ACM and DIM and outputs a net benefit result. To identify the four cost sub-components, each was broken down further. If no cost input value was discussed or determined through research, then default values built into the ESCT ACM were used. Battery cost sub-component breakdowns are shown in the following figures.

4.2.7.3 Non-Standardized Battery Systems Case

Battery Integration Cost

The battery integration costs are related to the cost of the battery itself. Given the cost of the battery,the researchers were able to determine the remaining battery integration costs and then sum all the sub-component costs to get the total Battery Integration Cost. Figure 291 and Figure 292 show the relationship between the battery integration sub-component costs. For a used non-standard EV battery stationary storage system,the researchersused the non-standard residual value of a used EV battery estimated at $40-$70/kWh for the cost of the battery[79]. Forty dollars represents the minimum cost (repurposer buy-price) of a used non-standard EV battery, while $70 represents the maximum cost of a used non-standard EV battery.

[79] Ricardo's residual value analysis. These costs do not include a battery repurposer's mark-up price.

Figure 291: Battery Integration Cost Input Breakdown[80]

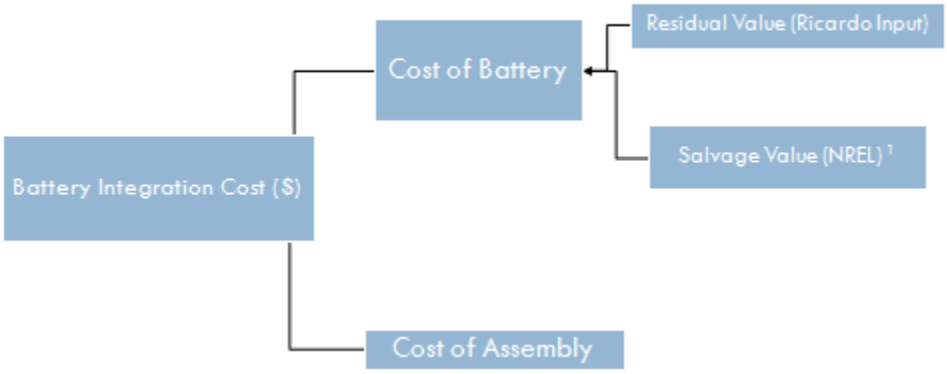


Figure 292: Battery Integration Cost Component Breakdown

Battery Integration Cost Components	Cost estimate as a percentage of battery cost (Y)
Battery(ies) (Y)	100%
Power Conditioning System	919%
Engineering Commissioning	919%

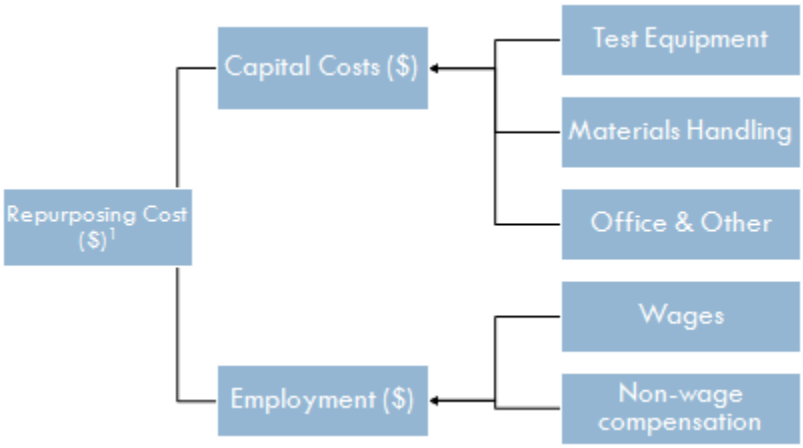
Repurposing Cost

The repurposing cost of a used non-standard Li-Ion electric vehicle (EV) battery ($25/kWh) was obtained from secondary research.[81] In the research study, a hypothetical repurposing facility was designed. Using an assigned annual module throughput of the facility, the repurposing cost per kWh was estimated. Figure 293 shows a breakdown of all the repurposing costs for informational purposes, only, sincethe researchers were able to pull the total repurposing cost directly from secondary research.

[80] Neubauer, Pesaran, Williams, Ferry, Eyer,"Techno-Economic Analysis of PEV Battery Second-Use: Repurposed-Battery Selling Price and Commercial and Industrial End-User Value. 2012

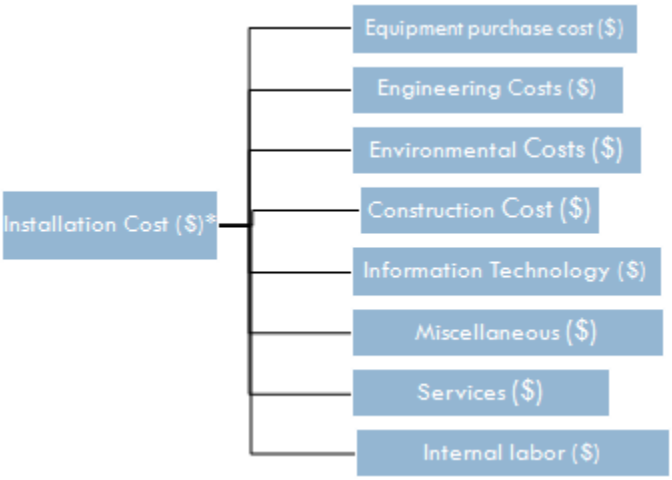
[81] Neubauer, Jeremy; Pesaran, Ahmad; Williams, Brett, Ferry, Mike; Eyer, Jim: A Techno-Economic Analysis of PEV Battery Second Use: Repurposed-Battery Selling Price and Commercial and Industrial End-User Value. 04/16/2012.

Figure 293: Repurposing Cost Input Breakdown[82]



Installation Cost

Figure 294: Installation Cost Input Breakdown



The installation cost can be broken down further into sub-costs as seen in Figure 295. These sub-costs were obtained via discussions with San Diego Gas & Electric (SDG&E) service staff members about currently deployed stationary storage systems.[83] A breakdown of the installation costs as a percentage of the battery cost are shown in Figure 295. The researchers used the forecasted 2020 cost of a new non-standard Li-Ion EV battery pack (approximately $300/kWh) to find the explicit values for each installation cost sub-component. This provided the researchers with the installation costs of a stationary storage system that utilized a new non-

[82] Neubauer, Pesaran, Williams, Ferry, Eyer,"Techno-Economic Analysis of PEV Battery Second-Use: Repurposed-Battery Selling Price and Commercial and Industrial End-User Value. 2012
[83] Conversations with John Holmes, Sr. Technology Development Advisor, et al.

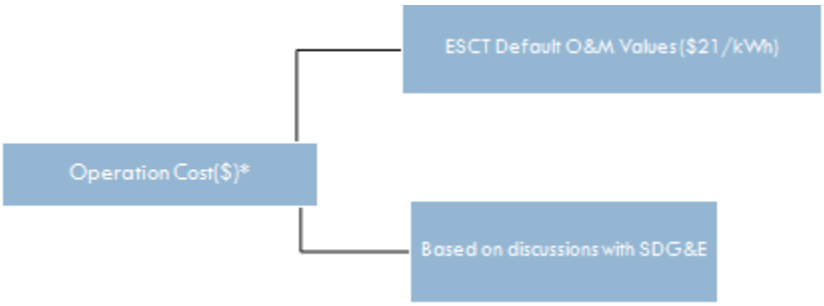
standard Li-Ion EV battery pack. The researchers use these costs as estimations for installing a used non-standard Li-Ion EV battery pack. This assumption is probably fair for the majority of the installation cost components because most are fixed between new and used battery systems.

Figure 295: Installation Cost Component Breakdown

Installation Cost Components	Cost estimate as a percentage of battery cost (Y)
Equipment Purchases	7%
Engineering	6%
Environmental Concerns	2%
Construction	15%
Information Technology	1%
Miscellaneous	2%
Services	2%
Internal Labor	1%

Operation Cost

Figure 296: Operation Cost Input Breakdown



If there was not a default value present in the ESCT, then the general Operations and Maintenance (O&M) costs obtained through discussions with SDG&E for an energy storage system were used. The general O&M cost was $100/kWh.[84]

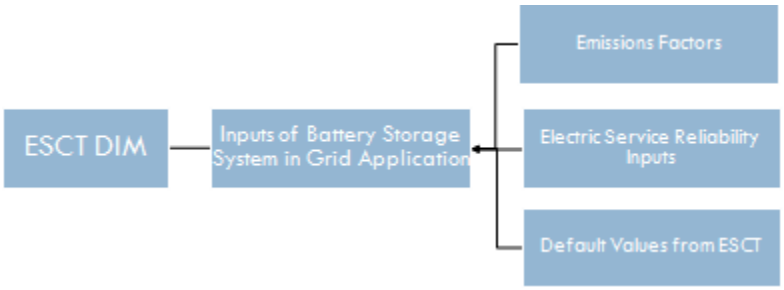
After the Asset Characterization Module was complete, the next step was to complete the Data Input Module (DIM). This module displayed all the benefits of deployment to the operator that would be providing to the electrical grid, customer, and utility owner. Figure 298 breaks down the inputs to the DIM for the particular application of Electric Service Reliability. There were a number of other applications that could be selected in the DIM and the researchers chose to analyze a select number of those applications, which included the following as listed in Figure 297.

[84] Conversations with John Holmes, Sr. Technology Development Advisor, et al.

Figure 297: Multiple-Application Scenario Overview[85]

Location	Distribution (CES)	G&T	End-User		
Market	Deregulated	Deregulated	Deregulated		
Owner	Utility	Utility	End-User		
Primary Application	Electric Service Reliability	Electric Service Reliability	Renewable Time-Shift	DCM	TOU
Secondary Application			Electric Service Reliability	Electric Service Reliability	Electric Service Reliability
Second Secondary Applications			Power Quality	Power Quality	Power Quality

Figure 298: ESCT DIM Cost Inputs



The ESCT allows the operator to create a scenario where multiple applications are selected. For purposes of this report, the researchers have called multiple-application scenarios, bundled applications. Up to three applications were allowed and they were termed the primary, first secondary, and second secondary utility grid applications. When the system was not performing the primary application, it would go onto the first secondary, and then onto the second secondary, but at any time if the system was capable of performing the higher order application it would switch over. The lifetime of an energy storage system (80 percent SOC to 40 percent SOC) assigned to primary, secondary, and second secondary applications was determined using a weighted average of lifetimes of each energy storage system under one application.

A total of 28 different scenarios that varied by battery system cost, capacity, customer, and grid location were run through the ESCT as summarized in Figure 280. Input pairings were based on technically feasible and realistic scenarios. For example, when a Generation & Transmission scenario was selected, the researchers constrained storage system capacity to between 1-20

[85] CES: Community Energy Storage

MWh. When a Transmission & Distribution scenario was selected, the researchers constrained storage system capacity to between 25-250 kWh. Lastly, when end-user scenarios were selected, the researchers constrained storage system capacity to between 25-250 kWh.

4.2.7.4 Energy Storage Economics Modeling

Summary of ESCT scenarios listed by location and customer include:

- G&T and Utility Owned (Scenario Count: 4)
    - Application: Electric Service Reliability
    - Storage System Capacity Range: 1 MWh -20 MWh
- T&D and Utility Owned (Scenario Count: 6)
    - Application: Electric Service Reliability
    - Storage System Capacity Range: 25-250 kWh
- End-User & End-User (Scenario Count: 18)
    - Bundled Applications: TOU, Electric Service Reliability, Electric Service Power Quality (aka in this report: TOU_Reliability_Quality)
    - Renewable Time-Shift, Electric Service Reliability, Electric Service Power Quality (aka in this report: Renewable_Reliability_Quality)
    - DCM, Electric Service Reliability, Electric Service Power Quality (aka in this report: DCM_Reliability_Quality)
    - Storage System Capacity Range: 25-250 kWh

In order for the ESCT to calculate the dollarized benefit of a particular system under a particular application, the user must either leave default ESCT values for benefits of that particular application or adjust the benefits of a particular application accordingly. A list of potential benefits that the user has the option of adjusting in the DIM is shown in Figure 299. As an example, Figure 300 provides benefit values for the Electric Service Reliability application.

Figure 299: Potential Benefits

Benefit Category	Benefit Sub-category	Benefit
Economic	Market Revenue	Arbitrage Revenue Capacity Market Revenue Ancillary Services Revenue
	Improved Asset Utilization	Optimized Generator Operation Deferred Generation Capacity Investments Reduced Congestion Cost
	T&D Capital Savings	Deferred Transmission Investments Deferred Distribution Investments
	Energy Efficiency	Reduced Electricity Losses
	Electricity Cost Savings	Reduced Electricity Cost
Reliability	Power Interruptions	Reduced Outages
	Power Quality	Improved Power Quality
Environmental	Air Emissions	Reduced CO_2 Emissions Reduced SO_x, Reduced NO_x Reduced Particulate Matter (PM) Emissions

Figure 300: Electric Service Reliability Benefit Inputs[86]

Energy Storage Application Requirements and Benefits

Table 2-5
Representative Benefit PVs of Selected Energy Storage Benefits

SNL Report		EPRI White Paper		PV $/kW-h				PV $/kW			
				SNL Benefits		EPRI Benefits		SNL Benefit		EPRI Benefits	
Application	**Duration**	**Application**	**Duration**	**Low**	**High**	**Target**	**High**	**Low**	**High**	**Target**	**High**
Electric Energy Time-shift	2-8 hrs	Price Arbitrage	2-8 hrs	$50	$350	$67	$100	$400	$700	$134	$800
Electric Supply Capacity	5-6 hrs	System Capacity	5-6 hrs	$60	$142	$44	$121	$359	$710	$220	$726
Area Regulation	1 hr	Regulation (1 hr)	1 hr	$785	$2,010	$255	$426	$785	$2,010	$255	$426
Electric Supply Reserve Capacity	1-2 hrs	Spinning Reserves	1-2 hrs	$29	$225	$80	$110	$57	$225	$80	$220
Voltage Support	1 hr	Voltage Support	1 hr	$400	$400	$9	$24	$400	$400	$9	$24
Transmission Support	1 hr	VAR Support	1 hr	$192	$192	$4	$17	$192	$192	$4	$17
Transmission Congestion Relief	3-6 hrs	Transmission Congestion	3-6 hrs	$5	$47	$38	$368	$31	$141	$114	$2,208
T&D Upgrade Deferral 50th Percentile	3-6 hrs	Defer Transmission Investment	3-6 hrs	$80	$229	$414	$1,074	$481	$687	$1,242	$6,444
T&D Upgrade Deferral 90th Percentile	3-6 hrs	Defer Transmission Investment	3-6 hrs	$127	$360	$414	$1,074	$759	$1,079	$1,242	$6,444
Time-of-use Energy Cost Management	4-6 hrs	Retail TOU Energy Charges	4-6 hrs	$204	$307	$377	$543	$1,226	$1,226	$1,508	$3,258
Demand Charge Management	5-11 hrs	Retail Demand Charges	5-11 hrs	$53	$116	$142	$459	$582	$582	$710	$5,049
Electric Service Reliability	1 hr	Power Reliability	1 hr	$359	$978	$47	$537	$359	$978	$47	$537
Electric Service Power Quality	1 hr	Power Quality	1 hr	$359	$978	$19	$571	$359	$978	$19	$571
Renewables Energy Time-Shift	3-5 hrs	Price Arbitrage	3-5 hrs	$47	$130	$67	$100	$233	$389	$201	$500
Renewables Capacity Firming	2-4 hrs	System Capacity	2-4 hrs	$177	$458	$44	$121	$709	$915	$88	$484
Wind Generation Grid Integration, Short Duration	1 hr	Renewable Energy Integration	1 hr	$500	$1,000	$104	$311	$500	$1,000	$104	$311
Wind Generation Grid Integration, Long Duration	1-6 hrs	Renewable Energy Integration	1-6 hrs	$17	$782	$104	$311	$100	$782	$104	$1,866
Note: SNL included three benefit values, Load Following, Substation On-site Power, and Transmission Support which were not modeled using a similar methodology in the EPRI White Paper.											

[86] EPRI; Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs and Benefits. December 2010.

Further information on the various benefit definitions can be found in the ES Computational Tool Verision 1.2 –User Guide (See Appendix Chapter 4)

The ESCT program during DIM would ask for the capital cost of Conventional Electric Service Reliability, which is the amount of money that would be required to fix a reliability using a conventional solution This value will be used as a proxy to monetize the reliability benefit provided by the ES solution. In Figure 300, the researchers use the Electric Service Reliability Benefits Inputs to fill these user input values. The Electric Service Reliability Benefits Inputs, are related to the present value of benefits for each application compared against the total costs of installing an energy storage system.[10]

The DIM also takes into account benefits from emission reductions. Figure 301and Figure 302 list the input values used in the emission factors fields of the DIM. After all fields of the DIM have been completed, the last step is to run the Computational Module (CM). The CM incorporates all the inputs from the ACM and DIM to produce a result, that is, the net benefit (in USD) of the inputted system. From this net benefit, the equation in Figure 303 is used to achieve the dollarized net benefit ($/kWh). The dollarized net benefits for nine of the scenarios are summarized in Figure 305.

Figure 301: Emissions Rate Inputs

2012 Total System Power in Gigawatt Hours

Fuel Type	California In-State Generation (GWh)	Percent of California In-State Generation	Northwest Imports (GWh)	Southwest Imports (GWh)	California Power Mix (GWh)	Percent California Power Mix
Coal	1,580	0.8%	561	20,545	22,685	7.5%
Large Hydro	23,202	11.7%	12	1,698	24,913	8.3%
Natural Gas	121,716	61.1%	37	9,242	130,995	43.4%
Nuclear	18,491	9.3%	-	8,763	27,254	9.0%
Oil	90	0.0%	-	-	90	0.0%
Other	14	0.0%	-	-	14	0.0%
Renewables	34,007	17.1%	9,484	3,024	46,515	15.4%
Biomass	6,031	3.0%	1,025	23	7,079	2.3%
Geothermal	12,733	6.4%	-	497	13,230	4.4%
Small Hydro	4,257	2.1%	204	-	4,461	1.5%
Solar	1,834	0.9%	-	775	2,609	0.9%
Wind	9,152	4.6%	8,254	1,729	19,135	6.3%
Unspecified Sources of Power	N/A	N/A	29,376	20,124	49,500	16.4%
Total	199,101	100.0%	39,470	63,396	301,966	100.0%

Source: QFER and SB 1305 Reporting Requirements. In-state generation is reported generation from units 1 MW and larger

Contact: Michael Nyberg, Mnyberg@energy.ca.gov

Data as of August 1, 2013

Figure 302: Emissions Rate Inputs (lbs/MWh) by Fuel [87]

Emisions Factor Inputs		
	Fuel Type	**Emissions Factor**
CO2	Gas	865
	Oil	1826
	Coal	1968
SOx	Gas	0.0098
	Oil	0.2732
	Coal	2.0907
NOx	Gas	0.2307
	Oil	0.86
	Coal	3.5162

Emissions factors determined by looking at eGrid Version 1.1 (Year 2007 Data) dataset, specifically from the WECC California eGrid subregion.

Figure 303: Assumptions and Dollarized Benefit Analysis (SDF = Standardized Discount Factor)

$$Dollarized\ Benefit = \frac{Net\ Benefit}{ESS\ Battery\ Capacity}$$

$$SDF = \frac{Benefit - O\&M\ Cost - Disposal\ Cost}{Installed\ Cost}$$

Because the researchers are unable to obtain explicit cost inputs of used standardized EV batteries, the researchers determined what is called the standardized discount factor (SDF). The SDF is a percentage that the researchers can multiply by the original used battery cost in order to obtain the maximum allowable new battery cost. As SDF decreases, the reduction in battery cost required by standardization increases (*i.e. maximum allowable new battery cost = SDF x old battery cost*). It tells the team by how much the cost of an EV battery must be reduced via standardization in order for the benefits to be equal to the costs associated with utilizing this battery in a stationary energy storage system.

Figure 305 also lists the SDF for nine of the scenarios run. Using the SDF's for each of the scenarios, the researchers calculated the maximum allowable used EV battery cost for the

[87] Conversations Randy Armstrong - Senior Consultant at Navigant. July 2014.

system to provide a net zero benefit. Any used EV battery cost below the maximum allowable used EV battery cost will result in positive net benefits for the particular grid application and any used EV battery cost below the maximum allowable used EV battery cost will result in negative net benefits for the particular grid application. The maximum allowable costs are good indicators of the impact standardization must have on used EV batteries.Figure 306, Figure 307, Figure 308, Figure 309, Figure 310, Figure 311, Figure 312, and Figure 313 show the dollarized net benefits for the use of a used non-standard EV battery in different grid applications and the maximum allowable costs of a used standardized EV battery for different grid applications. Figure 304 provides a legend for reading the application scenarios in these results figures. It should be noted that only results for 10 different scenarios are shown because these were the ones out of the 28 identified that had positive net benefits.

Figure 304: Scenarios Labeling Legend

Abbreviation	**Applications**
Electric Service Reliability	Electric Service Reliability
TOU_Reliability_Quality	Primary Application: Time-of-Use Secondary Application: Electric Service Reliability Second Secondary Application: Electric Service Power Quality
Renewable_Reliability_Quality	Primary Application: Renewable Time-Shift Secondary Application: Electric Service Reliability Second Secondary Application: Electric Service Power Quality
DCM_Reliability_Quality	Primary Application: Demand Charge Management Secondary Application: Electric Service Reliability Second Secondary Application: Electric Service Power Quality

Figure 305: ESCT Module Results Summary

Categories	25 kWh Reliability	25 kWh Renewable_Reliability_Quality	250 kWh_Reliability	250 kWh Renewable_Reliability _ Quality	250 kWh DCM_Reliability_Quality	250 kWh TOU_Reliability_Quality	1000 kWh_Reliability	1000 kWh_DCM_Reliability_Quality	20000 kWh_Reliability
Benefit ($)	775-375	36720-36320	7450-3850	88220-84620	113520-109920	46720-46320	30150-15200	362420-347520	601775-303425
Dollarized Benefit ($/kWh)	31-15	1468.8-1452.8	29.8-15.4	352.9-338.5	454.1-439.7	1868.8-1852.8	30.2-15.2	362.4-347.5	30.1-15.2
Installed Cost to Obtain Zero Net Benefit ($)	11486.8-12236.8	51031.8-49281.8	115317.6-122817.6	206837.6-214337.6	232137.6-239637.6	58531.8-59281.8	461120.6-491070.6	836390.6-866390.6	9221636.8-9821886.8
Standardized Discount Factor for Installed Cost to Achieve Zero Net Benefit (%)	0.6-0.5	5.5-4.7	0.6-0.5	1.6-1.5	1.9-1.8	6.4-5.8	0.6-0.5	1.6-1.5	0.6-0.5
New Target ES Installed Cost ($/kWh)	459.5-489.5	2041.3-1971.3	461.3-491.3	827.4-857.4	928.6-958.6	2341.3-2371.3	461.1-491.1	836.4-866.4	461.1-491.1
Maximum Standardized Battery Cost ($/kWh)for Zero Net Benefit	183-213	1764.8-1694.8	184.8-214.8	550.9-580.9	652.1-682.1	2064.8-2094.8	184.7-214.6	559.9-589.9	299.5-214.6

Summarized in the following text are the dollarized net benefits for the scenarios considered.

For systems located at the generation and transmission (G&T) level, the results are as follows:

- Electric Service Reliability has positive net benefits with a range of $15.20/kWh to $30.15/kWh and $15.17/kWh to $30.09/kWh for 1 MWh and 20 MWh systems, respectively.

For systems located at the distribution level, the results are as follows:

- Electric Service Reliability has positive net benefits with a range of $15/kWh to $31/kWh and $15.40/kWh to $29.80/kWh for 25 kWh and 250 kWh systems, respectively.

For systems located at the end-user level, the results are as follows:

- Time-of-Use (TOU), coupled with Electric Service Reliability and Electric Service Power Quality show net benefits of $1,852.80-1,868.80/kWh and $745.68-760.08/kWh for 25 kWh and 250 kWh size systems, respectively.
- Renewable Time-Shift, coupled with Electric Service Reliability and Electric Service Power Quality show net benefits of $1,452.80-1,468.80/kWh and $338.48-$352.88/kWh for 25 kWh and 250 kWh size systems, respectively.

- Demand Charge Management (DCM) coupled with Electric Service Reliability and Electric Service Power Quality show net benefits of $439.68-454.08/kWh and $347.52-362.42/kWh for 250 kWh and 1000 kWh size systems, respectively.

Summarized in the following text are the maximum allowable standardized used battery cost results:

For systems located at the G&T level, the results are as follows:

- Under the Electric Service Reliability application, the battery second use (B2U) standardized battery cost must be below $184.65-214.60/kWh and $184.61-214.62/kWh for 1 MWh and 20 MWh systems, respectively.

For systems located at the distribution level (i.e. Community Energy Storage), the results are as follows:

- Under the Electric Service Reliability application, the B2U standardized battery cost must be below $183/kWh-213/kWh and $184.80-214.80 for 25 MWh and 250 MWh systems, respectively.

For systems located at the end-user level, the results are as follows:

- With TOU (primary application) coupled with Electric Service Reliability, and Electric Service Power Quality, the B2U standardized battery cost must be below $2,064.80-$2,094.80/kWh and $958.08-$988.08/kWh for 25 kWh and 250 kWh systems, respectively.
- With Renewable Time-Shift (primary application) coupled with Electric Service Reliability, and Electric Service Power Quality, the B2U standardized battery cost must be below $1,694.80-$1,764.80/kWh and $550.88-$580.88/kWh for 25 kWh and 250 kWh systems, respectively.
- With DCM (primary application), coupled with Electric Service Reliability, and Electric Service Power Quality, the B2U standardized battery cost must be below $652.08-$682.08/kWh and $559.92-589.92/kWh for 250 kWh and 1000 kWh systems, respectively.

25-kWh Stationary Storage System

Figure 306: ESCT Non-Standard Module Results (25 kWh Size)

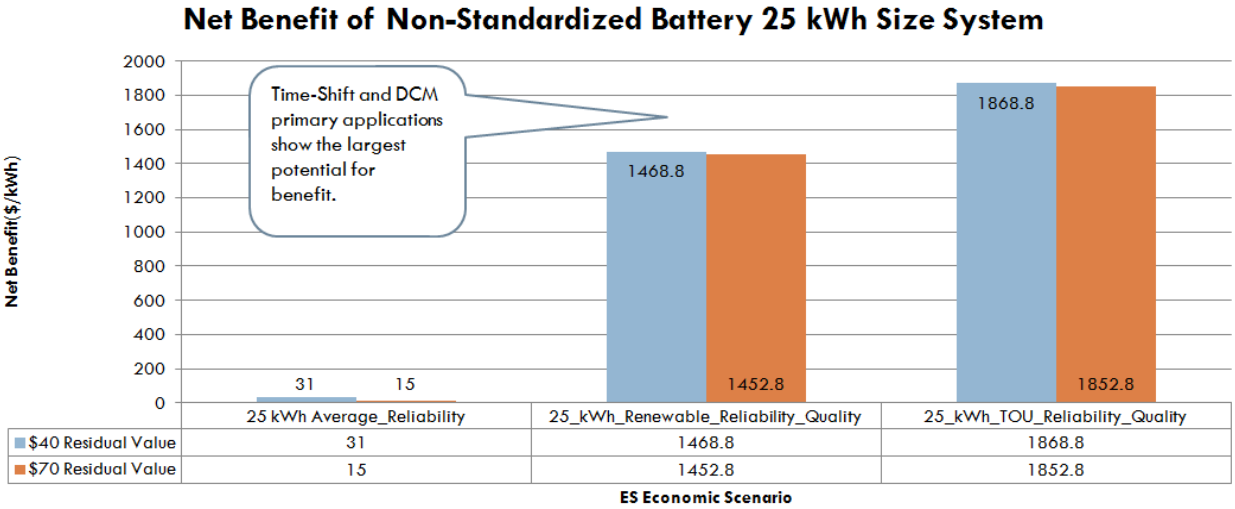
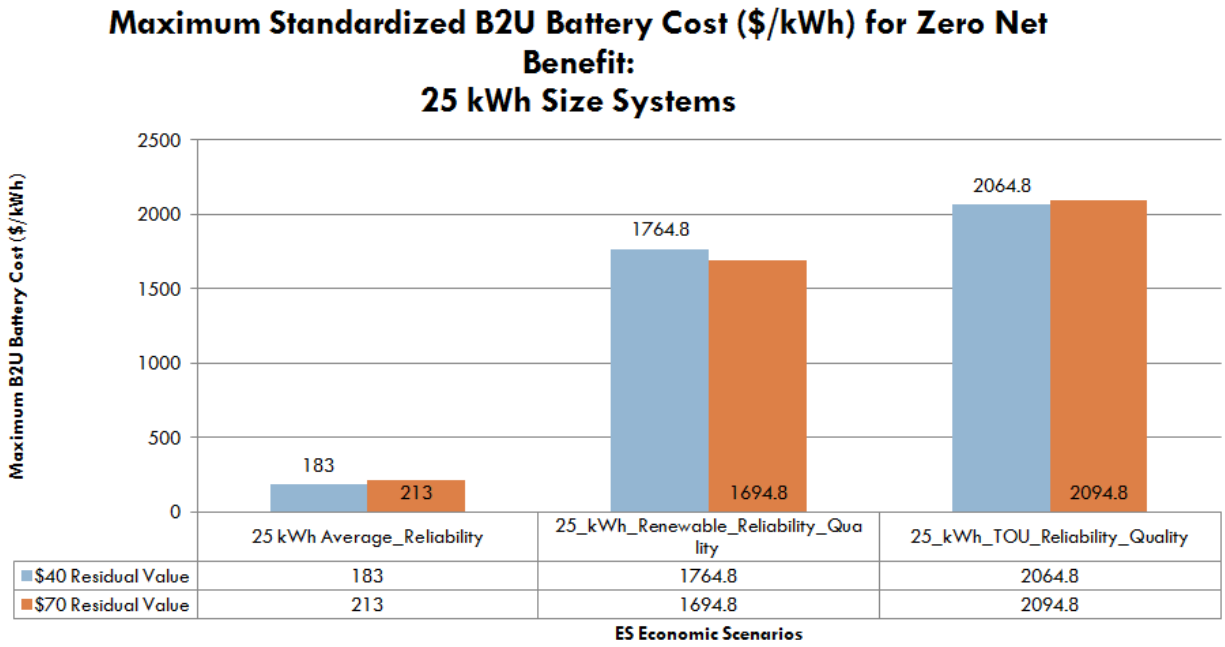


Figure 307: ESCT Standardized Module Results (25 kWh Size)



250-kWh Stationary Storage System

Figure 308: ESCT Non-Standard Module Results (250 kWh Size)

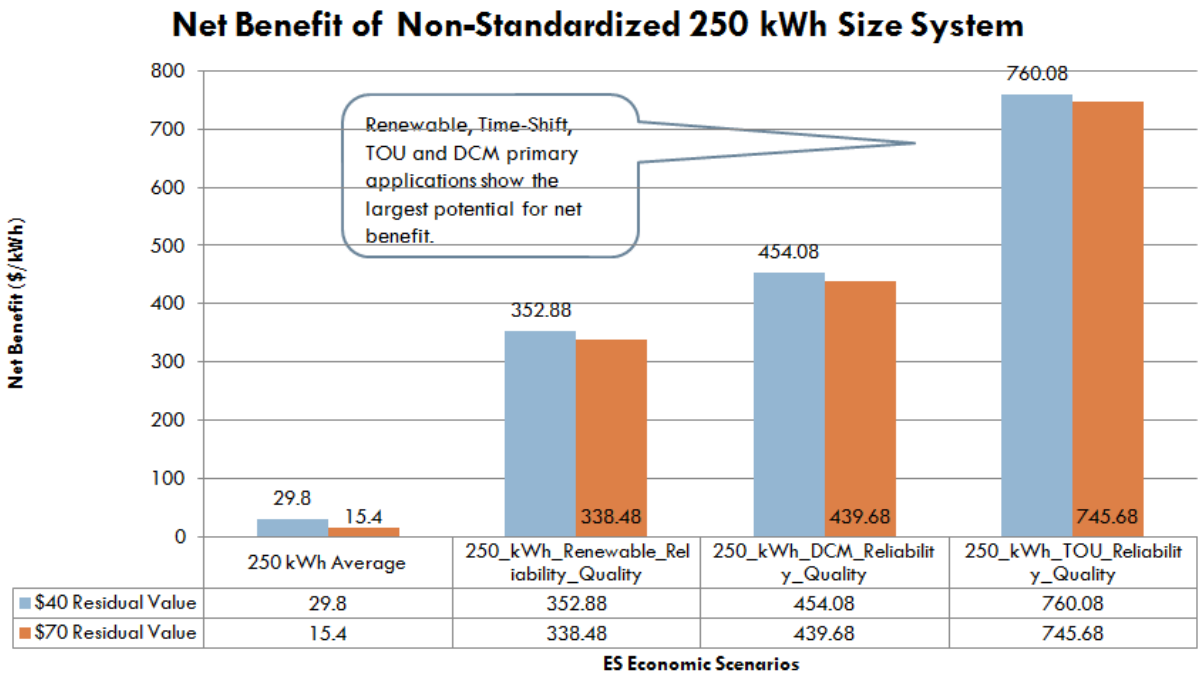
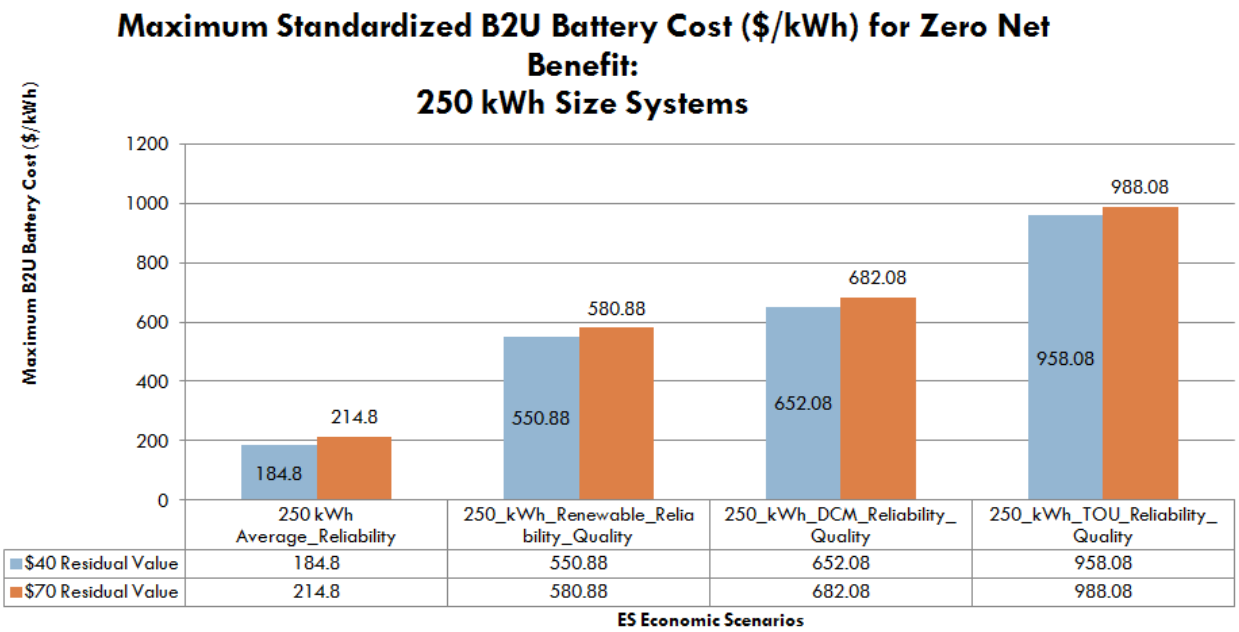


Figure 309: ESCT Standardized Module Results (250 kWh Size)



1000-kWh Stationary Storage System

Figure 310: ESCT Non-Standard Module Results (1000 kWh Size)

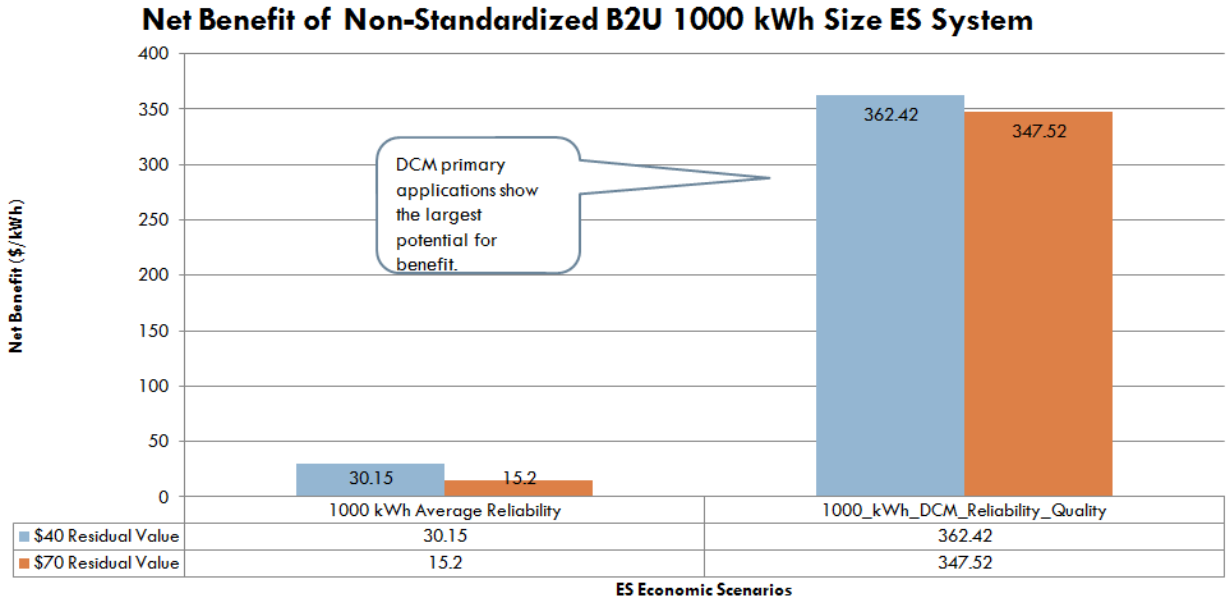
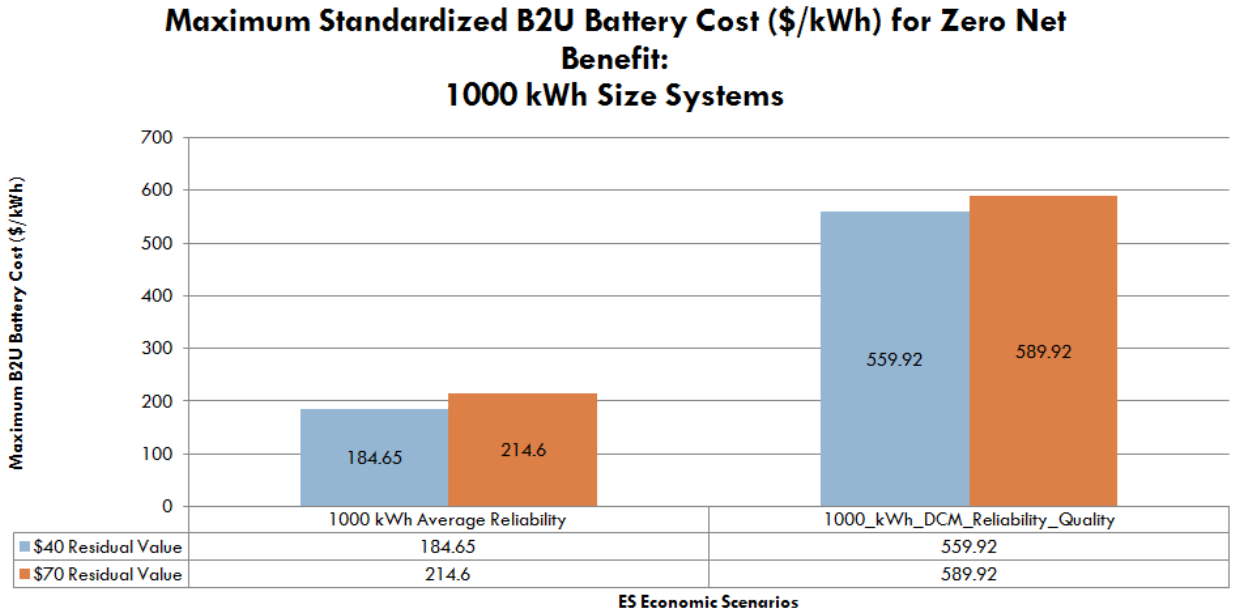


Figure 311: ESCT Standardized Module Results (1000 kWh Size)



20,000-kWh Stationary Storage System

Figure 312: ESCT Non-Standard Module Results (20000 kWh Size)

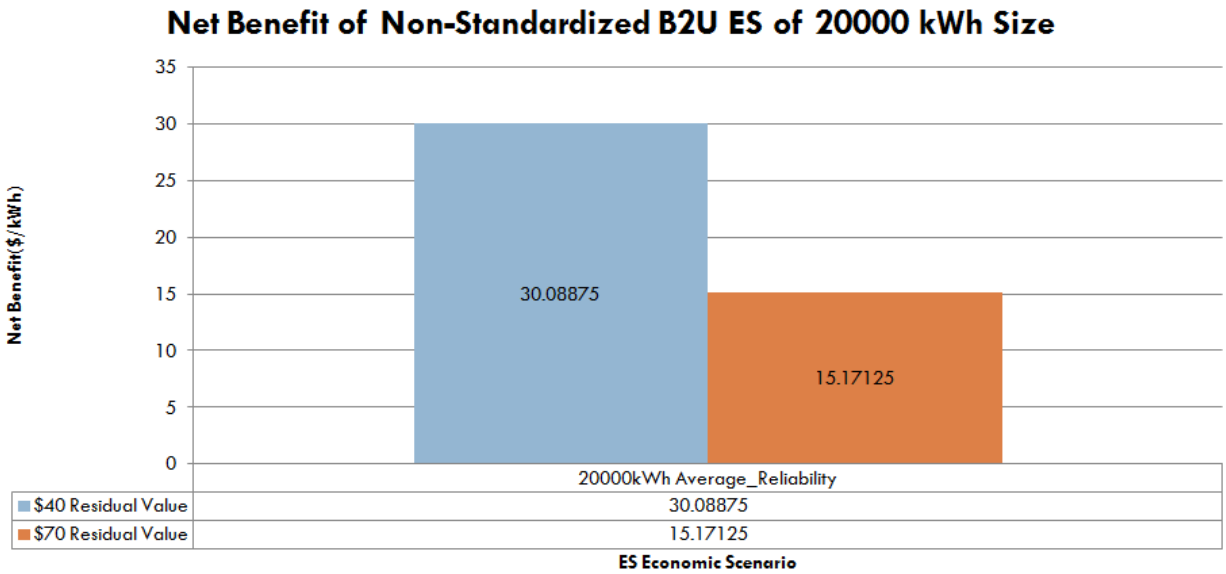
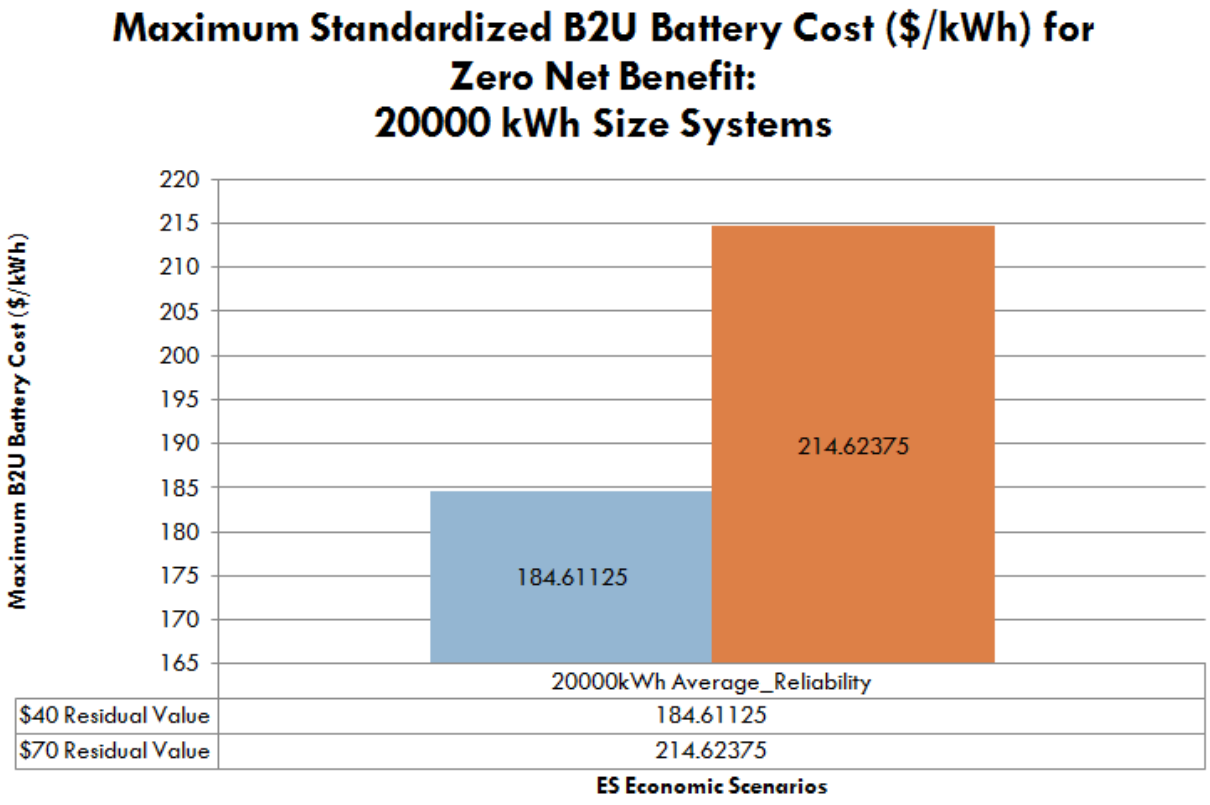


Figure 313: ESCT Standardized Module Results (20000 kWh Size)



The figures below show the relationship between dollarized net benefit of used non-standard batteries in different grid application scenarios, the maximum allowable battery cost, and the standardized discount factor.

Figure 314 shows that for all battery system sizes under the Electric Service Reliability application there are the following correlations:

- As maximum allowable battery cost increases, the dollarized benefit decreases. Above about $175/kWh, the dollarized benefit becomes negative.
- As standardized discount factor decreases, dollarized benefit increases. This indicates that the more the used battery cost is decreased by standardization, the more dollarized benefit the user will achieve.

Figure 314: Dollarized Net Benefit with Respect to Second Use Battery Cost and Standardized Discount Factor (Electric Service Reliabilty Scenerio)

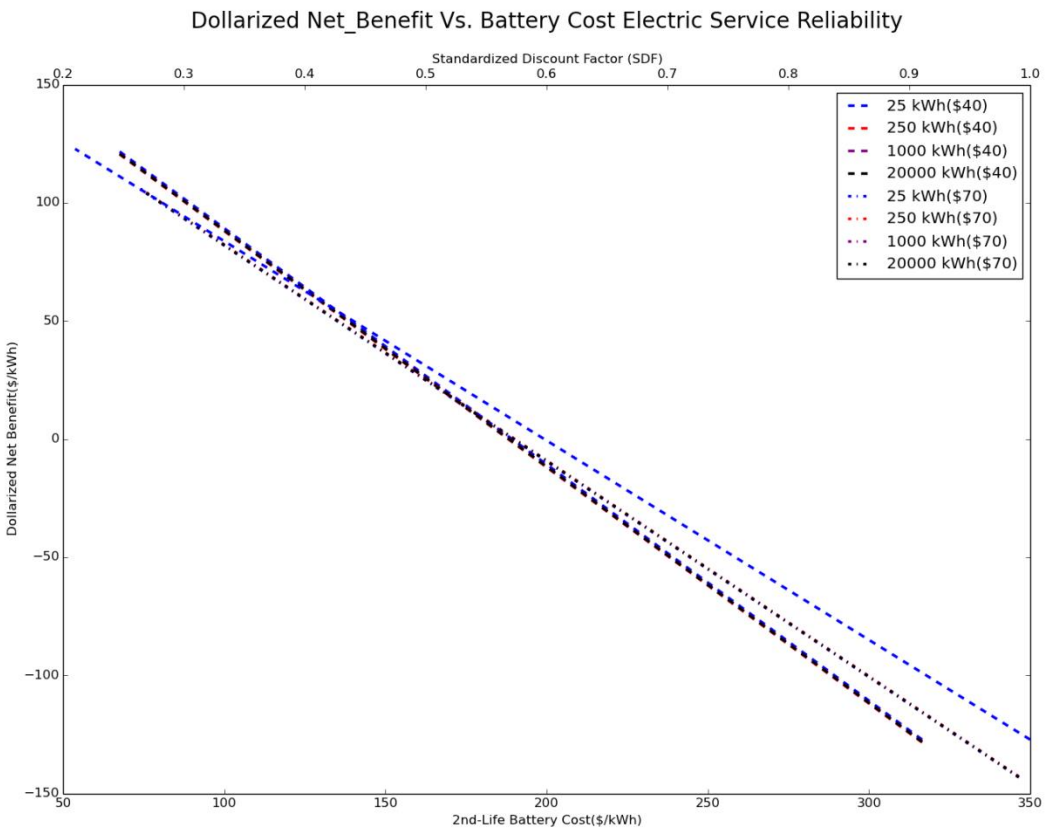


Figure 315 shows that for all battery system sizes under the TOU-Electric Service Reliability-Electric Service Power Quality scenario there are the following correlations:

- As maximum allowable battery cost increases, the dollarized benefit decreases.

- As standardized discount factor decreases, dollarized benefit increases.

For smaller systems though, the dollarized benefit is greater relative to the same maximum allowable battery cost and standardized discount factor. This indicates that if the used battery cost is reduced by the same amount due to standardization, smaller systems will have a greater dollarized benefit.

Figure 315: Dollarized Net Benefit with Respect to Second Use Battery Cost and Standardized Discount Factor (Electric Service Reliability Scenario) (TOU_Reliability_Quality Scenario)

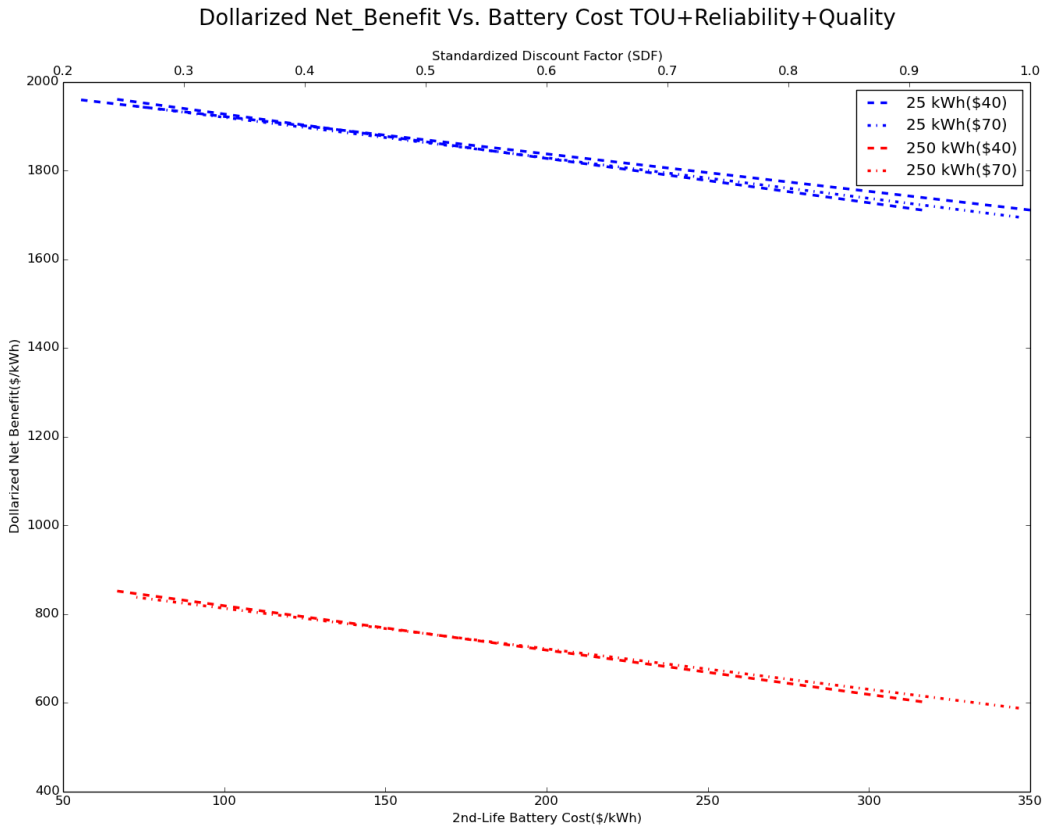


Figure 316 shows that for all battery system sizes under the Renewable Time-shift-Electric Service Reliability-Electric Service Power Quality scenario there are the following correlations:

- As maximum allowable battery cost increases, the dollarized benefit decreases.
- As standardized discount factor decreases, dollarized benefit increases.

For smaller systems though, the dollarized benefit is greater for this application relative to the same maximum allowable battery cost and standardized discount factor. This indicates that if the used battery cost is reduced by the same amount due to standardization, smaller systems will have a greater dollarized benefit.

Figure 316: Dollarized Net Benefit with Respect to Second Use Battery Cost and Standardized Discount Factor (Renewable_Reliability_Quality Scenario)

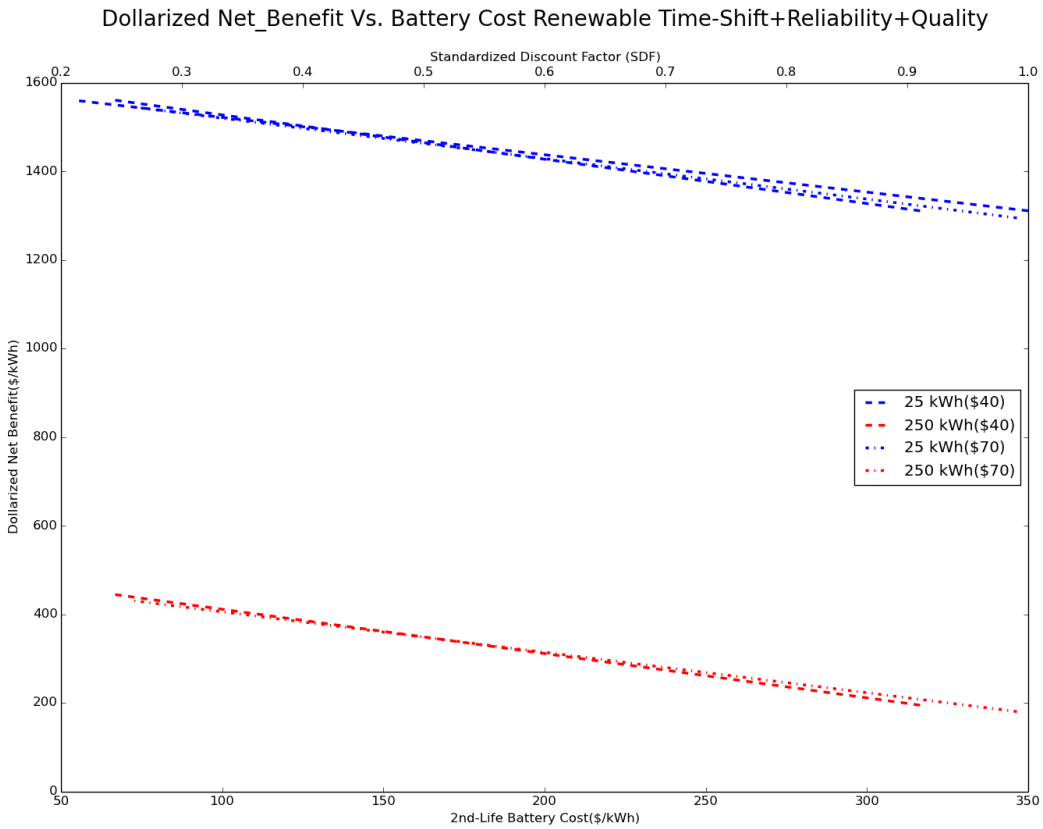
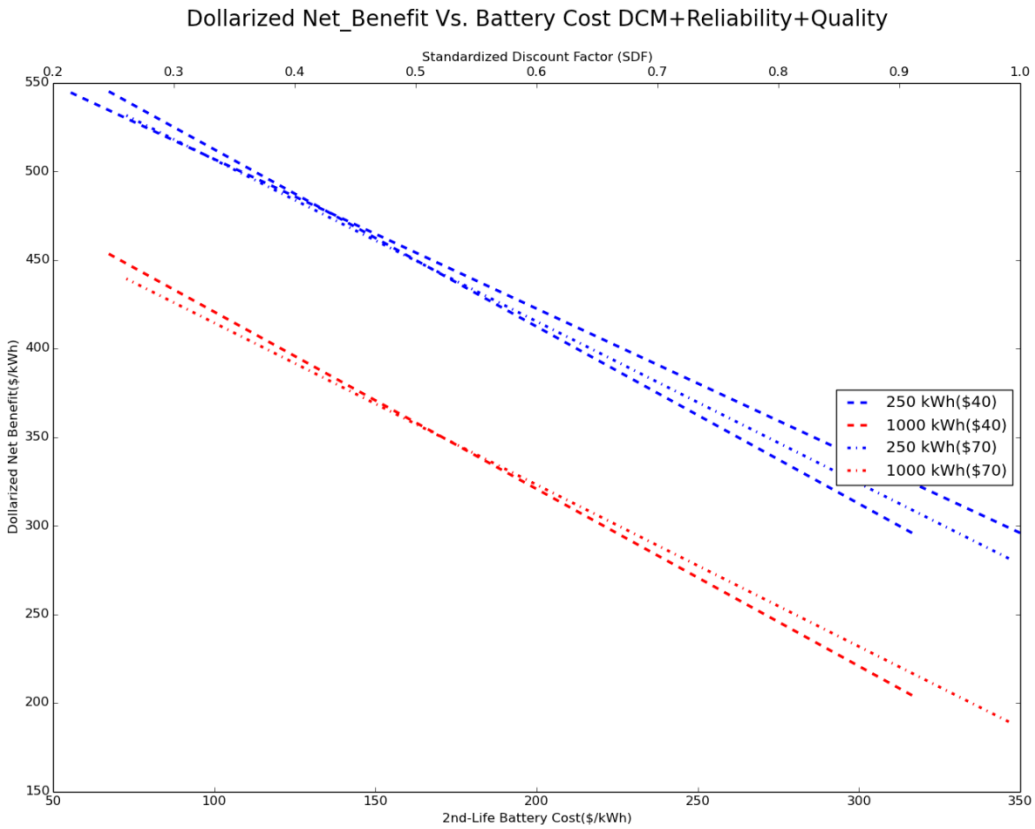


Figure 317 shows that for all battery system sizes under the Demand Charge Management-Electric Service Reliability- Electric Service Power Quality scenario there are the following correlations:

- As maximum allowable battery cost increases, the dollarized benefit decreases.
- As standardized discount factor decreases, dollarized benefit increases.

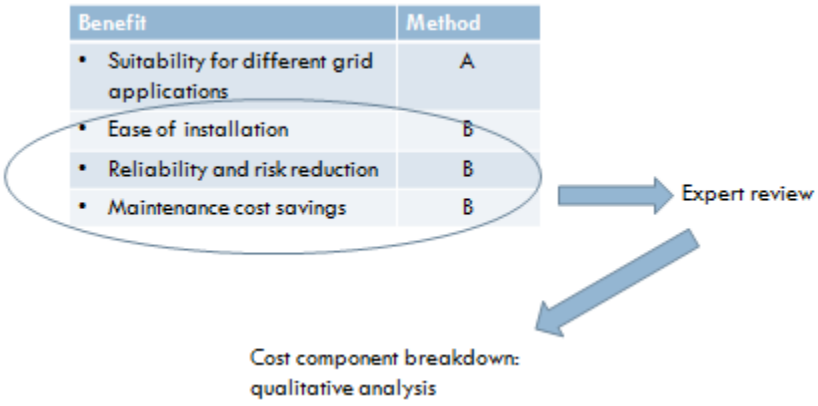
For smaller systems though, the dollarized benefit is greater relative to the same maximum allowable battery cost and standardized discount factor. This indicates that if the used battery cost is reduced by the same amount due to standardization, smaller systems will have a greater dollarized benefit. Compared to Figure 316 and Figure 317 the rate at which the dollarized benefit increases as the standardized discount factor decreases is greater also. This means that for the DCM-Electric Service Reliability-Electric Service Power Quality scenario, the battery operator will achieve a more significant increase in dollarized benefit for additional used battery cost reduction than for the TOU-Electric Service Reliability-Electric Service Power Quality and Renewable Time-shift-Electric Service Reliability-Electric Service Power Quality scenarios.

Figure 317: Dollarized Net Benefit with Respect to Second Use Battery Cost and Standardized Discount Factor (DCM_Reliability_Quality Scenario)



The impact of standardization on battery second-life integration and operation with respect to ease of installation, reliability and risk reduction, and maintenance cost savings was calculated using Method B as illustrated in Figure 318. The researchers used the Method B approach to solve the impact of standardization on these three second-life aspects because there is no commercial market for stationary storage systems with used EV batteries. With the first use EV battery space, there is a commercial market making standardization impacts easier to quantify.

Figure 318: Illustration of Method B: Impact of Standardization



The first step to qualitatively identify the impact of standardization on the three EV battery secondary life aspects was to discuss the cost component breakdown of the lifecycle of a second-life EV battery as seen in Figure 319.

Figure 319: Breakdown of Repurposing and Repackaging Cost Impacts

Cost components			
Repurposing			
	Breakdown (of packs)		
		Labor	
		Equipment	
		Facility area	
	Hardware inspection		
		Labor	
		Equipment	
		Facility area	
	Functional assessment		
		Labor	
		Equipment	
		Facility area	
	Testing		
		Labor	
		Equipment	
		Facility area	
	Certification (of modules)		
		Third-party company	
Repackaging (into subpacks/packs)			
		Labor	
		Equipment	
		Facility area	
		Materials	
		Universal BMS	
Operation			
	Cell failure and replacement		
		Labor	
		Materials	
	Firmware/software upgrades		
		Labor	
	Container maintenance		
		Materials	
		Labor	
	Safety/inspection		
		Labor	
Disposal			
	Fees		
	Transportation to recycling plant		

Four major lifecycle processes were identified for a second-use EV battery: repurposing, repackaging, operation, and disposal. The repurposing process involves the breakdown of packs into modules, inspecting the hardware of the modules, performing inspection and health benchmark tests on the modules, and certifying that the modules meet a market-defined second-life standard. Once the modules have been certified, the second process, repackaging, takes place. The repackaging process involves putting modules deemed"good enough" for second use into subpacks and packs that can be shipped for use in stationary systems.

Additionally, the researchers estimated the allowable standardized used battery price for there to be a commercially viable second-life market by looking at a current field demonstration project involving used EV batteries integrated into a stationary storage system. Figure 320 summarizes the standardization impact exercise the researchers conducted with information from the field demonstration project and current new battery pricing. Looking at Figure 320, the current price for new batteries is almost half the price for used repurposed and repackaged batteries, which does not bode well for a secondary-life market. Moreover, because there are no

commercial stationary energy storage systems currently on the market using non-standard retired EV batteries, current demonstration systems have a lot of non-recurring engineering costs. Standardized components will reduce installation and integration costs through economies of scale and balance of plant costs. Therefore, with standardization, used battery prices are expected to come down. If used batteries are going to compete with new batteries in the stationary energy storage market, standardization must reduce the repurposing and repackaging costs by about 85 percent. The price of used batteries will then be about $75/kWh.[88]

Figure 320: Repurposing and Repackaging Cost Impact Exercise Summary Table

Comparison of New Batteries vs. Used Batteries	
Current price for new batteries	$250/kWh
Current price for repurposing and repackaging used EV batteries	$450/kWh[89]
Standardized price for used batteries	$75/kWh

Next, the repurposed and repackaged battery packs will be operated at a stationary site. When operating a non-standard (and non-certified) used EV battery it is best to operate the battery conservatively in the interest of safety. It is well understood how a standard battery will perform, so an operator can safely push the battery to its limits. With a used electric vehicle battery, the operator will have to de-rate the battery, thus decreasing its value, because it is not well understood how the battery will perform. Therefore, with standardization the battery operator will safely be able to operate the battery system in the following ways, ultimately increasing its value:

- Maximizing usable capacity
- Maximizing power rating
- Pushing thermal limits
- Maximizing operational parameters of the system
- Intelligently manage a duty cycle in order to extend longevity, given the battery's degradation profile

Standardization will reduce battery risk and increase reliability of operation. Additionally, maintenance costs will be reduced due to better prediction of battery performance.

After the second-life battery packs have degraded to 40 percent of its nameplate state of charge SOC, they will be disposed and high-value components recycled. There are labor, engineering, equipment, materials, facility, transportation, and regulatory costs associated with the four

[88] It was assumed that used batteries are worth 30 percent of the value of new batteries, which is a conservative estimate.

[89] This assumes the purchase cost of the retied EV battery is $0.

main second-life battery lifecycle processes. By understanding the costs associated with each lifecycle process, the researchers estimated the impact due to standardization. The results of this expert discussion are summarized in Figure 321.

Figure 321: Impacts of Second-Life Battery Cost Components

Cost Component of Second-Life Battery	Qualitative Impact
Repurposing	Reduce cost
Repackaging	Increase value
Operation	Reduce cost
Disposal	Reduce cost

In conclusion, standardization of battery modules will reduce the costs of deploying a used electric vehicle battery in a stationary energy storage application as well as increase the value of the battery in that application. There are currently no commercial stationary storage systems that utilized used electric vehicle batteries. This is because of a lack of standardization. Standardization is necessary for certification, which ensures safety and reliability of a system.

Impact of Standardization on Market Size for Second Use Modules

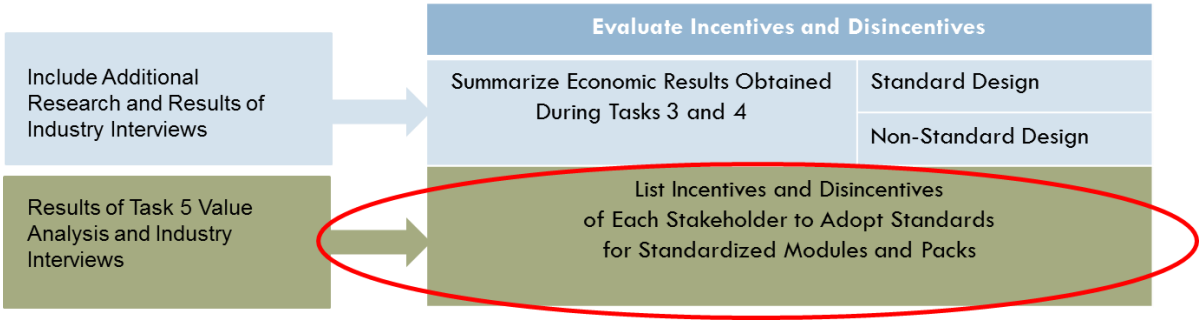
We showed that below a certain battery price summarized in Figure 305, the end user will make a profit using the battery in that particular application.[90] The likelihood that the market size for second use batteries to increase is greater when the end-user can make a profit. Therefore, it is expected that if standardization can reduce the used battery cost, the market size for second use modules will increase, but to what extent, the researchers cannot predict.

4.3 Sub-Task 2: Evaluation of Incentives and Disincentives to Each Stakeholder for Adopting Standard Designs

The second sub-task of the Chapter 4 of the study involves the definition incentives and disincentives associated with adopting standardized lithium-ion module and battery system designs. Information sources included a literature search and interviews with industry stakeholders.

[90] A positive dollarized net benefit indicates a positive profit.

Figure 322: Determination of Incentives and Disincentives is Part of Sub-Task 2



4.3.1 Industry Interviews: Non-Cost Impacts of Standardization on Industry Stakeholders

1. ***Question: What do you see as incentives for stakeholders to adopt standardized designs?***

Standardization of connectors, charging systems, inverters/converters, and electronic interfaces would offer significant benefits to first and second use stakeholders (references 33, 47, 49). Standardized designs would improve module and pack safety by identifying, classifying, and addressing failure modes across the battery life cycle. This is especially important in high-power stationary storage applications (references 33, 36, 45, 47). Standardized designs would also facilitate second use and recycling whether or not ownership of the modules and packs is retained by the vehicle OEM (reference 49).

Implementation of standardized designs can reduce first use manufacturing costs (references 30 and 52). Standardization will facilitate second use (energy storage) applications of PEV battery modules (reference 33):

1. Compatible communications/BMS interface
2. Standard pin-outs for electronics interface
3. Standard connectors and interfaces for balance-of-plant
4. No change to form factor
5. Compatible thermal management systems

2. ***Question: What disincentives are there for stakeholders to adopt standard designs?***

Because battery technology is still in a state of flux (significant research programs are underway and include chemistry, design, BMS, thermal management, and packaging), there is significant industry resistance to imposing constraints associated with standardization (references 36, 47). In addition, vehicle OEMs have expressed concern regarding form factor issues related to standard designs and corresponding vehicle design restrictions. Currently, modules and batteries are designed to occupy specific areas within the vehicle (for example, under the floor or within the cabin). Thus, there is a disincentive to pursue standardized modules (reference

52). It is noted that this restriction is relaxed for commercial vehicles, which typically have significant space to accommodate the battery systems.

Two participants in the Task 5 industry stakeholder interview, both of whom represent vehicle OEMs that also produce PEV battery modules and packs, both expressed the opinion that standardization of module and pack designs is not likely for the near future. Their position is that battery innovation and development is still undergoing fundamental change. In addition, both have substantial investments in the design of their current modules and packs as well as the associated manufacturing facilities (reference 24).

China has been able to mandate a common module, but this had a perceived negative impact on vehicle design options. The overall experience was not positive for producing acceptable passenger vehicle space and alternative approaches are now being sought. In the United States there are more significant hurdles to adopting standard designs. Even if standards are established, compliance will likely be voluntary. The decision to incorporate standard designs will reside with the vehicle OEM and will be determined primarily by economic and safety issues.

4.3.2 Other Comments Regarding Incentives and Disincentives for Adopting Standardized Designs

Commercial vehicle owners may elect to continue use of battery systems having energy storage capacities that drop below the level at which the vehicle manufacturer recommends they be replaced. Instead, the vehicle owners may elect to continue using the vehicle for duty cycles with lower energy requirements. This is reinforced by Ricardo's finding that 1/3 of the registered commercial vehicles in California are more than 15 years old (see Chapter 1). NREL's research indicates that commercial vehicle batteries will have 1st lives lasting 10-12 years.

NREL research also indicates commercial vehicle fleet owners are demanding warrantees that batteries maintain their original energy capacity for three to five years following initial vehicle purchase.

Fleet owners working to minimize total cost of ownership are expected to pressure vehicle manufacturers to improve the residual value of the battery packs. This would provide incentive to the manufacturers to evaluate designs, including standardization, that favorably impact battery residual value and reduce cost of ownership to the vehicle owner. Vehicle OEM representatives who participated in the industry interviews are of the opinion that cell costs are currently approaching minimum values due to the large volumes being produced. To move forward with the standardization process, the savings due to standardization of modules and battery systems must be demonstrated. At this time, vehicle OEMs are keeping their options open regarding standardization as the battery manufacturing industry is maturing technologies and chemistries are being evaluated to determine which will become "commodity" type products (and hence more appropriate for standardization).

There is more incentive for standardization of batteries for medium- and heavy-duty electric and hybrid electric vehicles compared to passenger cars due to the reduced packaging constraints and option for trading out standard packs.

Thermal systems will be more difficult to standardize compared to the electrical/control systems, due to the wide variation in packaging requirements and module topologies.

Standardization of the "balance of plant" for battery systems would stimulate small, vehicle system integrators, for example, manufacturers of niche electric vehicles, such as yard hostlers.

Lawrence Livermore National Laboratory (reference 20) completed a study for the California Energy Commission entitled "Automated Demand Response and Storage for Renewable Integration" (CEC-500-10-051). Models were developed to evaluate the impact of grid-scale energy storage on operation of the California Electric grid. Two conclusions of the study have an impact on the market for second use batteries:

- Storage Power: decreasing benefits after 1,200 MW of energy storage has been added to California grid.
- Storage Energy: decreasing benefits after 3-hour discharge time has been added to the California grid.

During the interviews with representatives from vehicle OEMs, questions were posed regarding the design of first use batteries to facilitate implementation of second use applications. Some of the responses were:

Light duty vehicle OEMs saw little incentive in adding features or standardized designs to accommodate second use because the OEM has no ownership interest in the battery once it is delivered to the first use purchaser (except for OEMs such as Tesla who retain ownership of the battery). This also means the vehicle OEM has little incentive, other than customer requests, to increase the residual value of the battery at the end of first use (reference 48). Light duty vehicle OEMs are unwilling to standardize voltages, so a BMS and power electronics system are required for second use applications that together can accommodate cells of varying voltages and resistances. Also, for these systems, the charging operation must operate within the current flow limits of the modules and cells (references 48 and 49).

4.3.3 Current Industry Standards for Rechargeable Energy Storage Systems

One approach to promoting lithium ion battery system standardization within the vehicle manufacturing industry is to build upon those standards already in place or pending and to demonstrate the advantages of standardization to the agencies maintaining current codes, standards, regulations, and recommended practices. A study was completed to define the agencies having jurisdiction and the associated codes, standards, regulations and recommended practices.

Available industry standards for Rechargeable Energy Storage System (high voltage battery, RESS) must address the severe service conditions of the automotive environment. Areas not covered in industry standards are generally included by OEM internal standards that provide further requirements for safety and functionality.

Developing module and battery design standards could be accomplished within the framework of existing standards organizations and could be an extension of the current industry standards for Rechargeable Energy Storage System (high voltage battery, RESS)

Identified Agencies Having Jurisdiction (AHJs) for battery and associated systems include:

1. U.S. Department of Energy, Office of FreedomCAR and Vehicle Technologies
2. Society of Automotive Engineers (SAE)
3. United Nations Economic Commission for Europe (UN)
4. International Organization for Standardization (ISO)
5. Federal Motor Vehicle Safety Standards and Regulations (FMVSS)
6. National Fire Protection Association, National Electrical Code (NEC)
7. International Electrotechnical Commission (IEC)
8. Verein Deutscher Elektrotechniker, Verband der Electrotechnik (VDE) Association for Electrical, Electronic and Information Technologies
9. General Motors Worldwide (GMW) Standards

Summaries of vehicle electrification standards are currently in effect are summarized in Figure 323 through Figure 326.

Figure 323: SAE Vehicle Electrification Standards

SAE INTERNATIONAL

Examples from the Society of Automotive Engineers

J1715/2 (WIP)	Battery Terminology	Define common terminology for automotive electrochemical energy storage systems at all levels; component, sub-component, subsystem and system-level architectures including terms pertaining to testing , measurement and system function related to energy storage
J1766 (RIP)	Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing	The purpose of this document is to define test methods and performance criteria which evaluate battery system spillage, battery retention, and electrical system isolation in Electric and Hybrid Electric Vehicles during specified crash tests.
J1772 (RIP)	Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler	Defines a common EV/PHEV and supply equipment vehicle conductive charging method.
J1773	Electric Vehicle Inductively Coupled Charging	Establishes the minimum interface compatibility requirements for electric vehicle (EV) inductively coupled charging for North America.
J1797	Recommended Practice for Packaging of Electric Vehicle Battery Modules	Provides for common battery designs through the description of dimensions, termination, retention, venting system, and other features required in an electric vehicle application.
J1798 (RIP)	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules	Provides for common test and verification methods to determine Electric Vehicle battery module performance.
J1850 (RIP)	Class B Data Communications Network Interface	Establishes the requirements for a Class B Data Communication Network Interface applicable to all On- and Off-Road Land-Based Vehicles.
J2288	Life Cycle Testing of Electric Vehicle Battery Modules	Defines a standardized test method to determine the expected service life, in cycles, of electric vehicle battery modules.
J2289	Electric-Drive Battery Pack System: Functional Guidelines	Describes common practices for design of battery systems for vehicles that utilize a rechargeable battery to provide or recover all or some traction energy for an electric drive system.

Figure 324: Industry Standards for Rechargeable Energy Storage Systems

Category:	Test
Code/Standard	**Description**
Freedom Car SAND 2005-3123	FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications
SAE J2929	Electric and Hybrid Vehicle Propulsion Battery System Safety Standard - Lithium-based Rechargeable Cells
SAE J2464	Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
UN Manual of Tests and Criteria	Section 38.3 Lithium Batteries
ISO 12405-1	Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 1: High-energy applications
ISO 12405-2	Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 2: High-energy applications
FMVSS 305	Electric Power Vehicles: Electrolyte Spillage and Electrical Shock Protection and enforcement.

Figure 325: Industry Standards for Rechargeable Energy Storage Systems, continued

Category:	Design
Code/Standard	**Description**
ISO 26262	Road Vehicles - Functional Safety
ISO 20653	Road vehicles -- Degrees of protection (IP code) -- Protection of electrical equipment against foreign objects, water and access
ISO 60529	Degrees of protection provided by enclosures (IP Code)
IEC 60664	Insulation Coordination for Equipment within Low-voltage Systems
IEC 60479-1	Effecs of Current on Human Beings and Livestock - Part: General Aspects
IEC 60950	Information Technology Equipment – Safety
NEC 500 - class III	Requirements for electrical equipment in fire or explosion hazard locations
UL 508	Industrial Control Equipment
UL 746c	Polymeric Materials - Use in Electrical Equipment Evaluations
UL 840	Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment
UL 1012	Power Units other than Class 2
UL 1642	Standard for Lithium Batteries
VDE 0110	General Standard For Electrical Equipment
VDE 0831	Electrical System For Railroads
SAE J1455	Recommended Environmental Practices for Electronic Equipment Design in Heavy-Duty Vehicle Applications

Figure 326: Industry Standards for Rechargeable Energy Storage Systems, continued

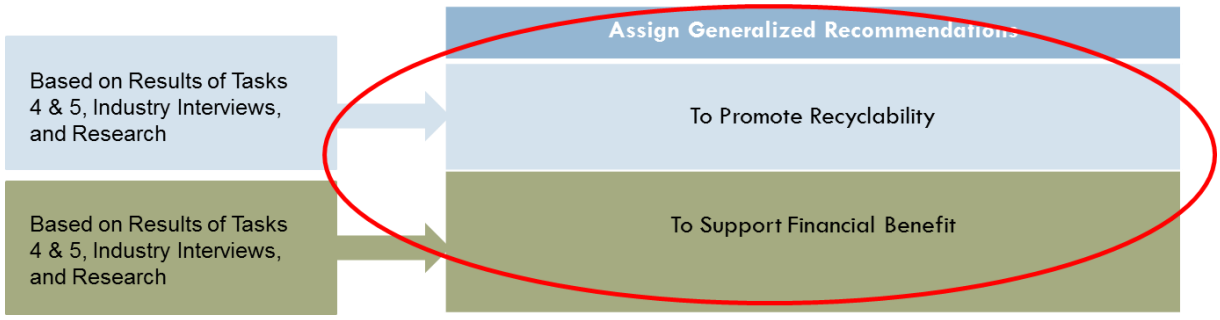
Category:	Supplier
Code/Standard	**Description**
GMW 8739	High-Voltage Safety Specification
GMW 16390	General Specification for Analysis/Development/Validation (A/D/V) of Rechargeable Energy Storage Systems (RESS)
GMW 3172	General Specification for Electrical/Electronic Component Analytical/Development/Validation (A/D/V) Procedures for Conformance to Vehicle Environmental, Reliability, Durability, and Performance Requirements
GMW 15738	Powertrain Cooling and Thermal Performance for Hybrid Passenger Vehicles
GMW 8287	Highly Accelerated Life Testing
GMW 3097	General Specification for Electrical/Electronic Components and Subsystems, Electromagnetic Compatibility, Requirements
GMW 3103	General Specification for Electrical/Electronic Components and Subsystems, Electromagnetic Compatibility, Validation Acceptance Process

Is was concluded that organizations such as SAE, FMVSS (NHTSA), UNMTC (UNECE), FreedomCAR, and ISO, have already put in place many components and testing standards for rechargeable energy storage systems, but have not yet addressed the basis for standardized designs. It is recommended that these organizations be approached regarding support for design standards aimed at commercial vehicle battery modules and systems.

4.4 Sub-Task 3: Assign Generalized Recommendations for Each Suggested Configuration of Standardized Modules

During Chapter 4, Sub-Task 3, the results of the literature search and industry interviews were employed to generate recommendations for standardized module and battery systems designs. Design suggestions that impact recyclability and reduced costs were included.

Figure 327: Sub-Task 2: Generalized Recommendations Were Generated for Standarized Modules



4.4.1 Guidelines: Designing Li-Ion Modules and Battery Systems for Recyclability

The literature search and industry interviews (repated to Interview Topic 6: Design for Recyclability, Question: Would standardization improve recyclability?), along with research

conducted during the current study, indicated that standardized module designs will facilitate recycling in a variety of ways, including:

- There will be fewer module types and chemistries, thus reducing the scope of the repurposing task.
- Construction will favor disassembly, and will thus facilitate repurposing and repackaging. Some current battery system designs require extensive processing to separate materials. It is recommended that future battey system designs incorporate more recyclable materials for all components, including housings (recyclable plastics) and mounting systems as well as adhesives that facilitate dismantling and clearly labeled materials (reference 45). Standardized module designs would promote more efficient recycling operations, including the development of standardized dismantling and processing systems (references 36, 45, 47).
- Components may be labeled with bar codes to enable identification of key materials and machine sorting, which will reduce costs.
- Future battery systems are anticipated to be larger (in terms of energy capacity) and available in larger volumes, thus promoting repurposing and recycling operations.
- It was noted that current lithium-ion battery recycling operations are driven by the revenues from cobalt recovery. As cobalt content declines, other incentives will be required to make the business of recycling Li-Ion batteries profitable (reference 45).

4.4.2 Generalized Recommendations for First Use Standardized Modules and Battery Systems

Current research on cell-level active balancing circuitry and algorithms are expected to facilitate standardization at the module level and allow isolation of failed cells. NREL, for example, is working with Utah State University under the ARPA-E funded AMPED Program (Reference 35): it is estimated the cell-level active balancing circuitry system could provide 20—40 percent life extension for vehicle Li-ion battery packs by overcoming the capacity limitations of the weakest cell in the pack. The system most benefits large packs in energy applications, for example, EV rather than HEV. The benefits of the system could be appreciable for 2nd use stationary applications.

- The cell balancing power is transferred to/from a shared bus within the pack. Multiple packs with disparate states of health could also be balanced on a continuous basis by simply connecting the shared bus from one pack to another.
- In developing the cell-level system, NREL anticipates that any module with one partially failed cell could still operate in a seamless manner at low rates.
- The same 20—40 percent life extension seems a reasonable expectation for second use applications.

It is therefore recommended that research be promoted to facilitate identification and isolation of failed cells relative to first use vehicle applications, repurposing operations, and second use stationary energy storage.

Interviews with industry stakeholders indicate automakers strictly adhere to the RESS design and safety standards (and the associated liability issues). A second use standard must therefore be compatible with the safety content of the first use batteries.

Current battery system warranties are typically based on the expected first use duration of the battery system, which ranges from 8 years to 12 years. Current warranties do not extend to second use applications. Vehicles purchased using the California EV price credit must meet associated warranty requirements (10 years or 100,000 miles, reference 32). Since transferable warranties would benefit second use applications, it is recommended that battery system designs be developed that support compliance with common first and second use standards.

Commercial vehicles were recommended as primary candidates for standardized module/pack system designs because of the favorable economics associated with electric drive systems for these vehicles, the packaging options available for implementing standardized battery systempacks, and the projected supply of second use batteries originating from these vehicles.

- Example module and pack designs have been developed based on energy capacity increments of 25 kW-hrs that meet the identified duty cycles. These are intended to establish a basis for developing a family of module and pack design standards applicable to the commercial vehicle industry. It is projected that three to four sets of designs standards can eventually be developed for various electric drive vehicle categories (design standards for HEVs are expected to be different than those for BEVs, for example).
- The design standards are to include sections on accommodations of 1) repurposing and second use applications and 2) recycling.
- It is recommended that initial module and pack design standardization activity be focused on commercial vehicle applications.

Module production volumes for application to commercial vehicles are projected to exceed 100,000 units during 2018 (See Figure 328). According to the ANL study (reference 36), significant cost reductions associated with large volumes and standardized designs occur at this production level.

- Thus, design activity associated with standard modules and packs aimed at the commercial vehicle market should begin during 2015.

Figure 328: Battery Packs Associated with Electric Drive Commercial Vehicles

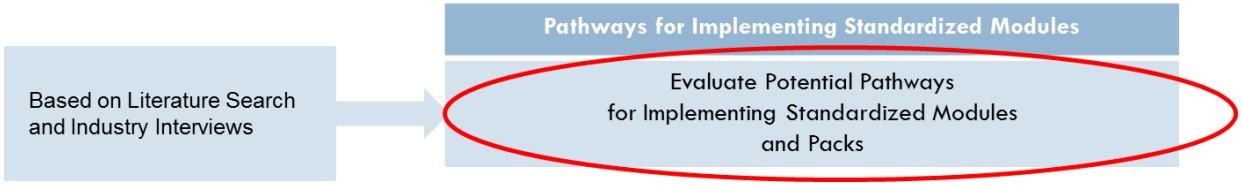
Battery Packs Associated with Electric Drive Commercial Vehicles (U.S. Sales Projections)									
	Selected Vocational Vehicles (see Task 2 results)						Total for Six Selected Vocations[1]	Total for All Vocational Vehicles[2]	Total for All Commercial Vehicles
Year	Class 3 Vans	Class 6 Box Truck	Class 4-6 Delivery	Class 7-8 Transit Bus	Class 4-6 Work Trucks	Class 3-6 Shuttle Bus			
2017	7,709	2,137	3,918	1,448	5,596	1,270	22,078	59,670	93,722
2018	12,500	3,131	5,058	2,238	6,437	1,759	31,123	84,116	132,118
2019	18,406	4,043	6,487	3,377	7,323	2,401	42,037	113,614	178,448
2020	22,800	5,784	6,643	4,219	8,248	3,106	50,800	137,297	215,648

[1]The six selected vocational vehicles represent 37% of new U.S. yearly vocational vehicle registrations

[2]New Vocational vehicles represent 64% of new U.S. yearly commercial vehicle registrations.

4.5 Sub-Task 4: Evaluation of Potential Pathways for Implementing Standardized Modules and Battery Systems

Figure 329: Sub-Task 4 Evaluate Potential Pathways for Implementing Standardized Modules and Battery Systems



4.5.1 Industry Interviews: Pathways for Implementing Standards

1. ***Question: Do you have recommendations regarding potential pathways for implementing PEV battery system standards for commercial/vocational vehicles?***

Two participants in the Task 5 industry stakeholder interview, both of whom represent vehicle OEMs that also produce PEV battery modules and packs, both expressed the opinion that standardization of module and pack designs is not likely for the near future. Their position is that battery innovation and development is still undergoing fundamental change. In addition, both have substantial investments in the design of their current modules and packs as well as the associated manufacturing facilities (reference 24).

The following recommendations include those obtained during the Chapter 2 industry interviews, Chapter 3 industry interviews, literature searches, and discussions involving the research team.

4.5.2 Potential Pathways to Lithium-Ion System Standardization

- Identify commercial and technical advantages of standard designs for all portions of the module/pack life cycle.
- Participate in standards committees for OEM and stationary battery industry organizations, such as SAE, ISO/IEC, IEEE, and IEC.
- Improved education regarding industry requirements for both first and second use applications. Prepare and present technical papers containing results of battery standardization analyses.

- Promotion of cost savings, savings, and performance improvements resulting from standardization
- Development of cells and modules that are compatible with a wide range of battery chemistries and performance specifications (voltage, watt-hours, resistance)
- Include monetary incentives for implementing standardized battery designs as part of government-funded battery-electric vehicle adoption rate programs (based on clear benefits to entire value chain).
- Identification of acceptable module specifications to facilitate "building block" approach to both vehicle and energy storage applications and preparation of "Draft" specifications for delivery to standards organizations
- Development of expanded communications and battery management systems containing options to facilitate a range of vehicle and energy storage applications
- Development of modules that facilitate remanufacturing processes for stationary energy storage and remain compatible for EV use.
- There is a need for improvement in supply chain reliability – the supply chain has been erratic in recent years as a result of changes in ownership and strategy. To effectively implement design standards, an improvement in supply chain coordination and cooperation will be required. (reference 46)

4.6 Chapter 4 Summary and Conclusions

1) Determination of the impact of standardization on each stage of the value chain: this included research on the residual value of battery systems at the end of first use and an economic analysis of second use, stationary energy storage applications.

Additional interviews were conducted with industry stakeholders (vehicle OEMs, battery manufacturers, national laboratories, and battery recyclers) to obtain comments on the impact of standardization from both commercial and technical perspectives, as well as views regarding the impact of standardization on residual value of first use battery systems and definition of incentives and disincentives to standardization.

It is projected that significant cost reductions due to module and battery design standardization will not occur until production volumes exceed 100,000 units per year, at which time price reductions on the order of 10% to 15% are expected relative to current first use battery system prices. It is noted that continuing improvements in lithium-ion chemistries for the electric vehicle market are likely to reduce prices to below $300/kWh by 2020, assuming large-volume production facilities are put in place.

It is the opinion of the industry experts interviewed during this portion of the study that standardization will lead to improved battery safety, through the implementation of improved separators, coatings, thermal management systems, and housing designs.

Industry stakeholders are recommending that a family of up to four design standards be implemented to account for differences in applications, chemistries, and performance specifications. Currently, economic and technical considerations dictate that assembled second

use modules and packs will contain like cells. As standard designs become available, this assumption can be relaxed.

The residual value of lithium-ion batteries at the end of their first use was determined using a variety of methods, including: 1) scrap materials prices, 2) battery recycle values, 3) results of research conducted that the national laboratories, 4) vehicle battery pack trade-in values, and 5) evaluation of second use value based on economics of second use grid energy storage applications. The resulting values ranged from -$30/kWh (battery owner must pay to have battery recycled) to +$150/kWh (based on high value second use application).

The suitability of the standardized module/battery system configurations for different grid applications was assessed and compared to the suitability of the current non-standardized PEV system architectures. An energy storage economics model was utilized to determine the dollarized benefit of selected grid/storage scenarios for both non-standardized and standardized battery designs. It was determined that, in general, all applications show potential for net benefit results if battery modules are standardized. Key grid applications that will benefit from battery energy storage include electric service reliability, renewable time shift, and power quality. The maximum, economically feasible installed battery costs (below this cost the system is has a favorable return on investment) range from $183/kWh to over $1,000/kWh.

2) Evaluation of incentives and disincentives to each stakeholder for adopting standard designs: the purpose of this sub-task was to inform recommendations for standardization.

A list of incentives and disincentives for implementing standardized battery designs for electric-drive commercial vehicles was assembled. Many of the stakeholders expressed concern regarding possible negative impacts on battery development if design standards are imposed too early in the maturation of the industry.

3) Assignment of generalized recommendations for each suggested configuration of standardized modules: to promote recyclability and define financial benefits.

Organizations such as SAE, FMVSS (NHTSA), UNMTC (UNECE), FreedomCAR, and ISO, have already put in place many components and testing standards for rechargeable energy storage systems, but have not yet addressed design standards. It is recommended that these organizations be approached regarding support for design standards aimed at commercial vehicle modules and packs.

Standardized modules will facilitate recycling because 1) there will be fewer module types and chemistries, 2) construction will favor disassembly, 3) components may be labeled with bar codes to enable identification and machine sorting, and 4) future packs are anticipated to be larger (energy capacity) and available in larger volumes, thus promoting recycling operations

Commercial vehicles have been identified as primary candidates for standardized module/pack designs because of the favorable economics associated with electric drive systems, the packaging options available for implementing standardized packs, and the projected supply of second use batteries originating from these vehicles.

As described in Chapter 3, example module and pack designs have been developed based on energy capacity increments of 25 kW-hrs that meet the identified duty cycles. These are intended to establish a basis for developing a family of module and pack design standards applicable to the commercial vehicle industry. It is projected that three to four sets of designs standards can eventually be developed for various electric drive vehicle categories (design standards for HEVs are expected to be different than those for BEVs, for example).

The design standards are to include sections on accommodations of 1) repurposing and second use applications and 2) recycling.

It is recommended that initial module and pack design standardization activity be focused on commercial vehicle applications.

Module production volumes for application to commercial vehicles are projected to exceed 100,000 units during 2018. Significant cost reductions associated with large volumes and standardized designs occur at this production level.

Thus, design activity associated with standard modules and packs aimed at the commercial vehicle market should begin during 2015.

4) Evaluation of pathways for implementing standardized modules based on research and industry interviews.

Pathways to implementing standardized modules and battery systems, in addition to those defined in Chapter 3, were identified and include:

- Identify commercial and technical advantages of standard designs for all portions of the module/pack life cycle.
- Include monetary incentives for implementing standardized battery designs as part of government-funded battery-electric vehicle adoption rate programs (based on clear benefits to entire value chain).
- Improve supply chain reliability – the supply chain has been erratic in recent years as a result of changes in ownership and strategy. To effectively implement design standards, an improvement in supply chain coordination and cooperation will be required.

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GLOSSARY

Term	Definition
A	Amperes
AHJ	Agency having jurisdiction
Ahr	Ampere hours
B2L	Battery second life
B2U	Battery second use
BatPaC	Argonne National Laboratory lithium-ion manufacturing analysis tool
BEV	Battery Electric Vehicle
Battery Value Chain	The process or activity by which the battery value is impacted, including production, marketing, repurposing, second use, and recycling
BMS	Battery management system
DIM	Data Input Module
ECU	Engine control unit
ECV	Electric Commercial Vehicle
ESCT	Energy storage computational tool
ESS	Energy Storage System
First use	Initial application of battery system (time it resides in the vehicle)
FMVSS	Federal Motor Vehicle Safety Standards
FreedomCAR	U.S. Department of Energy Cooperative Automotive Research and Vehicle Technologies Program
G&T	Generation and transmission
GSA	General, selling, and administration expenses
GWh	Gigawatt-hours
H	Height
h	Hours
HCV	Heavy-Duty Commercial Vehicle
HECV	Hybrid Electric Commercial Vehicle
HEV	Hybrid Electric Vehicle
HMI	Human-machine interface
Hv	High voltage
IEC	International Electrochemical Commission
IP	Intellectual property
ISO	International Organization for Standardization
kW	Kilowatts
kWh	Kilowatt-hours
L	Length
LCOE	Levelized Cost of Electricity
LCV	Light-Duty Commercial Vehicle
LV	Low voltage
MCV	Medium-Duty Commercial Vehicle

MWh	Megawatt-hours
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
PAS	ISO/IEC Passenger Car Standards
PEV	Plug in Electric Vehicle
PHECV	Plug-in Hybrid Electric Commercial Vehicle
PV	Present Value
R&D	Research and Development
RESS	Rechargeable Energy Storage System
SAE	Society of Automotive Engineers
Second Use	Time during which battery system is used for stationary energy storage
SOC	State of Charge
T	Temperature
TCO	Total Cost of Ownership
TOU	Time of use (electricity rate plan)
UL	Underwriters Laboratory
UNECE	United Nations Economic Commission of Europe
UNMTC	United Nations Manual of Tests
V	Volts
VDA	Verband der Automobileindustrie
Vdc	Direct current voltage
W	Width

APPENDIX A:
Market Analysis: Supply vs. Demand

Below is a detailed review of the individual assumptions and characterization of each resource.

Figure 330: Review of the individual assumptions and characterization of each resource

Resource	Assumptions	Original Data	Scaled To
CPUC	Geographical Scope	California	United States
	Time Range	2014; 2016; 2018; 2020	2014-2025
	Grid Applications	Transmission, Distribution, Customer	Transmission, Distribution
	Units	MW	GWh
	Technologies	All Energy Storage Technologies except Pumped Hydro, Compressed Air Energy Storage (CAES), and Lead Acid Batteries	Li-Ion Batteries
	Market Factors	Market Proposal	N/a
CESA	Geographical Scope	California	United States
	Time Range	2015 & 2020	2015-2025
	Grid Applications	Transmission, Distribution, Demand-Side	Transmission, Distribution
	Units	MW	GWh
	Technologies	Any Energy Storage Technology	Li-Ion Batteries
	Market Factors	Market Proposal	N/a
KEMA	Geographical Scope	U.S.	N/a
	Time Range	2012 & 2017	2012-2025

Resource	Assumptions	Original Data	Scaled To
	Grid Applications	Ancillary Services, Community Energy Storage (CES), Renewables, Transmission, Other Distributed	N/a
	Units	MW	GWh
	Technologies	Pumped Hydro, CAES, Thermal, Flywheels, and Li-Ion, Lead Acid, Nickel, Sodium, and Flow Batteries	Li-Ion Batteries
	Market Factors	Market Estimates	N/a
Lux	Geographical Scope	Global	U.S.
	Time Range	2012-2017	2012-2025
	Grid Applications	Renewable Shifting, Renewable Integration, Upgrade Deferral, Ancillary Services, Residential Storage, Commercial Storage	Renewable Shifting, Renewable Integration, and Ancillary Services
	Units	GWh	N/a
	Technologies	Li-Ion, Vanadium Redox, Sodium Sulfur, Sodium Nickel Chloride, and Zinc Bromine Batteries, Flywheels	Li-Ion Batteries
	Market Factors	Market Estimates	N/a
Navigant	Geographical Scope	North America	U.S.
	Time Range	2013-2022	2013-2025
	Grid Applications	Grid Asset Optimization, Arbitrage, Renewable Integration, Transmission & Distribution Deferral	N/a

Resource	Assumptions	Original Data	Scaled To
	Units	MW	GWh
	Technologies	Li-Ion, Sodium Sulfur, Lead Acid, and Flow Batteries, Hydrogen, Flywheels, Compressed Air	Li-Ion Batteries
	Market Factors	Market Estimates	N/a
Sandia	Geographical Scope	U.S.	N/a
	Time Range	2010 & 2020	2012-2025
	Grid Applications[91]	Electric Energy Time-Scale Electric Supply Capacity Load Following Area Regulation Electric Supply Reserve Capacity Voltage Support Transmission Support Transmission Congestion Relief T&D Upgrade Deferral 50th Percentile T&D Upgrade Deferral 90th Percentile Substation On-Site Power Time-of-Use Energy Cost Management Demand Charge	N/a

[91] For additional information on the energy storage applications used in the Sandia resource, see Figure 325.

Resource	Assumptions	Original Data	Scaled To
		Management Electric Service Reliability Electric Service Power Quality Renewables Energy Time-Shift Renewable Capacity Firming Wind Generation Grid Integration (Short Duration) Wind Generation Grid Integration (Long Duration)	
	Units	MW	GWh
	Technologies	Li-Ion and Flow Batteries, Capacitors, Compressed Air, Flywheels, Pumped Hydro, Superconducting Magnetic Energy Storage, Thermal Energy Storage	Li-Ion Batteries
	Market Factors	Maximum Market Proposal	N/a

Figure 331: Grid applications assumed in the Sandia National Laboratories' Report

		Storage Power		
#	Type	Low	High	Note
1	Electric Energy Time-shift	1 MW	500 MW	Low per ISO transaction min. (Can aggregate smaller capacity.) High = combined cycle gen.
2	Electric Supply Capacity	1 MW	500 MW	Same as above.
3	Load Following	1 MW	500 MW	Same as above.
4	Area Regulation	1 MW	40 MW	Low per ISO transaction min. Max is 50% of estimated CA technical potential of 80 MW.
5	Electric Supply Reserve Capacity	1 MW	500 MW	Low per ISO transaction min. (Can aggregate smaller capacity.) High = combined cycle gen.
6	Voltage Support	1 MW	10 MW	Assume distributed deployment, to serve Voltage support needs locally.
7	Transmission Support	10 MW	100 MW	Low value is for substransmission.
8	Transmission Congestion Relief	1 MW	100 MW	Low per ISO transaction min. (Can aggregate smaller capacity.) High = 20% of high capacity transmission.
9.1	T&D Upgrade Deferral 50th percentile	250 kW	5 MW	Low = smallest likely, High = high end for distribution & subtransmission.
9.2	T&D Upgrade Deferral 90th percentile	250 kW	2 MW	Same as above.
10	Substation On-site Power	1.5 kW	5 kW	Per EPRI/DOE Substation Battery Survey.
11	Time-of-use Energy Cost Management	1 kW	1 MW	Residential to medium sized commercial/industrial users.
12	Demand Charge Management	50 kW	10 MW	Small commercial to large commercial/industrial users.
13	Electric Service Reliability	0.2 kW	10 MW	Low = Under desk UPS. High = facility-wide for commercial/industrial users.
14	Electric Service Power Quality	0.2 kW	10 MW	Same as above.
15	Renewables Energy Time-shift	1 kW	500 MW	Low = small residential PV. High = "bulk" renewable energy fueled generation.
16	Renewables Capacity Firming	1 kW	500 MW	Same as above.
17.1	Wind Generation Grid Integration, Short Duration	0.2 kW	500 MW	Low = small residential turbine. High = larged wind farm boundary.
17.2	Wind Generation Grid Integration, Long Duration	0.2 kW	500 MW	Same as above.

California Public Utilities Commission (CPUC)[92]

Figure 332: Table of CPUC mandated energy storage procurement targets for by application and IOU

Table 2

Proposed Energy Storage Procurement Targets (in MW)[22]

Storage Grid Domain Point of Interconnection	2014	2016	2018	2020	Total
Southern California Edison					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal SCE	**90**	**120**	**160**	**210**	**580**
Pacific Gas and Electric					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal PG&E	**90**	**120**	**160**	**210**	**580**
San Diego Gas & Electric					
Transmission	10	15	22	33	80
Distribution	7	10	15	23	55
Customer	3	5	8	14	30
Subtotal SDG&E	**20**	**30**	**45**	**70**	**165**
Total - all 3 utilities	**200**	**270**	**365**	**490**	**1,325**

A Note about the cost effectiveness of utility grid energy storage applications: According to the CPUC proposal procurement document, the authors stated, "To that end [AB 2514 energy storage targets],the researchersdevoted a great deal of attention and effort into formulating a cost-effective approach that would be sufficient to meet Section 2836.2(d)". AB 2514 requires that energy storage systems procured be cost effective.

[92] California Public Utilities Commission (CPUC). Procurement Targets. 03 September 2013.

Sandia National Laboratories: Resource used for standardizing applications and time durations.[93]

The Figure below lists the minimum and maximum time durations for each grid application. These time durations were used to convert energy storage demand values from units of power to units of energy.

Figure 333: Time durations for grid applications

Table 1. Summary of Key Standard Assumptions and Calculations for Applications of Storage in the State of California

Application/Benefit	Discharge Duration* Minimum	Discharge Duration* Highest	Lifecycle Financial Benefits ($/kW)	Maximum 10-year Market Potential (MW)	Ten-year Economic Benefits ($Million)**
Bulk Electricity Price Arbitrage	1	10	200 to 300	735	147 to 220
Central Generation Capacity	4	6	215#	3,200	688
Ancillary Services	1	5	72***	800	58
Transmission Support	2 Seconds	5 Seconds	169	1,000	169
Reduce Transmission Access Requirements	1	6	72***	3,200	230
Transmission Congestion Relief	2	6	72***	3,200	230
Distribution Upgrade Deferral 50th Percentile of Benefits	2	6	666#	804	536
Distribution Upgrade Deferral 90th Percentile of Benefits	2	6	1,067#	161	172
Transmission Upgrade Deferral	4	6	650#	1,092	710
Time-of-Use Energy Cost Management	2	see tariff	1,004	4,005	4,021
Demand Charge Management	6	11	465#	4,005	1,862
End-user Electric Service Reliability	0.25	5	359#	4,005	1,438
Electric Service Power Quality	10 seconds	1 Minute	717#	4,005	2,872
Renewables Capacity Firming	6	10	172##	1,800	310
Renewables Contractual Time-of-Production Payments	6	10	655##	500	328

*Hours unless other units are specified.
**Over ten years, based on lifecycle benefits times maximum market potential (market *estimates* will be lower).
***Placeholder values. The actual benefit was not estimated.
#Does not include incidental energy-related benefit.
##Wind generation.

[93] Eyer, James M., Joseph J. Iannucci, and Garth P. Corey. Sandia National Laboratories. Sandia Report: Energy Storage Benefits and Market Analysis Handbook. A Study for the DOE Energy Storage Systems Program. December 2004.

APPENDIX B:
Alternative Technical Approaches to Integration without Standardization

Details about each partnership/project identified in the Task 3 section which integrated electric vehicle batteries into a stationary storage system without standardization are presented below.

1. Partnership between BMW, Princeton Power, EVGrid, and CCSE (2013)[94]
    a. BMW installed a pre-commercial demonstration research project at the UC San Diego campus.
    b. The project consists of a containerized energy storage solution, utilizing 6 used MINI E battery packs, having been dismantled and reconfigured, and a Princeton Power inverter. EVGrid has designed what is termed a super-BMS to control all 6 packs as a single parallel unit.

2. Partnership between CCSE and AeroVironment (2011)[95]
    a. With funding from the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL), CCSE built a $220,000 hardware installation at the UC San Diego campus to test used electric vehicle battery packs in an operational microgrid environment.
    b. Two AeroVironment ABC-150 battery testers were used as inverters for the installation. AeroVironment also designed a software application to control both of these inverters with a single user interface.

3. Prototype designed by Manitoba HVDC Research Centre (2013-2014)[96]
    a. The team designed and implemented DC-DC converters that served as both an isolation and bi-directional energy flow interface for each battery module.
    b. A 5 kW and a 10 kW DC-DC converter was created. The battery side voltage (incoming to the pack) was 300-700 V and the collection bus voltage was 950 V (outgoing). This was a two-stage boost-buck converter.
    c. The project team could communicate to the battery BMS via a master control. Software architecture supported many BMS protocols, provided documentation was available.

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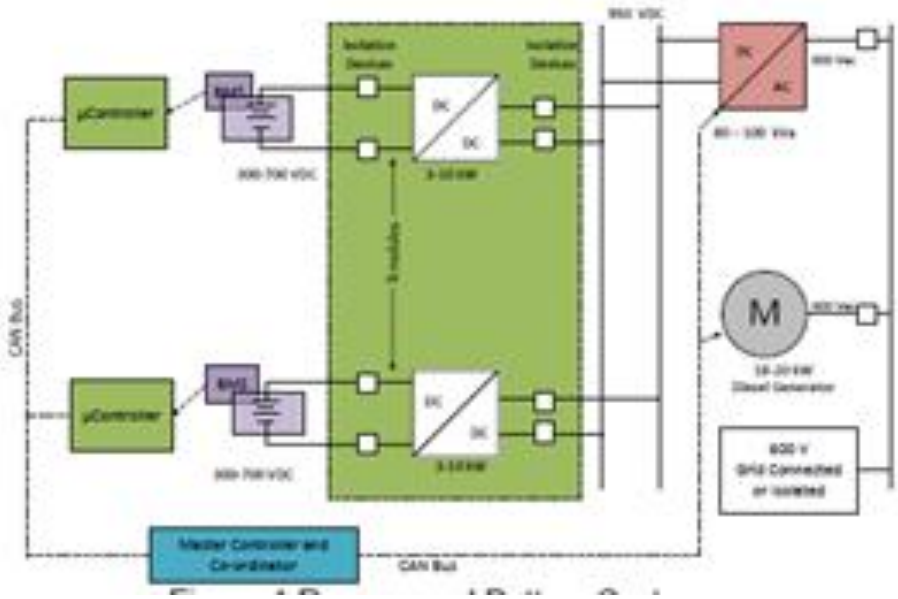
[94] Information obtained from CSE's direct participation in partnership.

[95] Information obtained from CSE's direct participation in partnership.

[96] Wachal, Randy: "Stationary Energy Storage System Using Repurposed Electric Vehicle Batteries". Manitoba HVDC Research Center. 2013.

d. An easy-to-use computer interface was designed known as the "master coordinator" for the battery system user to monitor battery health and performance.
e. Figure 334 shows a schematic of the prototype.

Figure 334: Microgrid-islanded test system schematic



4. Partnership between General Motors (GM) and ABB (2010)[97]
    a. ABB designed the power electronics to reuse Chevrolet Volt battery packs in back-up power, arbitrage, or renewables integration applications. ABB used its existing inverter to control the battery packs in a stationary environment.

5. Partnership between Nissan and Sumitomo (2009)[98]
    a. Nissan and Sumitomo looked at the business case for using LEAF battery packs in stationary energy storage applications after they are retired from the vehicle
    b. This partnership led to a joint venture company called 4R Energy
        i. 4R Energy manufactures three products using the retired LEAF packs. They are the following.
            1. Residential storage system
            2. Commercial/industrial storage system

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97 http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2012/Nov/electrification/1114_reuse.html
www.edmunds.com/autoobserver-archive/2011/07/gm-and-abb-give-chevy-volt-battery-second-life.html

98 http://www.nissan-global.com/EN/NEWS/2009/_STORY/091020-03-e.html
http://translate.google.com/translate?hl=en&sl=ja&u=http://www.4r-energy.com/&prev=/search%3Fq%3D4r%2Benergy%26espv%3D2%26biw%3D1440%26bih%3D760

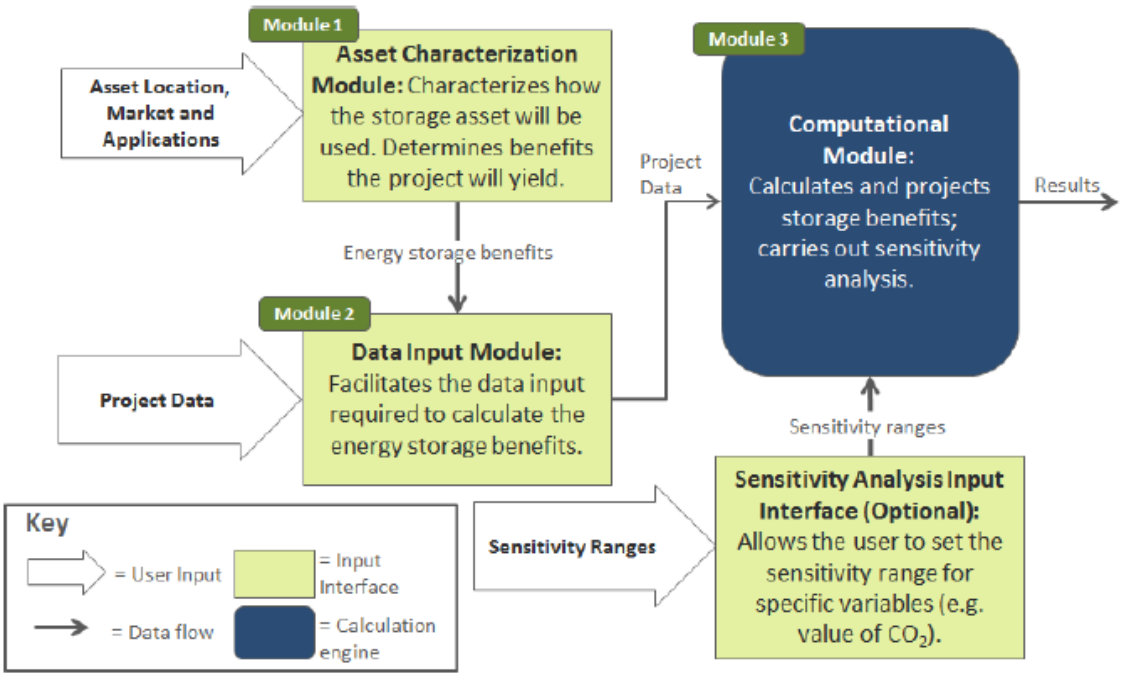
3. Refrigerator system for trucks

6. Partnership between Duke Energy and Itochu (2010)[99]
    a. Duke Energy provided the engineering designs and test sites for reusing EnerDel Li-ion battery packs from Th!nk vehicles in stationary energy storage systems. Itochu provided the power electronics behind these stationary energy storage systems.

[99] http://www.duke-energy.com/news/releases/2010112301.asp
http://www.itochu.co.jp/en/news/2010/101124_02.html

APPENDIX C:
Value Analysis

Figure 335: ESCT Architecture Overview[100]



[100] http://en.openei.org/wiki/Energy_Storage_Computational_Tool

Figure 336: ESCT Asset Characterization Module (ACM)

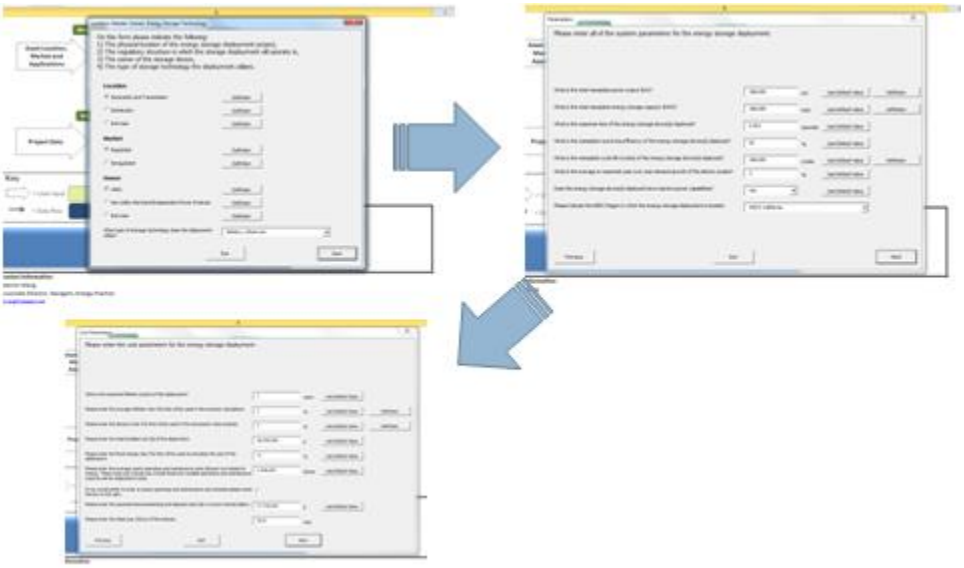


Figure 337: ESCT Asset Characterization Module (ACM) (continued)

Figure 338: ESCT Data Input Module (DIM)

Input Name	Units	Input Definition	Default Values	Values 100	101	102	103	104
Annual Fixed Charge Rate for Generation Capital Investment	%	The rate used to convert capital plant installed cost into an annuity equivalent (payment) representing annual carrying charges for capital equipment. It includes consideration of interest and equity return rates, annual interest payments and return of debt principal, dividends and return of equity principal, income taxes, and property taxes. Please only enter a single value per deferral in the initial year of deferral. If there is no deferral in a given year, leave that entry cell blank.	Use Default	11				
Capital Cost of Conventional Generation Capacity used for Load Following	$/kW	The base overnight capital cost of the conventional generation typically used to provide load following services.	Use Default	$ 992	$ 992	$ 992	$ 992	$ 992
Total Energy Discharged for Load Following	MWh	The total energy discharged by energy storage for the purposes of load following.	Use Default	94,000	94,000	94,000	94,000	94,000
Marginal Operating Cost of Load Following Generation	$/MWh	The typical marginal operating costs of conventional generation if it was being used to provide load following. If the generator is being run at sub-optimal load conditions the marginal operating costs may be higher than normal.	Use Default	$ 46	$ 46	$ 46	$ 46	$ 46
Marginal Operating Cost of Base Load Generation	$/MWh	The typical marginal operating costs of conventional base load generation. It is assumed that this is the type of generation that will be used to charge the energy storage that is providing load following services.	Use Default	$ 24	$ 24	$ 24	$ 24	$ 24
Energy Storage Capacity for Area Regulation	MW	The amount of energy storage capacity being used to provide area regulation services annually.	Use Default	188	188	188	188	188
Conventional Capacity Required for Equivalent Level of Area Regulation	MW	Because energy storage can respond to system regulation needs more accurately and quickly than some conventional generation sources, less capacity could be required if energy storage devices rather than conventional devices were used to provide this service. This input captures the amount of conventional capacity that would need to be devoted to area regulation annually in order to achieve the same level of service as the energy storage device.	Use Default	376	376	376	376	376
Price of Conventional Capacity	$/MW	The annual price of conventional generation capacity. This can be estimated by assuming a base overnight cost of new generation and multiplying this cost by an annual fixed charge rate.	Use Default	$ 121,580	$ 121,580	$ 121,580	$ 121,580	$ 121,580
Annual Reactive Power Capacity Available for Voltage Support	MVAR-yr	The annual energy storage capacity available for providing voltage support.	Use Default	188.0	188.0	188.0	188.0	188.0
Annual Capacity Payment for Voltage Support	$/MVAR-yr	The approximate annual payment to generators for providing voltage support. These services are often procured through longer term, negotiated, agreements.	Use Default	2,000	$ 2,000	$ 2,000	$ 2,000	$ 2,000

END END

Finish Data Entry

Figure 339: Benefits Definitions

Table 9. Description of Benefits

Benefit	Description
Arbitrage Revenue	ES can be used to store electricity purchased when prices are low, during off-peak periods, and discharge when electricity prices are high during peak periods, resulting in a revenue stream for the storage owner.
Capacity Market Revenue	As demand on the electricity grid grows from year-to-year, the need to install additional generation capacity to meet this demand also grows. In a deregulated market, where the electric supply capacity market is evolving, ES capacity could sold to the capacity to the market in order to generate a capacity credit revenue stream for a storage owner.
Ancillary Services Revenue	In deregulated electric service territories there may be organized markets for ancillary services such as load following, area regulation, reserve capacity, voltage support, and black start. The ability of ES devices to rapidly charge and discharge to the grid enables them to effectively provide these services resulting in a revenue stream for the owner.
Optimized Generator Operation	Using ES to respond to changes in load by absorbing or discharging energy as needed by the system can enable generators to run closer to their optimum operating zone. Therefore, by smoothing the load curve that the generation fleet must meet, storage can improve generation performance as measured by improved heat rate efficiency and lead to lower operating costs.
Deferred Generation Capacity Investments	By shifting peak demand or providing ancillary services that are typically provided by conventional generation assets, ES can result in deferred generation capacity investment benefits. By shifting peak demand, less generation capacity will be required to meet the system needs and by providing ancillary services more generation capacity will be freed up to meet system energy needs.
Reduced Congestion Costs	If storage is located close to load centers it may be used to reduce congestion by charging during periods of no congestion and discharging during congested periods. Charging and discharging in this way will meet peak demands while reducing the amount of electricity that must be passed through the congested transmission pathways. If congestion can be reduced in this way the costs associated with congestion can also be reduced.
Deferred Transmission Investments	Utilities build transmission with capacity sufficient to serve the maximum amount of load that planning forecasts indicate. The trouble is, this capacity is only required for very short periods each year, when demand peaks. Providing stored energy capacity closer to the load reduces the power flow on transmission lines, potentially avoiding or deferring capacity upgrades.
Deferred Distribution Investments	Electricity storage can be used to relieve load on overloaded feeders and distribution assets, potentially extending the time before upgrades or additions are required.
Reduced Electricity Losses	By charging electricity close to load centers during periods of low demand and discharging during peak demand period, ES can reduce the peak load on the grid. Because losses proportional to the square of current on the system, reducing peak load will result in a reduction of the total amount of electricity line losses on the system.

Figure 340: Benefits Definitions

Benefit	Description
Reduced Electricity Cost (Consumer)	Electricity storage can be used to reduce the cost of electricity for a consumer by enabling the consumer to avoid peak-demand charges and peak electricity prices. A consumer can charge their device when prices are low and discharge the device when prices are high. Because high prices tend to coincide with peak-times, this activity will also lower the customer's overall peak usage, which will lead to additional savings if the customer has a demand charge associated with their tariff.
Reduced Electricity Cost (Utility/Ratepayer)	Charging ES when demand is low, and discharging the devices when demand is high may decrease a utilities energy costs by allowing the utility to run a more cost effective mix of generation. This is because discharging the stored electricity during peak times may eliminate the need to dispatch additional expensive on-peak conventional generation.
Reduced Outages	Electricity storage can be used during a power outage as a backup power supply for one or more customers until normal electric service can be restored. The backup would only be available for a limited time (a few hours) depending on the amount of energy stored. However, even a temporary backup power supply can reduce the number of outages experienced by customers and/or greatly mitigate the impact of a disturbance event. Alternatively, storage can be used to provide grid support that will inherently increase the reliability of the system.
Improved Power Quality	ES can be used to protect on-site loads downstream from storage against short-term duration events affecting power quality. ES can also be located on the system and used to help regulate voltage thereby improving power quality for end-users. Manifestations of poor power quality include variations in voltage magnitude, variations in the primary 60-Hz frequency at which power is delivered, and interruptions in service ranging from a fraction of a second to several minutes.
Reduced CO_2, NO_x, SO_x, and Particulate Emissions	Electricity storage can reduce electricity peak demand and thereby reduce feeder losses. This translates into a reduction in emissions if peak generation is produced by fossil-based electricity generators. However, since electricity storage has an inherent inefficiency associated with it, electricity storage could increase overall emissions if fossil fuel generators are used for charging. Alternatively, by providing certain ancillary services, storage can enable conventional generation resources to be operated at more optimal conditions resulting in an emissions benefit. Finally, storage can yield a reduced emissions benefit by enabling greater utilization of renewable resources.