# Table of Contents

**Introduction** ....................................................................................................................................... 1

## Hydrogen Fuel R&D .......................................................................................................................... 10

### Hydrogen Production R&D ........................................................................................................... 12

| P-102: | Analysis of Advanced Hydrogen Production Pathways ......................................................................... 12 |
| P-143: | High-Temperature Alkaline Water Electrolysis ..................................................................................... 18 |
| P-177: | Proton-Conducting Ceramic Electrolyzers for High-Temperature Water Splitting .................................. 22 |
| P-178: | Industrially Scalable Waste Carbon Dioxide Reduction to Useful Chemicals and Fuels ......................... 26 |

### Hydrogen Production R&D: HydroGEN Seedling .............................................................................. 32

| P-148: | HydroGEN Overview: A Consortium on Advanced Water-Splitting Materials ........................................ 32 |
| P-152: | Proton-Conducting Solid Oxide Electrolysis Cells for Large-Scale Hydrogen Production at Intermediate Temperatures ................................................................. 38 |
| P-153: | Degradation Characterization and Modeling of a New Solid Oxide Electrolysis Cell Utilizing Accelerated Life Testing .................................................................................. 43 |
| P-154: | Thin-Film, Metal-Supported High-Performance and Durable Proton–Solid Oxide Electrolyzer Cell ........ 48 |
| P-155: | High-Efficiency Polymer Electrolyte Membrane Water Electrolysis Enabled by Advanced Catalysts, Membranes, and Processes .......................................................... 52 |
| P-156: | Developing Novel Platinum-Group-Metal-Free Catalysts for Alkaline Hydrogen and Oxygen Evolution Reactions ....................................................................................... 58 |
| P-157: | Platinum-Group-Metal-Free Oxygen Evolution Reaction Catalysts for Polymer Electrolyte Membrane Electrolyzer ...................................................................................... 64 |
| P-158: | High-Performance Ultralow-Cost Non-Precious-Metal Catalyst System for Anion Exchange Membrane Electrolyzer ......................................................................................... 70 |
| P-159: | Scalable Elastomeric Membranes for Alkaline Water Electrolysis .......................................................... 76 |
| P-160: | Best-in-Class Platinum-Group-Metal-Free Catalyst Integrated Tandem Junction Photoelectrochemical Water-Splitting Devices ......................................................... 80 |
| P-161: | Protective Catalyst Systems on III-V and Silicon-Based Semiconductors for Efficient, Durable Photoelectrochemical Water-Splitting Devices .......................................... 85 |
| P-162: | Novel Chalcopyrites for Advanced Photoelectrochemical Water Splitting ............................................ 90 |
| P-163: | Monolithically Integrated Thin-Film/Silicon Tandem Photoelectrodes for High-Efficiency and Stable Photoelectrochemical Water Splitting ................................................. 94 |
| P-165: | Accelerated Discovery of Solar Thermochemical Hydrogen Production Materials via High-Throughput Computational and Experimental Methods ............................................. 98 |
| P-166: | Computationally Accelerated Discovery and Experimental Demonstration of High-Performance Materials for Advanced Solar Thermochemical Hydrogen Production .............. 104 |
| P-167: | Transformative Materials for High-Efficiency Thermochemical Production of Solar Fuels ..................... 109 |
| P-168: | Mixed Ionic Electronic Conducting Quaternary Perovskites: Materials by Design for Solar Thermochemical Hydrogen .............................................................................. 114 |
| P-169: | High-Temperature Reactor Catalyst Material Development for Low-Cost and Efficient Solar-Driven Sulfur-Based Processes ........................................................................... 118 |
TABLE OF CONTENTS

P-170: Benchmarking Advanced Water-Splitting Technologies: Best Practices in Materials Characterization ................................................................. 124
P-175: Intermediate-Temperature Proton-Conducting Solid Oxide Electrolysis Cells with Improved Performance and Delivery .......................... 131
P-176: Development of Durable Materials for Cost-Effective Advanced Water Splitting Utilizing All-Ceramic Solid Oxide Electrolyzer Stack Technology ................................................................. 135

**Hydrogen Storage R&D** ........................................................................................................................................................................... 139
ST-001: System-Level Analysis of Hydrogen Storage Options .................................................................................................................. 139
ST-100: Hydrogen Storage Cost Analysis ......................................................................................................................................................... 144
ST-130: Hydrogen Materials–Advanced Research Consortium (HyMARC): Lawrence Berkeley National Laboratory Technical Activities ........................................................................................................... 168
ST-144: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Optimized Hydrogen Adsorbents via Machine Learning and Crystal Engineering ........................................................................................................... 194
ST-146: Precursor Processing Development for Low-Cost, High-Strength Carbon Fiber for Composite Overwrapped Pressure Vessel Applications ........................................................................................................... 200
ST-147: Developing a New Polyolefin Precursor for Low-Cost, High-Strength Carbon Fiber ........................................................................................................... 205
ST-148: Novel Plasticized Melt-Spinning Process of Polyacrylonitrile Fibers Based on Task-Specific Ionic Liquids ........................................................................................................... 209

**Fuel Cell R&D** ................................................................................................................................................................................................. 213
FC-017: Fuel Cell System Modeling and Analysis ........................................................................................................................................... 215
FC-135: FC-PAD: Fuel Cell Consortium for Performance and Durability ........................................................................................................... 220
FC-140: Tailored High-Performance Low-Platinum-Group-Metal Alloy Cathode Catalysts ........................................................................................................... 227
FC-141: Platinum Monolayer Electro catalysts ........................................................................................................................................... 231
FC-144: Highly Accessible Catalysts for Durable High-Power Performance ........................................................................................................... 236
FC-145: Corrosion-Resistant Non-Carbon Electro catalyst Support s for Proton Exchange Fuel Cells ........................................................................................................... 242
FC-146: Advanced Materials for Fully Integrated Membrane Electrode Assemblies in Anion Exchange Membrane Fuel Cells ........................................................................................................... 247
<table>
<thead>
<tr>
<th>Project Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC-147</td>
<td>Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells</td>
</tr>
<tr>
<td>FC-155</td>
<td>Novel Ionomers and Electrode Structures for Improved Polymer Electrolyte Membrane Fuel Cell Electrode Performance at Low-Platinum-Group-Metal Loadings</td>
</tr>
<tr>
<td>FC-156</td>
<td>Durable High-Power Membrane Electrode Assemblies with Low Platinum Loading</td>
</tr>
<tr>
<td>FC-157</td>
<td>High-Performance Polymer Electrolyte Fuel Cell Electrode Structures</td>
</tr>
<tr>
<td>FC-158</td>
<td>Fuel Cell Membrane Electrode Assemblies with Ultralow-Platinum Nanofiber Electrodes</td>
</tr>
<tr>
<td>FC-160</td>
<td>ElectroCat (Electrocatalysis Consortium)</td>
</tr>
<tr>
<td>FC-161</td>
<td>Advanced Electro catalysts through Crystallographic Enhancement</td>
</tr>
<tr>
<td>FC-162</td>
<td>Vapor Deposition Process for Engineering of Dispersed Polymer Electrolyte Membrane Fuel Cell Oxygen Reduction Reaction Pt/NbOx/C Catalysts</td>
</tr>
<tr>
<td>FC-163</td>
<td>Fuel Cell Systems Analysis</td>
</tr>
<tr>
<td>FC-170</td>
<td>ElectroCat: Durable Manganese-Based Platinum-Group-Metal-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells</td>
</tr>
<tr>
<td>FC-171</td>
<td>ElectroCat: Advanced Platinum-Group-Metal-Free Cathode Engineering for High Power Density and Durability</td>
</tr>
<tr>
<td>FC-172</td>
<td>ElectroCat: Highly Active and Durable Platinum-Group-Metal-Free Oxygen Reduction Reaction Electro catalysts through the Synergy of Active Sites</td>
</tr>
<tr>
<td>FC-173</td>
<td>ElectroCat: Platinum-Group-Metal-Free Engineered Framework Nanostructure Catalysts</td>
</tr>
<tr>
<td>FC-174</td>
<td>Highly Efficient and Durable Cathode Catalyst with Ultralow Platinum Loading through Synergetic Platinum-/Platinum-Group-Metal-Free Catalytic Interaction</td>
</tr>
<tr>
<td>FC-178</td>
<td>Lab Call Fiscal Year 2018 (Membrane): Spirocyclic Anion Exchange Membranes for Improved Performance and Durability</td>
</tr>
<tr>
<td>FC-179</td>
<td>Lab Call Fiscal Year 2018 (Membrane): Stable Alkaline Membrane Based on Proazaphosphatranes Organic Super Base</td>
</tr>
<tr>
<td>FC-180</td>
<td>Lab Call Fiscal Year 2018 (Membrane): High-Performing and Durable Pyrophosphate-Based Composite Membranes for Intermediate-Temperature Fuel Cells</td>
</tr>
<tr>
<td>FC-181</td>
<td>Lab Call Fiscal Year 2018 (Reversible Fuel Cells): Microstructured Electrodes and Diffusion Layers for Enhanced Transport in Reversible Fuel Cells</td>
</tr>
<tr>
<td>FC-182</td>
<td>Lab Call Fiscal Year 2018 (Reversible Fuel Cells): Bipolar Membrane Development to Enable Regenerative Fuel Cells</td>
</tr>
<tr>
<td>FC-183</td>
<td>Lab Call Fiscal Year 2018 (Reversible Fuel Cells): Technology-Enabling Materials, Cell Design for Reversible Polymer Electrolyte Membrane Fuel Cells</td>
</tr>
<tr>
<td>FC-302</td>
<td>Developing Platinum-Group-Metal-Free Catalysts for Oxygen Reduction Reaction in Acid: Beyond the Single Metal Site</td>
</tr>
<tr>
<td>FC-303</td>
<td>Mesoporous Carbon-Based Platinum-Group-Metal-Free Catalyst Cathodes</td>
</tr>
<tr>
<td>FC-304</td>
<td>Fuel Cell Membrane Electrode Assemblies with Platinum-Group-Metal-Free Nanofiber Cathodes</td>
</tr>
<tr>
<td>FC-305</td>
<td>Active and Durable Platinum-Group-Metal-Free Cathodic Electro catalysts for Fuel Cell Application</td>
</tr>
<tr>
<td>FC-306</td>
<td>High-Performance Non-Platinum-Group-Metal Transition Metal Oxide Oxygen Reduction Reaction Catalysts of Polymer Electrolyte Membrane Fuel Cells</td>
</tr>
<tr>
<td>Project Code</td>
<td>Project Title</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>FC-307</td>
<td>Cyclic Olefin Copolymer-Based Alkaline Exchange Polymers and Reinforced Membranes</td>
</tr>
<tr>
<td>FC-308</td>
<td>Advanced Anion Exchange Membranes with Tunable Water Transport for Platinum-Group-Metal-Free Anion Exchange Membrane Fuel Cells</td>
</tr>
<tr>
<td>FC-309</td>
<td>Polymerized Ionic Liquid Block Copolymers and Ionic Liquids (PILBCP-IL) Composite Ionomers for High Current Density Performance</td>
</tr>
<tr>
<td>FC-310</td>
<td>Composite Polymer Electrolyte Membranes from Electrospun Crosslinkable Poly(Phenylene Sulfonic Acid)</td>
</tr>
<tr>
<td>FC-311</td>
<td>Novel Non-Perfluorosulfonic Acid Proton Exchange Membrane for Fuel Cell Application</td>
</tr>
<tr>
<td>FC-312</td>
<td>Molten Hydroxide Dual-Phase Membranes for Intermediate-Temperature Anion Exchange Membrane Fuel Cells</td>
</tr>
<tr>
<td>FC-313</td>
<td>Novel Bifunctional Electrocatalysts, Supports, and Membranes for High-Performing and Durable Unitized Regenerative Fuel Cells</td>
</tr>
<tr>
<td>FC-314</td>
<td>Efficient Reversible Operation and Stability of Novel Solid Oxide Cells</td>
</tr>
<tr>
<td>FC-315</td>
<td>High-Efficiency Reversible Alkaline Membrane Fuel Cells</td>
</tr>
<tr>
<td>FC-316</td>
<td>Durable, High-Performance Unitized Reversible Fuel Cells Based on Proton Conductors</td>
</tr>
<tr>
<td>FC-317</td>
<td>Stationary Direct Methanol Fuel Cells Using Pure Methanol</td>
</tr>
<tr>
<td>FC-318</td>
<td>Lab Call Fiscal Year 2019: Accessible Platinum-Group-Metal-Free Catalysts and Electrodes: ElectroCat</td>
</tr>
<tr>
<td>FC-319</td>
<td>Lab Call Fiscal Year 2019: Low-Cost Gas Diffusion Layer Materials and Treatments for Durable High-Performance Polymer Electrolyte Membrane Fuel Cells</td>
</tr>
<tr>
<td>FC-320</td>
<td>Lab Call Fiscal Year 2019: Electrode Ionomers for High-Temperature Fuel Cells</td>
</tr>
<tr>
<td>FC-321</td>
<td>Lab Call Fiscal Year 2019: Solid Phase Processing for Reduced Cost and Improved Efficiency of Bipolar Plates</td>
</tr>
<tr>
<td>FC-322</td>
<td>Lab Call Fiscal Year 2019: Polymer Electrolyte Fuel Cell Electrode Structures with Encased Catalysts to Eliminate Ionomer Adsorption on Catalytic Sites</td>
</tr>
</tbody>
</table>

**Infrastructure and Systems R&D** ............................................................................................................. 424

**Hydrogen Infrastructure R&D** ............................................................................................................... 426

<table>
<thead>
<tr>
<th>Project Code</th>
<th>Project Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN-001</td>
<td>Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Steels</td>
<td>426</td>
</tr>
<tr>
<td>IN-004</td>
<td>Magnetocaloric Hydrogen Liquefaction</td>
<td>430</td>
</tr>
<tr>
<td>IN-005</td>
<td>Electrochemical Compression</td>
<td>434</td>
</tr>
<tr>
<td>IN-007</td>
<td>Metal Hydride Compression</td>
<td>438</td>
</tr>
<tr>
<td>IN-008</td>
<td>Dispenser Reliability</td>
<td>442</td>
</tr>
<tr>
<td>IN-009</td>
<td>Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks</td>
<td>447</td>
</tr>
<tr>
<td>IN-010</td>
<td>Cryogenically Flexible, Low-Permeability Hydrogen Delivery Hose</td>
<td>450</td>
</tr>
<tr>
<td>IN-011</td>
<td>Coatings for Compressor Seals</td>
<td>453</td>
</tr>
<tr>
<td>IN-012</td>
<td>Low-Cost Magnetocaloric Materials Discovery</td>
<td>457</td>
</tr>
</tbody>
</table>
Technology Acceleration ....................................................................................................................... 461
TA-001: Membrane Electrode Assembly Manufacturing Research and Development ......................... 461
TA-005: In-Line Quality Control of Polymer Electrolyte Membrane Materials ............................................ 464
TA-007: Roll-to-Roll Advanced Materials Manufacturing Lab Consortium ............................................. 468
TA-008: Material–Process–Performance Relationships in Polymer Electrolyte Membrane Catalyst Inks and Coated Layers ........................................................................................................... 473
TA-009: Maritime Fuel Cell Generator Project ...................................................................................... 476
TA-012: Northeast Demonstration and Deployment of FCRx200 ............................................................... 482
TA-014: Hydrogen Station Data Collection and Analysis ........................................................................ 490
TA-015: Dynamic Modeling and Validation of Electrolizers in Real-Time Grid Simulation ...................... 496
TA-016: Fuel Cell Hybrid Electric Delivery Van ...................................................................................... 501
TA-017: Innovative Advanced Hydrogen Mobile Fueler ........................................................................... 505
TA-018: High-Temperature Electrolysis Test Stand ................................................................................ 509
TA-019: Modular Solid Oxide Electrolizer Cell System for Efficient Hydrogen Production at High Current Density ........................................................................................................................................... 514
TA-020: Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller) ................. 518
TA-022: H2@Scale: Experimental Characterization of Durability of Advanced Electrolizer Concepts in Dynamic Loading .................................................................................................................... 527
TA-023: Hydrogen Stations for Urban Sites .............................................................................................. 532
TA-024: Analysis of Fuel Cells for Trucks ............................................................................................... 537

Systems Analysis .................................................................................................................................... 542
SA-044: Cost–Benefit Analysis of Technology Improvement in Medium- and Heavy-Duty Fuel Cell Vehicles ............................................................................................................................. 542
SA-169: Market Segmentation Analysis of Medium- and Heavy-Duty Trucks with a Fuel Cell Emphasis ................................................................................................................................. 546
SA-170: Analysis of Cost Impacts of Integrating Advanced Onboard Storage Systems with Hydrogen Delivery ..................................................................................................................................... 551
SA-171: H2@Scale Analysis ...................................................................................................................... 555
SA-172: Hydrogen Demand Analysis for H2@Scale ................................................................................ 560

Safety, Codes and Standards ................................................................................................................. 565
SCS-001: National Codes and Standards Deployment and Outreach ....................................................... 567
SCS-005: Research and Development for Safety, Codes and Standards: Materials and Component Compatibility ..................................................................................................................... 573
SCS-007: Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards ............................................................................................................. 576
| SCS-010:   | Research and Development for Safety, Codes and Standards: Hydrogen Behavior .............. 580 |
| SCS-011:   | Hydrogen Quantitative Risk Assessment ........................................................................ 585 |
| SCS-019:   | Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources ........................................................... 589 |
| SCS-021:   | National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory .................. 593 |
| SCS-022:   | Fuel Cell and Hydrogen Energy Association Codes and Standards Support .................... 598 |
| SCS-026:   | Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Polymers .................... 603 |

**Appendix A: Program and Sub-Program Review Comments** ...........................................606

**Appendix B: Attendee List** ........................................................................................................627

**Appendix C: Evaluation Forms** ............................................................................................656

**Appendix D: Projects Not Reviewed** ....................................................................................677