6 Systems Development and Integration

6.1 Overview

Goals and Objectives

The **Systems Development and Integration** (SDI) subprogram conducts targeted hydrogen and fuel cell systems integration and demonstration activities to enable the **H2@Scale**[55] vision, supporting the ***U.S. National Clean Hydrogen Strategy and Roadmap***,[56] and aligned with opportunities identified in the ***Pathways to Commercial Liftoff: Clean Hydrogen***[57] report. SDI coordinates closely with the other HFTO subprograms in the RD&D of hydrogen and fuel cell technology subsystems and systems integration. It also collaborates with other DOE offices, including collaborations with OCED on the Regional Clean Hydrogen Hubs program, as described in the Bipartisan Infrastructure Law.[58] The Clean Hydrogen Hubs provision in the law aims to enable the demonstration and development of networks of clean hydrogen producers, potential consumers, and connective infrastructure. The hubs themselves aim to advance the production, processing, delivery, storage, and end-use of clean hydrogen, enabling sustainable and equitable regional benefits, as well as market liftoff.

Supporting national decarbonization priorities, integrated energy systems leveraging clean hydrogen and fuel cell technologies in high-impact end uses are foundational to the H2@Scale vision and are core to the success of regional clean hydrogen networks.

The overarching goals of the SDI subprogram are to validate R&D innovations at a systems level under real-world conditions, determine gaps to help guide R&D programs, identify and demonstrate new and promising integrated energy systems for various end uses of clean hydrogen, and inform larger scale demonstration and deployment programs. The subprogram directly supports the strategic priority to target high-impact end uses and includes a portfolio of activities in transportation, industrial and chemical uses, as well as energy storage and power generation, including grid integration.

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[55] Hydrogen and Fuel Cell Technologies Office. "H2@Scale." https://www.energy.gov/eere/fuelcells/h2scale.

[56] U.S. Department of Energy. *U.S. National Clean Hydrogen Strategy and Roadmap.* 2023. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

[57] U.S. Department of Energy. *Pathways to Commercial Liftoff: Clean Hydrogen*. March 2023. https://liftoff.energy.gov/clean-hydrogen/.

[58] Infrastructure Investment and Jobs Act. Public Law 117–58. 2021. Section 40314, (42 U.S.C. 16161c). https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

Specific objectives include validating the performance of integrated hydrogen and fuel cell technologies; enabling cost reductions through economies of scale; and expediting private-sector commercialization. In support of these objectives, the SDI subprogram:

- Identifies hydrogen applications and system configurations that can provide affordable, reliable, and beneficial uses of clean hydrogen, aligned with national goals.
- Bridges the gaps between component-level RD&D and commercialization by integrating technologies into functional systems in first-of-a-kind demonstrations.
- Tests and validates integrated energy systems under actual and/or simulated real-world operating conditions, providing valuable feedback to guide RD&D priorities in hydrogen and fuel cell technologies.
- Generates data on integrated energy systems used in techno-economic assessments of market readiness relevant to manufacturers, investors, and potential end users.
- Coordinates with crosscutting and enabling activities (including systems analysis; safety, codes and standards; workforce development, supply chain development, and manufacturing RD&D) to accelerate pathways to commercialization and deployment.
- Coordinates with other programs and offices to foster activities promoting environmental justice, safety, and environmental stewardship.

Figure 6.1 illustrates how SDI helps bridge the gap between RD&D and deployments with first-of-a-kind demonstrations, including integrated clean hydrogen systems. The subprogram’s project portfolio includes work to validate individual hydrogen or fuel cell technologies, as well as efforts to integrate multiple technologies into a system for evaluation in real-world environments. Results from these tests are used to assess the commercial readiness of the technology/system for the end users. The demonstration data are also supplied to the hydrogen and fuel cell RD&D teams and to the Systems Analysis subprogram. The feedback helps the subprograms to refine the technologies, analyze and model the results, and set new technical targets. The SDI subprogram also works closely with the enabling activities to allow for safe demonstrations and to identify manufacturing and workforce needs for commercialization of the technologies.

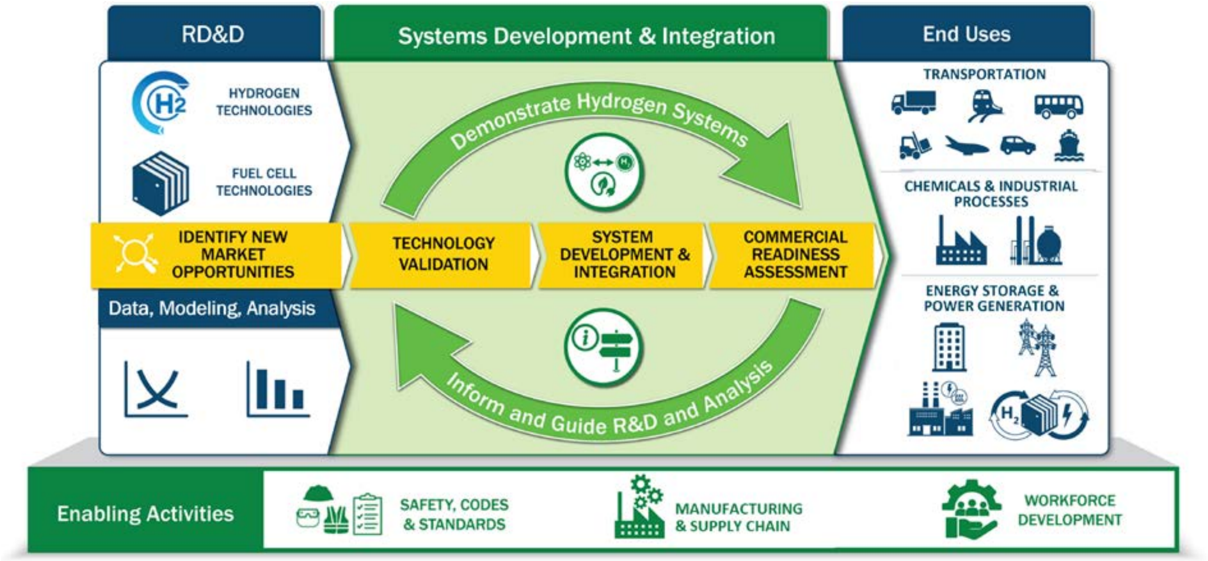

Figure 6.1. The Systems Development and Integration subprogram conducts technology and systems integration and validation activities to advance hydrogen and fuel cell commercialization and to provide data that feeds back to further guide hydrogen and fuel cell technologies RD&D

Technology Applications

The SDI subprogram focuses its activities on key emerging markets and technology applications relevant to the H2@Scale vision, illustrated in Figure 6.2, focusing particularly on high-impact end uses.

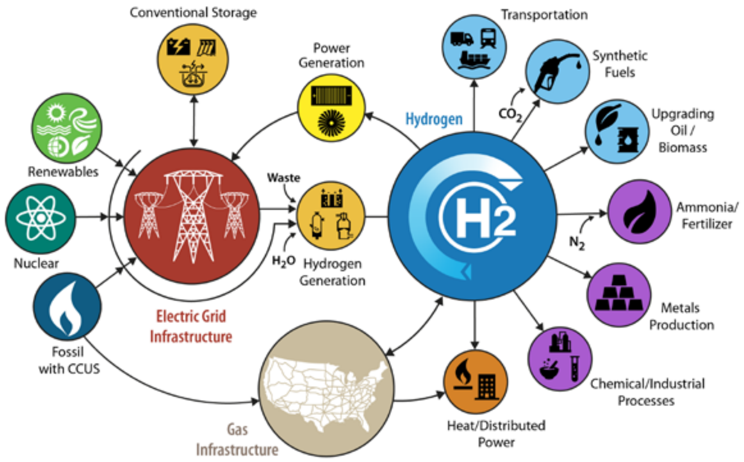

Figure 6.2. DOE's H2@Scale initiative to enable decarbonization across sectors using clean hydrogen

These high-impact end uses fall under three broad technology application areas:

- **Transportation** applications include medium- and heavy-duty trucks, maritime, rail, offroad equipment, and other heavy-duty applications requiring significant power, range, and up-time. These applications also support the *U.S. National Blueprint for Transportation Decarbonization: A Joint Strategy to Transform Transportation.*[59]
- **Chemical and industrial** applications include integrating clean hydrogen technologies into hard-to-decarbonize industrial sectors such as steel manufacturing and ammonia synthesis. These applications align with the DOE *Industrial Decarbonization Roadmap*.[60] Applications also include clean hydrogen as a feedstock in processing biomass to support the DOE Clean Fuels and Products Shot[61] and clean hydrogen in high-heat industrial processes, supporting the DOE Industrial Heat Shot.[62]
- **Energy storage and power generation** applications focus on grid integration and direct coupled renewable and nuclear hybrid systems, as well as distributed and backup power generation. These applications align with the DOE Long Duration Storage Shot[63] and the DOE Grid Modernization Initiative.[64]

SDI Focus Areas

Transportation and H_2 fueling demonstrations, including heavy-duty applications

Chemical and Industrial Processes integrating H_2 technologies, focusing on decarbonization

Energy Storage and Power Generation, including innovative hybrid energy systems

6.2 Strategic Priorities

As shown in Figure 6.3, the SDI subprogram's strategy incorporates near-, mid-, and longer-term focus areas, aligned with national clean hydrogen priorities, and consistent with HFTO's overall strategic framework described in the Introduction. While there are near-term opportunities to address development and integration of hydrogen and fuel cell systems across all technology application areas (particularly in the heavy-duty transportation applications), it is expected that

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[59] U.S. Department of Energy. *The U.S. National Blueprint for Transportation Decarbonization.* January 2023. DOE/EE-267. https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.

[60] U.S. Department of Energy. *Industrial Decarbonization Roadmap*. September 2022. https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.

[61] Office of Energy Efficiency and Renewable Energy. "Clean Fuels & Products Shot™: Alternative Sources for Carbon-Based Products." https://www.energy.gov/eere/clean-fuels-products-shottm-alternative-sources-carbon-based-products.

[62] Office of Energy Efficiency and Renewable Energy. "Industrial Heat Shot." https://www.energy.gov/eere/industrial-heat-shot.

[63] Office of Energy Efficiency and Renewable Energy. "Long Duration Storage Shot." https://www.energy.gov/eere/long-duration-storage-shot.

[64] U.S. Department of Energy. "Grid Modernization Initiative." https://www.energy.gov/gmi/grid-modernization-initiative.

the subprogram's RD&D activities in all high-impact end uses will continue into the mid- or long-term, to the point that industry commercialization has proven to be viable. Supporting the RD&D, enabling activities—including manufacturing RD&D, supply chain development, workforce development, and safety, codes and standards—fill out an integrated portfolio addressing challenges throughout all the phases of research, technology development, integration, demonstration, and commercial deployment.

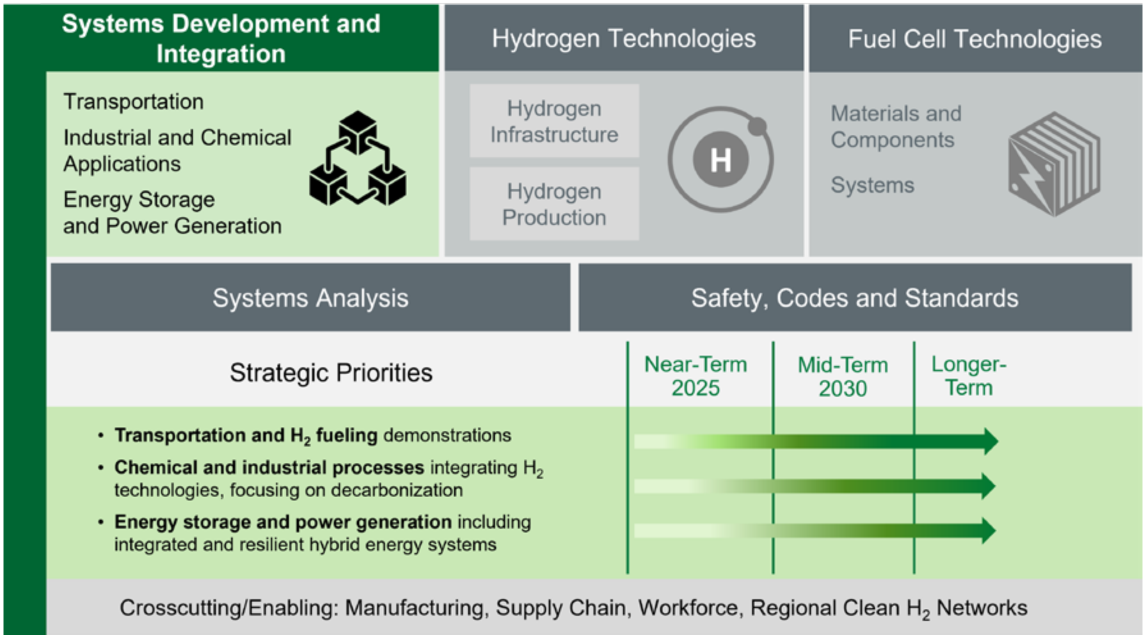

Figure 6.3. Strategic priorities guiding Systems Development and Integration RD&D

The three application categories shown in Figure 6.3 align with the near- to longer-term phases of clean hydrogen end-use adoption shown in Figure 6.4, reproduced from the *U.S. National Clean Hydrogen Strategy and Roadmap* and described in more detail below. The subprogram supports strategically targeted projects in these categories aimed at accelerating market adoption through technology validation and first-of-a-kind demonstrations of integrated systems. Developments and learnings from the projects in each category can often be applied to the others, and also provide valuable feedback to RD&D technology areas in other HFTO subprograms.

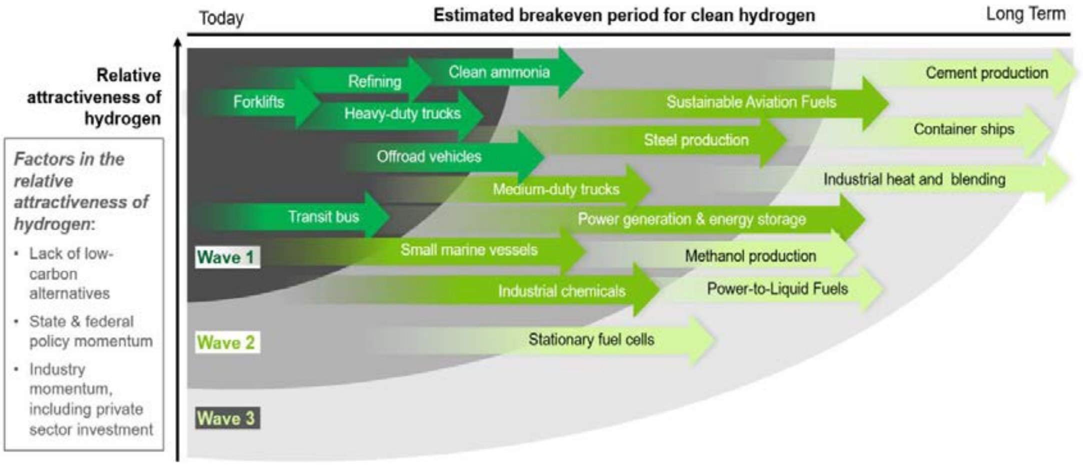

Figure 6.4. Clean hydrogen will be developed in waves, based on the relative attractiveness in each end-use application. Arrows depict the time frame when hydrogen is expected to be competitive with incumbent technologies at scale throughout the United States.

Transportation

Transportation activities focus on demonstrating medium- and heavy-duty fuel cell trucks and on low-cost, high-flow hydrogen fueling infrastructure that can be deployed in zero-emissions transportation corridors. The objective of these SDI projects is to demonstrate and validate fuel cell durability and performance under real-world conditions. Projects will also demonstrate and validate high-flow fueling to support these transportation modes. Analysis will be conducted to determine total cost of ownership and to define future requirements needed to compete with incumbent technologies.

In the near term, SDI projects in the transportation space will focus on accelerating commercial viability and adoption of medium and heavy-duty fuel cell electric trucks operating on clean hydrogen. The impact of these projects will reduce emissions and improve the energy and operational efficiency of moving freight while still providing operating range and fueling times on par with incumbent technologies. Technology advances will include optimized hybridization strategies, long-duration fuel cell systems, thermal management, onboard storage, and high-flow hydrogen fueling. In addition, new market opportunities for hydrogen and fuel cells in the other ultra-heavy-duty transportation sector such as marine, rail, and offroad equipment will continue to be evaluated. Transportation activities will be coordinated with EERE’s Vehicle Technologies Office.

Chemical and Industrial Processes

Within hard-to-decarbonize chemical and industrial processes, SDI focuses on demonstrating the ability of clean hydrogen to be used as a feedstock (e.g., ammonia and synthetic aviation fuel production) or direct reducing agent (e.g., steel and float glass production) or to provide process heat (e.g., steel and cement production). The subprogram will coordinate these activities with EERE's Industrial Efficiency and Decarbonization Office, as well as other DOE offices such as Fossil Energy and Carbon Management, Nuclear Energy, and OCED.

One of the most promising industrial applications to decarbonize with clean hydrogen is iron and steelmaking, which is an essential segment of the U.S. economy. In iron and steelmaking processes, syngas (a blend of carbon monoxide and hydrogen) has potential to be used in direct iron ore reduction. Several RD&D and demonstration projects worldwide, including some in the U.S. funded through SDI, are exploring the use of clean hydrogen in iron ore refining. To validate technical and economic requirements in U.S. markets, additional demonstrations of iron ore reduction using hydrogen can assist enabling economies of scale for hydrogen, while ensuring higher energy efficiency compared to conventional blast furnaces.

In the chemical industry, the *DOE Industrial Decarbonization Roadmap* notes that using hydrogen as a feedstock provides an important option for decarbonizing the chemical industry. Clean hydrogen can serve as a precursor to provide a low-carbon route to methanol, ammonia, hydrazine, and other compounds that serve as feedstocks for other chemicals and fuels (e.g., sustainable aviation fuels).

Energy Storage and Power Generation

Hydrogen and fuel cells can be incorporated into existing and emerging energy and power systems to avoid curtailment of variable renewable sources such as solar and wind; enable a more optimal capacity utilization of baseload nuclear, as well as natural gas and other hydrocarbon-based plants; provide voltage and frequency stabilization support for the electric grid; and/or provide clean, reliable distributed and backup power generation. The use of hydrogen for energy storage can play a key role in these systems.

SDI projects in this application space will help enable the production, storage, and/or transport of low-cost clean hydrogen from intermittent and curtailed renewable sources, while providing grid reliability and dynamic response to match grid demands. They will also support market penetration of renewable energy systems such as wind and solar, and they will help provide additional revenue streams for nuclear power plants by producing clean hydrogen with otherwise curtailed power when power prices are low.

6.3 RD&D Targets

Target Setting

The SDI subprogram has adopted a holistic target-driven approach to achieve life cycle cost parity of hydrogen and fuel cell technologies with incumbent and emerging systems across diverse high-impact end uses under different demand scenarios. Figure 6.5 depicts scenarios for the demand projected for specific end-use sectors if clean hydrogen is available (produced, delivered, and dispensed) at the threshold price shown. For instance, approximately $5/kg for hydrogen produced, delivered, compressed, and dispensed would pave the way for early adopters in the fuel cell truck market. At DOE's 2030 target of approximately $4/kg,[65] scenario analyses have shown that 10 to 14% of all medium- and heavy-duty fuel cell trucks would demand about 5 to 8 MMT of hydrogen per year. The lighter shaded bars represent a more optimistic demand scenario for each market shown.

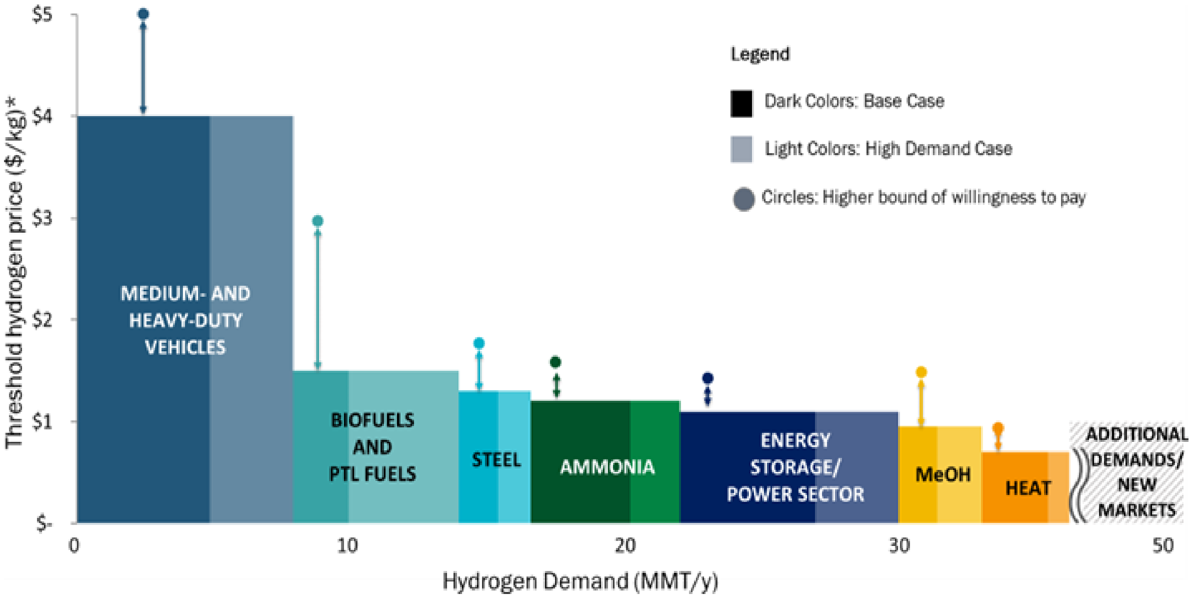

Figure 6.5. Scenarios showing estimates of potential clean hydrogen demand in key sectors of transportation, industry, and the grid, assuming hydrogen is available at the corresponding threshold cost

The subprogram develops technology- and system-level performance targets based on the application-specific threshold price ranges, specifically to guide and prioritize RD&D in areas that incentivize clean hydrogen adoption across the different sectors. These targets were developed using sophisticated techno-economic analysis with input from industry stakeholders and are updated regularly based on the latest data; they are used to guide subprogram activities and collaborations in systems integration, verification, and validation (including support of the Regional Clean Hydrogen Hubs).

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[65] Satyapal, Sunita. June 5, 2023. "U.S. DOE Hydrogen Program Annual Merit Review (AMR) Plenary Remarks." https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/plenary1_satyapal_2023_o.pdf. (slide #28)

End-Use Specific Targets

The SDI subprogram coordinates with other HFTO subprograms and DOE offices to address specific targets in alignment with DOE clean energy and decarbonization priorities in transportation, chemicals and industry, and energy storage and power generation.

Key DOE Target Examples Relevant to Systems Development and Integration

- 90% cost reduction in energy storage systems with 10+ hour duration by 2031
- 100% clean electricity grid by 2035
- 85% lower GHG emissions for industrial heat applications by 2035
- 85% lower GHG emissions in clean fuels and products compared to fossil products by 2035
- Conduct research and demonstrations of clean hydrogen refueling technologies to support the commercialization of trucks and other applications by 2030
- Develop a flexible and scalable blueprint for a successful hydrogen station corridor that is investment-ready by 2025
- Ensure that 100% of medium- and heavy-duty federal fleet acquisitions are zero-emissions by 2035

The SDI subprogram specifically works closely with the other HFTO subprograms to develop detailed technical targets for hydrogen and fuel cell technologies that are integrated into systems for commercial implementation. As an example, SDI has worked in concert with the Fuel Cell Technologies subprogram to develop technology targets for hydrogen fuel cells for use in commercial Class-8 long-haul heavy-duty trucks. The fuel cell system design parameter targets take into account the performance, durability, and cost requirements related to the specific drive-cycle and operations associated with this vehicle class. More detailed targets at the component or materials level (e.g., catalyst, membrane, MEA, bipolar plates, BOP components) are developed by the Fuel Cell Technologies subprogram.

Table 6.1 shows DOE's technical system targets for Class 8 long-haul tractor-trailer trucks powered by hydrogen and fuel cells. These targets were developed with input from the 21st Century Truck Partnership to provide the technical foundation for research priorities for hydrogen-fueled long-haul trucks. These hydrogen targets were developed for the long-haul use case, assuming trucks can be driven the maximum daily range (750 miles) between refueling. Additional background and assumptions can be found in the associated Program Record.[66]

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[66] Marcinkoski, Jason. October 31, 2019. "Hydrogen Class 8 Long Haul Truck Targets." DOE Hydrogen Program Record #19006. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

Table 6.1. Technical System Targets for Class 8 Long-Haul Tractor-Trailers (With Detailed Notes and Assumptions)

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[i]
Fuel Cell System Lifetime[a, b]	Hours	25,000	30,000
Fuel Cell System Cost[a, c, d]	$/kW	80	60
Fuel Cell Efficiency (peak)	%	68	72
Hydrogen Fill Rate	kg H_2/min	8	10
Storage System Cycle Life[e]	Cycles	5,000	5,000
Pressurized Storage System Cycle Life[f]	Cycles	11,000	11,000
Hydrogen Storage System Cost[d, g, h]	$/kWh ($/kg H_2 stored)	9 (300)	8 (266)

[a] The fuel cell system excludes hydrogen storage, power electronics, batteries, and electric drive.

[b] The lifetime target is intended to cover the entire useful life of the vehicle. Fuel cell system lifetime is defined as hours of use with an appropriate duty cycle that considers real-world driving conditions (i.e., not steady-state operation). Corresponding vehicle lifetime range is 1M miles (Interim) and 1.2M miles (Ultimate) based on an average speed of 40 mph.

[c] Interim and ultimate cost targets assume 100,000 units per year production volumes (except where specified within parenthetical references). Note that meeting fuel cell and hydrogen storage component cost targets may require leveraging automotive production volumes to achieve the necessary economies of scale for cost competitiveness. 2019 heavy-duty vehicle fuel cell technology was estimated to cost ~$190/kW at 1,000 units per year manufacturing volume (Fuel Cell Systems Analysis, 2019 DOE Hydrogen and Fuel Cells Program Review Presentation, https://www.hydrogen.energy.gov/pdfs/review19/fc163_james_2019_o.pdf).

[d] Costs are in 2016 dollars.

[e] The storage system cycle life target is intended to represent the minimum number of operational cycles required for the entire useful life of a vehicle used in long-haul operation. This target is technology-agnostic.

[f] Pressurized storage systems must meet cycle life requirements in applicable codes and standards (i.e., SAE J2579 and United Nations Global Technical Regulation No. 13). These codes and standards cycle life requirements require significantly more cycles than Storage System Cycle Life. For example, the baseline initial pressure cycle life in the United Nations Global Technical Regulation can require 11,000 cycles for a heavy-duty application.

[g] Hydrogen storage system cost includes the storage tank and all necessary BOP components. This target is technology-agnostic.

[h] A 700-bar hydrogen storage system was estimated to cost ~$36/kWh at 1,000 units per year manufacturing volume and $15/kWh at high volume (extrapolated from DOE Hydrogen and Fuel Cells Program Record #15013 "Onboard Type IV Compressed Hydrogen Storage System—Cost and Performance Status 2015," https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/15013_onboard_storage_performance_cost.pdf). Note: Hydrogen storage targets will be updated and are currently based on U.S. DRIVE fuel cell electric vehicle targets.

[i] Analysis based on 2050 simple cost of ownership assumptions and reflects anticipated time frame for market penetration.

DOE's hydrogen fill rate target for Class 8 long-haul trucks listed in Table 6.1 was determined based on the desired filling time comparable to incumbent technologies (i.e., 6 minutes) to deliver approximately 60 kg H_2, which would achieve a 750-mile range assuming a 12.4 mpkg fuel economy. The fueling rate requirements for other applications will depend on onboard hydrogen capacity needed for that specific application and the flow rate that the hydrogen can be dispensed at while also meeting applicable codes and standards. Figure 6.6 shows approximate fill rates required for various transportaton applications powered by hydrogen.

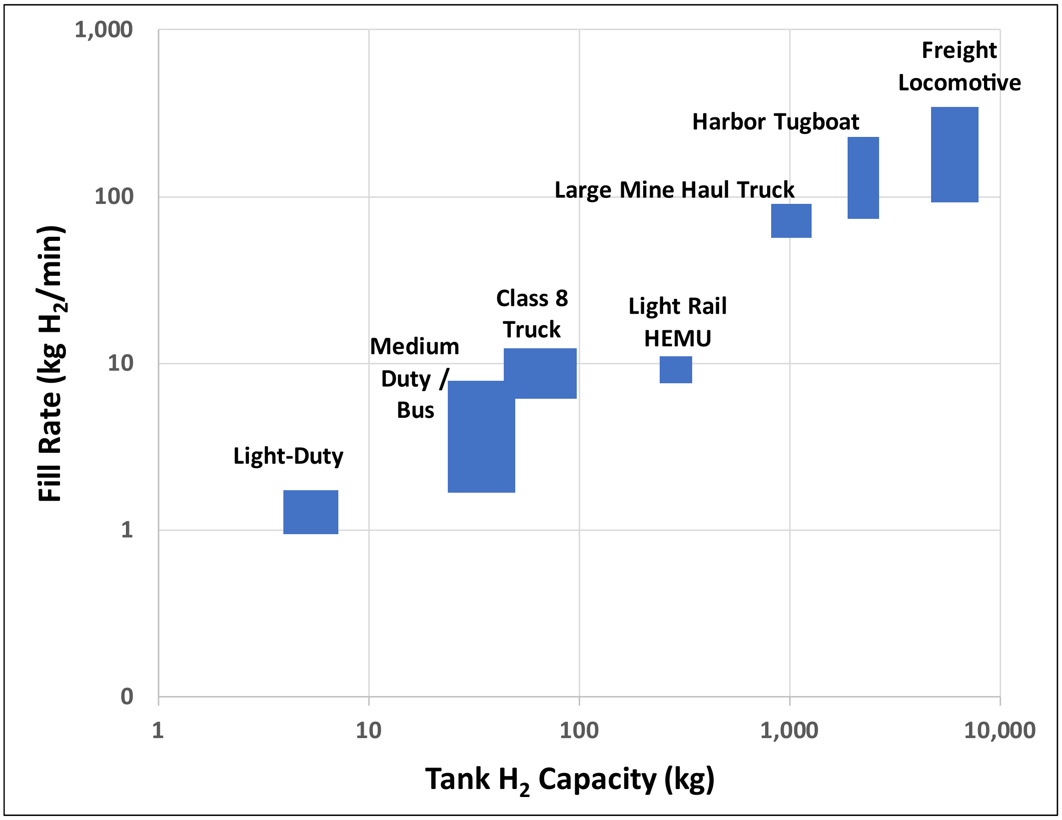

Figure 6.6. Approximate hydrogen fill rates required for various transportation applications

Related to the long-haul truck targets, the SDI and Fuel Cell Technologies subprograms have developed preliminary interim and ultimate targets covering a broader range of ultra-heavy-duty transportation end uses, including ferries, rail, and mining equipment, among others. These are shown in Table 6.2. These targets were developed based on analysis of competitiveness with incumbent technologies in these ultra-heavy-duty end uses; for example, multiple unit rail and passenger ferries are projected to be cost-competitive with incumbent diesel options when ultimate targets in the table have been met, including a clean hydrogen cost of \$4/kg H_2.

Table 6.2. System Design Targets for Ferries, Rail, Mining Equipment, and Other Ultra-Heavy-Duty Transportation Applications Powered by Hydrogen Fuel Cells

Characteristic	Units	Interim Target	Ultimate Target
Fuel Cell System Lifetime	Hours	25,000	30,000
Fuel Cell System Cost	\$/kW	80	60
Beginning-of-Life Fuel Cell System Efficiency at Rated Power	%	55	55

End-of-Life Fuel Cell System Efficiency at Rated Power	%	50	50
Hydrogen Storage System Cost	$/kWh	9	8
H_2 Storage System Life	Cycles	5,000	5,000
Liquid H_2 Dispensed Cost	$/kg	7	4

In addition to targets for heavy-duty and ultra-heavy-duty transportation applications, the SDI subprogram continues to develop and refine targets in other high-impact end uses, including those in the industry and chemicals application areas, as well as the energy storage and power generation applications. The technology baselines and targets in all areas are periodically assessed and adjusted as needed based on updated information, analysis, and stakeholder feedback.

For example, the SDI subprogram is also supporting projects that address the Hydrogen Production Technical Targets for Electrolyzer Stacks and Systems shown below in Table 6.3 through validation of electrical efficiency improvements leading to lower hydrogen production costs. [67]

Table 6.3. Hydrogen Production Technical Targets for Electrolyzer Systems

Technology	Characteristic	Units	Baseline	2026 Target	Ultimate Target
PEM	Energy Efficiency	kWh/kg H_2 (% LHV)	55 (61%)	51 (65%)	46 (72%)
Liquid Alkaline	Energy Efficiency	kWh/kg H_2 (% LHV)	55 (61%)	52 (64%)	48 (70%)
High-Temperature Electrolysis	Energy Efficiency[a]	kWh/kg H_2 (% LHV)	47 (71%)	44 (76%)	42 (79%)

[a] Includes both electrical and thermal energy inputs. The difference between "electrical efficiency" and "energy efficiency" values is the thermal energy input.
LHV: lower heating value.

For the latest, most up-to-date information on technical targets and the status of the technologies covered by HFTO, see:
www.energy.gov/eere/fuelcells/mypp

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[67] Office of Energy Efficiency and Renewable Energy. "Water Electrolyzer Technical Targets." https://www.energy.gov/eere/fuelcells/hydrogen-production-related-links#targets.

6.4 Addressing Challenges

While technical and economic challenges related to hydrogen production, delivery, storage, and conversion technologies are addressed through ongoing RD&D in other HFTO subprograms, the SDI subprogram addresses important component and integrated system issues aimed at achieving performance targets under real-world operating conditions at scale and enabling market adoption across sectors.

Systems Integration Challenges

Hydrogen and fuel cell technologies offer a number of opportunities to provide value to diverse sectors through their integration into hybrid energy systems, which are broadly defined as systems that integrate functions, components, or cross-sector applications such as electricity generation, energy storage, and/or energy conversion technologies through an overarching control framework to achieve enhanced capabilities, value, and/or cost savings compared to the standalone alternatives.[68] Figure 6.7 illustrates an example where electrolyzers and fuel cells can be integrated into an energy system powered by multiple generation sources and serving multiple end uses. Demonstrating these complex first-of-a-kind systems presents technical, system integration, and scale-up challenges.

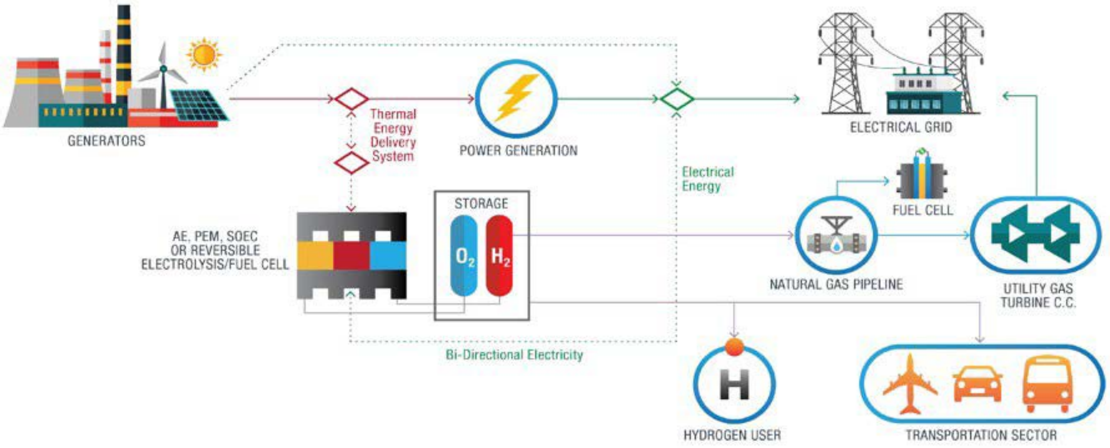

Figure 6.7. Diagram of a generalized hybrid energy system enabled by hydrogen and fuel cell technologies, leveraging multiple generation sources with potential service to multiple end uses

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[68] Office of Energy Efficiency and Renewable Energy. "Hybrid Energy Systems: Opportunities for Coordinated Research." https://www.energy.gov/eere/analysis/hybrid-energy-systems-opportunities-coordinated-research.

Example Challenges in Systems Integration

- Development of rigorous application-specific targets for hydrogen utilization
- Cost, durability, reliability, and efficiency in industrial-scale electrolyzers, fuel cell systems integrated into hybrid energy systems
- Component- and system-level integration and optimization, including BOP components and subsystems
- Optimized controls of integrated systems, including cybersecurity
- Affordable manufacturing and scale-up, including process intensification
- Safe use of materials, components, and subsystems requiring hydrogen use under pressure and/or temperature in diverse end uses
- Harmonized codes and standards, including refueling protocols
- System-level life cycle assessments of environmental and social impacts

While integrated hybrid energy systems with hydrogen and fuel cell technologies offer benefits across sectors, this can come at the expense of added complexity and potentially higher capital and operations costs. Systems integration must provide performance and durability at scale, while addressing complex challenges associated with integrating components, and subsystems for hydrogen use in different applications. In addition to effective management and controls of interdependent mechanical, electrical, electrochemical, and thermal functionalities in such systems, materials compatibility in hydrogen services at required temperatures and/or pressures must be addressed, as well as overall system safety. Continued RD&D and related enabling activities are needed to develop and demonstrate cost-competitive integrated systems that are efficient, durable, and safe. These include optimized component and subsystem integration schemes; innovations in manufacturing to enable scale-up and help address supply chain bottlenecks; data and information sharing in hydrogen safety awareness; and specialized workforce development meeting diverse end-use needs.

Diverse Cross-Sectoral Opportunities

There are many examples of integrated energy systems incorporating hydrogen and fuel cell technologies, each with its own set of end-use requirements, challenges, and opportunities. Tri-generation technologies refer to systems where hydrogen, electricity, and heat are produced; the high efficiency and low emissions of local production of hydrogen, electricity, and heat may make tri-generation systems a bridge technology for introducing and sustaining hydrogen infrastructure. An example of an integrated hybrid system in the transportation sector includes heavy-duty vehicles that incorporate hydrogen fuel cell systems (including hydrogen storage, electrical and thermal management, etc.) as well as batteries to meet energy capacity and dynamic response requirements of the respective drive cycles. Another example is a hydrogen emergency relief vehicle including hydrogen storage and fuel cells for providing load-following exportable power. In the industrial and chemicals space, systems integrating clean hydrogen production and/or storage with processes for steel production or ammonia synthesis offer an important strategy for decarbonization. In the energy storage and power generation sectors, integrated energy systems incorporating hydrogen and fuel cell technologies offer unique benefits in both on-grid and off-grid applications. Examples include mid- to long-duration/seasonal energy storage; grid leveling and stabilization services; and highly reliable backup power, e.g., for data centers.

Comprehensive Approach

To address the challenges across hydrogen and fuel cell technologies in integrated systems across end uses, the SDI subprogram supports a portfolio of RD&D projects implemented through funding mechanisms described in the Program Implementation section. This portfolio is closely coordinated with activities in the other HFTO subprograms and across the DOE Hydrogen Program,[69] as illustrated in Figure 6.8. The SDI subprogram supports first-of-a-kind demonstrations; it is critical that lessons learned from those demonstrations are fed back to the applied research programs so that innovative solutions are developed to challenges identified in the demonstrations.

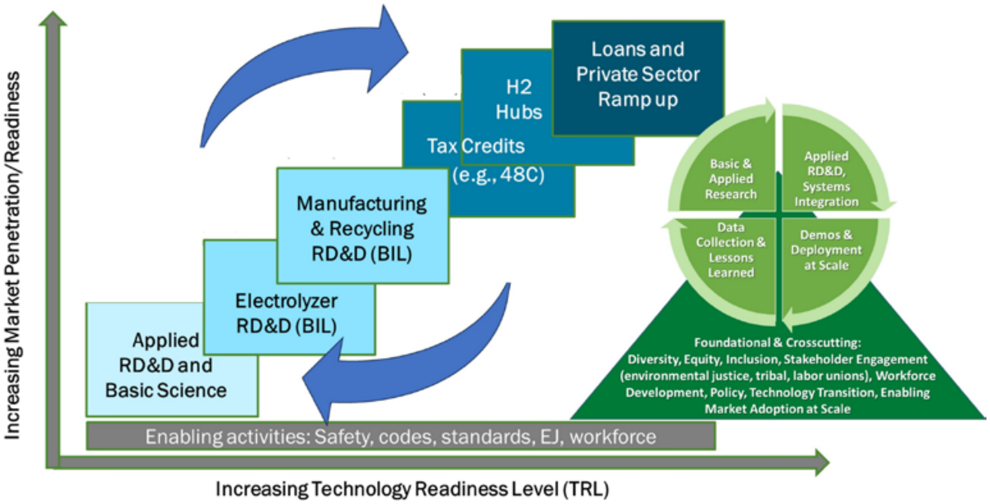

Figure 6.8. SDI integrates hydrogen and fuel cell technologies into systems that are validated in real-world conditions, through first-of-a-kind demonstrations, enabling commercial deployments (e.g., in the Regional Clean Hydrogen Hubs).

The SDI subprogram identifies potential end-use applications and uses hydrogen and fuel cell system components to assemble an integrated system that meets end-user needs. The system undergoes testing and evaluation during assembly and is then taken to the field or laboratory proving site for validation of the integrated technologies; this can include integration with actual

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[69] U.S. Department of Energy. "Hydrogen Program." https://www.hydrogen.energy.gov/.

components (such as wind turbines or nuclear plants), or with virtual hardware-in-the-loop. The first-of-a-kind demonstration of the integrated system is then tested and evaluated under real-world operating conditions. Data collection is used to analyze system performance and durability, which in turn provides valuable feedback for continued optimization at the component, subsystem, and system levels, including through RD&D prioritization in SDI and the other HFTO subprograms.

In addition to the close coordination within HFTO and DOE's Hydrogen Program, SDI also works closely with other DOE offices and with other federal agencies. As examples, the SDI team works closely with OCED on the implementation of the Regional Clean Hydrogen Hubs including the gathering of data and lessons learned to help inform future RD&D priorities within SDI and HFTO. In addition, industrial decarbonization RD&D leveraging hydrogen and fuel cell technologies is coordinated with DOE's Industrial Efficiency and Decarbonization Office, and manufacturing innovations are coordinated with the DOE Advanced Materials and Manufacturing Office. Outside of DOE, SDI engages with the Hydrogen Interagency Taskforce to help ensure that clean hydrogen activities are well coordinated across federal agencies and also participates in key partnerships with private-sector and nonprofit stakeholders to ensure that the RD&D efforts of government, academia, and industry are well aligned, their diverse capabilities are well integrated, and their resources are effectively utilized. Examples of successful partnerships have included U.S. DRIVE,[70] the 21st Century Truck Partnership,[71] and the H2@Scale project consortium.[72]

H2@Scale℠
U.S. Department of Energy

Stakeholders participate in cooperative research and development agreement (CRADA) projects with DOE's national laboratories in support of H2@Scale, leveraging world-class laboratory capabilities in systems integration and demonstration including NREL's Advanced Research on Integrated Energy Systems, or ARIES, platform.

6.5 RD&D Focus Areas

Technical and economic barriers common to the challenges addressed by the Systems Development and Integration subprogram include *Cost; Durability/Reliability; Efficiency/Performance; Life Cycle/Sustainability; Systems Integration; Safety, Codes and Standards; Manufacturing/Scale-Up; and Operations Support*. These barriers are summarized in Table 6.4 with some application-specific examples of the associated challenges related to components, subsystems, and/or systems.

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[70] Vehicle Technologies Office. "U.S. DRIVE." https://www.energy.gov/eere/vehicles/us-drive.

[71] Vehicle Technologies Office. "21st Century Truck Partnership." https://www.energy.gov/eere/vehicles/21st-century-truck-partnership.

[72] Hydrogen and Fuel Cell Technologies Office. "H2@Scale." https://www.energy.gov/eere/fuelcells/h2scale.

Table 6.4. Systems Development and Integration Barriers and Associated Challenges

Barrier	Associated Challenges
C: Cost ***components, subsystems, systems***	• Validated data on total cost of ownership compared with incumbent and emerging technologies • Standardized/modular designs to achieve economies of scale for multiple applications • Operations, maintenance, and replacement costs • Feedstock costs • Siting and permitting costs
D: Durability & Reliability	• System reliability and lifetime under real-world, dynamic operating conditions
E: Efficiency/Performance	• System operating performance that meets all targets/requirements under real-word, dynamic operating conditions • Fuel cell and hydrogen storage performance necessary to meet performance and range for transportation applications • Hydrogen refueling rate • Round-trip efficiency
LC: Life Cycle Impacts / Sustainability	• Validated data on life cycle environmental impacts • Standard recycling/disposal processes for sustainable use of critical materials
SI: Systems Integration	• Integration of electrolyzers with various power sources including the grid, behind-the-meter renewables, and nuclear (including both low- and high-temperature electrolyzers) • Data on large-scale hydrogen production from renewable resources: operational, dynamic response, cost, durability, and efficiency • Integration of hydrogen and fuel cells into industrial processes (e.g. steel, ammonia) needs to be developed to assess energy efficiency and potential emissions reduction • Integration of hydrogen fuel cells and hydrogen storage systems into transportation applications • Thermal and electrical integration of various systems including required power electronics and thermal management • Hybridization of various systems including integration of fuel cells with batteries for transportation applications • Complete system integration/design from renewables/nuclear, to hydrogen production, storage, transportation, and end use to balance performance, cost, and reliability
S: Safety, Codes & Standards	• Speed and cost of permitting

	• Protocols such as hydrogen fueling protocols for large transportation applications • First responder training • Code official training • Public awareness
M: Manufacturing, Scale-Up, and Supply Chain	• Number of parts in a component and the number of processing steps to scale-up manufacture of components • Materials, components, and systems compatible with processes for affordable scale-up and large-scale manufacturing • Limited domestic supply chain and manufacturing facilities
OS: Operations Support	• Manufacturing supply chain availability/diversity/resiliency • Supply chain for replacement parts for routine or unplanned maintenance • System operators and maintenance workforce development and training • Manufacturing workforce development and training

The SDI subprogram's comprehensive RD&D portfolio comprises projects and collaborative activities in areas addressing one or more of the barriers described in Table 6.4. Tables 6.5 through 6.7 provide a detailed summary of the subprogram's RD&D focus areas that address specific barriers and challenges for different applications in various end uses, along with examples of key targeted milestones. These RD&D focus areas are aligned with the subprogram's near-, mid-, and longer-term priorities. Based on project results, along with continued analysis and stakeholder engagement, the portfolio is assessed on a regular basis and is refined to align with the technology applications and system integration activities that can have the greatest impact on accelerating hydrogen and fuel cell technology commercialization and achieving economies of scale across sectors.

Heavy-Duty Transportation

The subprogram's strategic priorities in transportation include end uses such as medium-/heavy-duty trucks, as well as maritime, rail, and other offroad applications. Specific RD&D focus areas addressing barriers and challenges are described in Table 6.5.

Table 6.5. SDI Focus Areas Addressing Transportation Applications

Application	RD&D Focus Area	Barriers Addressed	Example Milestones
Medium-/ Heavy-Duty Trucks	Validate technical and cost performance relative to conventional diesel engine trucks	C, D, E, LC, SI	• With EERE's Vehicle Technologies Office, complete prototype commissioning of multiple Class 4-8 fuel cell electric trucks through the SuperTruck 3 program to demonstrate how a substantial
	Demonstrate fuel cell durability of 30,000 hours under real-world driving conditions	D, SI	

	Validate fuel economy of various classes of hydrogen fuel cell trucks with different duty cycles as well as Class 8 long-haul range of 750 miles on single fill	E	reduction of 75% or greater in GHGs and local pollutants can be achieved relative to diesel-equivalent trucks by 2028 • Complete I-10 H_2 fueling corridor study in collaboration with Vehicle Technologies Office by 2025
	Develop flexible, low-cost heavy-duty stations able to achieve a 10 kg/min fueling rate	E, S	
Maritime	Demonstrate hydrogen fuel cell cargo handling equipment at a port including necessary hydrogen infrastructure / fueling equipment	D, E, LC, S	• Demonstrate zero-emissions cargo movement at ports using clean hydrogen by 2030
	Demonstrate portside power (hoteling loads) using hydrogen for oceangoing vessels	D, E, LC, S	
	Analyze potential of hydrogen for small marine equipment such as ferries	C, D, E	
	Analyze potential for multi-use offshore wind power platform for hydrogen production, energy storage, and vessel refueling	E, SI, S	
Rail	Develop and integrate hydrogen storage and fuel cell systems on board trains	D, E, LC, SI, S	• Perform gap assessments for large-scale H_2 applications including bulk storage and rail by 2026
	Demonstrate integration of hydrogen production, storage, distribution, and refueling for rail applications	C, E, SI, S	
Aviation	Analyze potential for onboard fuel cell and hydrogen storage systems with comparable payload and range capability for urban and regional aircraft	C, D, E, LC, SI, S	• By 2035, validate fuel storage and power system for urban and regional aircraft
Off-Road	Validate the technical and cost performance relative to diesel-powered mining/construction equipment	C, D, E, SI	• By 2028, validate technical and economic performance of hydrogen and fuel cell integration in offroad applications
	Design and integrate hydrogen production (on- or off-site), hydrogen storage, and/or distribution infrastructure at mining and construction sites	C, D, E, SI	

Chemical and Industrial Processes

The subprogram's strategic priorities in chemical and industrial processes include metals refining as well as synthesis of clean fuels and products. Specific RD&D focus areas addressing barriers and challenges are described in Table 6.6.

Table 6.6. SDI Focus Areas Addressing Chemical and Industrial Applications

Applications	Activities	Barriers Addressed	Example Milestones
Metals	Optimize key aspects of existing processes that use hydrogen (e.g., operating temperature and pressure, iron ore particulate size and morphology, kinetics)	D, SI	• Demonstrate 1 metric ton/week direct reduction of iron with H_2 by 2024, and pathway to 5,000 metric tons/day
	Demonstrate integration of hydrogen systems with iron reduction technologies	C, D, E, LC, SI, S	• By 2025, show the technical and economic feasibility of the thermal and process integration between an SOEC module and a direct reduced iron furnace with an electric-to-hydrogen production efficiency of < 35 kWh/kg of H_2 • By 2025, complete a location-specific reference design where hydrogen can be produced at less than $2/kg for an off-grid behind-the-meter renewable power-to-hydrogen integrated energy system that includes an industrial end-use application
	Enable large-scale deployments through pre-front-end engineering and design (FEED) and FEED studies, market analysis, workforce analysis, techno-economic analysis/life cycle analysis	C, E, LC, SI	• Complete pre-FEED studies for the integration of clean hydrogen in hard-to-decarbonize industrial processes by 2027 to allow industry to develop a more detailed understanding of cost, performance, and emissions
Chemicals	Integrate and optimize key aspects of existing processes that use hydrogen	D, SI	• Validate emerging concepts for integration with industrial processes for synthetic fuels and chemicals by 2025
	Identify opportunities to reduce costs through innovative integration (e.g., thermal and chemical)	C, D, E, SI	

	Enable large-scale deployments through pre-FEED and FEED studies, market analysis, workforce analysis, TEA/LCA	C, E, LC, SI	• Enable four or more end-use demos (e.g., steel, ammonia, storage) at scale by 2036; Demonstrate that clean hydrogen can enable 85% GHG emissions reductions at an industrial facility, either as a feedstock input or direct use for heating

Energy Storage and Power Generation Systems

The subprogram's strategic priorities in energy storage and power generation focus on grid integration of hydrogen and fuel cell technologies; integration with renewables and nuclear power; and primary or backup power, such as for data centers. Specific RD&D focus areas addressing barriers and challenges are described in Table 6.7.

Table 6.7. SDI Focus Areas Addressing Energy Storage and Power Generation Applications

Applications	Activities	Barriers Addressed	Example Milestones
Grid Integration and Renewable Hybrid Systems	Validate dynamic response, efficiency, and durability of electrolyzers	D, E, SI	• Demonstrate at least six integrated electrolyzer systems by 2025 with a combined total capacity greater than 3 MW, using at least two different electrical generation sources and targeting at least three different hydrogen end-use applications • Develop 10-MW low- and high-temperature electrolysis validation facilities by 2027
	Demonstrate reliable, quick-response performance of hydrogen-producing electrolyzers for at-scale energy storage that support the grid through ancillary services and demand response	D, E, SI	
	Validate communications and controls, including cybersecurity requirements for successful participation in electricity markets and demand response programs	E, SI	
Nuclear Hybrid Systems	Develop and validate a hybrid nuclear hydrogen production system (in collaboration with the DOE Office of Nuclear Energy)	D, E, SI, S	• Demonstrate integrated (behind-the-meter) 1.25-MW PEM electrolyzer installation at nuclear plant for H_2 production by 2024 • Test 250 kW high-temperature electrolysis system using fully emulated nuclear integrated test stand by 2025
	Demonstrate 90% efficiency using high-temperature electrolysis technology and nuclear power plant thermal energy	E, SI	

Distributed Power Systems	Demonstrate and validate prime power and/or backup power systems to meet data center reliability requirements	D, E	• By 2024, validate an integrated minimum of 1-MW H_2 fuel cell system at a real-world data center; conduct performance tests operating the system between 24 and 48 hours to evaluate the system's ability to • Ramp up to full power and maintain that power for any necessary power outages • By 2025, evaluate in the lab and demonstrate in the field a grid-forming fuel cell inverter that can provide grid-forming services in a microgrid while utilizing hydrogen's energy storage scalability
	Design and integrate hydrogen production (on- or off-site), hydrogen storage, and/or distribution infrastructure with data centers	D, E, SI	
	Evaluate and demonstrate the operation of hydrogen systems to support microgrids for remote or underserved communities	D, E, SI, S	