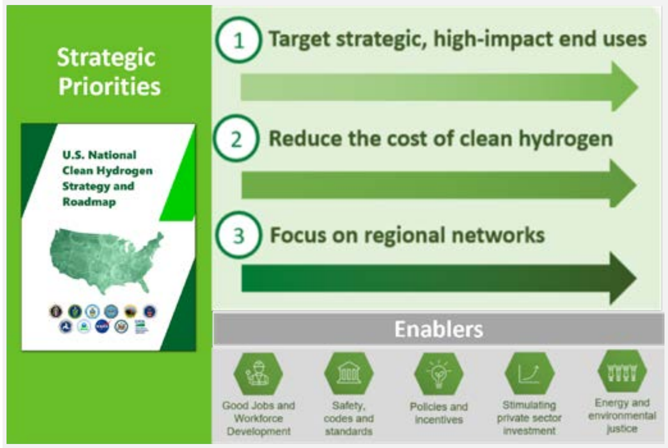
7 Systems Analysis

7.1 Overview

Goals and Objectives

The **Systems Analysis** subprogram is a crosscutting HFTO function, informing direction, prioritization, and decision making. The program funds analyses to identify technology pathways that can facilitate large-scale use of clean hydrogen and fuel cell systems to enable decarbonization, enhance energy system flexibility and resilience, and advance energy and environmental justice.

The overarching goal of the Systems Analysis subprogram is to inform the HFTO decision-making process, supporting RD&D to enable the adoption of hydrogen and fuel cell technologies across applications and sectors at scale, with focus on hydrogen from diverse clean and renewable resources. To achieve this goal, the Systems Analysis subprogram:



Rigorous data, modeling, and analysis activities support all aspects of the ***U.S. National Clean Hydrogen Strategy and Roadmap***, enabling strategic planning in RDD&D to achieve commercial liftoff of clean hydrogen and fuel cell technologies.

- Identifies strategic markets for hydrogen and assesses the associated benefits to inform HFTO strategy.
- Develops tools that characterize the cost and value proposition of hydrogen to inform real-world deployments.
- Quantifies the cost, emissions, and sustainability impacts of hydrogen production, delivery, fuel cell, and other end-use technologies to inform market models and real-world deployments.

Analytical Portfolio

The Systems Analysis subprogram's goals and objectives are addressed by implementing a portfolio of models and tools indicated in Figure 7.1. Techno-economic assessments, shown at the bottom of the pyramid in the figure, focus on key resource, technology, and economic issues, and form the basis of all Systems Analysis activities. Results and data generated from techno-economic assessments are leveraged to develop a wide range of higher-level analysis capabilities, including supply chain, impact, life cycle, decision, workforce, and market analyses, as well as more forward-looking or strategic planning, system optimization, and scenario development capabilities, as shown in upper portions of the pyramid.

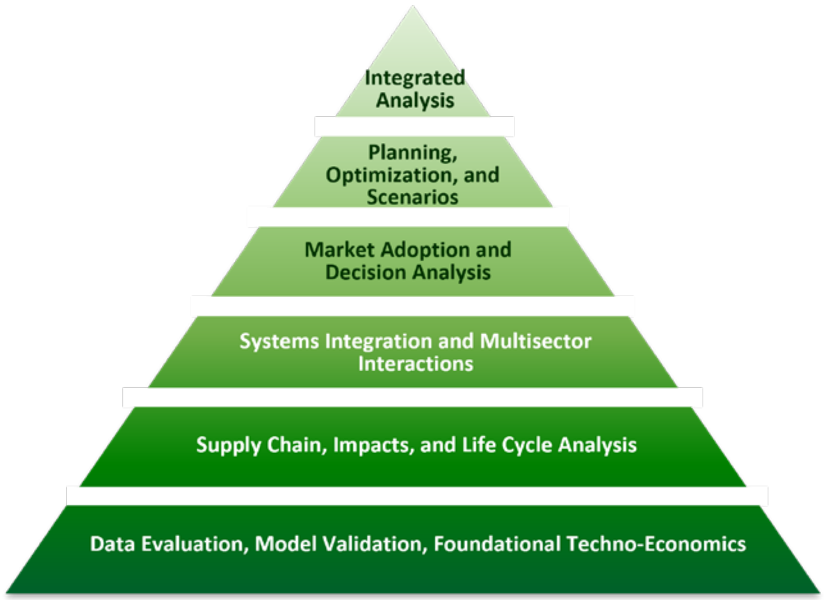


Figure 7.1. The Systems Analysis portfolio pyramid ranging from foundational tools and modeling capabilities through sophisticated integrated analysis of hydrogen and fuel cell technologies in promising market scenarios

Brief descriptions of each of the categories in the analytical portfolio are provided below:

- **Techno-Economic Analysis:** This category of model and tool capabilities provides several types of detailed technology assessments, including estimates of the cost of hydrogen production and delivery in potential future scenarios, sensitivities emerging by varying key input parameters (e.g., R&D advancement, electricity prices, natural gas prices), and total costs for hydrogen and fuel cells in specific applications and scenarios of interest (e.g., for medium- and heavy-duty transportation).
- **Supply Chain, Impact and Life Cycle Analysis:** These efforts account for a wide range of different impacts, such as life cycle emissions and energy consumption, water use and land use restrictions, and employment and gross domestic product impacts. The analysis scope can be very broad, allowing for technology comparisons useful for prioritization, sensitivity runs, and cost-benefit analyses.
- **Systems Integration and Multisector Interactions:** These models contribute a higher-level perspective on integrated systems. Analyses evaluate the relationships between hydrogen and other energy sectors, such as the electricity grid; large-scale infrastructure rollout scenarios; and sector-wide impacts, such as workforce analysis or system-wide costs. These models build upon the more discrete, component-level techno-economic and life cycle models, and they add value by generating results based upon an integrated

systems analysis. As more clean hydrogen facilities are deployed worldwide, these analyses will be informed by real-world data. Key metrics of interest in the early years of large-scale deployment will include the number and types of jobs created; real-world costs and impacts of economies of scale; financial parameters; and regional impacts on energy systems.

- **Market Assessment and Decision Analysis:** The impacts and benefits of many technology innovations depend upon market acceptance and consumer decisions**.** This analysis capability examines market dynamics and associated impacts on technology RD&D priorities and investment decisions. Analysis topics include hydrogen demand analysis, market barrier analysis, market simulations, and market-segmentation analysis, which characterizes the cost and potential market adoption of hydrogen and fuel cells relative to current and emerging alternatives.
- **Planning, Optimization and Scenario Development:** Analytical tools in this category focus on scenario development to inform planning and optimization of hydrogen and fuel cell technology systems in diverse end-use applications, taking a high-level view considering integrated systems and multisector interactions as well as market dynamics. Examples include infrastructure planning to support multisector coupling, including transportation fueling; supply chain optimization to minimize costs and increase resource utilization efficiency; and scenario development to provide insights into a range of future market conditions and uncertainties, stakeholder strategies and initiatives, and external market constraints and drivers.
- **Integrated Analysis:** Integrated and macro-system models link other models in the Systems Analysis portfolio as well as data and modeling resources from external stakeholders and facilitate consistency and communication between them in high-level assessments of technologies, resources, and markets. As an example, Systems Analysis continues to refine and update regional analyses across the hydrogen value chain, including supply based on the availability of clean electricity, water, and other resources, as well as demand. Using data from national laboratory and industry analyses, the technical potential for producing hydrogen from diverse domestic clean and renewable resources was estimated as shown in Figure 7.2 (left). This figure represents a compilation of analysis addressing domestic resources such as wind, solar, biomass, and hydropower. Integrated analysis has also projected ranges in potential hydrogen demand in 2050 in five key sectors: transportation; biofuels and power-to-liquid fuels; industry; blending; and energy storage and grid balancing, as illustrated in Figure 7.2 (right).[73]

[73] Clean hydrogen supply and demand potential analysis included in: 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.

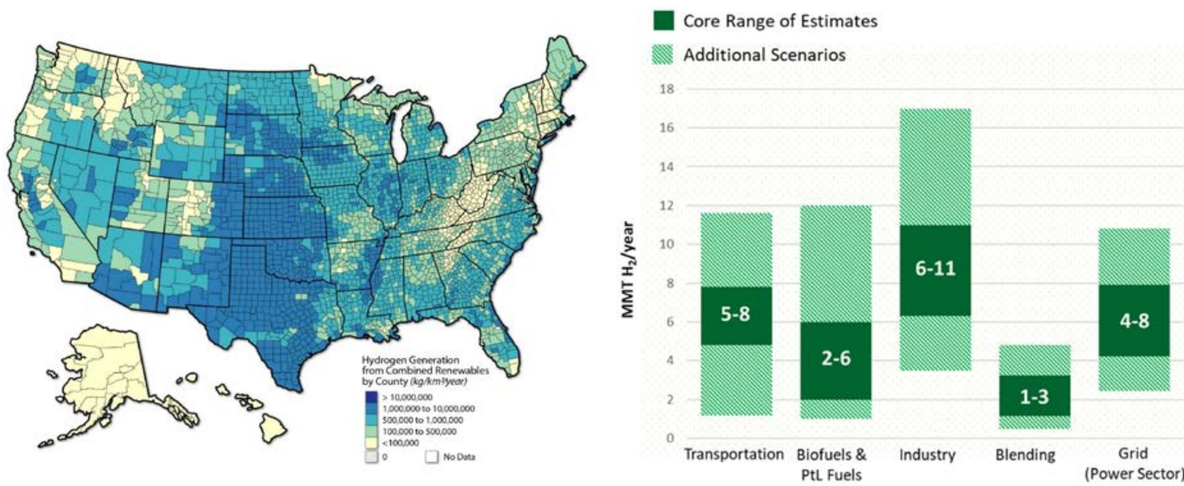


Figure 7.2. Examples of clean hydrogen supply and demand scenario analysis: production potential of hydrogen across the United States (left); potential hydrogen demand by sector in 2050 (right)

7.2 Strategic Priorities

As shown in Figure 7.3, the Systems Analysis subprogram addresses ongoing priorities to inform RD&D across all the HFTO subprograms and broader DOE and interagency efforts, as well as near-, mid-, and longer-term strategic priorities to accelerate planning and implementation of a clean energy transition leveraging hydrogen and fuel cell technologies. This is consistent with HFTO's overall strategic framework described in the Introduction and supports national clean hydrogen priorities.

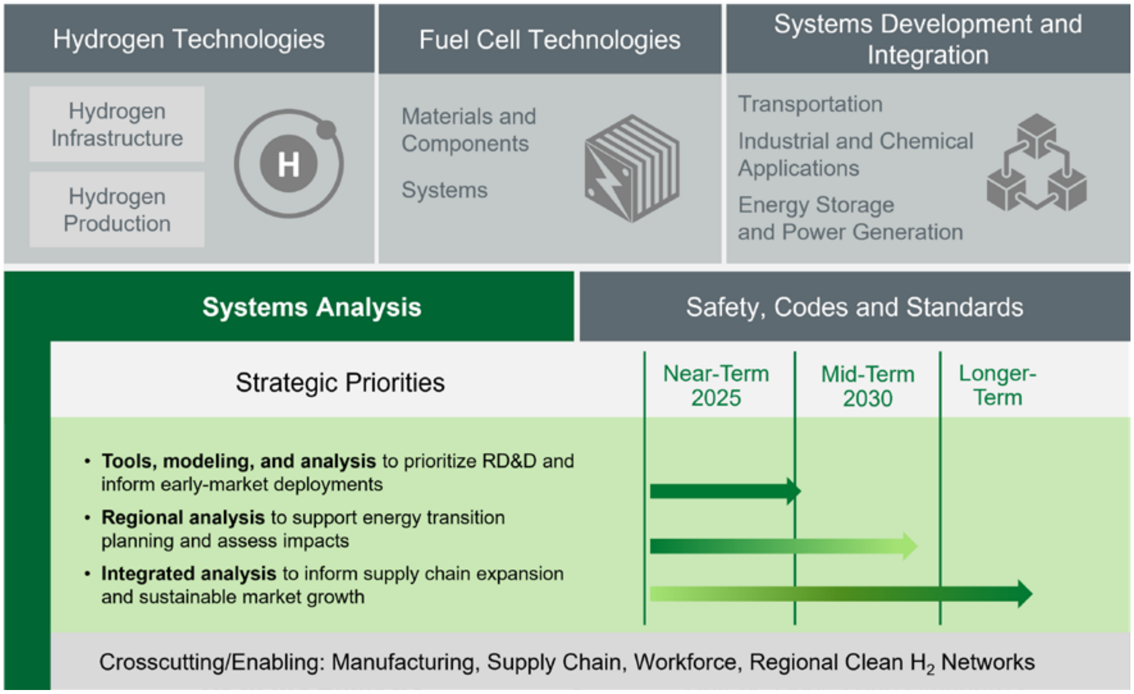


Figure 7.3. The Systems Analysis subprogram supports all HFTO subprograms and the overall national vision to enable the adoption and benefits of hydrogen and fuel cell technologies.

Near-Term Priorities

Tools, modeling, and analysis to prioritize RD&D for early markets: The Systems Analysis subprogram develops, refines, and uses analytical models and tools and helps to develop technology targets and milestones as well as technology readiness goals relevant to RD&D supported by other HFTO subprograms. Modeling and analysis elucidate the total cost of ownership of hydrogen and fuel cell technologies in specific sectors; cost and performance requirements to displace incumbent fuels; regional impacts of deployments on criteria pollutant emissions, water, and land resources; potential for job creation; and impacts on national climate goals. Systems Analysis results also provide assessments of hydrogen and fuel cell technologies in the context of the energy transition, and they inform decisions made by stakeholders with different concerns and decision time frames, such as informing community benefits plans and providing transparency for disadvantaged communities, tribal communities, and others not as familiar with hydrogen technologies. The initial focus is on identification and support of hydrogen and fuel cell technologies for early-market opportunities consistent with the national strategy, such as existing end uses in refining, chemicals, and industrial applications.

Mid-Term Priorities

Assess niche and early to mid-term market entry opportunities, with associated RD&D needs: The Systems Analysis portfolio's activities include techno-economic modeling to identify cost and performance requirements for hydrogen and fuel cell technologies to enter new markets and to identify sectors that may be early adopters. Examples of these efforts include **H2@Scale** analyses that characterize the potential for hydrogen demand in varying future scenarios of RD&D, impact of policies (e.g., tax credits), target-setting exercises, cradle-to-grave emissions analyses, and updates to the Annual Technology Baseline for Transportation. Additionally, models developed with the Systems Analysis subprogram's support, such as the Hydrogen Analysis (H2A) and Hydrogen Delivery Scenario Analysis Model (HDSAM) tools to estimate the costs of hydrogen production, delivery, and dispensing, are routinely updated and refined for use by external stakeholders in the development of RD&D plans and technology outlooks.[74]

Assess opportunities in major growing markets and inform multisector coupling RD&D: As hydrogen and fuel cell technologies are commercialized, real-word data regarding cost, performance, durability, and emissions are used to validate and refine existing models and inform macro-scale estimates of sector outlooks and sector coupling. These efforts account for multisector connections, supply chain expansion dynamics, policy impacts (e.g., tax credits, demand side incentives) and interactions between regional, national, and international developments such as exports.[75] These macro-scale estimates typically rely on capabilities higher up in the pyramid in Figure 7.1. Examples of recent efforts in this space include techno-economic analysis of the cost of clean hydrogen supply to industrial end uses, such as steelmaking, being informed by early relevant demonstrations.

Longer-Term Priorities

Inform large-scale production and manufacturing decisions, as well as supply chain expansion, and energy transition implementation: Adapting to increasing uncertainties and disruptions in domestic and international energy markets will require new analytic tools and strategies. Key focus areas of long-term analysis efforts include enhancing estimates of the export potential and supply chain for hydrogen to address increasing global demand, employment analyses to support the development of a workforce trained to develop and operate hydrogen and fuel cell technologies, manufacturing and supply chain analyses to inform scale-up of hydrogen and fuel cell technologies, and analyses to characterize the impacts of new technology trends, such as automation, on the value proposition of hydrogen and fuel cell technologies.

7.3 RD&D Targets

The Systems Analysis subprogram supports the development of technology targets and milestones as well as technology readiness goals relevant to RD&D supported by other HFTO subprograms, relying on its diverse portfolio of both focused and integrated models that characterize technology costs, performance, impacts, and cross-sector market potential.

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[74] Office of Energy Efficiency and Renewable Energy. *2019 Fuel Cell Technologies Market Report.* September 2020. ANL-20/58. https://publications.anl.gov/anlpubs/2021/08/166534.pdf.

[75] Reeves, Martin, and Johann Harnoss. June 6, 2017. "The Business of Business is No Longer Just Business, The Boston Consulting Group. https://www.bcg.com/publications/2017/corporate-strategy-business-no-longer.

Examples of recent analyses that have informed strategic program documents, such as the *U.S. National Clean Hydrogen Strategy and Roadmap*, the *U.S. National Blueprint for Transportation Decarbonization*,[76] and *Clean Hydrogen: Pathways to Commercial Liftoff* report[77] include:

- Life cycle analyses that inform annual updates to Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model, which is used to characterize the emissions reduction potential of hydrogen.[78]
- Vehicle cost and choice modeling to identify priority market segments for fuel cell vehicles in the heavy-duty trucking sector.[79] Underlying assumptions on vehicle costs in business-as-usual scenarios and scenarios where R&D targets are achieved are described in DOE's Annual Technology Baseline website.[80]
- Development and use of the National Renewable Energy Laboratory's (NREL's) H2A tools to characterize the cost of hydrogen production under varying scenarios of energy cost and capacity factor,[81] infrastructure modeling tools such as Argonne's HDSAM,[82] and models such as NREL's Hydrogen Financial Analysis Scenario Tool (H2FAST) that evaluate financial performance of user-defined systems.[83]
- Use of the state-of-the-art grid models such as NREL's Regional Energy Deployment System (ReEDS)[84] model, as well as newly developed models of energy storage such as StoreFAST,[85] to characterize the role of hydrogen in a clean grid.[86]

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[76] 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.

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

[78] Argonne National Laboratory. R&D GREET. https://greet.anl.gov/.

[79] Ledna, Catherine, Matteo Muratori, Arthur Yip, Paige Jadun, and Chris Hoehne. March 2022. "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis." National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/82081.pdf.

[80] National Renewable Energy Laboratory. "2020 Transportation Annual Technology Baseline." https://atb.nrel.gov/transportation/2020/index.

[81] National Renewable Energy Laboratory. "H2A-Lite: Hydrogen Analysis Lite Production Model." https://www.nrel.gov/hydrogen/h2a-lite.html.

[82] Argonne National Laboratory. "Hydrogen Delivery Scenario Analysis Model." https://hdsam.es.anl.gov/index.php?content=hdsam.

[83] National Renewable Energy Laboratory. "H2FAST: Hydrogen Financial Analysis Scenario Tool." https://www.nrel.gov/hydrogen/h2fast.html.

[84] National Renewable Energy Laboratory. "Regional Energy Deployment System." https://www.nrel.gov/analysis/reeds/.

[85] National Renewable Energy Laboratory. "StoreFAST: Storage Financial Analysis Scenario Tool." https://www.nrel.gov/storage/storefast.html.

[86] Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf.

7.4 Addressing Challenges

General Challenges

Fidelity of Existing Tools and Models

The existing suite of models and tools address a wide range of topics, but as industry markets and applications expand in scope, the analysis portfolio must expand accordingly. This can include new applications, new technologies, and new market interactions. Core assumptions within hydrogen models and analyses must also be continuously informed by real-world data. Key aspects of near-term deployments that can inform ongoing analyses include real-world financial metrics, technology costs, and system performance.

Future Consumer, Stakeholder and Market Behavior

Understanding underlying factors and expected trends in future markets is critical to the development of robust analytic tools to assess the costs, benefits, potentials and strategic advantages of hydrogen and fuel cell technologies. Consumer and stakeholder behavior can play important roles in new and emerging energy markets, especially as key strategic decisions can influence market transformation dynamics. To better understand the role of hydrogen and fuel cell applications in future markets, forward-looking analysis efforts must continually update assumptions and data related to consumer, stakeholder, and market behavior.

Regional Deployments Analysis

Regions can have unique resources, industrial capabilities, demand trends, and other market drivers or constraints that need to be considered in market assessments and scenario planning. Hydrogen supply chain networks will tend to expand outward from high-activity industrial clusters, metropolitan regions or megaregions, or along key transportation corridors. Positive economic conditions and economies of scale must be achieved early on within such clusters to reach market competitiveness. Planning processes and government-industrial initiatives are often focused on regions with strong policy drivers, low-cost energy, or concentrated demands. In addition, specific regional impact analyses for disadvantaged communities and other stakeholder groups such as tribal communities are lacking.

Specific Challenges and Opportunities

In addition to addressing general challenges, the Systems Analysis subprogram continually updates and improves its modeling tools and analysis in all categories of the portfolio pyramid. Examples of challenges and opportunities in these categories include:

Technoeconomic Analysis

- Providing updated current and future cost and technology performance estimates for fuel cell and hydrogen production, storage, delivery, and dispensing technologies.

- Integrating empirical data and stakeholder feedback into ongoing analysis projects and initiatives to improve model validation, refine project scope and align with industry and market priorities.
- Updating resource utilization and market potential estimates.

Supply Chain, Impact and Life Cycle Analysis

- Estimating current and future supply chain needs (e.g., critical materials, recycling potential), life cycle greenhouse gas emissions, air quality impacts, resource limitations (e.g., land and water requirements) and other social and environmental impacts associated with the deployment and market adoption of hydrogen and fuel cell technologies.
- Estimating market adoption impacts, including employment effects, revenue potential, and GDP.
- Providing a quantitative basis for a broad range of sustainability indicators across hydrogen and fuel cell technology supply chains and life cycles.

Systems Integration and Multisector Interactions

- Assessing technology and market opportunities to support electricity grid services, including ancillary services and long-duration energy storage.
- Improving characterizations of technology and market opportunities for hydrogen and fuel cells in industrial applications (steel, fertilizers, chemicals), liquid transportation fuels (biofuels and synfuels), and emerging transportation applications (rail, marine, aviation).
- Identifying opportunities to enable and optimize efficient utilization of resources across energy, transportation, and industrial sectors, as well as optimization for specific use cases such as industry clusters, ports, offroad vehicles, or microgrids.
- Identifying and characterizing synergies across applications and sectors, including advanced clean technologies and fuel pathways.

Market Assessment and Decision Analysis

- Estimating mid- and long-term market potential for fuel cell applications and hydrogen utilization across multiple sectors and market segments, including policy impacts (e.g., tax credits, demand side strategies to avoid stranded assets).
- Examining infrastructure investment decisions with respect to future market constraints, various financial metrics, technology path-dependencies, policies, and potential technology innovations.

Planning, Optimization, and Scenario Development

- Improving resource assessments and technology characterizations to include metrics for systems resilience and sustainability.

- Enhancing long-term models to account for multisector coupling opportunities and balance supply and demand trends using market feedback mechanisms.
- Developing and optimizing assessments for regional cluster developments, including colocating large-scale production with multiple end-use applications (e.g., ports, industrial clusters).
- Coordinating with federal and state agencies and the private sector to optimize investment decisions and leverage resources.

Comprehensive Approach

The Systems Analysis subprogram coordinates closely across HFTO, DOE, and interagency programs as well as external collaborators in the continued development and validation of tools, models, and analysis comprising an analytic portfolio suited to the challenges and opportunities facing hydrogen and fuel cell technologies. Examples of tools widely used by stakeholders include the GREET model, which has over 50,000 users spanning industry, regulatory bodies, and academia; the H2A Production Case Studies, which have costs and performance estimates for current and future hydrogen production technologies; HDSAM, which characterizes cost of hydrogen infrastructure, including fueling stations; and H2FAST, which characterizes financial performance of user-defined facilities.

These and other tools have become more sophisticated in scope and increasingly refined over time through empirical validation with RD&D advances, bench-scale and demonstration project results, and an increasing number of real-world commercial applications. As hydrogen and fuel cell technologies expand rapidly around the world, opportunities to validate and expand analysis tools will increase by incorporating additional technical characterizations, empirical data, and stakeholder feedback. This feedback process of empirical validation and capability refinement and expansion is illustrated in Figure 7.4, which includes examples of specific tools and models implemented in the different analytical categories in the portfolio pyramid as well as the feedback loop advancing all categories.

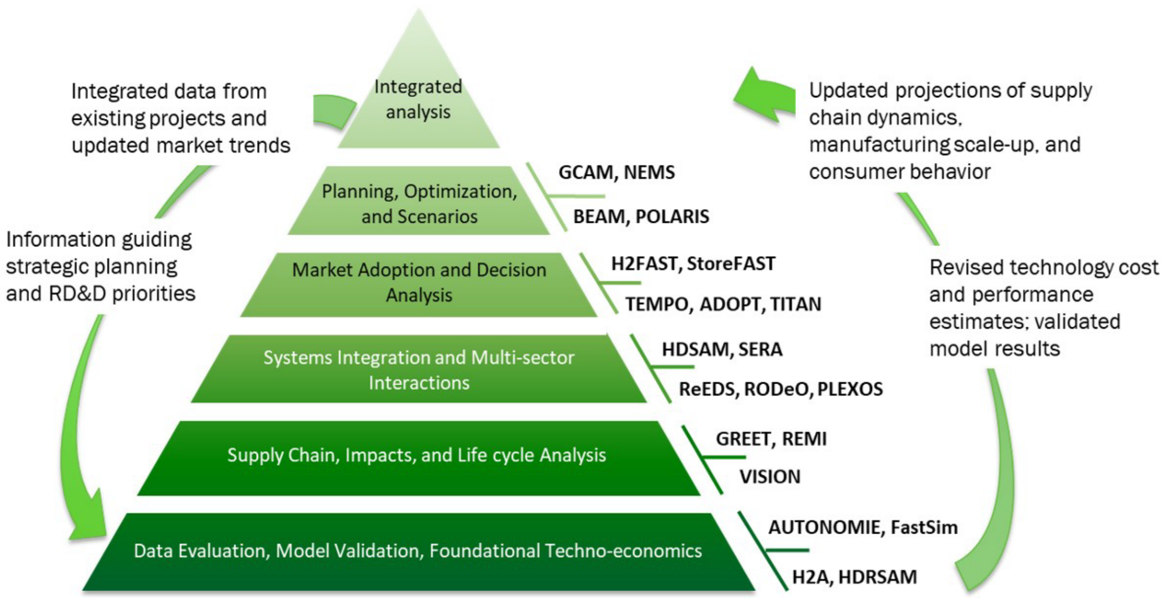

Figure 7.4. Process diagram of the Systems Analysis subprogram's comprehensive approach, including data inputs and exchanges with external activities and between models (see Table 7.1 for definition of acronyms)

Table 7.1 provides a more complete list of the tools and models in the Systems Analysis portfolio.

Table 7.1. Systems Analysis Capabilities and Tools

Model/Tool	Short Description
Scenario Evaluation and Regionalization Analysis Model (SERA)[87]	Designs cost-optimal hydrogen supply chain infrastructure for user-provided scenarios of hydrogen demand.
Global Change Analysis Model (GCAM)[88]	Energy system tool that simulates scenarios that can achieve national and global decarbonization goals. Model is used in international climate modeling, such as reports of the Intergovernmental Panel on Climate Change, and hydrogen representation is currently being expanded.
Hydrogen Financial Analysis Scenario Tool (H2FAST)	Simulates financial performance (e.g. cash flow, levelized cost) of user-defined systems, such as fueling stations, production facilities, infrastructure.

[87] National Renewable Energy Laboratory. "SERA: Scenario Evaluation and Regionalization Analysis Model." https://www.nrel.gov/hydrogen/sera-model.html.
[88] Joint Global Change Research Institute. "GCAM: The Global Change Analysis Model." Github. https://github.com/JGCRI/gcam-core.

Hydrogen Delivery Scenario Analysis Model (HDSAM)	Simulates cost and design of hydrogen infrastructure, including fueling stations, under user-defined scenarios of fleet size, utilization rate, region, etc.
Regional Energy Deployment System Model (ReEDS)	Simulates makeup of electricity grids under future scenarios of load and capacity expansion, technology cost, and policy drivers.
PLEXOS[89]	Simulates prices of electricity under future grid scenarios.
Revenue Operation and Device Optimization Model (RODeO)[90]	Price taker optimization model for the design and optimization of energy conversion and storage systems
Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET)	Simulates life cycle emissions of hundreds of fuel pathways, including hydrogen production, infrastructure, and use.
AUTONOMIE[91]	Simulates cost and performance of current and future vehicles, accounting for cross-sector technology improvements, such as in fuel cell cost, storage cost, and lightweighting.
Hydrogen Analysis (H2A)	Models cost of hydrogen production technologies based on bottom-up modeling of system design.
Future Automotive Systems Technology Simulator (FASTSim)[92]	Optimizes design of fuel cell, battery, and internal combustion engine vehicles based on consumer preferences and impacts of technology cost and performance on vehicles.
TEMPO	A consumer choice model that estimates shares of fuel cell electric vehicles, battery electric vehicles, and combustion engine vehicles in future scenarios of technology and fuel price.
National Energy Modeling System (NEMS)[93]	Projects future prices, production, and consumption of fuels. Used in EIA's Annual Energy Outlooks

Ongoing analysis projects are focused on informing real-world deployments, using long-standing expertise in hydrogen technologies to inform other offices (OCED, Office of Technology Transitions, etc.), and better quantifying the role of hydrogen technologies in a net-zero economy. Example objectives of these projects include:

[89] Energy Exemplar. "PLEXOS." https://www.energyexemplar.com/plexos.
[90] Eichman, Josh, Mariya Koleva, Omar J. Guerra, and Brady McLaughlin. 2020. *Optimizing an Integrated Renewable-Electrolysis System.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-75635. https://www.nrel.gov/docs/fy20osti/75635.pdf.
[91] Argonne National Laboratory. "Autonomie Vehicle System Simulation Tool." https://www.anl.gov/es/autonomie-vehicle-system-simulation-tool.
[92] National Renewable Energy Laboratory. "FASTSim: Future Automotive Systems Technology Simulator." https://www.nrel.gov/transportation/fastsim.html.
[93] U.S. Energy Information Administration. "Documentation of the National Energy Modeling System (NEMS) Modules." https://www.eia.gov/outlooks/aeo/nems/documentation/.

- Harmonizing methods of life cycle analysis and verification internationally, through partnerships such as with IPHE.
- Characterizing indirect impacts of hydrogen, including as an indirect greenhouse gas, emissions associated with component manufacturing, and impacts on the electricity grid.
- Developing criteria to assess sustainability, and environmental and environmental justice impacts of hydrogen deployments.
- Assessing cost and emissions of novel and emerging methods of hydrogen production and infrastructure (e.g. geologic hydrogen, methane pyrolysis).
- Enhancing hydrogen representation in market models, such as Pacific Northwest National Laboratory's Global Change Assessment Model (GCAM) or the National Energy Modeling System (NEMS), to ascertain the role of hydrogen relative to other decarbonization solutions.

As RDD&D projects progress, developments and improvements in hydrogen technologies and fuel cell systems are incorporated into the models, and new simulations help guide future HFTO RD&D activities. Likewise, data from demonstrations are incorporated into the models to allow for higher fidelity assessments and guidance for RD&D activities along with support and guidance for clean hydrogen and decarbonization activities.

Stakeholder Engagement and Collaboration

The Systems Analysis subprogram works closely on joint analysis projects, such as roadmap and strategy documents; updates to crosscutting tools, such as GREET; potential demand sectors for hydrogen; and cost and rollout of hydrogen production and infrastructure.

Systems Analysis works across EERE on studies and roadmaps to identify optimal pathways for decarbonizing industry, transportation, and the grid through clean fuels and electrification.

Systems Analysis also collaborates with other federal agencies and external organizations through formal partnerships, merit reviews, workshops, and listening sessions.

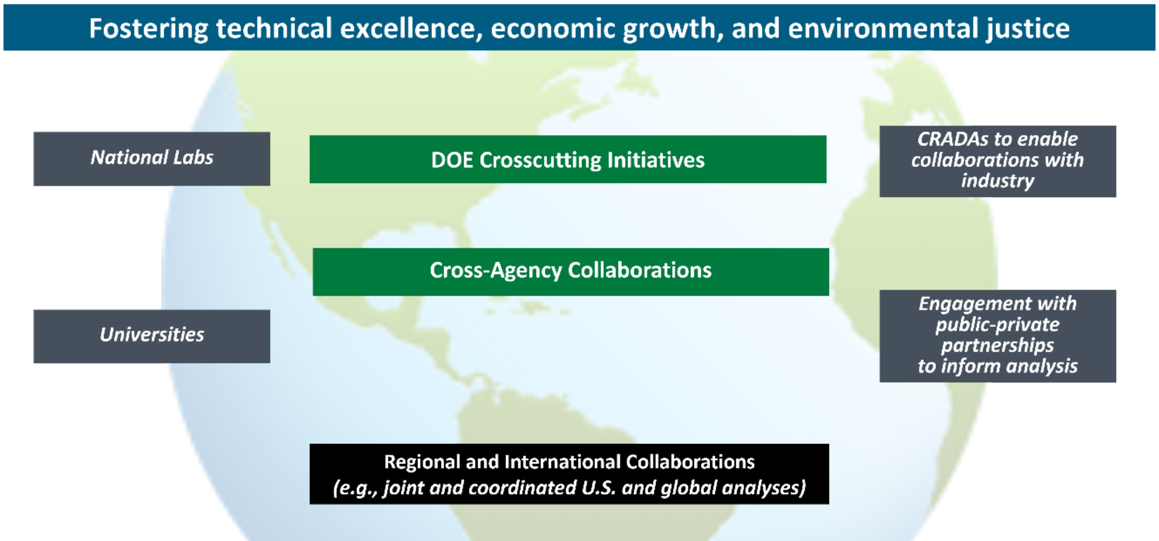

Figure 7.5. Systems Analysis collaboration network

Examples of recent and ongoing collaborations are shown in Figure 7.5. These include:

- The Analysis and Global Competitiveness working group being launched under the HIT. This working group will be led by DOE, the U.S. Environmental Protection Agency, and the Department of Commerce and will comprise representatives from across federal agencies. The working group will address priority crosscutting areas of analysis, such as sustainability and verification.
- Task forces within IPHE. The United States has co-led and supported activities within various IPHE working groups and task forces, including the Hydrogen Production Analysis and Certification task forces, which published two white papers documenting best practices associated with analysis of emissions associated with hydrogen production and infrastructure.[94,95]
- Interagency agreements, such as the one recently launched between DOE and the National Oceanic and Atmospheric Agency to evaluate the indirect global warming potential of hydrogen. This interagency agreement followed a workshop that was co-organized by the European Commission and the DOE to identify gaps in knowledge

[94] International Partnership for Hydrogen and Fuel Cells in the Economy. "Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen." October 2021. https://www.iphe.net/iphe-working-paper-methodology-doc-oct-2021.
[95] International Partnership for Hydrogen and Fuel Cells in the Economy. "Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen." July 2023. https://www.iphe.net/iphe-wp-methodology-doc-jul-2023.

associated with indirect impacts of hydrogen, and the capabilities of hydrogen sensor technologies.[96]

- The 21st Century Truck Partnership and U.S. DRIVE, two public-private partnerships between DOE and members of the transportation industry. These partnerships jointly execute analyses, such as the quadrennial cradle-to-grave analysis of emissions associated with fuel cell, battery, and combustion engine-based vehicles.[97]
- Listening sessions and opportunities for public comment on key strategic DOE documents, such as the *U.S. National Clean Hydrogen Strategy and Roadmap* and the *Clean Hydrogen Production Standard*.[98]

Internationally, the United States was co-lead with the IPHE to publish best practices associated with life cycle analysis of hydrogen production and the associated infrastructure. In association with the IPHE and the International Energy Agency, the United States supports the development of best practices associated with emissions verification. Examples of key Systems Analysis collaborations are depicted in Figure 7.5.

7.5 Subprogram Support

The Systems Analysis subprogram supports other HFTO subprograms through development and implementation of its tools and models. Examples are included in Table 7.2 below.

Table 7.2. Examples of Systems Analysis Support to Other HFTO Subprograms

Analysis Capability Type	Models and Analysis Methods	Main Subprograms Supported
Techno-Economic Assessment	• Hydrogen production case studies (H2A) • Hydrogen refueling station analysis (HDSAM) • Vehicle simulation (AUTONOMIE)	• HP • HI • MO, HI, FC, SDI
Supply Chain, Impacts and Life Cycle Analysis	• Life cycle analysis (GREET) • Resource analyses (estimates of technical potential, economical potential) • Manufacturing analysis (Design for Manufacturing and Assembly methods)	• MO • MO • HI, FC, HP, SDI

[96] Arrigoni, Alessandro, and Laura Bravo Diaz. 2022. *Hydrogen emissions from a hydrogen economy and their potential global warming impact*. EUR 31188 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-55848-4. https://publications.jrc.ec.europa.eu/repository/handle/JRC130362.
[97] Kelly, Jarod C., Amgad Elgowainy, Raphael Isaac, Jacob Ward, Ehsan Islam, Aymeric Rousseau, Ian Sutherland, et al. June 2022. *Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2020) and Future (2030-2035) Technologies*. Argonne National Laboratory. ANL-22/27. https://publications.anl.gov/anlpubs/2022/07/176270.pdf.
[98] U.S. Department of Energy. "Clean Hydrogen Production Standard Guidance." https://www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard.

Systems Integration and Multi-sector Interactions	• Hydrogen delivery scenario analysis (HDSAM) • Electricity grid integration and services (PLEXOS, ReEDS, RODeO) • Hydrogen infrastructure planning (SERA)	• HI • MO, SDI • MO, HI
Market Assessment and Decision Analysis	• Estimating future vehicle market share (TEMPO) • Financial and investment decision analysis (H2FAST)	• MO • MO
Planning, Optimization and Scenario Development	• Future market prices and production volumes (NEMS) • Optimal future decarbonization scenarios (GCAM)	• MO • MO
Program area acronyms: HP - Hydrogen Production, HI - Hydrogen Infrastructure Technologies, FC - Fuel Cells, SDI - Systems Development and Integration, MO - Multiple Offices and Subprograms		

Key deliverables and milestones that correspond to these modeling tools include:

- Life cycle analyses of hydrogen pathways, such as:
  - Near-term:
    - Improved interface to enable user-friendly assessments of emissions of user-defined hydrogen production, infrastructure, and end use pathways.
    - Representation of new hydrogen production pathways (e.g. pyrolysis, geologic hydrogen).
  - Mid-term:
    - Improved background assumptions, such as regional values of upstream methane emissions.
    - Representation of indirect greenhouse gas impacts of hydrogen, based on atmospheric modeling and experimentation completed by the National Oceanic and Atmospheric Administration.
- Improved representation of hydrogen in market models, such as:
  - Near-term:
    - Endogenous representation of hydrogen energy storage in state-of-the-art grid models, such as NREL's ReEDS model
    - Assessments of infrastructure requirements for heavy-duty vehicles.
  - Mid-term:

    - Simulation of industrial hydrogen end uses in global decarbonization models, such as GCAM.
    - Analysis of hydrogen cost and supply and demand potential given new policies enacted by the Inflation Reduction Act.
- Annual updates to standard hydrogen modeling resources, such as:
    - Updates to the Transportation Annual Technology Baseline website to reflect best available information regarding the cost and performance of hydrogen fuel cell vehicles.
    - Updates to H2A and HDSAM to reflect current and potential future costs of hydrogen production and infrastructure.

As real-world deployments and RD&D advance, the Systems Analysis portfolio will continuously adapt to ensure that projects are addressing priority knowledge gaps, conducted transparently, coordinated with other programs and offices, and using the best available information to inform underlying assumptions.