DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Fuel Pathway Integration Tech Team Roadmap

July 2017

This roadmap is a document of the U.S. DRIVE Partnership. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) is a voluntary, non‑binding, and non-legal partnership among the U.S. Department of Energy; USCAR, representing FCA US LLC, Ford Motor Company, and General Motors; five energy companies – BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US; two utilities – Southern California Edison and DTE Energy; and the Electric Power Research Institute (EPRI).

The Fuel Pathway Integration Tech Team is one of 13 U.S. DRIVE technical teams that work to accelerate the development of pre‑competitive and innovative technologies to enable a full range of efficient and clean advanced light‑duty vehicles, as well as related energy infrastructure.

For more information about U.S. DRIVE, please see the U.S. DRIVE Partnership Plan, at www.vehicles.energy.gov/about/partnerships/usdrive.html or www.uscar.org.

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Acknowledgements

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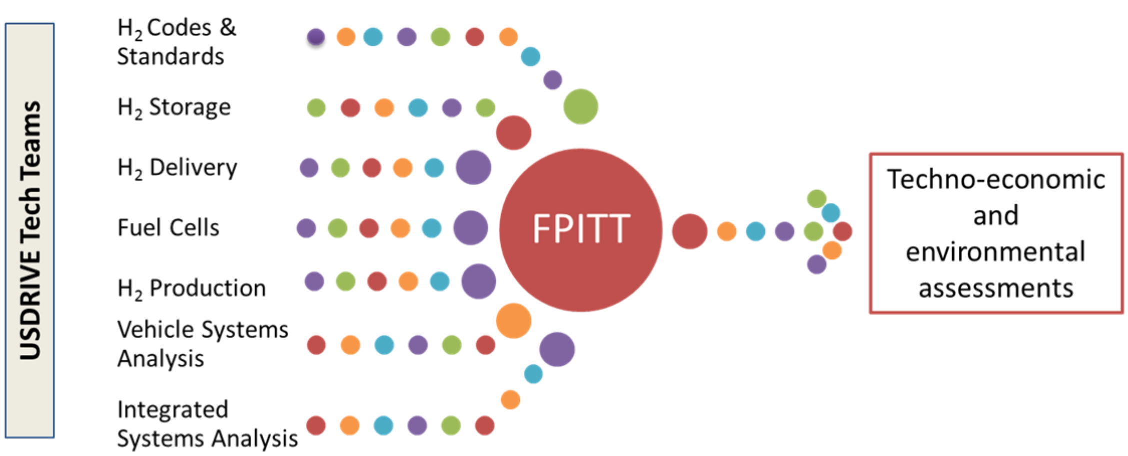
Team Mission and Scope

Mission: The Fuel Pathway Integration Tech Team (FPITT) supports the U.S. DRIVE Partnership (the Partnership) in the identification and evaluation of implementation scenarios for hydrogen and fuel cell electric vehicles (FCEVs) in the transportation sector, both during a transition period and in the long term.

Scope: The FPITT conducts assessments of hydrogen and fuel cell technology pathways, with particular focus on techno-economic and environmental evaluations of integrated hydrogen production, delivery, dispensing, and use pathways and comparison to other fuel pathways; identifies and bridges knowledge gaps that limit the ability to evaluate implementation scenarios for fuel cell technology pathways; identifies technical and institutional barriers to implementation of fuel cell technology pathways; and provides industry-based perspective on research and development (R&D) needs, targets, direction, and potential ramp-down for consideration by DOE in the management of the DOE Hydrogen and Fuel Cells Program.

The FPITT interacts across U.S. DRIVE technical teams to enable a common set of assumptions and parameters and the development of a consistent set of targets and analysis that can readily be used to evaluate integrated fuel pathways. U.S. DRIVE technical teams are pursuing multiple strategies for advancing hydrogen production, hydrogen delivery, hydrogen storage, and fuel cells. These teams have developed targets and identified barriers that require FPITT to connect their efforts with a holistic assessment of the fuel and vehicle pathways. The FPITT provides a key cross-functional connecting point between technical teams for assessing techno-economic and environmental benefits of integrated hydrogen production, delivery, dispensing, and use pathways and comparing to other fuel pathways.



The FPITT is aligned with the Partnership's goals, especially the second goal: *Enable reliable fuel cell electric vehicles with performance, safety, and costs comparable to or better than advanced conventional vehicle technologies,* *supported by viable hydrogen storage and the widespread availability of hydrogen fuel.*

This roadmap outlines an approach for achieving this mission.

Key Challenges to Technology Commercialization and/or Market Penetration

Hydrogen transportation fuel pathways will need to compete against an existing fuel infrastructure that is well understood, fully deployed, highly efficient, and highly accepted by consumers. Although certain aspects of potential hydrogen fuel pathways are understood, the interfaces between the technologies, costs, emissions, and operational requirements of complete hydrogen fuel pathways have not been fully assessed, and these technologies continue to evolve, therefore needing additional analysis, especially onboard hydrogen storage and infrastructure technologies. Furthermore, with the continual introduction of new vehicle technologies, the market conditions in which hydrogen fuel must compete are continually evolving. One of the most important technical challenges in implementing hydrogen as a transportation fuel, therefore, is estimating the costs, benefits, and risks of potential hydrogen fuel pathways.

Gaps and Barriers

The following gaps and barriers describe challenges faced in the analysis of hydrogen fuel pathways.

A. **Inconsistent Data, Assumptions, and Guidelines for Communicating Parameters and Results.** Putting the results and recommendations from one analysis in context with other analyses and the overall objectives of the Partnership is difficult, as many of the assumptions and much of the data in existing analyses are not explicitly documented. The problem is compounded by the limited availability of publicly available, reliable, up-to-date, real-world data on hydrogen and fuel cell technologies and deployment as well as a limited understanding of the uncertainty within the data.
B. **Stove-Piped/Siloed Analytical Capabilities.** Analytical capabilities and resources have been largely segmented, both functionally by technology (production, storage, fuel cells, etc.) and organizationally (laboratories, specialized teams, industry/academia, etc.). Successful systems analysis requires the integration of analysis resources across all facets of the issue, including vehicle and fuel facets.
C. **Lack of Cohesion between Temporal and Spatial Aspects of Analysis.** Analytical techniques available today are not yet rigorous and extensive enough to address concurrently the temporal and spatial characteristics inherent in utilizing fuel cells and hydrogen fuel, limiting the ability to satisfactorily assess both transition and end-state issues.

D. **Limited Understanding of Technological Progress and Technology Adoption and Learning Curves.** In the early stages of adoption, technologies exhibit high costs and highly variable performance. As dominant designs emerge, and as manufacturing volumes increase, costs decrease.
E. **Limited Understanding of Market Behavior for Hydrogen as a Transportation Energy Alternative.** Understanding the behavior and motivations of potential fuel cell users is necessary to determine how the markets will respond in the long-term to fuel cell and hydrogen products. Market pull and the factors affecting it are important to setting targets and recognizing business-case barriers. In addition, the behavior in initial markets (i.e., of early adopters) is likely to be different than that of the mainstream markets (i.e., of average, pragmatic consumers and late-adopters), so multiple timeframes and penetration levels need to be considered.
F. **Uncertainty Regarding Technologies, Markets, and Infrastructure Evolution.** As the technologies across the entire hydrogen and fuel cell supply chains evolve, market conditions, market interactions, infrastructure needs, and the extant infrastructure also evolve, resulting in high levels of uncertainty in analyses of future technology deployments. Potential interactions between hydrogen fuel and onboard equipment such as fuel storage devices and fuel cells depend on the technologies to be deployed. Since the technologies continue to evolve, these interactions are difficult to predict and model. Further, external factors such as fuel costs and natural gas supply, as well as consumer response to FCEVs and competing vehicle technologies, are intrinsic to the regional selection of hydrogen transportation fuel pathways for implementation. These factors are non-deterministic and present modeling challenges as the correctness of the underlying model assumptions can only be determined over time.

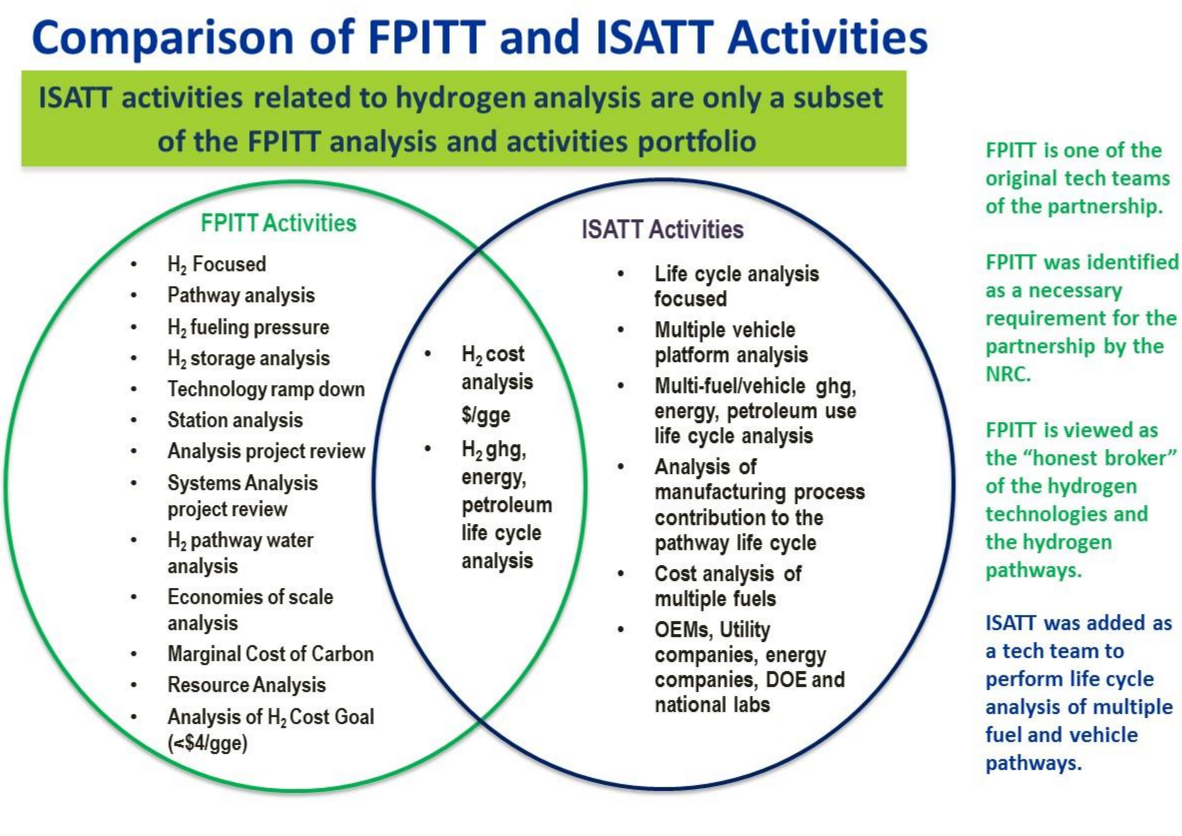
Strategy to Overcome Barriers and Achieve Goals

The FPITT provides critical industry feedback to the DOE Fuel Cell Technologies Office Systems Analysis on activities that are aligned with the barriers and challenges listed above. It also coordinates closely with the technology-focused U.S. DRIVE technical teams to ensure that their projects employ a consistent set of assumptions and that R&D focuses on pathways and solutions that are practical and realistic. The following interactions between the FPITT and other technical teams are examples of ways that the FPITT ensures integration across the Partnership's roadmaps.

- Dialogue with the Hydrogen Production, Hydrogen Delivery, and Hydrogen Storage Tech Teams, as well as the Fuel Cells Tech Team, to establish requirements for technologies needed to meet the pathway-independent hydrogen R&D cost target.
- Integration with Vehicle Systems Analysis Tech Team to assess well-to-wheels (WTW) fuel-cycle implications of hydrogen pathways and compare

them to the WTW and lifecycle Cradle-to-Grave performance of evolving internal combustion engine and hybrid electric systems.

- Coordination with the Hydrogen Production, Hydrogen Delivery, Hydrogen Storage, and Codes & Standards Tech Teams, as well as the Fuel Cells Tech Team, to identify, bridge, and communicate analysis and knowledge gaps and resulting suggestions for R&D and analysis directions.
- Integration with Vehicle Systems Analysis Tech Team to assess vehicle cycle analysis and knowledge gaps and to ensure transparency in vehicle cycle analyses.
- Discussion of R&D off-ramping criteria with the Hydrogen Production, Hydrogen Delivery, Hydrogen Storage, and Fuel Cell Tech Teams
- Coordination with the Hydrogen Storage, Hydrogen Delivery, and Vehicle Systems Analysis Tech Teams in the investigation of the optimum hydrogen working pressure for hydrogen powered fuel cell vehicles.
- Communication of the hydrogen R&D cost target developed by the DOE Fuel Cell Technologies Office to the Hydrogen Production, Hydrogen Delivery, Hydrogen Storage, and Fuel Cell Tech Teams for evaluation of their feasibility and comparison with “bottom up” goals.
- Leadership of a working group involving all hydrogen fuel technical teams to assess interactions between potential advanced onboard hydrogen storage options and hydrogen refueling infrastructure.
- Coordination with the Integrated Systems Analysis Tech Team through cross-membership, ensuring consistency of assumptions and multi-stakeholder assessment of calculations and results.



The following sections outline strategies for achieving the goals of the Fuel Pathway Integration Tech Team.

Section 1: Analyze hydrogen fuel pathways

Goal: Conduct and review system-level analyses of hydrogen fuel pathways from production to end use and compare to other fuel pathways.

Objectives:

- **Identify and, where possible, quantify the challenges associated with using a pathway on a large scale, e.g., cost, primary energy input, land and water use, other infrastructures, scalability, and WTW fuel-cycle emissions.**

  Hydrogen production, delivery, dispensing, onboard storage, and use pathways will have economic, feedstock, supply, emissions, utility, land, and infrastructure issues that must be addressed and quantified. As the pathways are evaluated, these attributes will require definition to understand supply, peripheral infrastructure, and environmental impacts. These elements may increase the capital cost, impact timing, and require detailed technical and environmental assessment.

- **Identify related technologies not addressed in the Partnership's research goals that will be needed to successfully implement pathways.**

  Related requirements will be identified as part of the evaluation of pathways and pathway technologies. This will enable related issues such as specific emissions and utility components to be identified and quantified. Based on the results of this assessment, the FPITT will identify any additional research and/or analysis projects that should be explored and developed by the responsible DOE program or other entity to provide the technical solutions for the identified issue.

- **Conduct periodic assessments and updates for selected pathways.**

The issues associated with a pathway technology will be assessed periodically based on technology evolution or changes in external factors. The evaluation will provide direction to the Partnership on component research in a given pathway.

Section 2: Develop strategies and priorities for hydrogen fuel pathways

Goal: Identify and bridge knowledge gaps that limit the ability to evaluate implementation scenarios for fuel cell technology pathways.

Objectives:

- **Review the DOE portfolio of non-policy related hydrogen analysis programs to identify current pathway analysis capabilities.**

  In order to adequately provide hydrogen pathway analysis input to the Partnership, the DOE analysis portfolio needs to be periodically reviewed. Gaps in analysis capabilities will be identified, and observations on the breadth and depth of existing analyses will be developed. In addition, the ongoing analysis tasks that need to be modified to better integrate with other DOE analysis tasks will be identified.

- **Identify and prioritize pathway analysis needs for long term and transitional analysis.**

  Upon the completion of any analysis portfolio review, gaps in analysis capabilities will be identified. These gaps will need to be prioritized with regards to analyses focusing on the long-term hydrogen transportation scenarios, along with analyses for transitional hydrogen transportation scenarios. The prioritization of these gaps will be used to plan future analysis activities.

- **Survey available literature and institutional knowledge of the U.S. DRIVE partners to identify knowledge gaps that limit the ability to evaluate hydrogen production, delivery, dispensing, onboard storage, and use pathways.**

  The credibility of analytical efforts undertaken within the Partnership can be challenged when the assumptions are not transparent, well documented, and well supported. One objective of the FPITT, therefore, is to identify assumptions in Partnership-related analyses that require additional research or documentation, and to determine appropriate methods to fulfill the analytical needs. For some knowledge gaps, existing literature may provide needed information. For others, uncertainties may be addressed through risk analysis and sensitivity studies.

- **In coordination with other technical teams, suggest R&D directions to address knowledge gaps.**

  Some knowledge gaps can be addressed through R&D projects funded by DOE or the industrial partners. Where appropriate, and in coordination with other relevant technical teams, the FPITT may provide input and recommendations for use by the Partnership on the direction of R&D programs to address knowledge gaps.

- **Communicate gaps and R&D suggestions to the relevant U.S. DRIVE operations groups.**

  Decisions regarding R&D and analysis directions within the Partnership are made by various operations groups. The FPITT will communicate analysis results, gaps, and suggestions for future R&D directions to these groups to inform decision-making.

- **On an ongoing basis, review and provide feedback for consideration in DOE-funded analysis projects to ensure the consistency and transparency of analysis parameters and results.**

  DOE's Hydrogen and Fuel Cells Program develops standard and consistent analysis data, assumptions, guidelines, and scenarios for hydrogen transportation fuel implementation. The FPITT will provide feedback to selected efforts to ensure that they enable analysis of complete pathways and achieve transparency of analysis activities.

Section 3: Accelerate hydrogen and fuel cell implementation

Goal: Identify technical and institutional barriers to implementation of fuel cell technology pathways.

Objectives:

- **Assess the impacts of technology advancement, refueling pressure optimization, learning curves, and station duplication on the costs of hydrogen fueling stations.**

  It is expected that high-volume manufacturing of station components, design standardization, and learning rates will significantly reduce hydrogen fueling station costs, but these impacts are not well understood. The FPITT will estimate potential hydrogen cost reductions possible through dispensing technology advancement, fueling pressure optimization, station installation learning curves, integration of the hydrogen value chain from production through onboard storage, and station duplication.

- **Identify the resource requirements, including water, land, and feedstock requirements, for fuel cell technology implementation pathways, as well as resource limitations on both a national and regional level.**

Fuel cell technology implementation pathways require adequate long-term supply of various resources, for which other industrial, commercial, and residential activities also compete. The requirements change as technologies advance, specific pathways are selected and implemented, and the costs of various resources change in relation to each other. Resource limitations may arise due to supply challenges, contamination, environmental factors, cost escalation (e.g., from demand increases or resource depletion), or any of a variety of other issues. The FPITT will identify both the resource requirements and potential limitations of fuel cell technology implementation pathways and will incorporate this information into its analysis as appropriate.

- **Determine infrastructure requirements and potential infrastructure-related limitations, on both a national and regional level, for fuel cell technology implementation pathways.**

  Infrastructure elements for fuel cell technology implementation scenarios include roads, railways, barges, pipelines, the electrical grid, and others to deliver feedstocks, process components, fuels, and hydrogen and fuel cell products. Individual installations have specific requirements for gas lines, electrical transmission and distribution, and water quality. Some elements of fuel cell technology implementation scenarios require manufacture of unique infrastructure components; inadequate supply of these components can limit the viability or timeliness of implementing particular pathways. The availability and cost of various infrastructure components and systems needed for fuel cell technology implementation will be studied, and insights gained will be used in FPITT analysis as appropriate.

Section 4: Facilitate alignment of hydrogen R&D cost and subsystem cost and performance targets

Goal: Promote consistency between goals, analysis, and modeling efforts of various technical teams of the U.S. DRIVE Partnership to ensure consistent overall targets and effective use of resources.

Objectives:

- **Provide input to the Partnership on setting and updating goals for full pathways and pathway subsystems.**

  Goals aimed at enabling commercialization must ensure that the resulting pathways are at least economically equivalent to competing technologies expected to be available. The DOE hydrogen R&D cost target is based on anticipated future market conditions and is pathway independent. It is expressed in dollars per gasoline gallon equivalent, untaxed at the pump. The hydrogen R&D cost target is periodically reassessed in light of changes in vehicle system energy efficiency characteristics, competitive technologies, and gasoline price projections. The target is only changed when a cost review determines that the likelihood and magnitude of the changes require an update of the target.

- **Assess pathway subsystem goals for consistency with the high-level goal and identify subsystems that should be the primary focus of R&D. Provide the results of that analysis to the Hydrogen Production, Hydrogen Delivery, and Hydrogen Storage Tech Teams as input to their goal setting processes.**

  Operating from the high-level, pathway-independent hydrogen R&D cost target, individual pathways must be sub-divided into subsystems. The development of subsystem goals will consider the contribution of the subsystem within and across pathways. An integrated hydrogen fuel pathway will include some or all of the following subsystems depending on location of the production facility:

  - Feedstock
  - Production: Processes that convert an energy source to hydrogen
  - Delivery
    - Purification
    - Production storage: For central production processes, storage necessary to ensure uninterrupted flow of hydrogen to the distribution system
    - Distribution preparation: Process for preparing hydrogen from the production process and/or storage for introduction to the distribution system, e.g., compression, liquefaction, charging solid carrier
    - Terminals: Facilities that buffer capacity between production and retail and have the capability to change the state of the hydrogen (e.g., liquid-to-gas, liquid-to-solid)
    - Distribution: Facilities used to transport hydrogen between production, terminals, and retail locations (e.g., pipeline, compressed gas tank truck, liquid tank truck)
  - Ground (supply) storage: Storage capacity needed at the retail site to handle peak demand periods and ensure an uninterrupted flow of hydrogen to consumers
  - Compression: Includes vaporization and compression if needed to interface between ground/supply storage and the vehicle
  - Dispensing: Facilities needed to transfer hydrogen from ground/supply storage to vehicle tanks
  - Onboard storage: Tanks or advanced hydrogen storage technologies interface with dispensing facilities and enable the vehicle driving range demanded by consumers

- **Ensure consistency between pathways.**

  The establishment of consistent goals requires commonality in the bases and assumptions used to develop subsystem goals. All central plant cases will be evaluated on a common scale, as will all distributed production cases; furthermore, the central plant and distributed cases will be based on a common scenario to the extent possible.

- **Identify pinch points.**

  Barriers that make attainment of a subsystem goal difficult will be identified, including possible mitigation via trade-offs with other goals.