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Inventory and Gap Analysis of Federally Funded Research and Development Activities

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Abstract

Technologies for hydrogen as an energy carrier and fuel have been funded by the U.S. government since the oil embargo of the early 1970's. Hydrogen's potential lies in its ability to serve as an energy carrier that can be consumed at the point of use with little or no pollution. It is not a primary energy source, rather an energy storage medium. When we speak of hydrogen, we are talking about its production, storage, and utilization. It can be produced from renewable or fossil resources. It can be used as a storage medium for intermittent and seasonal renewable technologies and plays an important role in the decarbonization of fossil fuels. It is a fuel for vehicles and propellant for space missions and weaponry. It is used for upgrading chemicals and in many metallurgical processes. The term "Hydrogen R&D" encompasses a broad scope of technologies. The maturity of technologies range from advanced defense and chemical industry applications to fundamental studies of hydrogen-producing microorganisms.

Introduction

Conducting an inventory of federal hydrogen research and development is important for understanding the status of technology development, minimizing duplication of effort and identifying gaps in the federal portfolio. Much effort has been invested in developing future energy scenarios and roadmaps that identify efforts needed to position us to meet future energy requirements. With today's strained R&D budgets, leveraging every available dollar becomes that much more important. Thus, the available interagency portfolio must be well understood and this information used when planning priorities for the coming years.

Methodology

A tiered categorization (taxonomy) is used to summarize those technologies that have been identified as necessary and/or applicable for realizing a hydrogen future. The taxonomy includes a broad range of near-, mid- and long-term technologies that fall under the heading of analysis, production, purification, storage, utilization or infrastructure and was developed in cooperation with the U.S. DOE and its Hydrogen Technical Advisory Panel (HTAP). The taxonomy is a living document that is updated as needs are identified and new technologies emerge. The first three tier levels of the taxonomy are shown in the Appendix.

The Rand Corporation developed (for the Office of Science and Technology Policy) a comprehensive annual database of the ongoing research and development projects sponsored by the twenty-four federal agencies. This Research and Development in the United States (RaDiUS) database compiles information about the efforts of the twenty-seven federal agencies at the project level. Additional database resources include the USDA Current Research Information Search (CRIS) and the DOE Office of Energy Bioscience. These three databases were searched for all research efforts related to hydrogen energy. The taxonomy was used for developing the search criteria. The results of these searches were merged into a single database.

Fiscal year 1999 was selected as the funding year for the inventory, since this was the most recent funding year for which the database information was fairly complete. Even then, there were several records that did not contain FY99 funding information. For these projects, estimates were made based on the period of performance, total project funding and average annual funding. For the DOE, available documentation, including the DOE Office of Power Technologies' Hydrogen Program and NREL Annual Operating Plans, was used to validate project and funding information.

No funding information was available for the DOD and NASA (through the RaDiUS database or other easily accessible resources). This information will need to be obtained from the performer contacts on a project-by-project basis. Thus, DOD and NASA information only rolls up into the project counts for the inventory (they are excluded from the funding analyses).

Results

All records were reviewed and identified as directly related to hydrogen R&D or relevant to the development of hydrogen technologies. The records were then binned by technology area. Up to four tier levels were used to bin the individual records. Seven federal agencies were identified as providing support for hydrogen R&D projects: Department of Commerce (DOC), Department of Defense (DOD), Department of Energy (DOE), Department of Transportation (DOT), National Aeronautics and Space Administration (NASA), National Science Foundation (NSF) and the U.S. Department of Agriculture (USDA). These agencies combined to fund a total of 426 projects that were identified as directly related (345) or relevant (81) to hydrogen energy R&D. Figure 1 shows the percentages of direct hydrogen projects by agency. The DOE accounted for more than two-thirds of the total funded projects. NSF provided the second greatest number of projects at 12.5%. DOD and NASA contributed similar numbers of projects, accounting for 8.4% and 7.6% of the total federal portfolio, respectively. The remaining agencies account for less the 3% of the total portfolio. By technology area (Figure 3), utilization and production dominate at 39.7% and 26.4%, respectively. Storage and infrastructure are next at around 10% each.

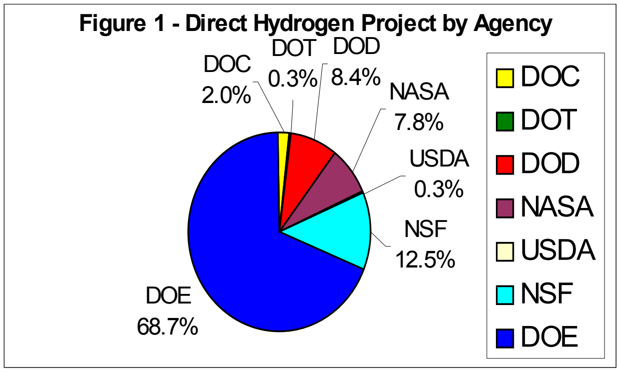
Figure 1 - Direct Hydrogen Project by Agency

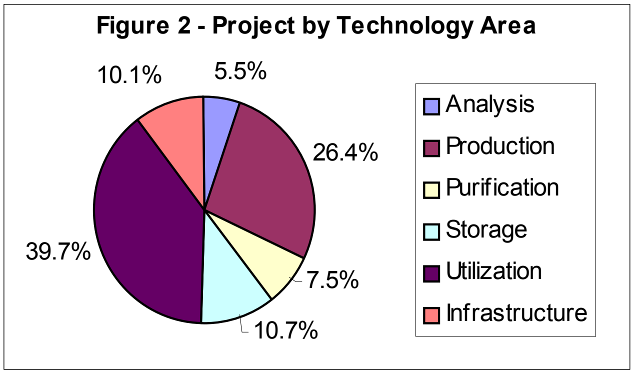
Figure 2 - Project by Technology Area

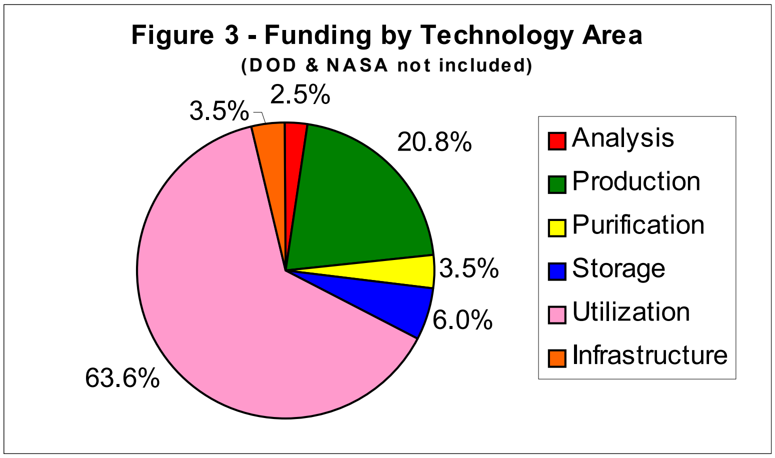
Figure 3 - Funding by Technology Area
(DOD & NASA not included)

The non-DOD or NASA projects accounted for $120 million directed towards hydrogen R&D. An additional $8.9 million supported technologies relevant to hydrogen. The DOE provided nearly 90% of the total funding. The DOT and USDA accounted for less than 0.5% of the total funding, with the remainder nearly evenly split between the DOC and NSF. Nearly two-thirds of the total funding was directed towards utilization technologies, primarily fuel cell development (see Figure 3). Production was the next most supported research area. This trend is very closely mirrored within the DOE, which directed nearly $70 million towards utilization technologies, compared to $25 million for production and less than $5 million each for the remaining areas. As would be expected, the DOC effort was also primarily directed towards utilization technologies. The NSF had a fairly balanced portfolio across all areas, although none received more than $2.5 million.

Analysis

Analysis projects included development of cost models, technoeconomic assessments of technologies, and evaluation and optimization of integrated hydrogen systems. Feasibility studies and development of business plans for integrated hydrogen energy systems were also included in this area. The DOE is the primary funding source for analysis projects, with nearly $3 million of effort. The NSF sponsored a small project ($30K), for the conceptual design phase of a "sustainable homestead." In all, 19 projects were directed towards analysis of hydrogen technologies/systems.

Production

Production routes are divided into four categories: Biological, Chemical, Electrochemical, and Thermal. Of the 91 direct production projects, 24 were biological, 4 chemical, 11 electrochemical and 49 thermal. The thermal routes include both renewable and fossil technologies. The DOD had 2 thermal production projects, one on supercritical water gasification of toxic wastes, the other on plasma reforming. The DOD also had several semiconductor development projects that were identified as relevant to electrochemical hydrogen production. The NSF supported 11 production projects, 5 biological, 5 thermal and 1 chemical (photochemical). Both fermentative and photobiological routes were included. The thermal routes included biomass and fossil gasification, pyrolysis of diesel fuels and reforming technologies. The DOE supported a total of 78 production projects: 19 biological, 3 chemical, 11 electrochemical and 42 thermal. The biological projects included 4 fermentation projects, 13 photobiological studies and 1 bioreactor development. The chemical projects were all photocatalytic work. All four electrochemical routes were supported, with photoelectrochemical and halide electrolysis receiving the greatest support. A total of 13 biomass and fossil gasification projects were supported. Membrane and reforming technologies were included in 9 projects each. Pyrolysis (5), solar thermal (2) and partial oxidation (1) accounted for the remaining projects. Overall, very little work is being done on chemical production routes. Likewise, there was only one partial oxidation project. Hydrogen production by photobiological organisms received a great deal of support, as did hydrogenase-based fermentation. However, there was only a single project dedicated to bioreactor development. Gasification and reforming received the greatest amount of support for the thermal routes, with 14 and 9 projects, respectively.

On a funding basis, thermal technologies received, by far, the greatest amount of support, with more than $18 million, of which gasification received nearly half (see Figure 4). Biological routes received the next greatest level of support with $3.5 million, $2.7 million of which went towards photobiological studies. Again, funding information for the DOD was not available. Total production funding for the NSF and DOE was $1.6 and $23.3 million, respectively.

An additional 25 projects, for a total of $3 million, were found to be relevant to hydrogen production. 15 of these ($2.4 million) involved genetic modification of microorganisms. These projects generally concerned modification of the photosynthetic pathways of the microorganisms, but were not necessarily specific to the production of hydrogen. Other relevant technologies include gas filtration technologies for gasification processes, development of semiconductor materials for electrolytic devices, and on-line thermal process monitoring.

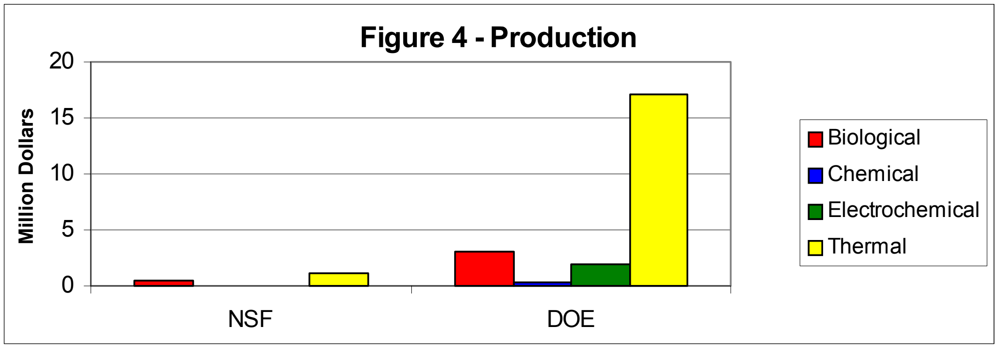
Figure 4 - Production

Purification

Twenty-six projects and a total of $4.1 million were directed by three agencies (DOC, NSF and DOE) towards developing purification technologies. Of this, no effort went towards improving the commercially-available absorbent-based technologies, nor in developing new technologies that utilize absorbent materials. One adsorbent project was funded for $18 K. The remaining went to membrane technologies. Half of the membrane projects and funding went towards ceramic materials. There were an additional 5 metallic membrane projects and 1 polymer membrane project. Funding was split fairly equally between these two technologies. An additional NSF membrane project ($72K) on zeolite adsorbants was identified that was relevant for hydrogen purification.

Storage

Storage is an area that receives a great deal of attention. It is considered to be one of the main limits for implementation of hydrogen technologies, particularly for mobile applications. The DOC, DOD, NSF and DOE all support the development of storage technologies. The DOC focused their efforts on metal hydrides. The DOD divided their efforts between absorbents, both chemical and metal hydrides; adsorbents, carbon nanotubes; and cryogenic storage, slush hydrogen. The NSF sponsored projects on metal hydrides, carbon nanotubes and zeolites. The broadest scope of projects came from the DOE with efforts in both chemical and metal hydrides, fullerines, carbon nanotubes, compressors, conformable and composite tanks, cryopressurized storage and cryogenic vessels. More than $2 million dollars went to support the single DOC metal hydride project. This is nearly 30% of the total storage funding. NSF projects received an average of $92K each for a total of $825K. The DOE sponsored $4.3 million dollars of storage work, which results in a project average of just under $230K.

An additional 14 projects were found that were relevant to hydrogen storage. Half of these focused on metal hydride material studies. DOD also sponsored a few projects on cryogenic hydrogen that were considered relevant to storage. In all, these projects accounted for just over $1 million (not including the DOD project).

Utilization

The largest area for support was Utilization, with a total of 137 projects and $76.3 million. With the exception of NASA, fuel cell development received the greatest amount of support by agency for a total of $75.1 million. Nearly 90% of the total fuel cell funding support came from the DOE (excluding DOD and NASA for which funding information was not available). As would be expected, NASA's greatest area of emphasis was their combustion-based space propulsion technologies, although they also supported fuel cell development. DOE was the only other agency that sponsored combustion engine development.

No projects were found directed towards development of alkaline fuel cells. Molten carbonate, PEM and solid oxide fuel cells were fairly equally supported at $27, $24 and $22 million, respectively. On a total number of projects basis, PEM fuel cells lead the way with 62 projects. Solid oxide is the next closest with 27, followed by molten carbonate at 9. There were 3 reversible fuel cell projects (2 NASA, 1 DOT) and 2 phosphoric acid projects (DOE). [The 2 phosphoric acid projects appeared to be close-out projects and, although they were active during FY99, they did not receive FY99 funding.] There were also several projects directed towards supporting fuel cell technologies, including material development and fuel processors.

An additional 33 projects and $4.2 million were found that were relevant to hydrogen utilization. Direct methanol fuel cells made up the majority of these efforts. Other efforts include military applications (explosive devices), emission control and material studies.

Infrastructure

Infrastructure development will be essential for the deployment of hydrogen technologies. This is especially true for mobile applications. Both DOD and NASA sponsor projects on hydrogen safety. Projects cover leak detection, detonation modeling and material integrity. The NSF also supported hydrogen safety work, including detection and modeling and a case study of HBr contributions to ozone depletion. As with the other agencies, safety was the subject of the largest number of projects for the DOE. Projects covered codes and standards, sensors and modeling. Education (interface) was a close second. Projects on hydride slurry transport, refueler development and policy were also supported.

A total of $4.2 million was spent by NSF and DOE on infrastructure development. Refueling received the greatest amount of funding support, with an average of around $0.9 million per project. Safety received the next greatest amount of funding with a total of $1.2 million, or an average of $100K per project. DOE's hydride slurry transport projects average $200K a piece for a total of $600K. The six education projects totaled just over $400K.

The only transport efforts sponsored by the agencies were hydride slurries. No testing and certification work was identified. Only one case study project was found for safety. For refueling, there were only the two projects sponsored by the DOE. There were no projects on interface standardization, nor on robotics. There was only one policy project and that was support for HTAP.

Eight projects and an additional $430K were identified that were relevant to infrastructure development. This includes sensor control software, ballistic material embrittlement, modeling and nuclear safety.

Summary

Of the seven agencies that supported hydrogen R&D during FY99, the DOE was the primary non-defense funding source. The DOE's portfolio covered a broad- and fairly-balanced range of technologies. The greatest emphasis was placed on utilization technologies, primarily fuel cells. Production was another area that received a great deal of support. Little work was on-going in the area of purification.

The importance of storage for implementing hydrogen technologies suggests a strong development effort is required in this area. Compared to the single DOC metal hydride project, other agencies only provided moderate funding support to their storage projects. For FY99 the emphasis was primarily directed towards metal hydrides. Most of these materials have not yet shown storage capacities suitable for on-board applications. Thus, the broad portfolio of storage technologies is appropriate.

Infrastructure is another enabling area that requires significant emphasis. FY99 efforts were primarily directed towards safety. Although transport of hydrogen is commercially practiced, the existing infrastructure may not be suited to mobile applications. Transportation costs may also restrict segregated production and utilization. Testing and certification is an area that did not receive much attention. As utilization technologies become commercially ready, the testing and certification gap may become significant. Standardization and robotics are other areas for which no effort was being undertaken. For mobile applications in particular, this may inhibit public acceptance and practicality.

On the production side, a lot of effort was put into biological production routes. However, bioreactor development may be a gap for realizing the potential of these technologies. The portfolio was almost evenly distributed between fossil, biomass and direct renewable based production routes.

Still missing from the portfolio are state and local government activities. Many of these involve partnerships for the deployment of fuel cell vehicles. Funding information from the DOD and NASA is also not yet included. Finally, to truly evaluate the hydrogen R&D portfolio, the international picture must be understood, including the private sector investment.

In conclusion, hydrogen energy represents a broad cross-cutting group of technologies that are supported by several federal agencies in the U.S. Effective coordination through information exchange, facilitation of technology transfer, development of national and international collaborations and leveraging of resources can accelerate the path towards a hydrogen future. This coordination is currently hindered by a lack of shared knowledge of hydrogen energy-related R&D programs at both the federal and state/local levels.

Appendix - Hydrogen Taxomony

- Hydrogen R&D
  - Analysis
  - Carbon Separation and Storage
  - Production
    - Biological
      - Fermentation
      - Anaerobic Digestion
      - Photobiological
      - Bioreactors
    - Chemical
      - Photochemical
      - Photocatalytic
    - Electrochemical
      - Water Electrolysis
      - Photoelectrochemical
      - Halide Electrolysis
      - H2S Electrolysis
    - Thermal
      - Gasification
      - Membrane Reactors
      - Partial Oxidation
      - Pyrolysis
      - Reforming
      - Solar Thermal
      - Thermal Cracking
  - Purification
    - Absorbents
      - MEA
      - DEA
      - MDEA
      - Selexol
      - Scrubbers
    - Adsorbents
      - Pressure Swing
      - Temperature Swing
    - Membranes
      - Ceramic
      - Ion Transport
      - Metallic
      - Polymer
  - Storage
    - Absorbents
      - Alanates
      - Chemical Hydrides
      - Metal Hydrides
      - Iron Sponge
    - Adsorbents
      - Activated Carbon
      - Aerogels
      - Graphite Fibers
      - Fullerines
      - Nanotubes
    - Compressed
      - Bulk
      - Compressors
      - Microspheres
      - Tanks
      - Zeolites
    - Cryogenic
      - Cryopressurized
      - Liquefaction
      - Slush
      - Storage Vessels
  - Utilization
    - Combustion Engines
      - Diesel
      - ICE
      - Stirling
      - Space Propulsion
    - Fuel Cells
      - Alkaline
      - Molton Carbonate
      - PEM
      - Phosphoric Acid
      - Reversible
      - Solid Oxide
    - Industrial
      - Annealing
      - Brazing
      - Casting
      - Hydrogenation
      - Reduction
  - Infrastructure
    - Transport/Delivery
      - On-road
      - Pipeline
      - Slurries
    - Safety
      - Case Studies
      - Codes and Standards
      - Detection
      - Materials
      - Modeling
    - Refueling
      - Personal Appliance
      - Centralized Station
      - Liquid Refuelers
    - Testing/Certification
      - Vessel Integrity
      - Lifetime
      - Maintenance
    - Customer Interface
      - Education
      - Standardization
      - Robotics
    - Policy/Regulation