U.S. DEPARTMENT OF ENERGY

2006 Annual DOE Hydrogen Program Merit Review

Hydrogen Storage

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Hydrogen Storage: The "Grand Challenge"

On-board hydrogen storage to meet all performance (wt, vol, kinetics, etc.) , safety and cost requirements and enable a more than 300 mile driving range.

These Are System Targets

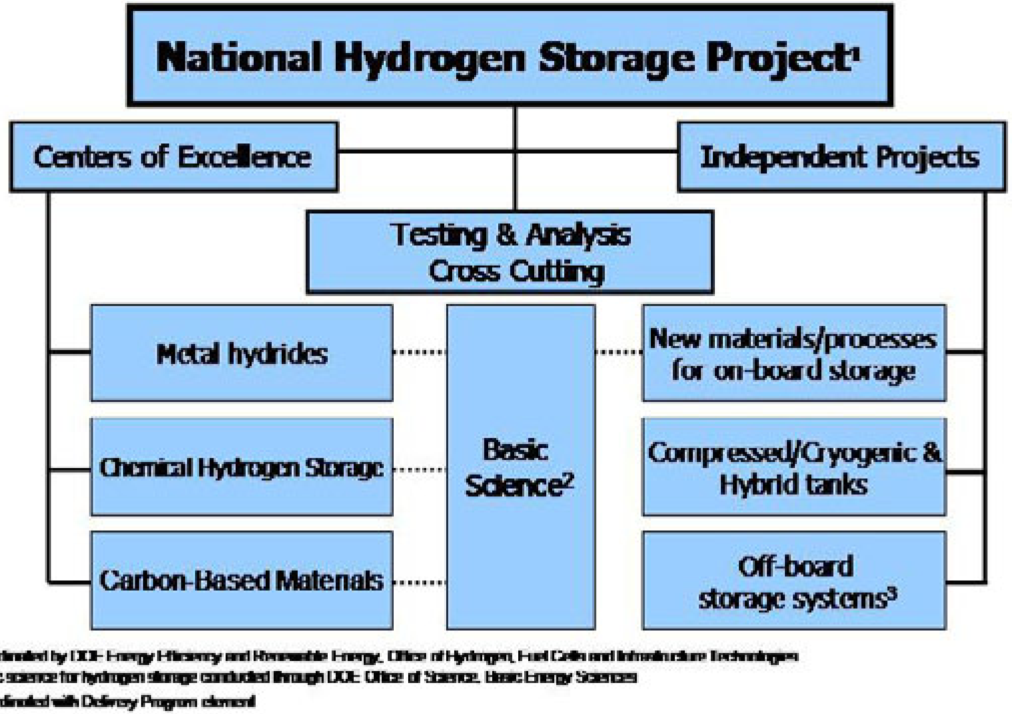
Material capacities must be higher!

Targets	2010	2015
System Gravimetric Capacity (net)= "specific energy"	6 wt.% (7.2 MJ/kg) (2.0 kWh/kg)	9 wt.% (10.8 MJ/kg) (3.0 kWh/kg)
System Volumetric Capacity (net)= "energy density"	1.5 kWh/L (5.4 MJ/L) (45 g/L)	2.7 kWh/L (9.7 MJ/L) (81 g/L)
Storage system cost	\$4/kWh (~\$133/kg H_2)	\$2/kWh (\$67/kg H_2)

Explanations at www.eere.energy.gov/hydrogenandfuelcells/

Many additional targets

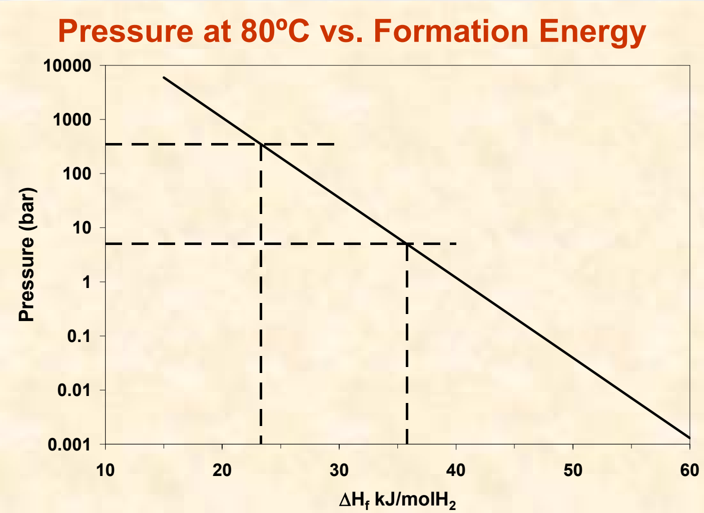
Strategy and Program Plans



- **Centers of Excellence** ($5-6M/yr) plus independent projects, launched at $150 M over 5 years (plan- subject to appropriations)
- **~ 40 universities, 15 companies, 10 federal labs** (including 17 new BES awards)
- **Diverse portfolio addresses NAS recommendations**

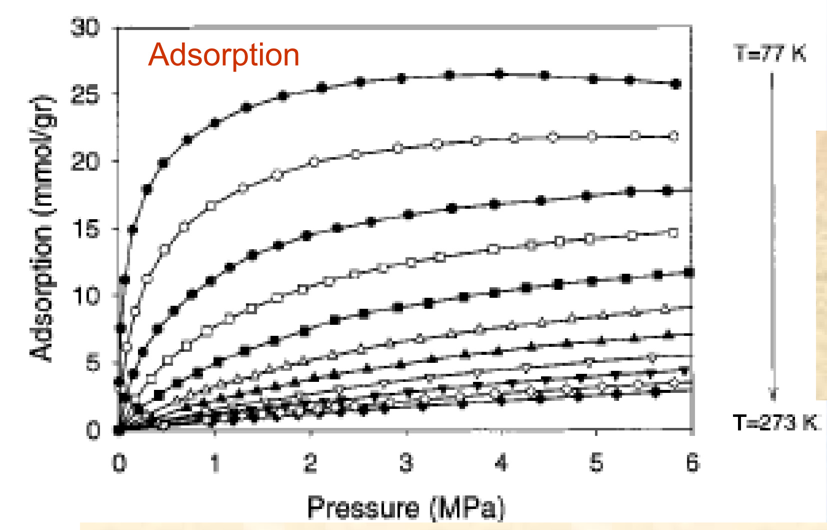
"…DOE should continue to elicit new concepts and ideas, because success in overcoming the major stumbling block of on-board storage is critical for the future of transportation use of fuel cells." (NRC Report,p.44)

Strategy: Optimize Materials Properties



Hydride heat of formation

- Pressure limits (20-35 kJ/molH_2)
- Refueling (<20 kJ/molH_2)

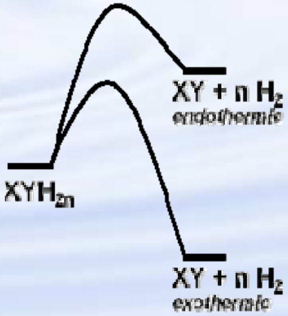


Surface heat of adsorption

- Operating temperature (> 100 K)
- Release temperature (< 80 C)

Activation barrier for regeneration

- Energy efficiency
- Thermoneutral for H_2 release



Results: Examples of Progress (2005-2006)

New materials with higher capacities being found

Material Capacities for Hydrogen Storage

Advanced Metal Hydrides	Chemical H_2 Storage	Carbon/ Sorbents & New Materials
Li Mg Amides ~5.5wt%, ~2.8 kWh/L (>200 C) Alane ~7-10 wt%, ~5 kWh/L (<150 C) Li borohydrides >9 wt%, ~3.5 kWh/l (~350 C) Destabilized Binary hydrides ~5-7wt%, ~2-3 kWh/L (250 C) LiMgAlane, M-B-N-H ~ 7-8.8 wt%, > 1.3 kWh/L (~150-340 C)	Phenanthraline/ organic liquids ~7 wt%,~1.8 kWh/L (>150 C) Ammonia Borane/Scaffolds ~6 wt%,~2-4 kWh/L (<100 C)	Metal/carbon hybrids, MetCars 6 to > 8wt%*, ~1.3* kWh/l (*theory) Bridged catalysts IRMOF-8 ~1.8 wt.%,~0.3 kWh/L (room T) Metal-Organic Frameworks IRMOF-177 ~7 wt%, ~1 kWh/L (77 K)

Note: Material capacities only. No balance of plant. Estimates for volumetric capacities.

We are excited by these results but there are still issues…

Next steps: Operability (Temperature, pressure, kinetics, etc.)

Other Examples of Accomplishments: Test Facility (SwRI), Storage Systems Analysis

Programmatic Accomplishments

- IPHE Hydrogen Storage Conference
  - Leveraging global activities
  - See www.iphe.net
- Expanded Basic Science
- Theory Focus Session
  - May 18, 2006
- Updated Targets & Multiyear Plan
  - New versions on web
- Addressing NAS recommendations (e.g. revolving solicitation for new concepts)

FreedomCAR & Fuel Partnership

- Water Availability Model
  - For hydrolysis
- Paper on Ammonia
  - Draft on web for public comment
- Updated Roadmap & Targets
  - New versions on web
- Joint Tech Team meetings
  - Defining requirements

See: www.eere.energy.gov/hydrogenandfuelcells/

Hydrogen Storage – Future Plans

IPHE Hydrogen Storage Conference Lucca, Italy

Centers of Excellence Launched

Solicitation Released

Ammonia Paper Released for Comment

Full Proposals Due

Pre-Proposals Due

Pre-Proposals Due

2005 | 2006 | 2007

Mar | Jun | Sep | Dec | Mar | Jun | Sep | Dec | Mar

Testing Workshop

Updated Roadmap

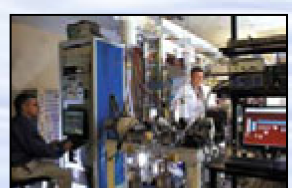
Theory Focus Session

Release Solicitation *

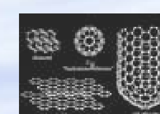
Storage Systems Analysis Working Group Launched

Test Facility Validation

Go/No Go Single - walled Nanotubes



Cryo-compressed Tank Assessment



*Subject to appropriations

Current Solicitations

1) Applied Research and Development (EERE)
– Up to $6M total ($2M planned in FY07, subject to appropriations)

Complements current DOE Centers of Excellence & existing Independent projects:

- Material discovery
- Engineering Science (including materials safety properties)
- Systems, safety and environmental analyses

– 3-6 awards at $200-400k/yr for 2-5 years
– Preproposals due **June 7**

2) Basic Science (Office of Science, BES)
– Up to $52.5M total ($17.5M/yr starting in FY07, subject to appropriations)

- Novel Materials for Hydrogen Storage
- Functional Membranes
- Nanoscale Catalysts

– Preproposals due **July 6**

See http://www.grants.gov or follow links from www.hydrogen.energy.gov

For More Information

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New Hire
Carbon/Sorbents, Carbon Center of Excellence
see website below
(closes May 19)

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Basic Science: Harriet Kung (harriet.kung@science.doe.gov) or Tim Fitzsimmons (tim.fitzsimmons@science.doe.gov)

www.hydrogen.energy.gov

Additional Information

Hydrogen Storage “Grand Challenge” Partners

Centers of Excellence

Metal Hydride Center

National Laboratory:
Sandia-Livermore

Industrial partners:
General Electric
HRL Laboratories
Intematix Corp.

Universities:
CalTech
Stanford
Pitt/Carnegie
Mellon
Hawaii
Illinois
Nevada-Reno
Utah

Federal Lab Partners:
Brookhaven
JPL
NIST
Oak Ridge
Savannah River

Carbon Materials Center

National Laboratory:
NREL

Industrial partners:
Air Products &
Chemicals

Universities:
CalTech
Duke
Penn State
Rice
Michigan
North Carolina
Pennsylvania

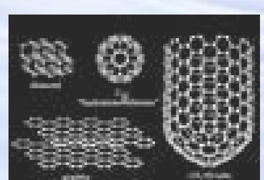
Federal Lab Partners:
Lawrence Livermore
NIST
Oak Ridge

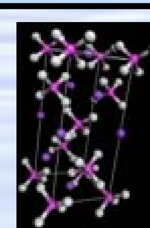
Chemical Hydrogen Center

National Laboratories:
Los Alamos
Pacific Northwest

Industrial partners:
Intematix Corp.
Millennium Cell
Rohm & Haas
US Borax

Universities:
Northern Arizona
Penn State
Alabama
California-Davis
UCLA
Pennsylvania
Washington





Independent Projects

New Materials & Concepts
Alfred University
Carnegie Institute of Washington
Cleveland State University
Michigan Technological University
TOFTEC
UC-Berkeley
UC-Santa Barbara
University of Connecticut
University of Michigan
University of Missouri

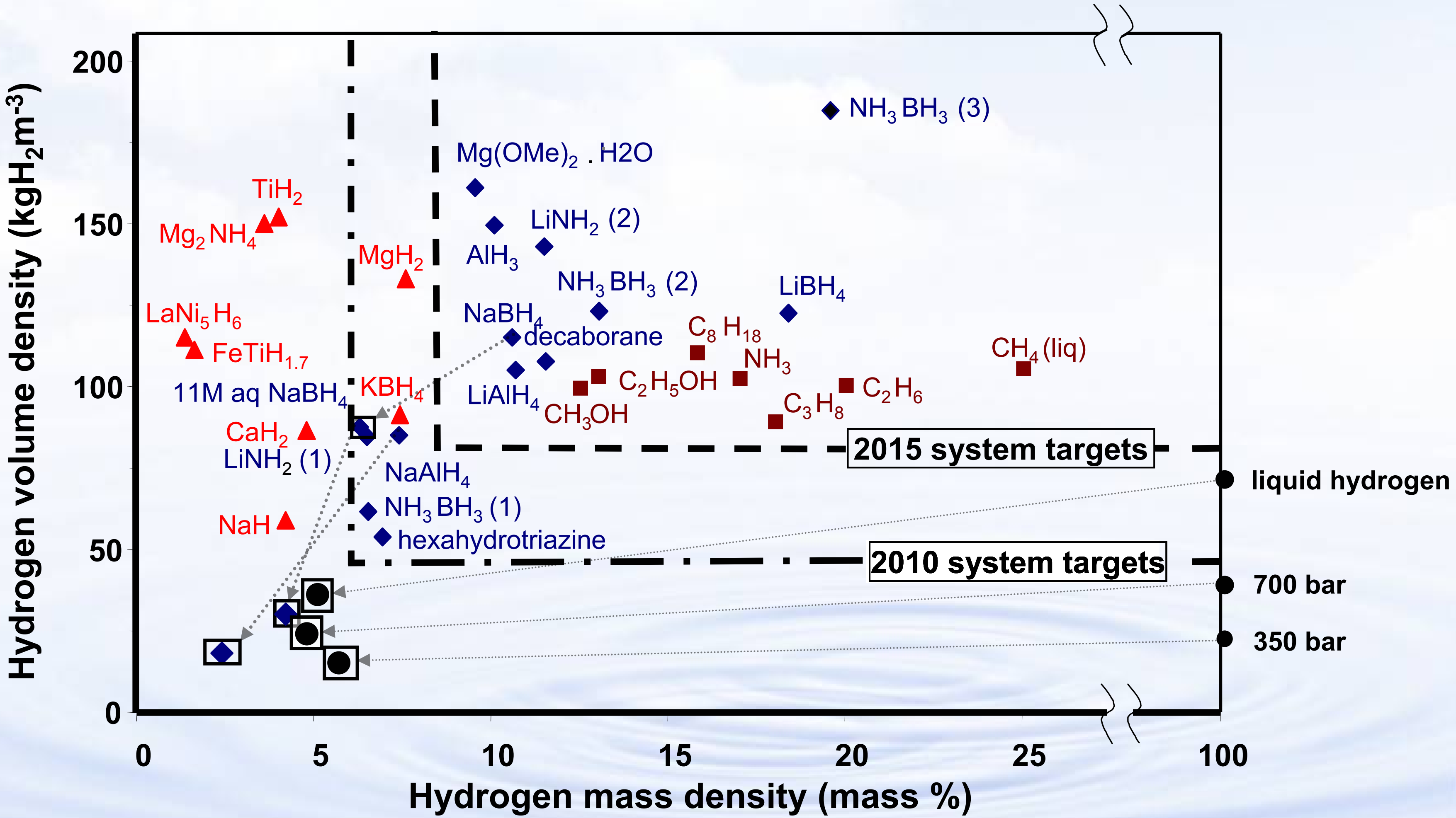
High-Capacity Hydrides
UTRC
UOP
Savannah River NL

Carbon-based Materials
State University of New York
Gas Technology Institute
UPenn & Drexel Univ.

Chemical Hydrogen Storage
Air Products & Chemicals
RTI
Millennium Cell
Safe Hydrogen LLC

OffBoard, Tanks, Analysis & Testing
Gas Technology Institute (w/Delivery)
Lawrence Livermore
Quantum
Argonne Nat’l Lab & TIAX LLC
SwRI

No current system meets targets, but there are some materials with potential…

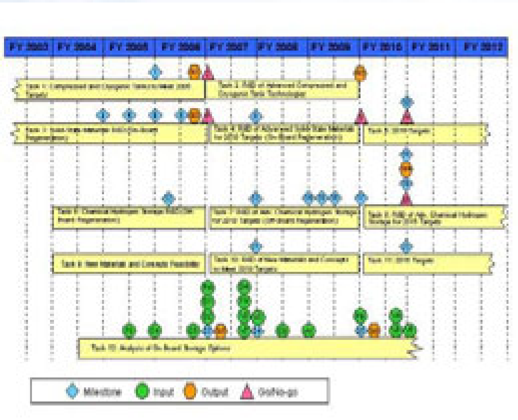


Strategy & Results

Broad Portfolio Focused on Materials Technologies

Challenges are technology specific: Pros and Cons for each

Tanks (to 10,000 psi), Chemical hydrides (CH), Metal Hydrides (MH), Carbon/Sorbents (S)



RD&D Plan: Tasks in each area

www.eere.energy.gov/hydrogenandfuelcells

Key 2010 Targets:	Tanks	CH	MH	S
Volume (1.5 kWh/L)	H	M	M	M/H
Weight (2.0 kWh/kg)	M	M	M/H	M
Cost ($4/kWh)	M/H	M/H*	M/H	M/H
Refueling Time (3 min, for 5 kg)	L	L	M/H	M
Discharge Kinetics (0.02 g/s/kW)	L	M	M	M
Durability (1000 cycles)	L	M	M	M

Thermal Mgmt: Key Issues for MH (CH, C) (refers to Refueling Time and Discharge Kinetics)

H = High (Significant challenge) M/H = Medium/High M = Medium L = Low (minimal challenge)

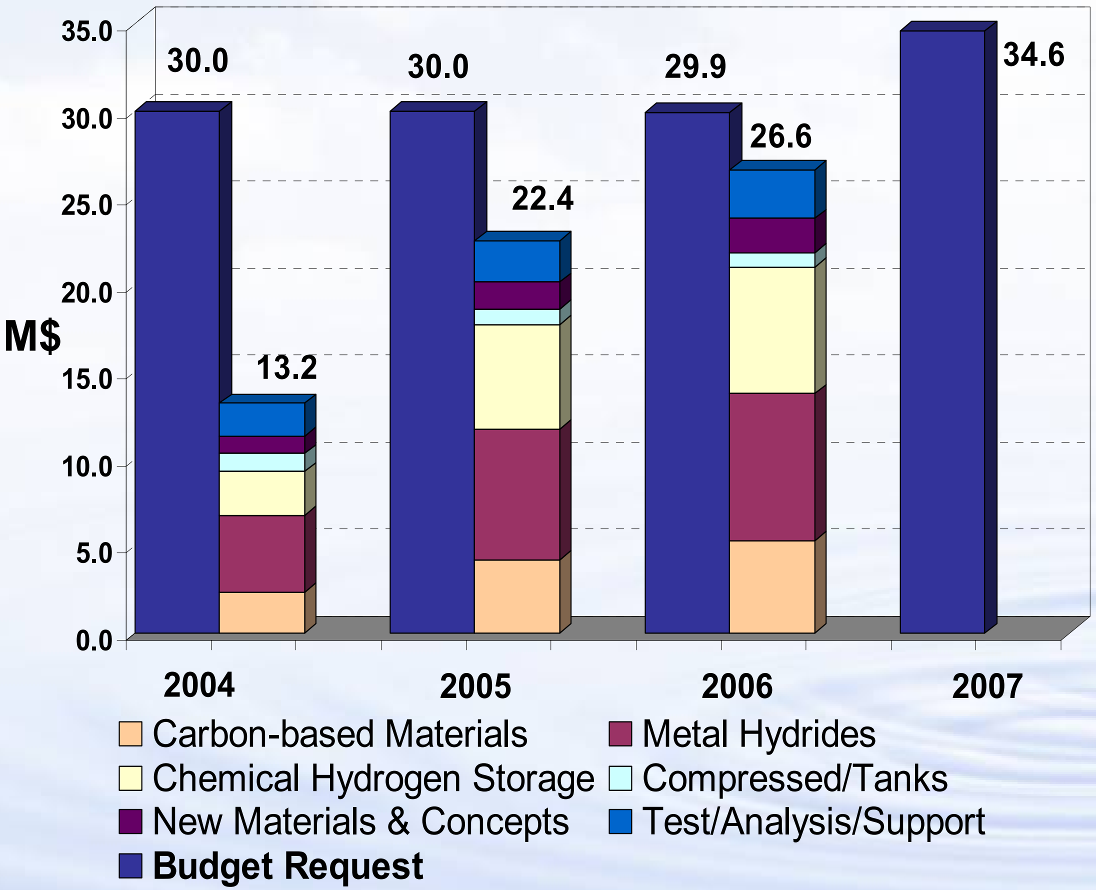
For CH, MH and S- assessment based on potential to meet targets, though systems not yet demonstrated in most cases.

*For CH: Storage system may meet cost but fuel cost of $2-$3/kg is challenge for CH regeneration.

Hydrogen Storage Budget

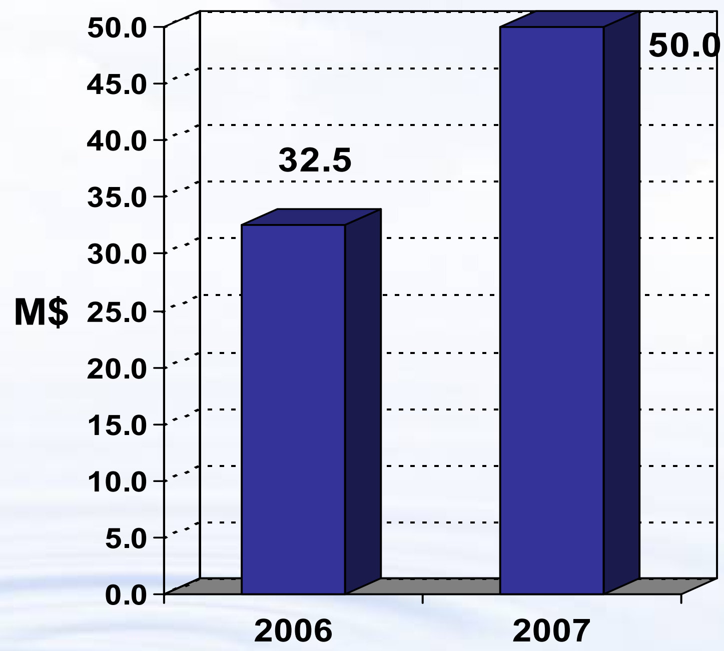
DOE- EERE

FY2007 Budget Request = $34.6M
FY2006 Funding = $26.6M



DOE- Office of Science

FY2007 Budget Request = $50.0M
FY2006 Funding = $32.5M



Planned funding for Basic Science in Hydrogen Storage in FY06: $7.13M