The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2245-4

Joint ICTP-IAEA Advanced School on the Role of Nuclear Technology in Hydrogen-Based Energy Systems

13 - 18 June 2011

Hydrogen storage research programs in Canada and North America

J. Huot

Universite du Quebec a Trois-Rivieres
Canada
&
Institute for Energy Technology
Norway

The Abdus Salam
International Centre for Theoretical Physics

IAEA.org
International Atomic Energy Agency

Hydrogen storage research programs in Canada and North America.

J. Huot

Université du Québec à Trois-Rivières

UQTR
Université du Québec
à Trois-Rivières

Present address: *Institute for Energy Technology, Norway*

IFE
Institute for Energy Technology

Joint ICTP-IAEA Advanced School on the Role of Nuclear Technology in Hydrogen-Based Energy Systems
Trieste – Italy, 13 – 18 June 2011

Content

Global perspective

Hydrogen in Canada

- Sector profile
- H2Can network
- Industry

United States

- Metal hydrides center of excellence
- Hydrogen storage engineering center of excellence

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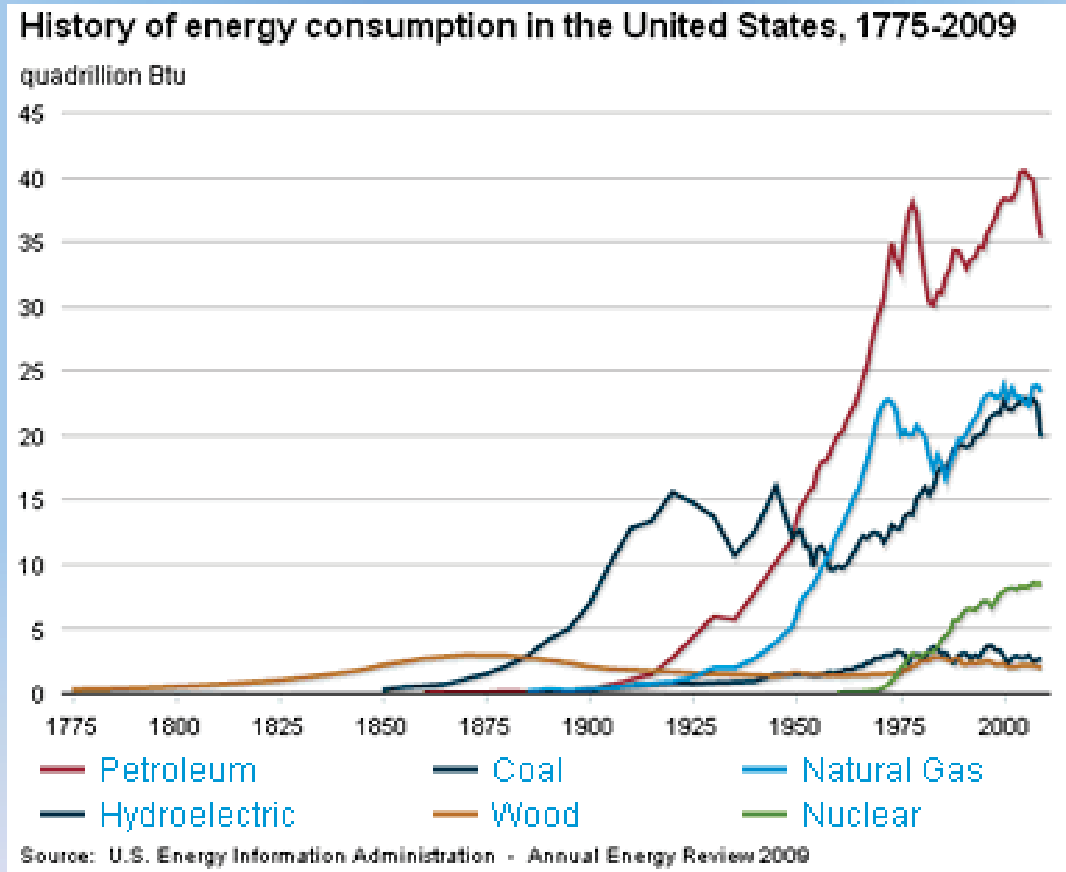
Global perspective

- Hydrogen vs other fuels
- Hydrogen vs batteries
- Hydrogen storage

Energy consumption



http://geology.com/articles/history-of-energy-use/

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New sources of energy

- Wind
- Sun (photovoltaic and thermal)
- Hydro
- Biomass
- Geothermal
- Tide
- Wave

But all these should be coupled to existing grid and means of production

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The energy production technologies

Technology	Issues and concerns
Nuclear	•Spent fuel, safety
Coal	•Emissions
Hydro	•Environmental impact
Photovoltaic	•Cost, intermittency
Wind	•Low density
Biomass	•Very low density
Geothermal	•Limited sites
Gas turbines/Fuel cells	•Needs hydrogen source

http://www.windbyte.co.uk/windpower.html

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Problems

Most of these new sources are intermittent.

⇒ Difficult to integrate to base power (about 20%)

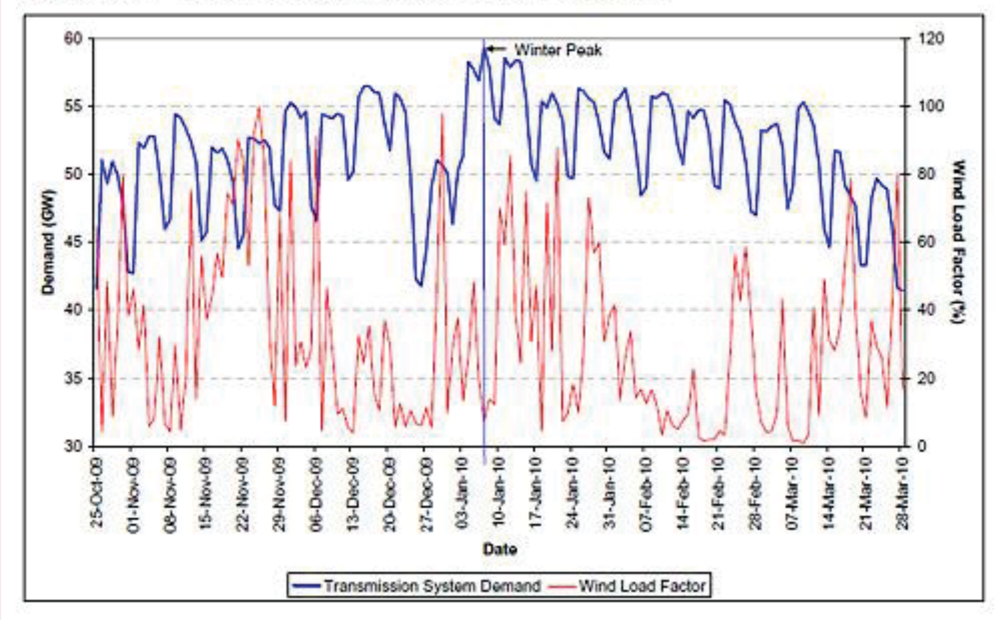
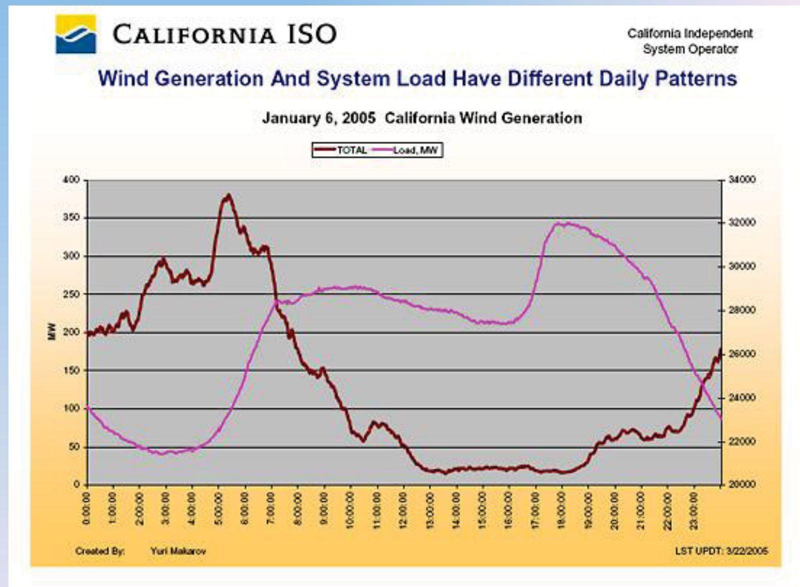


Figure A.30 – 2009/10 Daily Peak and Wind Generation



http://www.windbyte.co.uk/windpower.html

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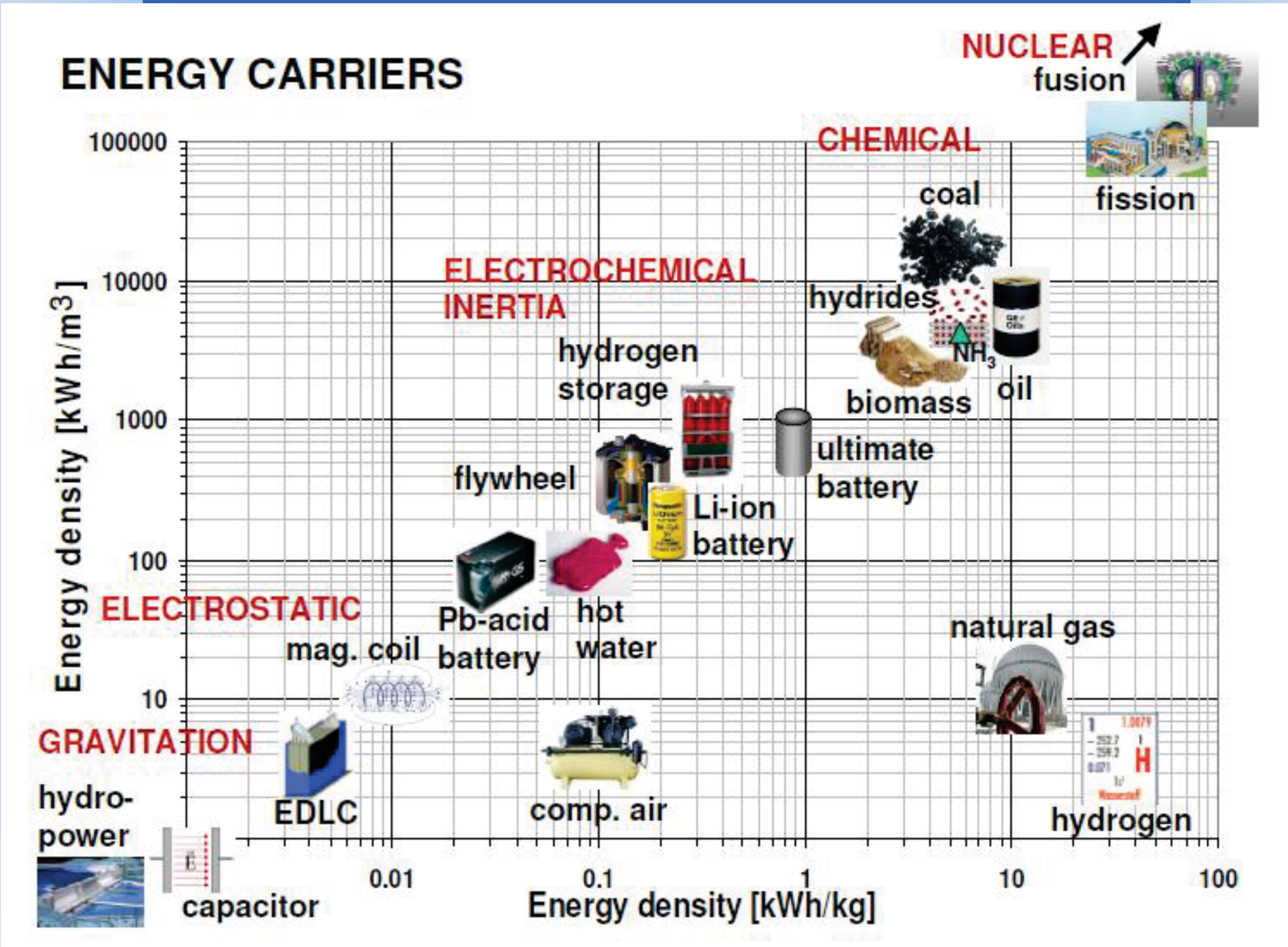
Energy vectors

We need an energy vector which will transport energy from the production site to the user. Electricity is a good energy vector but it could not be stored in large quantity. Thus, we need another type of energy vector.

http://www.windbyte.co.uk/windpower.html

Energy vectors



A. Zuttel, International Hydrogen Showcase, April 2011

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Energy vectors

	Petrol	Electricity	Hydrogen
Synthesis	No (but need millions of years!)	Yes	Yes
CO_2 release	Yes	Depends on production	Depends on production
Stockable	Yes	Batteries (low energy)	Yes
Could be transformed to the other two	Yes	Only with Hydrogen	Yes
Electronic	No	Yes	No (but micro fuel cells could replace batteries)
Chemistry	Yes	No	Yes

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Energy densities

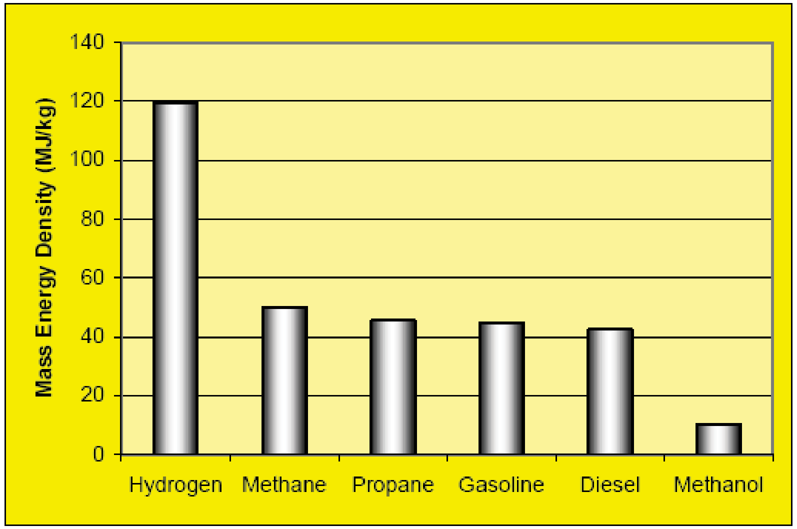

Figure 7 – Mass energy density of fuels (LHV)

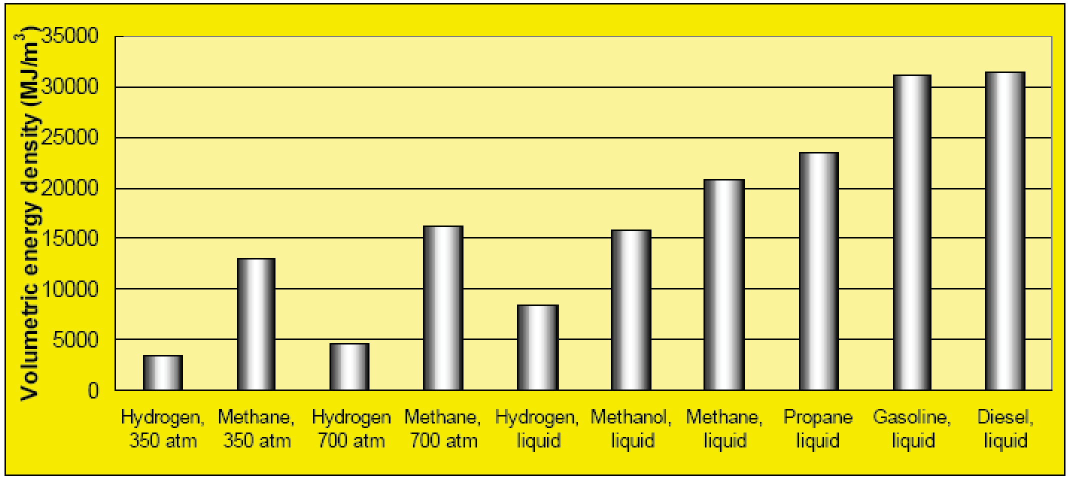

Figure 8 – Volumetric energy density of typical types of fuel (LHV)

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Hydrogen storage

A big problem with hydrogen is its low volumetric density. For practical applications this density has to be increased.

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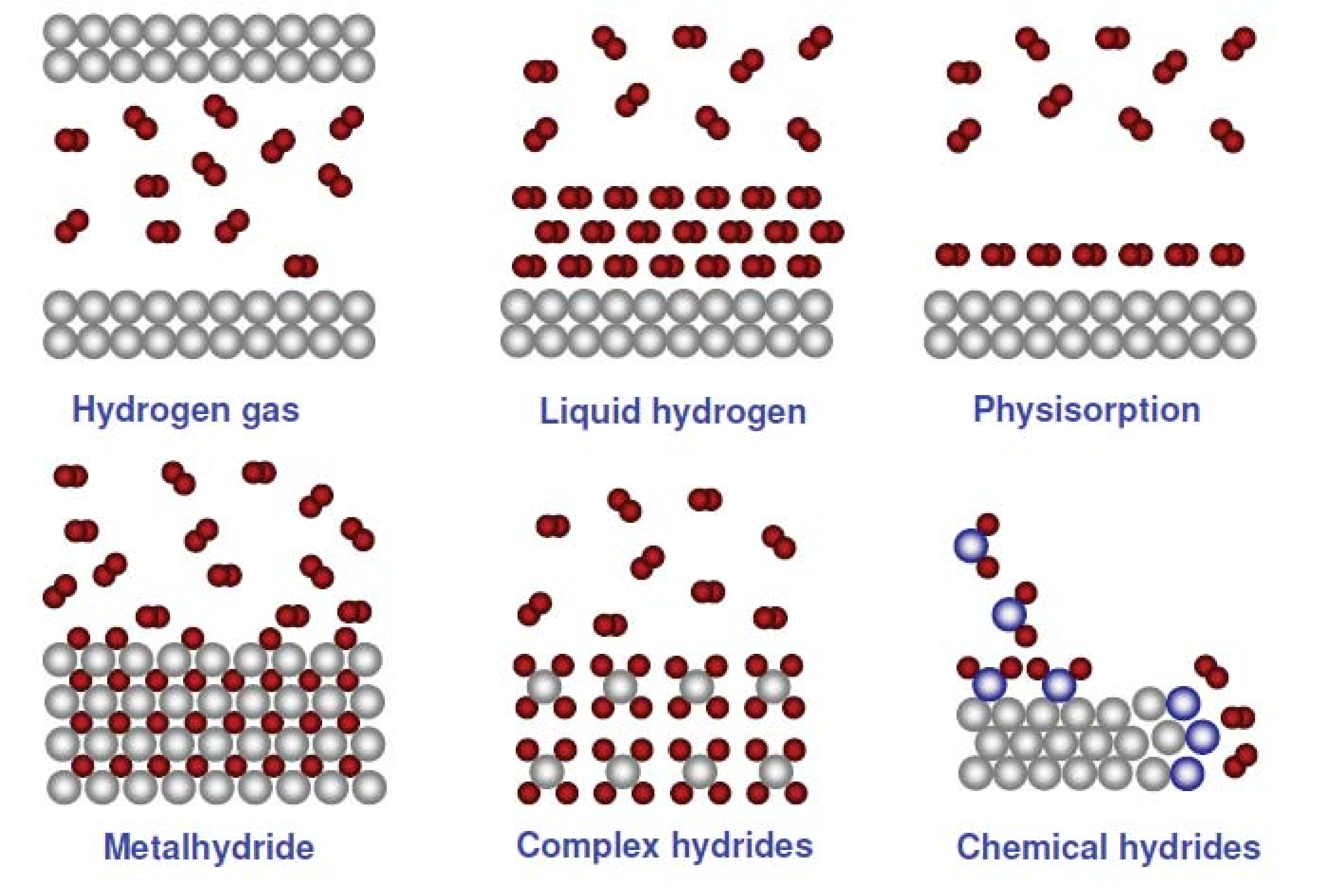
Types of hydrogen storage



A. Zuttel, International Hydrogen Showcase, April 2011

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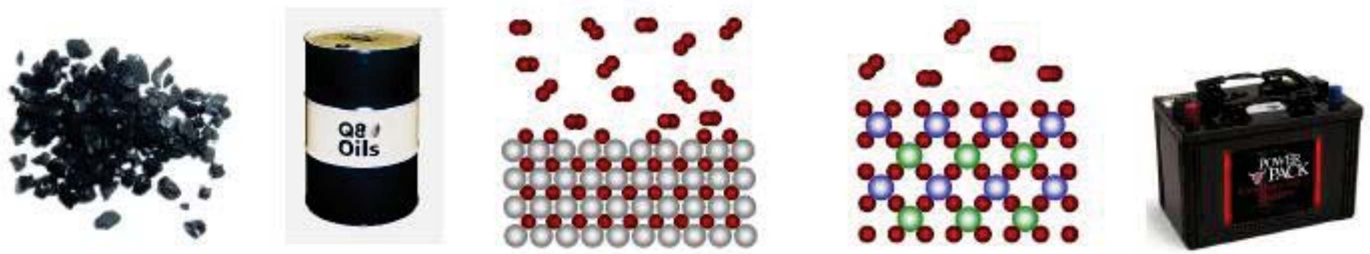
Comparison



Coal	Oil	Metal hydride	Complex hydride	Battery
		1.8 mass%	18 mass%	
10 kWh/kg	13 kWh/kg	0.6 kWh/kg	6 kWh/kg	1.0 kWh/kg
20 kWh/l	10 kWh/l	3 kWh/l	5 kWh/l	1.0 kWh/l
solid	liquid	solid	solid / liquid	solid

Hydrogen for vehicles

Hydrogen could be used directly in Internal combustion engine (ICE) or with a fuel cell (FC).

ICE:

- Low cost
- Well known engine
- Production of NOX
- Low efficiency
- Noise

FC:

- High cost
- New type of engine
- Pollution free
- High efficiency
- Silent

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Electric vs FC cars

Nissan Leaf
Range: 117 km (EPA)
Engine : 80 kW
Battery pack:
- Energy: 24 kW-h
- Weight: 300 kg
- Cost : 18,000$US

Daimler B-class F-Cell
Range: 385 km (manufacturer)
Engine : 100 kW
H_2 storage:
- 3 tanks 700 bar
- Energy: ≈ 120 kW-h
- Weight: ≈50 -100 kg
- Cost : ??

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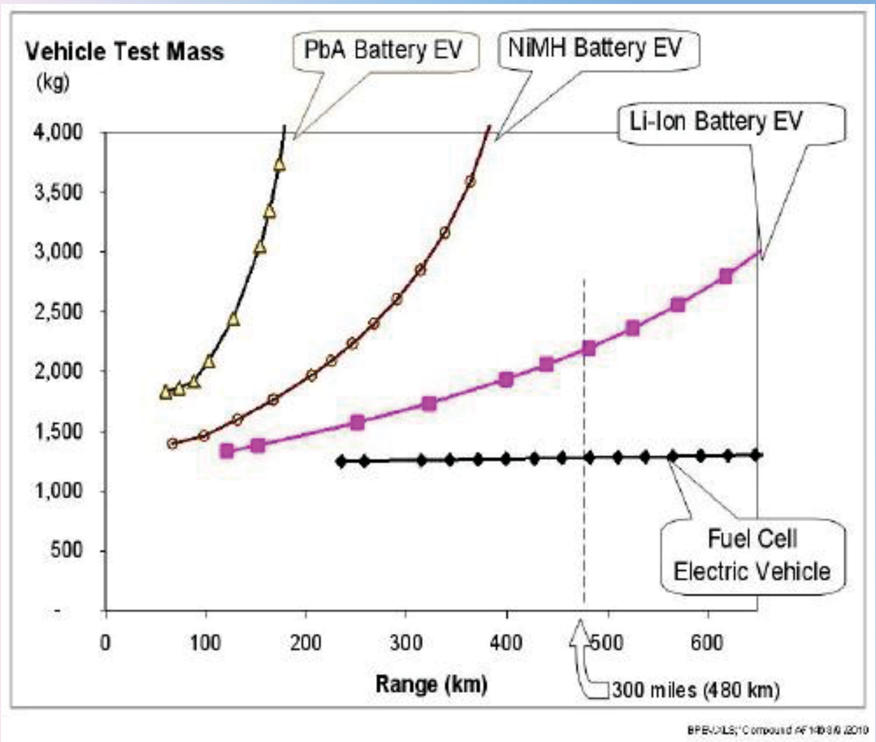
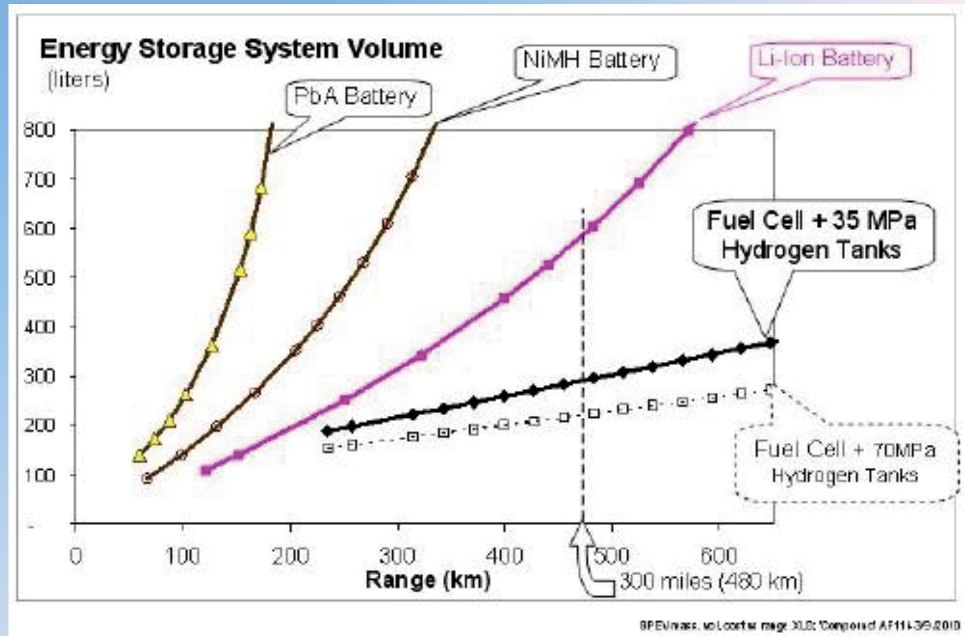
Batteries vs fuel cells

Mass



Volume



http://www.azocleantech.com/article.aspx?ArticleID=214

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Batteries vs fuel cells

Characteristic	Batteries	Fuel cells
Nominal range (km)	128	400
True range (km)	90	270
Worst (km)	50	160
Filling time (min)	400	3

From kevin kendall: k.kendall@bham.ac.uk

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Batteries vs fuel cells

EV use between 10 and 20 kW-h/100 km

Range of 400 km $\Rightarrow$ 40 kW-h of energy

Electrical outlet 240V, 14 A = 3.3 kW = 12 hours

Inductive paddle 62.5 kW (500V, 25A) $\Rightarrow$ 48 minutes (but lower efficiency and higher resistive heating)

Batteries vs fuel cells

Pollution

Today, 50% of the electricity in the United States comes from coal and 20% from natural gas. Plug-in battery vehicles could result in a massive increase in fossil fuel use.

Infrastructure

The United States National Research Council has estimated it would cost $2.2 million to build a hydrogen fuelling station to support 1,500 fuel cell vehicles - the equivalent of $1,500 per vehicle. Meanwhile, according to an Idaho National Laboratory estimate, the average cost of a 240V circuit needed for a PHEV-30 or PHEV-40 would be $1,500-$2,100.

http://www.afcc-auto.com/technology.php?name=facts

Batteries vs fuel cells

- Car manufacturers target a commercialization of FC vehicles by 2015
- Electric car will probably be competitive only for less than 100 km range
- Issue for FC cars: Probably cost of FC

http://www.afcc-auto.com/technology.php?name=facts

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Hydrogen economy

Present activities

As presented by P. Gauthier AIR LIQUIDE HYDROGEN ENERGY

- **200 filling stations in operations**
  40 in California
  40 in Germany and Scandinavia
- **Over 50 buses in operations, several hundreds of demonstration cars**
  "Class B" commercial series announced by Daimler for 2011.
- **Over 5000 stationary systems** installed in hospital, hotels, offices (back-up) or in off-grid sites
- **1000 hydrogen forklifts** announced in North-America in 2010
- **Over 25 000 micro-fuel cells** sold in toys or educational kits
- **1,2 B€/year public funding**

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Hydrogen markets

As identified by AIR LIQUIDE HYDROGEN ENERGY

1. Off-Grid sites (permanent or temporary)
2. Back-up power (protection of sensitive sites)
3. Captive fleets (forklift, airports, etc)
4. Mobile energy (events, cinema, rescue, etc)
5. Energy storage (windmill, solar)
6. Infrastructure for FCEV (refuelling stations)

Hydrogen in Canada

- Sector profile
- H2Can network
- Industry

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Hydrogen in Canada

One of the largest energy producer

Country	Btus produced ($x10^{15}$)
United States	71
China	67.7
Russia	53.3
Saudi Arabia	24.7
Canada	19.3
Iran	13.1

- Hydrogen production: 3 million tons/year
  - Highest per capita
- 300 million$ invested in H_2 + FC
- Largest H_2 bus fleet

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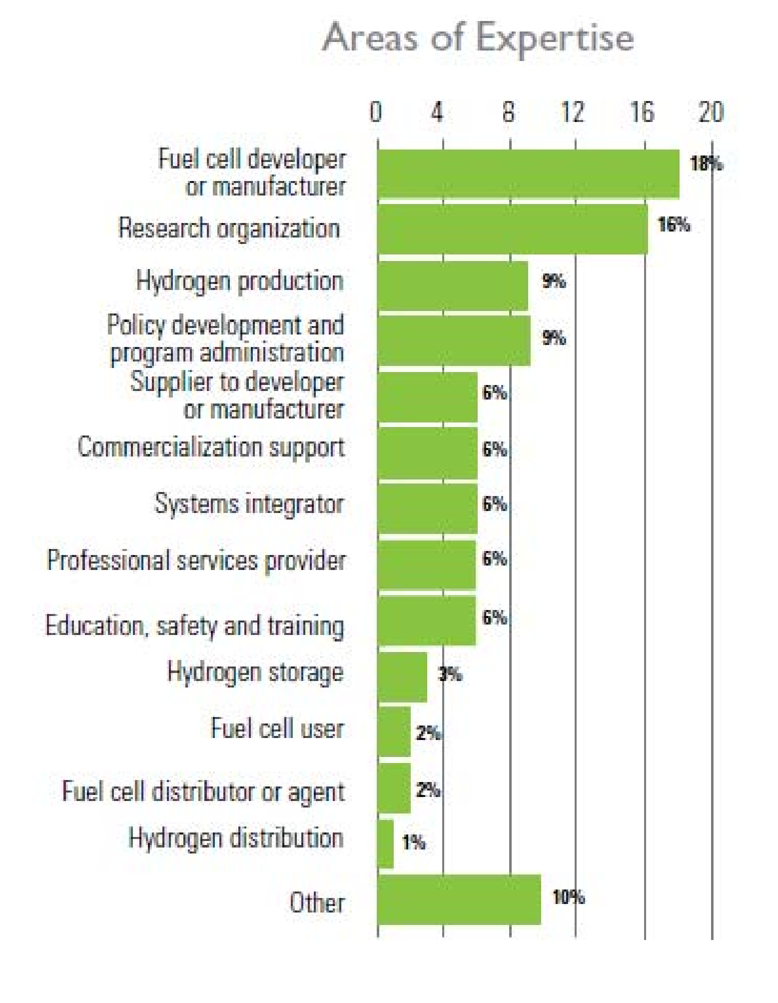
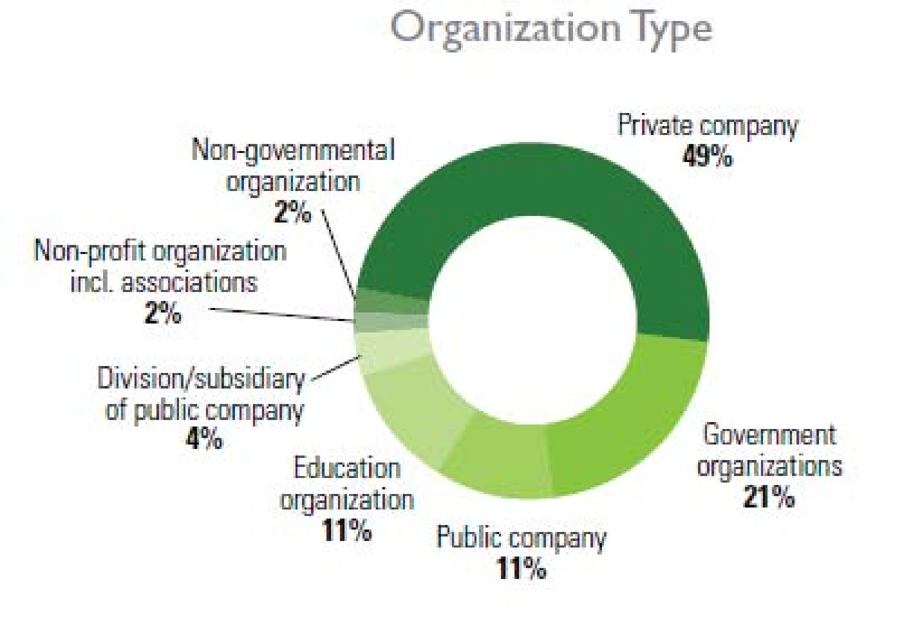
Hydrogen in Canada





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Canadian Hydrogen and Fuel Cell Sector profile 2010

- Revenue $215 million;
- Product sales $111 million;
- R&D and development expenditure $142 million;
- Employment 1765;
- 86 demonstration projects;
- 350 research partnerships.

A few programs

Hydrogen highway

Hydrogen village

Vehicle program

Canadian Hydrogen and Fuel Cell Association

http://www.chfca.ca/

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BC TRANSIT FUEL CELL ELECTRIC BUS FLEET

- 41 buses from Winnipeg bus manufacturer New Flyer

- Dynetek compressed hydrogen fuel storage,

- Valence lithium-phosphate batteries for energy storage,

- 150 kW fuel cell module provided by Ballard Power Systems.

- Air Liquide has built a 1,000 kg hydrogen fuelling station in Whistler, BC.

Hydrogen village

Installed projects

- Bell Canada Switching Station
- Exhibition Place Refueling Station
- Exhibition Place Gators
- UPS/BPS Data Centre
- Ford Shuttle Bus
- Enbridge Baseload Grid Power

Vancouver Fuel Cell Vehicle Program

- Three year $8.7 million joint initiative between the Government of Canada, Canadian Hydrogen and Fuel Cell Association, Ford Motor Company, and the Government of BC.

- Operating and evaluating five Ford Focus fuel cell electric vehicles in 'real world' conditions in British Columbia's Lower Mainland and Capital Region (Victoria).

Website:
http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/transportation/hydrogen_fuel_cells/demo_and_deployment.html

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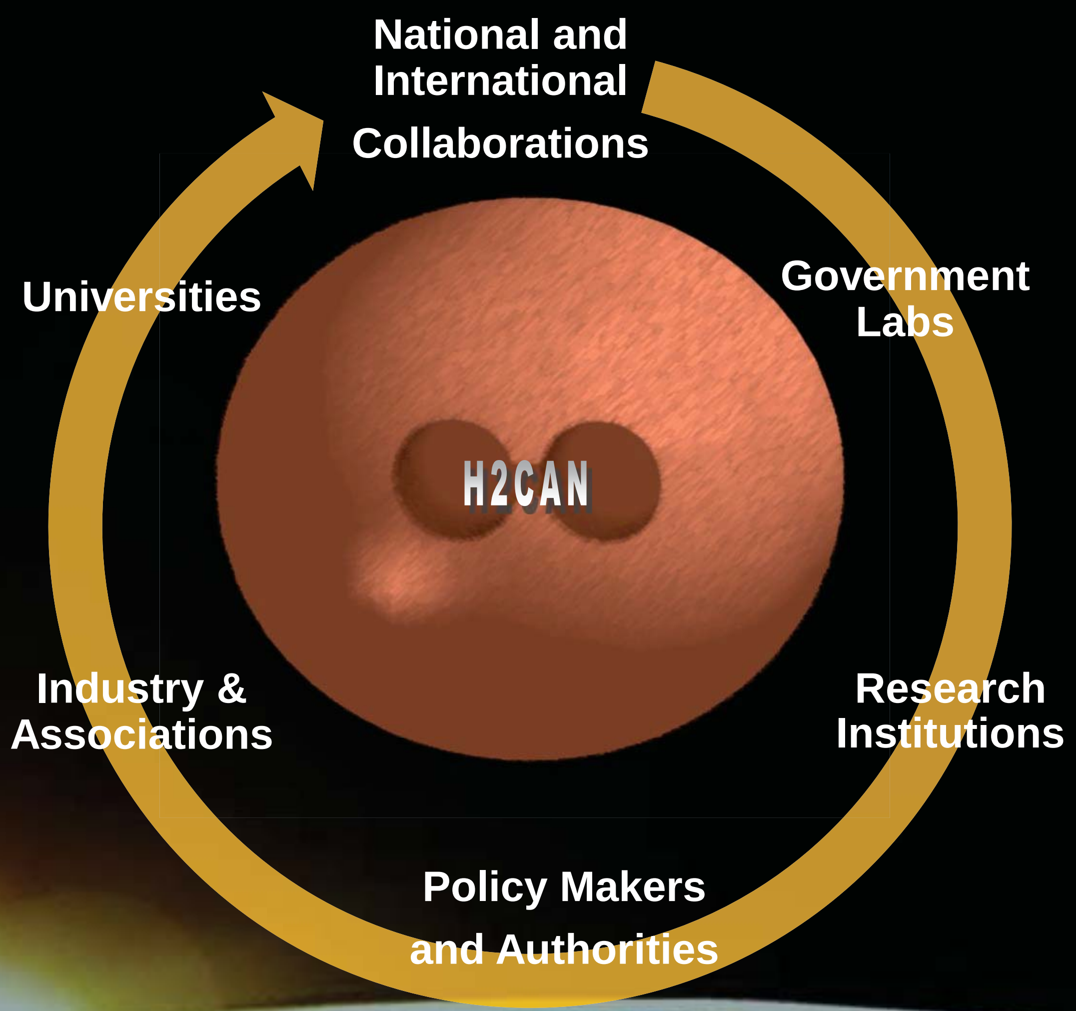
NSERC Strategic Network



Addressing the Challenges of Hydrogen

- ❑ Production from renewables
- ❑ Storage and Infrastructure
- ❑ Safety
- ❑ Budget 1 million$/year

(leveraged 4/1 with other R&D activities)

H2Can Academic

Université du Québec à Trois-Rivières

H2Can Industry

Production and purification

Project ID	**Title**	**Researcher**	Affiliation
Group A.1 H_2 production from wind power (group leader: Kodjo Agbossou)			
Project A.1.1	Optimized electrolyzer hydrogen production from renewable energy system for fuel cells and hydrogen powered generators	Kodjo Agbossou	UQTR
Group A.2 Production from biomass and renewable hydrocarbons (group leader: D. B. Levin)			
Project A.2.1	H_2 production via cellulose fermentation	David B. Levin	U of M
Project A.2.2	H_2 production via aqueous reforming of organic molecules	David B. Levin	U of M
Project A.2.3	H_2 production by biomass gasification	Jean Hamelin	UQTR
Project A.2.4	H_2 production by water gas shift reaction	Raphael Idem	U of Regina
Group A.3 Purification and Separation Technologies (group leader: Daniel Guay)			
Project A.3.1	Metallic membranes for H_2 gas separation	Daniel Guay with Lionel Roué	INRS
Project A.3.2	Purification and analysis of hydrogen derived from Biomass	Brant Peppley	Queens

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Hydrogen storage

Project ID	Title	Researcher	Affiliation
Group B.1 Theory and simulations of hydrogen storage materials (group leader: Sean McGready)			
Project B.1.1	DFT modeling of hydrogen storage materials	Sean McGready	UNB
Project B.1.2	Simulations of hydrogen adsorption isotherms for nanoporous materials	Pierre Bénard	UQTR
Group B.2 Development of materials for hydrogen storage (group leader: Richard Chahine)			
Project B.2.1	High volumetric density storage metal hydrides	Jacques Huot	UQTR
Project B.2.2	Light-element destabilized Mg-based alloys for hydrogen storage	David Mitlin,	U of Alberta
Project B.2.3	Catalyzed lithium alanate complex hydride and its composites	Robert A. Varin, Z. Wronski	U of Waterloo
Project B.2.4	Hydrogen storage in novel hybride nanoporous materials	Richard Chahine	UQTR
Group B.3 Storage systems design and optimization (group leader: Boyd Davis)			
Project B.3.1	Hydride Storage Systems	Andrew Rowe	U of Victoria
Project B.3.2	Heat and mass transfer in sorption-based storage systems	Jacques Goyette	UQTR
Project B.3.3	Novel chemical hydrogen storage concepts	Boyd Davis	Queens
Group B.4 Characterization (group leader: Gianluigi Botton)			
Project B.4.1	Microscopy of nanostructured hydrogen storage materials	Gianluigi Botton	McMaster
Project B.4.2	Neutron diffraction analysis	H. Fritsch	NRC-SIMS-CNBC
Project B.4.3	NMR characterization	John Ripmeester	NRC-SIMS-MSF

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Infrastructure and safety

Project ID	Title	Researcher	Affiliation
Group C.1 – Infrastructure (Group Leader A. Rowe)			
Project C.1.1	Techno-economics for Fleets	Ned Djilali (with A. Rowe and C. Crawford)	U of Victoria
Project C.1.2	Distribution by cryosorption storage technologies	R. Chahine (with P. Bénard)	UQTR
Project C.1.3	Magnetic Liquefaction	A. Rowe	U of Victoria
Group C.2 – Safety (Group leader: Luc Bauwens)			
Project C.2.1	Outflow modeling	Pierre Benard	UQTR
Project C.2.2	Experimental and numerical investigation of hydrogen outflow from pressurized vessels	Peter Oshkai, Ned Djilali	U of Victoria
Project C.2.3	Compressible Large Eddy Simulations of hydrogen dispersion	Marius Paraschivoiu	Concordia University
Project C.2.4	Jet ignition in hydrogen energy systems	Luc Bauwens	U of Calgary
Project C.2.5	Self ignition of hydrogen releases	Matei Radulescu	U of Ottawa

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Training

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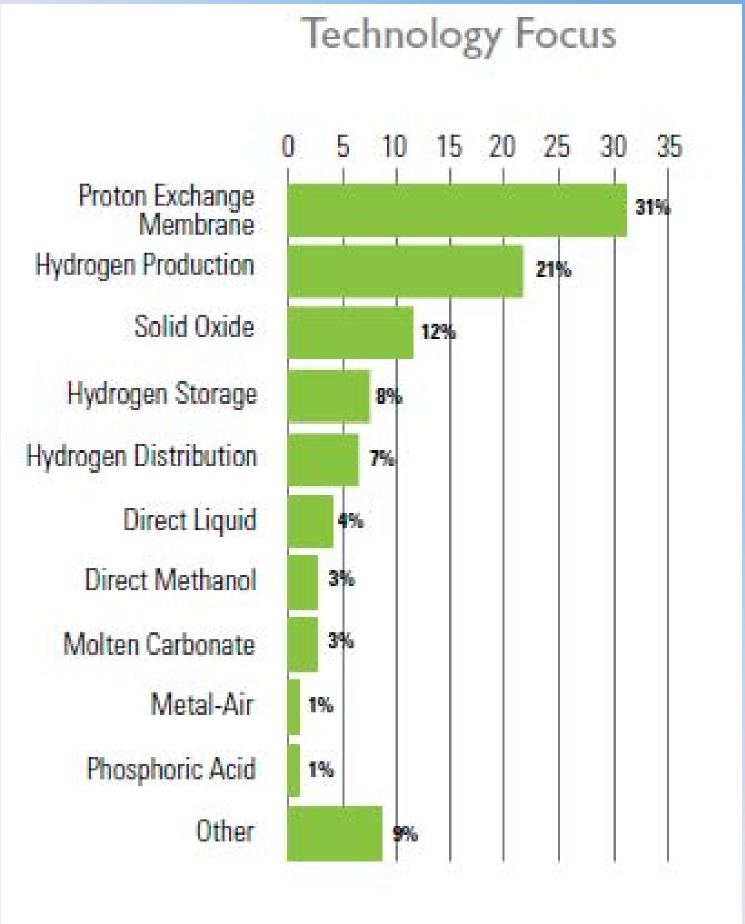
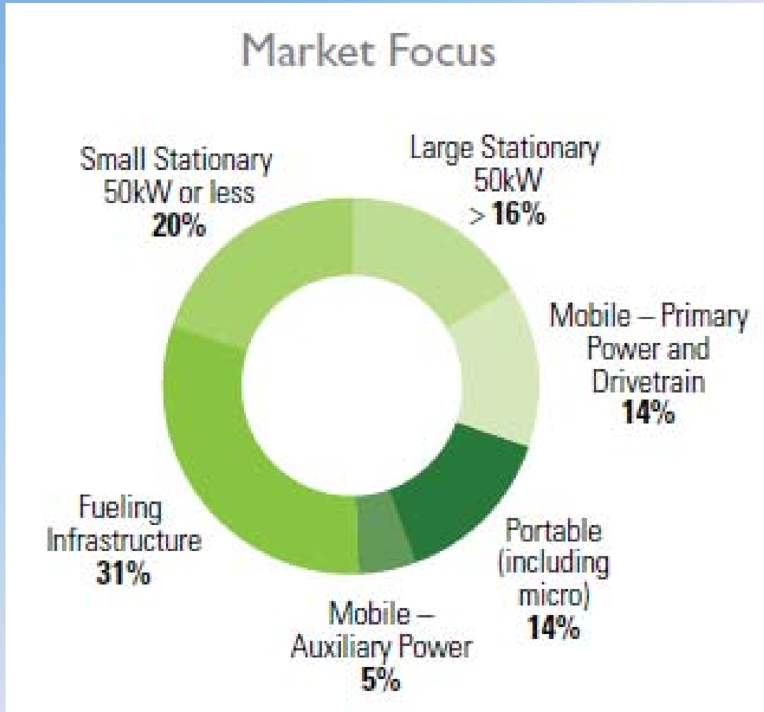
Hydrogen in Canada Industry





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Ballard

- Founded in 1979 for R&D in Li batteries

- 1983 development of PEM fuel cell

- 1992-1994 sub-scale and full-scale prototypes

- Headquarters in Burnaby, BC

Products

- Stationary power
- Motive power
- Materials

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Motive power

Material handling

• Forklifts, pallet trucks

Advantages

•Battery Changes Eliminated

•Consistent Power

•Fast Fuelling (one to three minutes)

•More Productive Warehouse Floor Space

•No onsite battery storage

•Zero Emissions

• FC: 4.4- 19.3 kW

Motive power, busses

Advantages

- Reduced Operating Costs
- Zero Tail Pipe Emissions
- Noise Reduction
- Improved Performance
- FC: 75 and 150 kW

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Automotive Fuel cell Cooperation (AFCC)

AUTOMOTIVE FUEL CELL COOPERATION®

www.afcc-auto.com

Founded in February 2008

Burnaby, east of Vancouver

Joint venture between

- Daimler (50.1%)
- Ford (30%)
- Ballard (19.9%).

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Mercedes-Benz B-Class F-CELL

The drive components of the Mercedes-Benz B-Class F-CELL are protected in the sandwich underfloor unit; thanks to this space-saving configuration, the interior and the trunk are fully usable.

Facts and figures	
Peak power	100 kW
Torque	290 Nm
Tank capacity	3,7 kg at 700 bar
Range	400 km
Consumption (diesel equivalent)	3.3 l/100 km

Mercedes-Benz

Mercedes-Benz to build its own production of fuel cell stacks in Canada

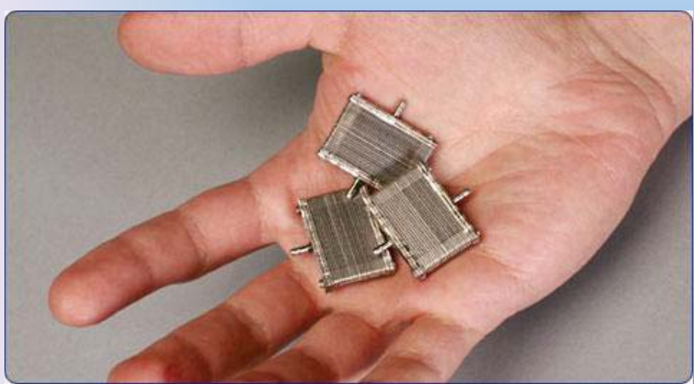
Preparation for the next generation of fuel cell drive systems

Vancouver/Stuttgart – Mercedes-Benz announced today that it will set up its own production of fuel cell stacks in Canada. By doing so, the company will bundle the development and production for one of the key components of fuel cell powered electric vehicles in Vancouver, British Columbia.

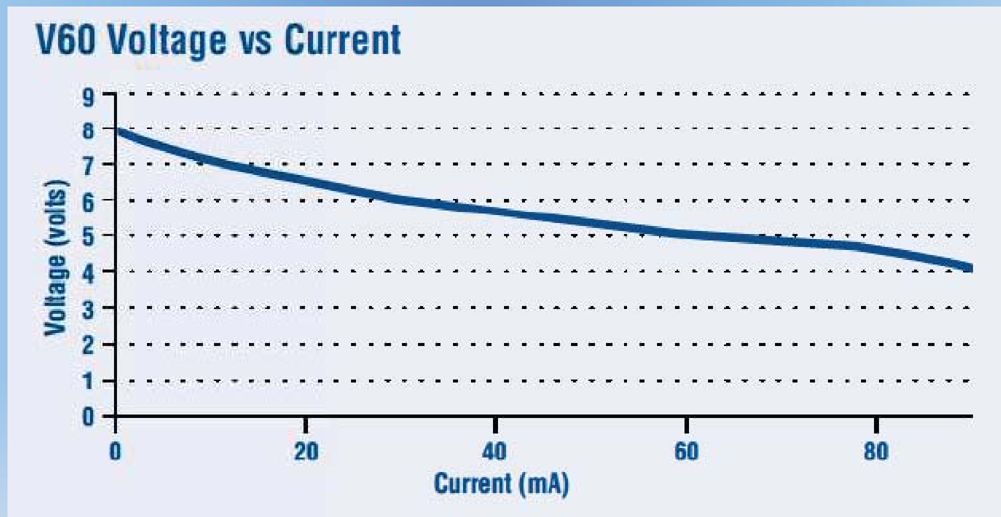
Press release March 17, 2011

ANGSTROM®

www.angstrompower.com



The Angstrom V60 Fuel Cell Module is an ultra-small power unit that delivers 200 mW of electrical output at 5 Volts.



http://www.angstrompower.com/

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Twenty four hours on a single charge.
on-board metal hydride storage system.
Refueling takes only minutes

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G2 Portable Fuel Cell Power Source

Eight V60 Fuel Cell Modules that all together provide two watts of power. That can be used to top off any device that charges with a USB.

Hydrogen in United States

Overview

Hydrogen storage

- Past activities
- Present activities

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Budget

EERE Budget: *FY09 – FY12*

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Funding (*$ in thousands*)			
Activity	FY 2009	FY 2010 Current Approp.	FY 2012 *Request*
Biomass and Biorefinery Systems	214,245	216,225	340,500
Building Technologies	138,113	219,046	470,700
Federal Energy Management Program	22,000	32,000	33,072
Geothermal Technology	43,322	43,120	101,535
Hydrogen Technology	164,638	0	0
Hydrogen and Fuel Cell Technologies	0	170,297	100,450
Water Power	39,082	48,669	38,500
Industrial Technologies	88,196	94,270	319,784
Solar Energy	172,414	243,396	457,000
Vehicle Technologies	267,143	304,223	588,003
Weatherization & Intergovernmental Activities	516,000**	270,000	393,798
Wind Energy	54,370	79,011	126,859
Facilities & Infrastructure	76,000	19,000	26,407
Strategic Programs	18,157	45,000	53,204
Program Direction	127,620	140,000	176,605
Congressionally Directed Activities	228,803	292,135	0
RE-ENERGYSE	0	0	0
Adjustments	-13,238	0	-26,364
Total	**$2,156,865**	**2,216,392**	**3,200,053**

* SBIR/STTR funding transferred in FY 2009 was $19,327,840 for the SBIR program and $2,347,160 for the STTR program.
** Includes $250.0 million in emergency funding for the Weatherization Assistance Grants program provided by P.L. 111-6, "The Continuing Appropriations Resolution, 2009."

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http://hydrogen.energy.gov/

Budget DOE

Funding ($ in thousands)			
Key Activity	FY 2009[4]	FY 2010 Current Appropriation	FY 2012 Request
Fuel Cell Systems R&D[1]	-	75,609	45,450
Fuel Cell Stack Component R&D	61,133		
Transportation Systems R&D	6,435		-
Distributed Energy Systems R&D	9,750		-
Fuel Processor R&D	2,750		-
Hydrogen Fuel R&D[2]	-	45,750	35,000
Hydrogen Production & Delivery R&D	10,000		-
Hydrogen Storage R&D	57,823		-
Technology Validation	14,789[5]	13,005	8,000
Market Transformation[3]	4,747	15,005	-
Early Markets	4,747	15,005	-
Safety, Codes & Standards	12,238[5]	8,653	7,000
Education	4,200[5]	2,000	-
Systems Analysis	7,520	5,408	3,000
Manufacturing R&D	4,480	4,867	2,000
Total	$195,865	$170,297	$100,450[6]

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http://hydrogen.energy.gov/

Metal Hydride Center of Excellence

Mandate

Research, develop and validate reversible on-board metal hydride storage materials that support the 2010 DOE system targets for hydrogen storage, with a credible path forward for supporting the 2015 DOE storage system targets

Technical targets

H Capacity:

– Synthesize and characterize hydride materials with high hydrogen capacity and favorable thermodynamics, as guided by theory

Charge/Discharge Rates:

– Develop materials that are fully reversible, assess nanoengineering and catalysis as means for promoting kinetics

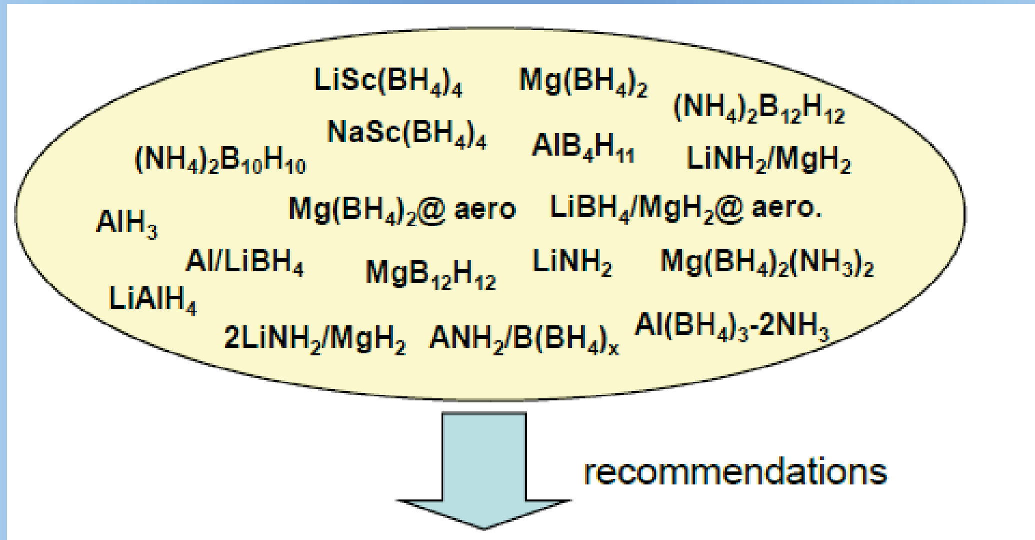
Hydrogen Purity (from Storage Material) :

– Assess release of NH_3, B_2H_6 and other volatile species, extend theory to account for these species during rxn

Cycle Life:

– Assess durability of materials, cycling behavior, effects of contaminants, structural stability, release of volatiles

Metal Hydride Center of Excellence



3 High-Level MHCoE Goals For The Final Project Year: Focus for the Future

1. Identify a near-term material for collaboration and subsystem testing in the HSECoE ✓ Recommended $2LiNH_2/MgH_2$, AlH_3, $LiAlH_4$
2. Identify medium-term materials that need more R&D, but would also be of eventual interest for HSECoE examination and subsystem testing
   ✓ Recommend $LiNH_2/MgH_2$, others (TBD)
3. Identify areas of further R&D that in the long-term have promise for fulfilling the 2015 targets

Hydrogen Storage Engineering
CENTER OF EXCELLENCE

D.L. Anton, H2Can meeting, Whistler, May 2011

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Hydrogen Storage Engineering
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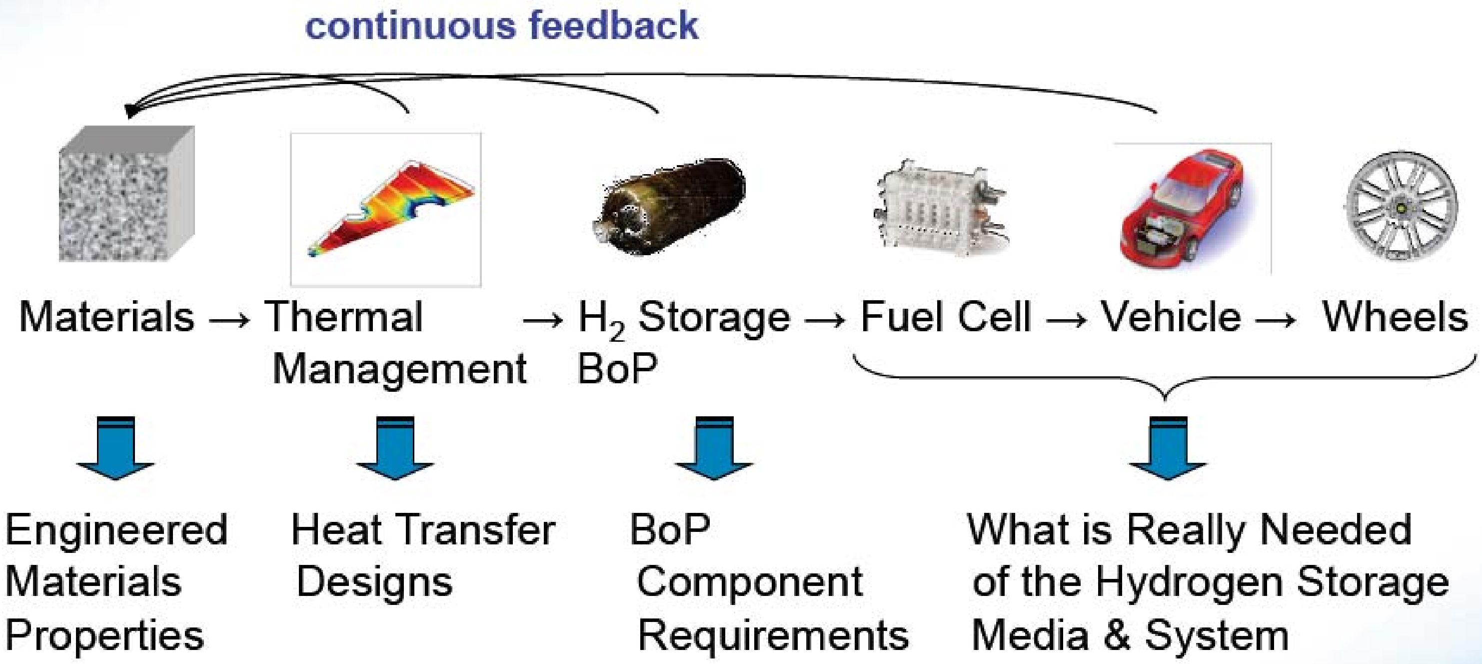
Center Goals

Develop the engineering technologies required for materials based light duty vehicle hydrogen storage delivery systems.



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Hydrogen Storage Engineering
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Role of Technology Area

- **Subscale Prototype Constructing Testing and Evaluation (SPCTE)**
  - Test subscale prototypes sufficiently to evaluate their performance relative to the DoE Technical Targets.
- **Performance, Cost and Energy Analysis (PCEA)**
  - Model hydrogen storage systems performance within a mid-size vehicle environment to determine energy utilization efficiency
- **Integrated Power Plant Storage System Modeling (IPPSSM)**
  - Model the integrated unit of PEM FC with BoP and Hydrogen Storage system to account for steady state and transient response dynamics.
- **Enabling Technologies (ET)**
  - Assess the availability and performance of BoP components a d design/modify as required to meet the demands of the hydrogen storage systems design concepts
- **Transport Phenomena (TP)**
  - Model and test advanced thermal and mass transport structures to meet the demanding requirements of both endothermic and exothermic reactions
- **Materials Operating Requirements (MOR)**
  - Assemble materials data required for the design of systems and experimentally determine data where it is not currently available.

Hydrogen Storage Engineering CENTER OF EXCELLENCE

Materials Candidate Matrix

	Tier 1 Developed Materials	*Tier 2* Developing Materials	Materials no longer considered
Adsorbents	AX-21	Pt/AC-IRMOF 8	MOF 177
	MOF 5	PEEK	
Chemical Hydrides	NH_3BH_3(f)		
	NH_3BH_3(s)		
	AlH_3	$LiAlH_4$	
Metal Hydrides	$NaAlH_4$	$Mg(NH_2)_2$+MgH_2+2LiH	MgH_2
		TiCr(Mn)H_2	$2LiNH_2$+MgH_2
			Mg_2NiH_4

D.L. Anton, H2Can meeting, Whistler, May 2011

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System Technical Targets

Parameter		units	2010	2015
Gravimetric	Density	KgH_2/ Kg system	0.045	0.055
Volumetric	Density	KgH_2/liter	0.028	0.04
Cost		$/KWh net	4	2
Operability	Min./Max. Op. T	°C	-30/50	-40/60
	Min./Max, Deliv. T	°C	-40/85	-40/85
	Cycle Life	N	1000	1500
	Min. Deliv. P	bar	4	3
	Max Deliv. P	bar	100	100
Rates	Fill Time	Min.	4.2	3.3
	Min. Flow	g/s•KW	0.02	0.02
	Start time 20°C	sec.	5	5
	Start Time -20°C	sec.	15	15
	Trans. Resp. 10%-90%	sec.	0.75	0.75
Fuel Purity		%	99.99	99.99
EH&S	H2 Loss	gH_2/hr•KgH_2	0.1	0.05

Conclusion

Hydrogen market is there and growing

Major automakers are targeting 2015 for FC vehicle commercialization

R&D effort should be targeted toward practical applications but we have to make room for some fundamental studies also