# Hydrogen vs Electricity:

## A skeptic's view of the hydrogen economy

**Harry Davitian**

Entek Power Services, Inc.

www.entekpower.com

631-751-9800

# Questions addressed

1. ***Does hydrogen have a role as a general purpose energy carrier?***

2. ***Are there important niches for hydrogen as a special purpose energy carrier?***

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*Note: See Chart 43 for sources of data used in this report.*
*Chart 44 contains the detailed references.*



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# How might hydrogen fit into our energy system?

# *Energy system*

## Resource

Petroleum

Gas

Coal

Nuclear

Geothermal

Hydro

Solar

Biomass

## Transport

## Storage

## End use

Transportation

Heating/ cooling

Lighting

Electronic

Appliances

Motors

Industrial

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# How we transport/store today

| Transport | Storage |
|---|---|
| Petroleum* | Petroleum* |
| Natural gas | Natural gas |
| Electricity | Hydro (dams) |
| | Batteries |

* *"Petroleum" includes refined products*

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# What is an energy carrier?

- A medium for conveniently transporting and storing energy
- Should be able to efficiently and cheaply produce it from energy resources
- End users should be able to make use of it efficiently and simply

**Examples**

- Electricity
- Natural gas
- Petroleum
- Hydrogen?
- Methanol?

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# Oil/gas—unique resources

- Petroleum and natural gas are unique because they are not merely resources but also serve as excellent energy carriers
- Relatively easy to extract
- Require little or no processing to convert into form that is can be used by end users
- Very high energy densities
- Relatively safe
- Storage devices are cheap
- End use technologies (combustion) were mastered a long time ago

# Awkward resources

Coal

Nuclear

Hydro

Geothermal

Wind

Solar

- The resources we will become more reliant on in the future are more problematic
- Difficult or impossible to transport and store in their original (resource) form
- Need to be converted to energy carriers so that they can be transported/stored easily and to make them convenient for end users

- *Question is: Which energy carrier is best for this purpose?*

# The bar hydrogen must pass

- Hydrogen must have significant relative advantages as an energy carrier compared to petroleum, natural gas and electricity for it to be realistically considered to be a competitor to them
- Petroleum and natural gas have so many advantages over hydrogen as energy carriers—convenience, efficiency, cost, and existing infrastructure—that it is inconceivable that hydrogen will displace them in their role as energy carriers so long as they continue to be major energy resources
- In the future, our use of petroleum and natural gas resources will decline and, therefore, so will their role as energy carriers but electricity is here today and will always be an option as an energy carrier in the future
- <u>The real test regarding hydrogen is whether it has such compelling advantages compared to electricity as to justify the creation of a new production/transport/delivery infrastructure that would be required to enable it to serve as an energy carrier, in competition with electricity, in a future energy system</u>



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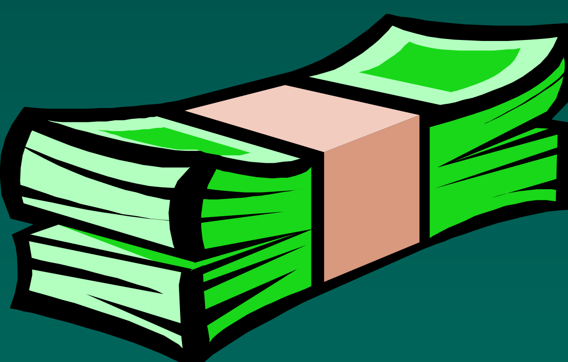
# Some basic physics



# and simple economics

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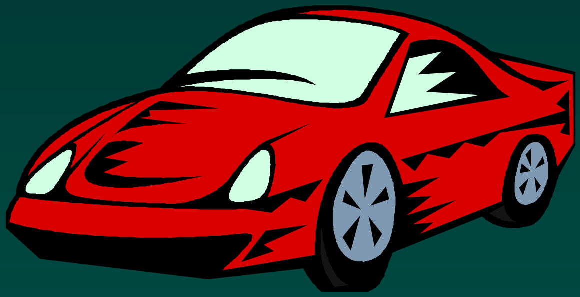
# Basic physics concepts

1. ***Energy can be neither created nor destroyed but it can be converted from one form to another.***

2. ***Some kinds of energy are more useful than other kinds because of their ability to do "work".***

# *Physics concept of "work"*



- Example: we need energy in the form of "work" to move a car or lift an elevator
- Energy comes in different forms
  - Energy in the form of heat (molecules randomly banging against each other) is contained in ambient air but energy in this form cannot be converted into work. No mechanism can be devised for extracting the thermal energy from the air around us and using it to move a car.
  - Energy in form of hot, pressurized steam can be partially converted into work. 200 years ago, James Watt developed a steam engine for this purpose. A steam engine can convert only 20-30% of the energy in the fuel used to generate the steam into work.
  - Energy in the form of electricity can be converted at almost 100% efficiency into work in a motor.



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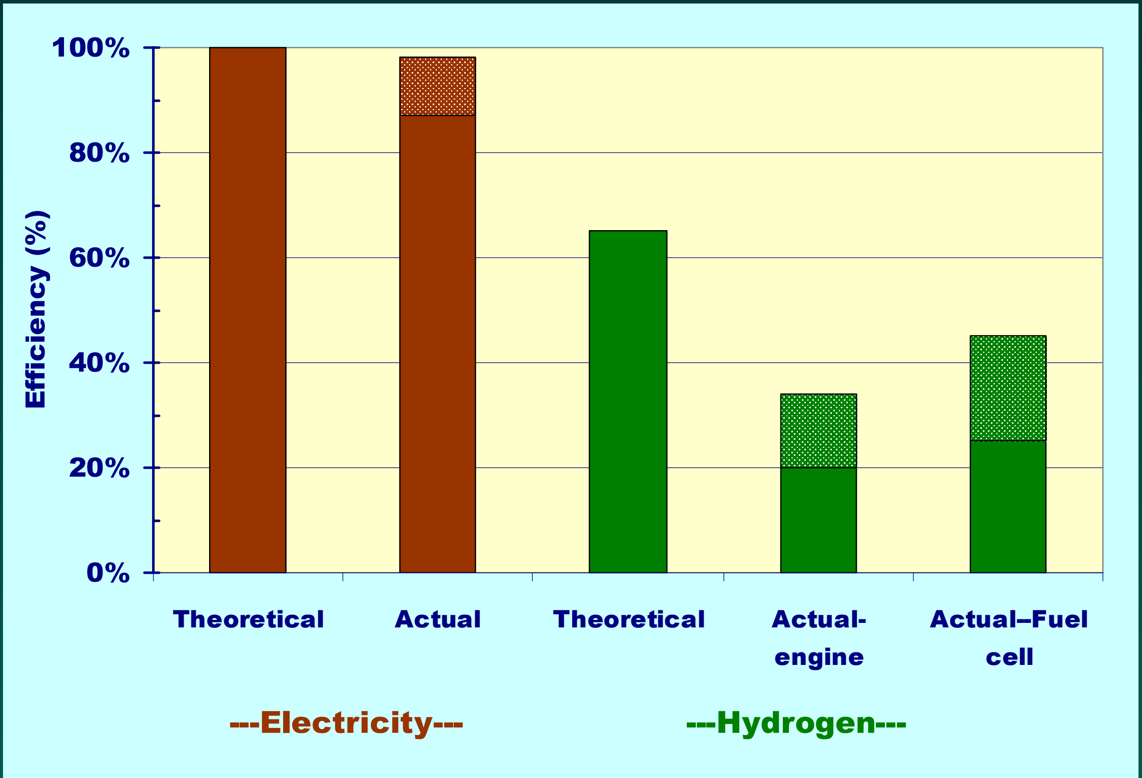
# Efficiency of conversion to work

- **Electric motors**
  - convert electricity to work at 88-95% efficiency
  - relatively inexpensive, compact, rugged, and highly reliable
- **Engines**
  - convert fuel (including $H_2$) to work at 20-38% efficiency
  - more expensive, less compact and less convenient than motors




- **Fuel cell/motor combination using hydrogen**
  - converts fuel to work at overall efficiency of 25-45%
- <u>Hydrogen is at a significant disadvantage compared to electricity in applications where energy is used as work</u>

*Note: See Chart 43 at end for sources of data used in this report.*

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# Electricity does it better/uniquely

| $H_2$ can't do | Electricity better at |
| --- | --- |
| Lighting | Refrigeration |
| Electronic equipment/computers | Heating/cooling |
| Appliances | Motors are cheaper & simpler than engines |
| Many industrial processes | |

- There are some end use applications that require electricity and cannot, in practice, use fuel
- For others, electricity—while not required—is the cheaper and more convenient alternative
- In terms of the variety of applications that can be served, electricity has considerable advantages over hydrogen



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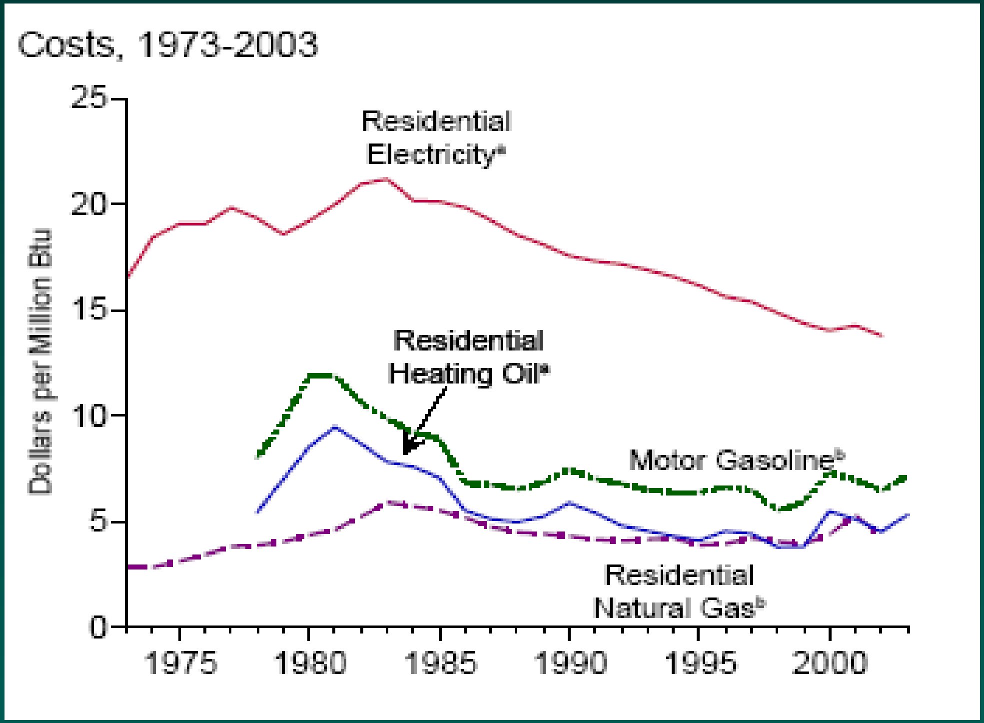
# Electricity is worth more than fuels




- Energy markets tell us that end users are willing to pay 2-3 times as much for electricity as for fuels
- Presumably, users are willing to pay more because electricity is worth more to them

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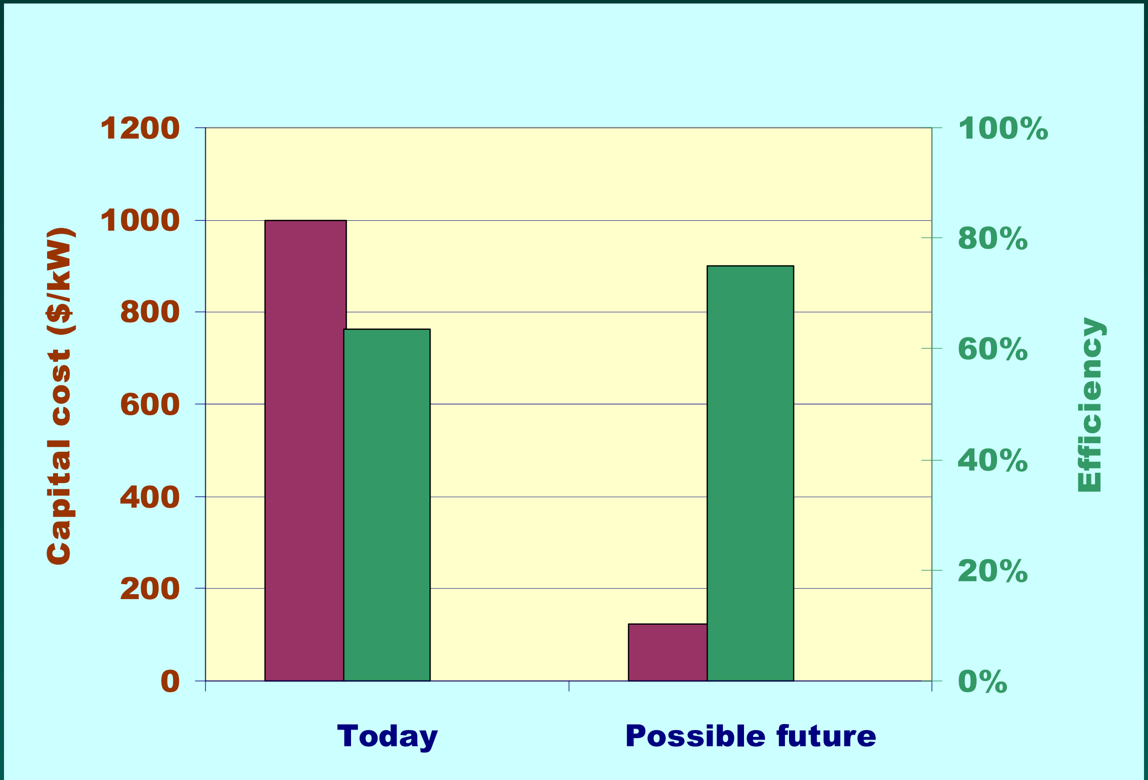
# Electrolysis




- Electrolyzers convert electricity to hydrogen
- Currently
  - capital cost of electrolyzers is very high—roughly the same as the cost of a powerplant
  - 1/3 of energy is lost in electrolysis
- Future potential
  - NAS says major improvement in capital cost is possible
  - However, at best, at least 25% of energy will be lost

- <u>To justify $H_2$ production from electricity, $H_2$ would have to be worth significantly more than the electricity from which it was produced yet the past history of energy prices is precisely the opposite</u>

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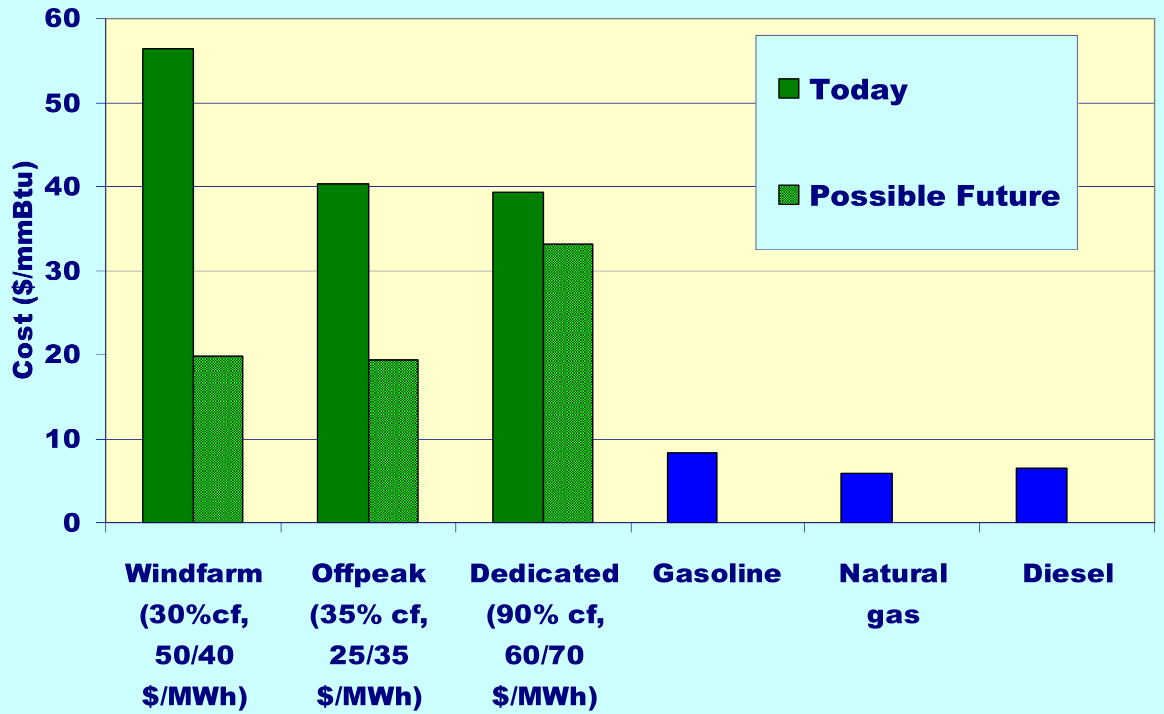
# Cost of hydrogen from electrolysis

- Consider 3 different electricity sources:
  - Wind farm: full output goes to $H_2$ production
  - Offpeak electricity: $H_2$ produced only when power prices are low
  - Dedicated powerplant
  - Compare to today's fuel prices
  - Does not include costs of transport & delivery of $H_2$




[cf= capacity factor of electrolyzer; xx/yy $/MWh = current/future cost of power]

- Key points:
  - Currently, $H_2$ from electrolysis costs 5-10 times as much as today's fuels
  - Even if the huge capital cost reductions projected by NAS are achieved, $H_2$ from electrolysis would still cost 2.5-6 times as much as today's fuels

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# Convert electricity to hydrogen?

- Intermittent resources are typically first converted to electricity
- A primary argument for the hydrogen economy is that electricity generated in these resources would be converted to hydrogen
- But, as a general proposition, converting electricity to hydrogen does not make sense

**Tough sell**

Make major capital investment for electrolyzers

Incur additional O&M costs

Lose >25% of the energy

Physics: $H_2$ has less value

Markets: $H_2$ worth only 33-50% as much as electricity



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# *Physics/economics—conclusions*

- Electricity is much more efficiently and easily converted to work
- Many end uses require electricity and cannot, in practice, operate using fuels
- Markets tell us electricity is worth 2-3 times as much as fuel
- As a general proposition, converting electricity to hydrogen doesn't make sense



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# Direct production of $H_2$ from coal

- Various chemical processes have been proposed and/or developed for converting coal into hydrogen
  - Depending on the process, $H_2$ could be either the sole product or a joint product along with electricity and/or other fuels
- Advantages
  - Coal is a plentiful energy resource (unlike oil and natural gas)
  - Overall energy efficiency is greater than that for a conventional coal-to-electricity power plant
  - Some of these processes produce carbon dioxide in a highly concentrated form, thereby greatly facilitating carbon sequestration, a major advantage with respect to reducing greenhouse gasses
- However . . .
  - Variations on these same processes can produce electricity or other fuels such as methane, without the production of $H_2$, while still achieving the advantages listed above
- Question is: What is the most valuable combination of products and should $H_2$ be part of the mix?



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# General purpose energy carrier?

- **Electricity**
  - Can be efficiently and easily converted into work
  - Versatile—can be used in a wide range of end-use devices
  - Convenient for the end user
  - Transport/delivery/end-use infrastructure in-place today
  - Storage is expensive today but technology is available and in commercial use
- **Hydrogen**
  - Substantial energy is lost when converted to work
  - Less convenient for end-user than electricity
  - Some end use applications, as a practical matter, cannot use
  - Requires that new production, storage and end use technologies be developed
  - No transport/delivery/end-use infrastructure
  - Can be stored but only at a loss in efficiency

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# Does $H_2$ have a role as a special purpose energy carrier?

Case A:
Intermittent resources



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# *Problem of intermittency*

- Wind and solar are intermittent resources
- Value of power from intermittent resources is less than the value of firm power
  - Capacity may not be there when needed
  - ISO needs to schedule more regulation and spinning reserves to accommodate intermittency so “ancillary services” costs are higher
- Economic hit to the generator is two-fold
  - Part or all of the capacity component of payment for electricity is lost
  - ISO passes on higher ancillary service costs to the generator
- *Next we look at the following issues related to intermittency:*
  - *When does intermittency become a problem for a utility?*
  - *Why not just incur the penalties associated with intermittency?*
  - *What about paying to have the power firmed up?*
  - *Is conversion to hydrogen a realistic alternative?*
  - *What other alternatives are there?*

# What are utilities doing today?

At penetration levels under 15-20%, utilities can accommodate intermittent resources in much the same way as they routinely deal with load variations

- Denmark today
  - 25% of electric energy and 60% of capacity from wind
  - There is no dedicated storage
- New Bonneville Power service
  - BPA will “firm up” wind power for $5/MWH
  - Wind power is delivered to BPA; BPA returns firm power
  - BPA uses its large hydro storage capacity to “store” the electricity
- Recent studies of various US utility systems conclude that ancillary service costs associated with wind are $0.17-5.5/MWH
  - Factor of 30 difference in results is very large; suggests further analyses needed to develop better estimates
  - At lower end of this range, the cost is *de minimus*
  - At high end, ancillary service cost still only ~10% of cost of windpower

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# Could hydrogen compete w/BPA?

**Option 1**

Pay BPA $5/MWH
(~10% of cost of wind energy) to firm up wind power

**Option 2**

Convert electricity to $H_2$
Lose 25-30% of the energy
Incur capital/operating costs for electrolyzers
End up with a fuel that has a lower value than the electricity you began with

- For the owner of a wind farm, using BPA service is far cheaper than converting electricity to $H_2$
- Today, only BPA is offering this service
  - BPA is offering the service to utilities which already buy power from BPA
  - However, any hydropower system with large seasonal storage can offer this service
  - This service could be offered to generators as well as utilities
- In general, this service can be offered using any type of storage—not just hydro—although cost would be higher



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# Other storage alternatives

- Electric storage technologies compete with hydrogen as a mechanism for dealing with intermittency
- Storage technologies in use today
  - Large-scale: pumped storage and large dams
  - Small-scale: batteries
- Potential future technologies for large-scale storage
  - Flywheels
  - Compressed air
  - Batteries

# The transmission alternative

- If intermittent resources exceed 20% of utility load, building new transmission lines is an alternative to converting electricity to hydrogen
- Transmission can distribute the intermittent resource across a broader load
- Transmission may also add to reliability and economic efficiency of the grid
- 200 miles of transmission costs $10-20/MWH*
  - This is approximately equivalent in economic value to the efficiency loss alone associated with converting electricity to hydrogen

** Assumes transmission line capacity factor of 30% (same as wind farm output); i.e., does not factor in benefits of multiple uses of the transmission line*



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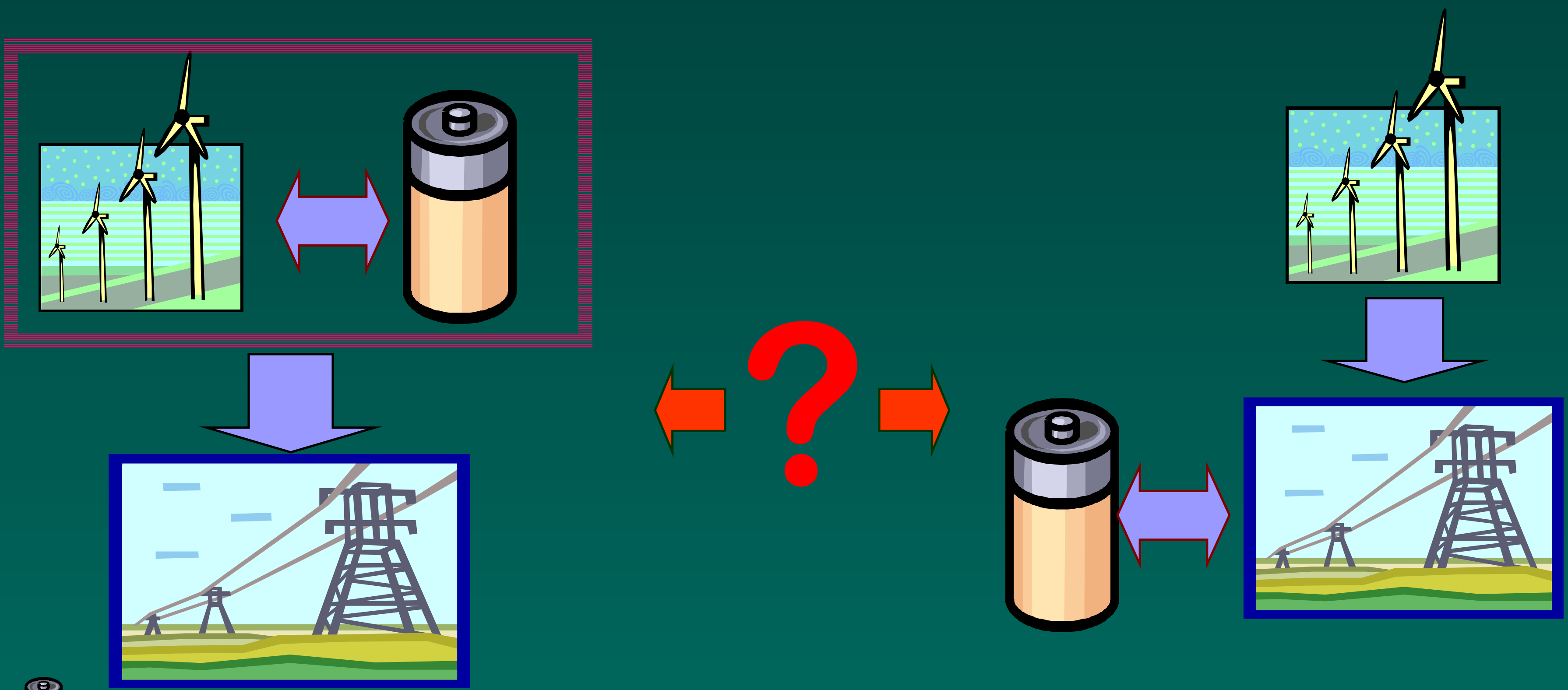
# *Does $H_2$ add value to wind farm?*

- **First consider which would be more profitable: dedicated or grid-connected hydrogen production**
- **Note that hydrogen and electrical “storage” (e.g., batteries, flywheels, pumped hydro) play similar roles in this application**




 **represents either hydrogen production or electrical storage**

# Economics of grid vs dedicated

- ISO pricing is critical issue:
  - If ISOs underprice capacity payments and overprice ancillary services charges to intermittent resource generators, artificial incentives are created for the installation of dedicated hydrogen or electrical "storage" systems
  - However, if ISOs price capacity & ancillary services to properly reflect the actual costs to the ISO of accommodating the intermittent resource, dedicated systems will not be competitive with grid-connected; grid-connection provides owners of these systems more options to make profitable use of their asset than they would have in a dedicated configuration
  - Potential investors will not take the "assumption of sustained stupidity" risk: *i.e.*, that the ISO would stubbornly maintain uneconomic pricing policies (upon which the profitability of the investment in dedicated storage would be predicated) over the 10-20 year life of their investment
- We have already demonstrated that grid-connected hydrogen generation is not economical; hence, with proper ISO pricing, dedicated is not economic either



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# Summary—intermittent resources

- With intermittent resource penetration levels less than 15-20%, utilities can deal with intermittency much as they do with load variations
- ISO pricing is critical factor
  - If ISO sets capacity and ancillary services prices rationally, it is cheaper for the generator to pay the added ancillary services charges or, where available, a special service charge to firm up the intermittent power than to add dedicated hydrogen or electric storage
- Transmission lines are a competitor to dedicated hydrogen or electric storage facilities



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# Does $H_2$ have a role as a special purpose energy carrier?

## Case B: Vehicular applications

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# $H_2$/electric compared to gasoline

- **Advantages of hydrogen fuel cell ($H_2$-FC)or battery electric (BEV) vehicles as compared to gasoline**
  - **Lower vehicle air emissions**
  - **Greater energy efficiency of on-board power system**
  - **Do not require petroleum or natural gas resources**
  - **Potential for greenhouse gas reduction, depending on energy resource used and the resource-to-energy carrier conversion technology**
- **Disadvantages of $H_2$-FC & BEV compared to gasoline**
  - **Cost, weight and volume of energy storage system is significantly greater than for gasoline**
  - **Hydrogen and battery storage technologies and fuel cell technology need substantial further development and cost reduction**
  - **Hydrogen production/delivery infrastructure does not exist**
- ***Next we compare $H_2$-FC to BEV with respect to***
  - ***Status of technology***
  - ***Weight and volume requirements***
  - ***Efficiency***



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# Status—hydride storage technology

- A variety of hydride materials absorb/release hydrogen in a reversible reaction and can serve as medium for storing hydrogen
- Hydride materials vary considerably in key properties:
  - Weight percent of hydrogen “stored” in hydride (typically <10%)
  - Weight of hydride per unit of hydrogen stored
  - Temperature/pressure at which hydrogen released
  - Rate at which hydrogen is absorbed/released
  - Energy lost when $H_2$ absorbed into storage medium
  - Energy that must be provided (as heat) to release $H_2$ from hydride
- <u>None of the hydride materials studied to date has an acceptable combination of performance characteristics and all are seriously deficient with respect to at least one characteristic</u>



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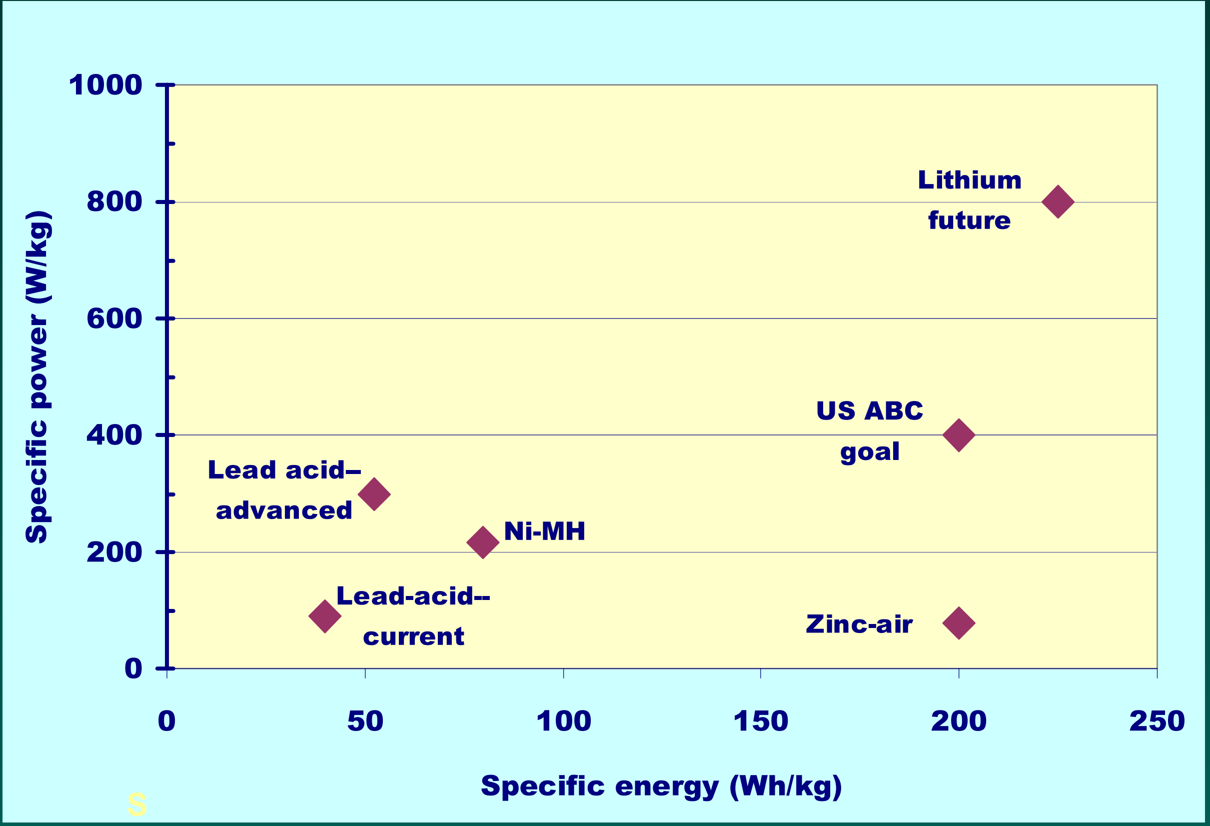
# Status—Battery technology

- Battery technology:
  - Key performance parameters for vehicular batteries are energy and power per unit weight
  - Performance characteristics of various battery technologies vary widely
  - Current hybrid electric vehicles (HEVs) use nickel-metal hydride (Ni-MH) batteries




- Lithium ion batteries
  - Performance is substantially better than other battery technologies
  - Performance exceeds goals established by US DOE Advanced Battery Coalition

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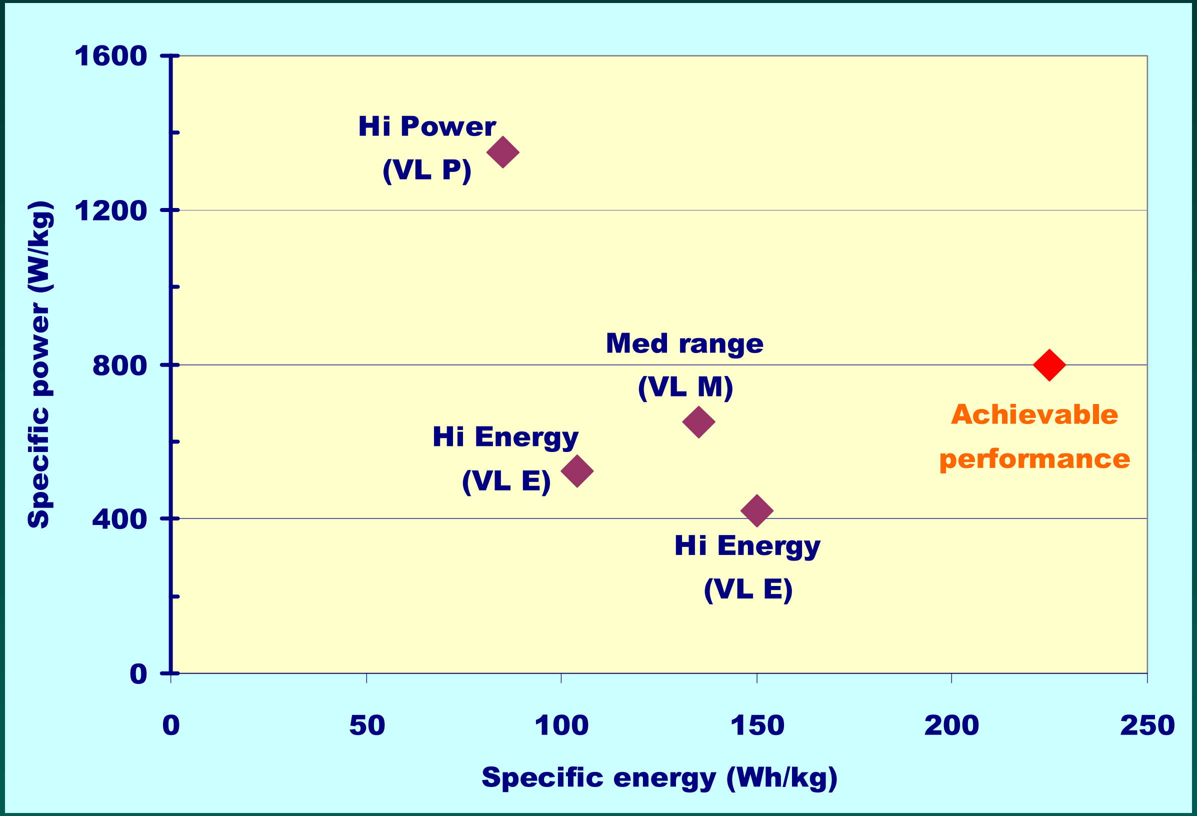
# Lithium battery potential

- Chart shows:
  - various cells currently available from one manufacturer (SAFT) are shown in graph
  - projected performance




- Li-ion technology:
  - has advanced rapidly in recent years
  - widely used in PDAs, cell phones, computers
  - does not require exotic or costly materials
  - Performance is acceptable for BEV
  - Cost is very high but substantial reductions can be expected
  - Long-term durability & cycle life not yet demonstrated
- <u>Li-ion battery poses difficult challenge to $H_2$-FC technology</u>

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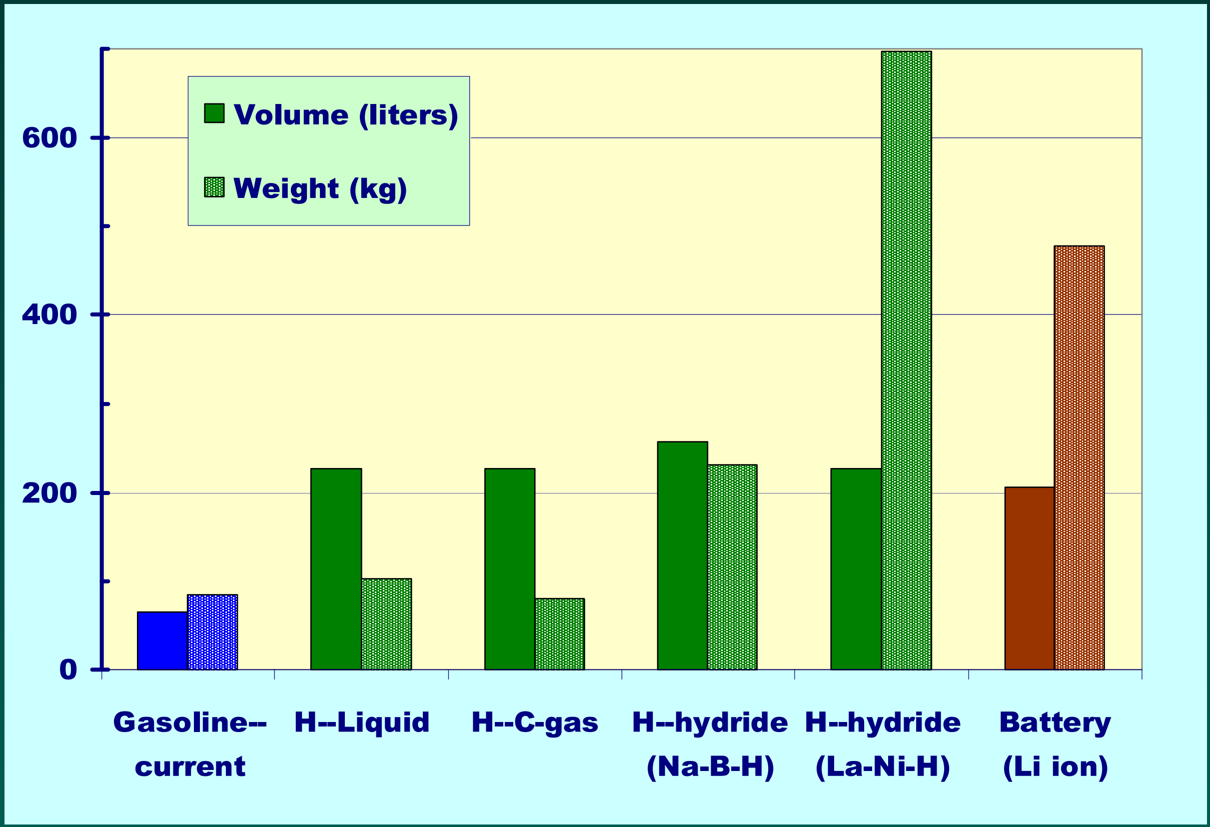
# Weight & volume comparisons

- **Assumptions:**
  - Driving range in all cases equivalent to current gasoline cars
  - Volume & weight adjusted for differences in powerplant efficiency
  - Weight & volume are for entire storage system (including storage vessel) but do not include power powerplant




- **Key Points:**
  - Liquid and compressed gas (C-gas) $H_2$ both have weight advantage over batteries
  - Volume requirements for electric & $H_2$ storage systems are similar; both are several times greater than gasoline storage volume
  - Weight of hydride storage systems vary greatly, depending on hydride material; some hydrides are substantially heavier than batteries

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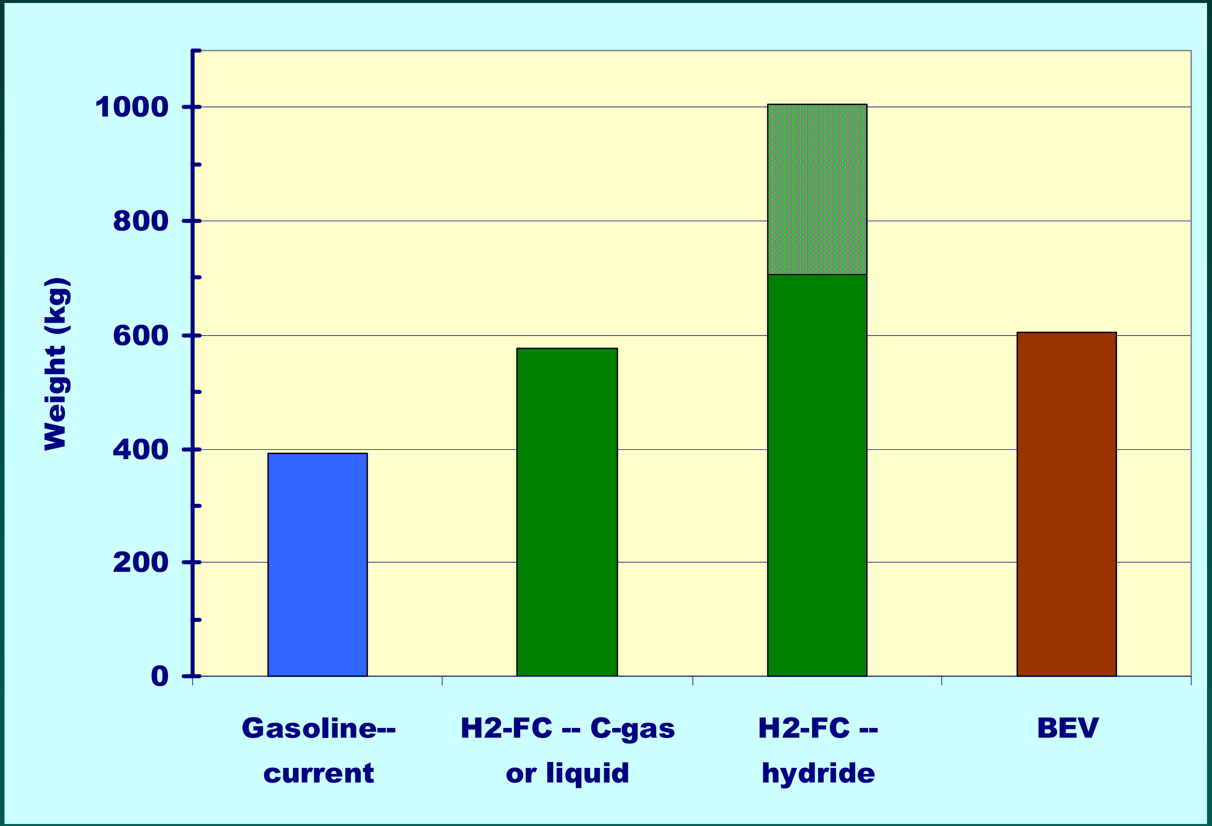
# Total propulsion system weight

- Compare weight of entire propulsion system including storage for
  - Current gasoline engine
  - $H_2$-FC using C-gas or liquid storage
  - $H_2$-FC using hydride storage
  - Li-ion based BEV
- Assumptions:
  - All vehicles comparable in size and range to current mid-size sedan




- Key points:
  - Overall propulsion system weight of BEV using Li-ion batteries is comparable to liquid and compressed gas $H_2$ systems
  - Depending on hydride material, cars with hydride storage may be substantially heavier

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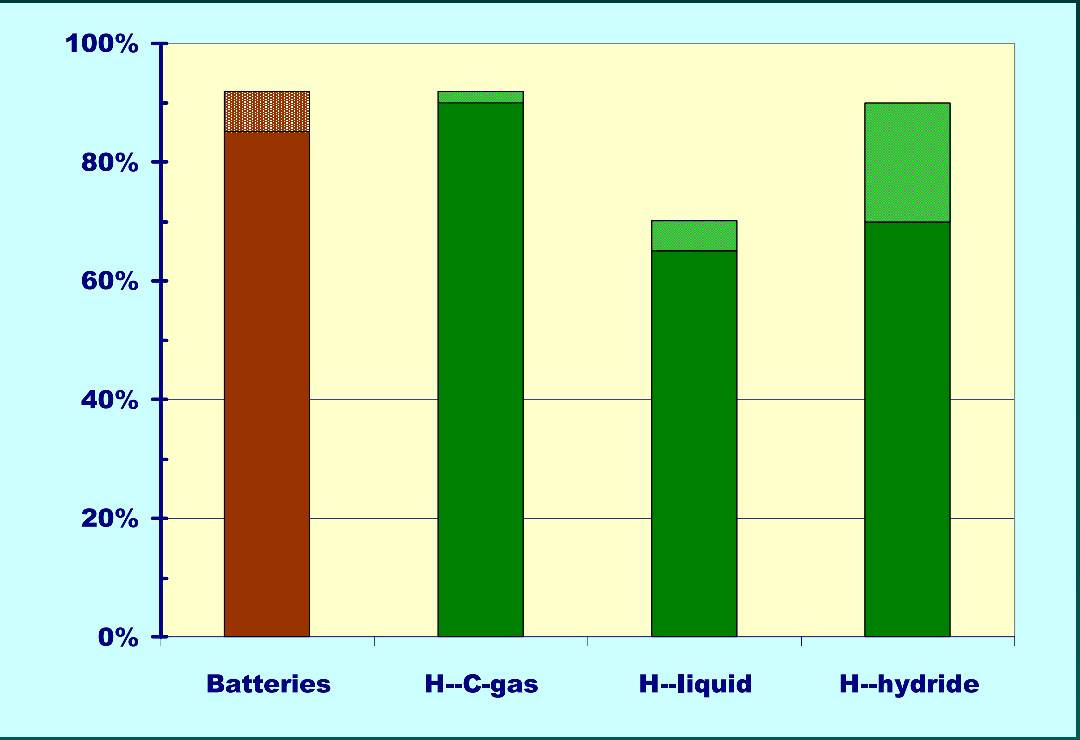
# Charge/discharge efficiency

- What is the efficiency of the charge/discharge cycle for $H_2$ and battery storage systems?
- Assumptions:
  - Exhaust heat from $H_2$-FC is sufficient to release $H_2$ from storage; no additional fuel is consumed to release $H_2$
  - Effect of regenerative braking not included
- Key points:
  - Losses in liquefaction of hydrogen are unacceptably high, effectively ruling out this storage alternative
  - Efficiencies of Li-ion batteries and of C-gas $H_2$ systems are comparable
  - Hydride materials vary considerably in the charge/discharge efficiency
  - Regenerative braking can recharge batteries, recapturing energy otherwise lost, thereby increasing overall efficiency of electric systems by 10-15% (not included for purposes of this chart)--this option is not available with $H_2$-FC systems

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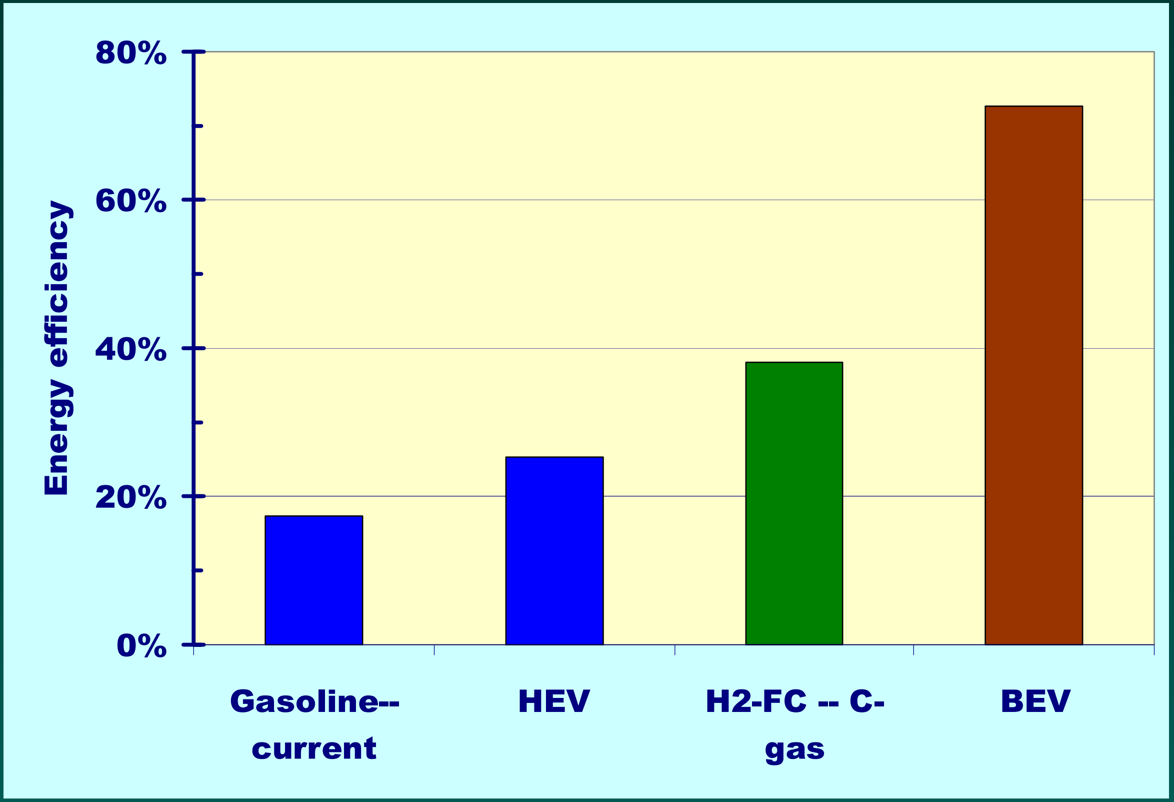
# Overall vehicle efficiency

- **Compare vehicles:**
  - Current gasoline
  - HEV (gasoline)
  - $H_2$-FC using compressed gas hydrogen storage
  - BEV using Li-ion batteries
- **Assumptions:**
  - Include energy required to charge/discharge storage system (including charger in case of BEV) as well as energy used in propulsion system




- **Key point:**
  - BEV is considerably more efficient than $H_2$-FC system

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# $H_2$-FC technology gaps

***[Findings of American Physical Society report regarding a hydrogen/fuel cell vehicle]***

1. *"None of the current [hydrogen engine] technologies are competitive options for the consumer. The most promising H-engine technologies require factors of 10 to 100 improvements in cost or performance . . . ."*
2. *"No material exists to construct a hydrogen fuel tank that meets the consumer benchmarks. A new material must be developed."*
3. *"There are enormous performance gaps. Incremental improvements to existing technologies are not sufficient to close all the gaps. . . . major scientific breakthroughs are needed."*



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# *Critical conclusions—vehicles*

- BEV
  - Primary remaining obstacle: cost of lithium ion batteries must be reduced substantially
  - Electric delivery infrastructure exists although battery exchange stations would be helpful to facilitate “recharge” on long trips
- $H_2$-FC vehicle
  - Overall vehicular energy use is twice that of BEV
  - Multiple technological obstacles:
    - fuel cell performance
    - fuel cell cost
    - hydrogen storage system
  - There is no hydrogen production and delivery system



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# *Hydrogen as an energy carrier?*

- **Hydrogen does not pass the test posed in Chart 9**
  - **It is not competitive with electricity because of electricity's greater versatility, ease of use, efficiency of conversion to work, and existing infrastructure.**
- **Nor does is hydrogen likely to be a special purpose energy carrier:**
  - **<u>Integrating intermittent resources into utilities:</u>**
    **Conversion of the electricity generated by these resources into hydrogen is unlikely to be competitive with other options for dealing with intermittency.**
  - **<u>Vehicular fuel:</u>**
    **Lithium-ion batteries are the first battery technology to provide the performance characteristics required for an acceptable BEV. Costs of these batteries are currently too high and need to be reduced substantially.**
    **Given the huge efficiency disadvantage of $H_2$-FC vehicles compared to BEVs and the multiple technological obstacles still facing $H_2$-FC technology, BEVs are much more likely to penetrate the vehicular sector than are vehicles using $H_2$-FC .**



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# Data sources

| Chart # | Sources<br>*(Numbers in brackets refer to References listed in Chart 45)* |
|---|---|
| 13 | Theoretical conversion efficiency for hydrogen based on thermodynamic limit. [1] provides efficiency for current and projected fuel cell technologies. Actual engines: high end of range taken from performance of large diesel-generators; low end taken from efficiency of conventional gasoline engines. |
| 15 | Cost graph taken from [2]. |
| 16 | [1] discusses current and projected costs and efficiency of electrolysis systems. |
| 17 | Electrolysis system costs and efficiencies taken from Chart 16. Current gasoline, natural gas, and diesel fuel costs are from [2] Costs and capacity factors of wind generated electricity, off-peak electricity and dedicated power plant are from author. |
| 24 | [3], [4], and [5] review recent utility studies of the impact of windpower on electric utilities. |
| 25 | See [6]. |
| 27 | Transmission cost calculations by author assume $1 million per mile costs of transmission line and project financing, and 30% utilization of line corresponding to capacity factor of wind farm. |
| 33 | Hydride and other solid hydrogen storage systems are discussed in [7] (scientific and technical discussion of various methods of hydrogen storage) and [8] (detailed technical discussion of storing hydrogen in solids, including hydrides). |
| 34 | [9], [10], [11], and [12] have broad information regarding performance parameters for a variety of battery technologies. [13], [14],[15] and [16]have information regarding recent developments in lithium ion batteries. [17] provides a projection of the ultimate performance capability of lithium ion batteries. |



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# Data sources (cont.)

| Chart # | **Sources** *(Numbers in brackets refer to References listed in Chart 45)* |
|---|---|
| 35 | [14] provides the current commercial offerings of SAFT for several types of lithium ion batteries. Achievable performance taken from Chart 34 |
| 36 | [18] provides the weight and volume parameters for compressed gas, liquid, and solid hydrogen storage systems including the vessel and compares these to a conventional gasoline system. See also [19]. Additional data regarding hydride systems was obtained from [7] and [8]. Weight and volume were adjusted for the relative propulsion system efficiency |
| 37 | [20] provides the total weight of propulsion system for various technologies normalized to driving range of existing conventional gasoline vehicles. Fuel cell weight was adjusted to strip out incremental improvements projected by authors to retain consistency with treatment of other technologies shown in chart. Hydride system estimate developed by author using incremental additional weight of hydride systems (range shown due to large variations in weight of hydride storage systems). |
| 38 | [21] discusses charge/discharge performance test results for lithium-ion cells. Battery charger efficiency is provided in [22]. [1] provides energy losses associated with compressing and for liquefying hydrogen. Reaction to form hydride is endothermic so no external energy is required to form hydride. Energy is required to reheat liquid hydrogen or disassociate hydrogen from hydride, it is assumed to be provided by waste heat from the fuel cell and no external energy is assumed to be consumed. |
| 39 | [1], [9] and [19] provide overall relative propulsion efficiency of $H_2$-FC vs existing gasoline engines. [9] and [21] discuss propulsion system and drive chain efficiency of BEVs taking into account regenerative braking. |
| 40 | These quotes are taken from [23] |

# References


1. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, National Research Council and National Academy of Engineering, National Academy Press Washington DC, available in pre-publication form at http:://books.nap.edu/books/0309091632/html/
2. US DOE Energy Information Administration.
3. Wind Power Impacts on Electric-Power System Operating Costs, JC Smith (Nexgen Energy LLC), Presented at American Wind Energy Association's Global Windpower 2004 Conference, Chicago, Illinois
4. Windpower and Wholesale Markets: An Evolutionary Approach, E Mainzer (Bonneville Power Administration), Presented at American Wind Energy Association's Global Windpower 2004 Conference, Chicago, Illinois
5. California RPS Integration Study: Phase I Summary and Results, M Milligan (National Renewable Energy Laboratory), Presented at American Wind Energy Association's Global Windpower 2004 Conference, Chicago, Illinois
6. BPA Wind Integration Services available on the internet at www.bpa.gov/Power/PGC/wind/BPA_Wind_Integration_Services.pdf
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