Institute for Lifecycle
Environmental Assessment
P.O. Box 22437
Seattle, WA 98122-0437
www.ilea.org

EXECUTIVE SUMMARY

Carrying the Energy Future

Comparing Hydrogen and Electricity for Transmission, Storage and Transportation

by Patrick Mazza and Roel Hammerschlag

Proposals to construct a new hydrogen energy system on the scale of the power grid are coming to the forefront. U.S costs alone are estimated at $200 billion-$500 billion. Such vast investment implies other energy pathways not taken, with ramifications for crucial issues including climate change and energy security. The envisioned hydrogen system must be considered in the larger context.

The keystone to understanding the proposed system is that hydrogen is an energy carrier, not an energy source. As with the only other commonplace energy carrier, electricity, hydrogen must be made. Almost all hydrogen on Earth is trapped in bonds with other elements which must be broken to make hydrogen an energy carrier. This requires energy.

Sustainable energy visionaries have long foreseen electrical generation by wind, sun or other renewable sources as the perfect source for this energy. The electricity feeds an electrolyzer which uses current to break hydrogen from oxygen in water. Electricity is later recovered when those two elements re-join in electrochemical reactions on the electrode of a fuel cell.

Since President George Bush announced his hydrogen car initiative in 2003, many environmentalists have perceived a hidden agenda to instead promote H_2 derived from fossil and nuclear energy. Indeed, 95% of hydrogen produced for merchant markets today is derived from heating natural gas, while coal gasification with deep geologic storage of carbon is under exploration as a future source. A new generation of nuclear reactors capable of generating temperatures high enough to break water's bonds is also envisaged.

An electrical and transportation system based on renewable hydrogen (ReH_2) is an attractive prospect. Renewable generation is theoretically limitless. It would not be subject to supply constraints facing natural gas. Unlike coal it would not require mining or risk carbon leakage into the atmosphere. It would face none of nuclear energy's waste disposal or safety issues.

But in the real world limits prevail. A critical question is how to leverage limited renewable resources for maximum environmental benefit, in particular for reduction of carbon dioxide (CO_2) emissions from fossil fuel burning that are the leading cause of global warming. Using renewable electricity to generate hydrogen would reduce global warming emissions. But other uses of the renewable energy can reduce emissions much more, while technologies that employ electricity directly provide greater end use benefits than H_2 technologies.

A transparent means to understand relative benefits of hydrogen and electricity is energy efficiency analysis. It clarifies how much useful work is derived from equivalent amounts of energy. Energy efficiency is also a more appropriate measure than economics when exploring longer term pictures. Economic projections tend to be subject to a greater degree of flux and uncertainty.

Renewable Hydrogen: Difficulties in the Dream

ReH_2 is envisioned as a means to transmit remote renewable resources to distant markets. A recent analysis of a commonly cited prospect, Great Plains wind fields, revealed hydrogen's significant disadvantages. The study compared transmission of 4,000 megawatts of wind generation to Chicago via H_2 pipelines or high voltage direct current lines.

Line loss is 8%. Pipeline energy consumption is 12%, a relative wash. But hydrogen requires additional conversion steps. Electrolysis consumes 10-15% of the original electricity. Re-converting H_2 to electricity takes 30-40% of remaining energy. Taking all penalties into account, only 45-55% of original energy remains compared to 92% if transmitted as electricity. Wind energy sent as electricity provides roughly twice the end use benefits as wind energy delivered as H_2.

Localized hydrogen generation is posed by others, to overcome hurdles of deploying a massive H_2 pipeline infrastructure. Electricity sent over wires runs hydrogen fueling station electrolyzers. Yet this scenario faces similar penalties. A highway hydrogen fueling station handling 2,000 cars per day requires 3,500 gigajoules (GJ) of energy delivered as H_2. Smaller electrolyzers, with only 80% efficiency, need 4,400 GJ of source electricity to make the H_2. Pumping water to the electrolyzer draws 130 GJ and H_2 compression takes 530 GJ. Total station energy use is 5,100 GJ. Average line loss of 10% brings source energy requirements to 5,600 GJ. By the time that energy reaches the fuel tank, only 63% remains. With 60% fuel cell engine efficiency, only 38% of the original energy is available to run the vehicle. The power load to fuel 2,000 cars is similar to that of the tallest skyscrapers or most sprawling institutional campuses. Widespread local H_2 production would require a massive expansion of the power grid.

ReH_2 energy penalties are well understood by hydrogen economy proponents. Nonetheless, hydrogen remains on the table because it is viewed as capable of providing services where direct electricity is seen as falling short - transportation and energy storage. But the electrical carrier medium offers competitive options.

Energy Storage: Hydrogen vs. Other Options

The electric grid is synchronized to generate power as it is used. Making intermittent renewables such as wind and sunlight available on demand will require energy storage. Hydrogen is only one of the options. Others at or near commercialization include:

Conventional batteries - Advanced options include lithium-ion (Li-on) and liquid (molten) sulfur batteries.

Flow batteries - Based on liquid salt solutions, two types are closing in on commercialization, vanadium redox and zinc bromide.

Compressed air energy storage (CAES) - Air is pressurized and pumped into underground geological structures. Energy is recovered when compressed air is fed through a gas turbine, dramatically increasing turbine efficiency.

Pumped hydro - Water is pumped to a higher reservoir when energy is generated and run through a hydroelectric plant into a lower reservoir - With 90 gigawatts of capacity worldwide, the oldest and most deployed storage technology.

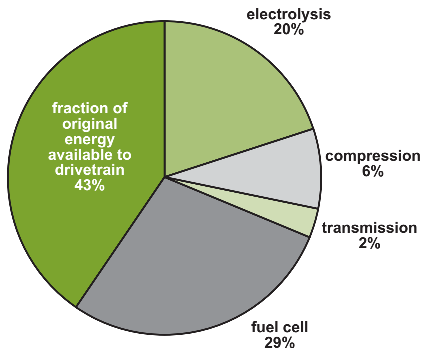
The accompanying table compares these options to hydrogen, giving H_2 very generous assumptions of 90% electrolyzer efficiency, compression efficiency of 92% at 350 bar and 60% fuel cell efficiency. Combined heat and power (CHP) increases hydrogen cycle efficiencies using waste heat from the fuel cell.

	energy efficiency
Li-ion battery	85%
sodium sulfur battery	75%
flow batteries	80%
CAES at 300 bar	75%
pumped hydro at 500 m	75%
H_2 in 350 bar tanks	47%
H_2 in geologic formations	47%
H_2 at 350 bar, 10% CHP	51%
H_2 at 350 bar, 50% CHP	66%

Envision two wind farms. One 100-turbine operation stores energy at 75% efficiency using conventional technology. The second, which uses H_2 storage at 47% efficiency, would need 160 turbines to provide the end-use energy of the first. Other storage options deliver far more of the economic and environmental benefits of intermittent renewables than H_2.

Future Cars: Electricity Might Beat Hydrogen

H_2 energy inefficiencies and a costly new infrastructure might be acceptable in the context of climate change, petroleum supply stress and national security concerns. All indicate the need for a new vehicle fuel. H_2 is seen as a natural successor to petroleum, and fuel cell vehicles (FCVs) the replacement for internal combustion technology. Another option is carbon-emissions-free electricity to propel battery electric vehicles (EVs).

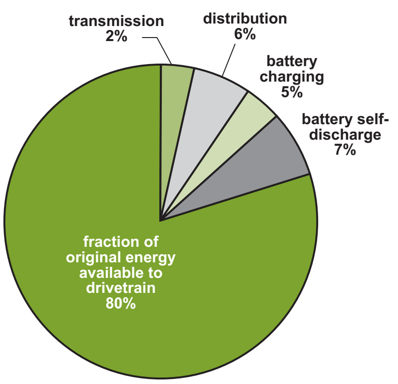


Energy losses in FCV fuel chain

The relative inefficiencies of H_2 vis-à-vis direct electricity detailed in earlier sections play out in vehicle technology, as detailed in the accompanying chart comparing relative losses along the fuel chain. In effect, using electricity directly rather than converting it into H_2 yields twice the miles per kilowatt hour.

Yet conventional wisdom has it that the EV is a technological dead-end hobbled by limited range and extended recharging times. Recent EV market development efforts have met only limited success. But advanced battery technologies could change the picture. EVs might meet the needs of a more substantial share of the market than is commonly understood.

Lithium ion batteries developed for portable electronics are now the favored advanced EV technology. Commercial Li-ion battery packs can store electricity at an energy density about six times greater than conventional lead acid batteries. A Li-ion battery can be expected to retain over 90% of its capacity after 500 full discharges. Battery life in typical driving could approach 10 years. Argonne National Laboratory projects an EV mean range of 360 kilometers (km) by 2020, with polymer lithium ion batteries the prevailing choice.



Energy losses in EV fuel chain

High-range advanced technology EV prototypes are already emerging. Electrovaya, which markets polymer Li-ion laptop batteries, uses the technology in its Maya-100 EV claiming a range of 360 km. It plans commercial production as the Maya-200. The 2003 Michelin Challenge Bibendum verified a 390-km range for AC Propulsion's Li-ion tzero sports car.

To make Li-ion EVs commercially viable costs must drop by a factor of three. Yet at least a tenfold reduction will be required for fuel cells. Batteries outcompete hydrogen in price, safety, calendar life and gross material availability. On cycle life, recyclability and toxicity, fuel cells do not show decidedly superior performance. A chart comparing all these aspects is available on pages 23-24 of the full report.

One developing option that can take advantage of EV efficiencies without range and charge time limitations, at or near market competitiveness today, is the plug-in hybrid electric vehicle (PHEV). Hybrids on the market today run much of the time on electric drive. Their large batteries are kept charged by small, on-board engines. PHEVs have even larger batteries that draw charge from both an on-board engine and, like a pure EV, from the power grid.

A PHEV with a nickel metal hydride battery, used in hybrids today, could go up to 100 km on grid power before the charging engine is needed. Driven a U.S. average number of miles each day over a 160,000 km lifetime, the PHEV would burn around 2,500 liters of gasoline, compared to 11,000 for an HEV without plug-in capacity or 15,000 liters for a conventional vehicle. Charged nightly with electricity generated in a typical new, natural-gas plant, the PHEV reduces lifecycle CO_2 emissions 60%. Lifetime expenses would be $2,500 more than the conventional vehicle. With a 32 km battery range PHEV lifetime costs would be $1,200 less.

PHEVs fueled with bioethanol could run free of global warming emissions. Made from cellulose, the stuff of most plant matter, bioethanol offers zero net carbon emissions and far larger potential feedstocks than today's starch-based ethanol. Running the U.S. vehicle fleet entirely on bioethanol could require around 110 million square kilometers, well within the scope of the farmland Conservation Reserve. A comparable fleet of highly efficient PHEVs would require even less territory.

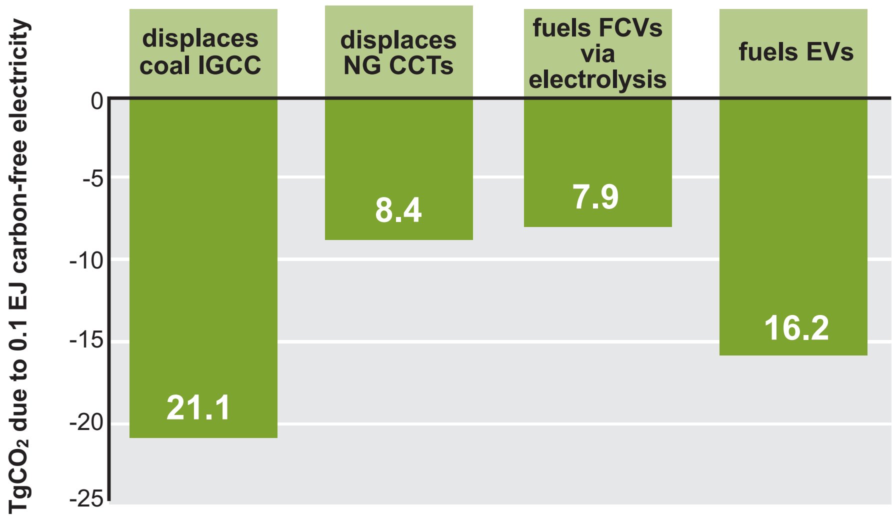
Crucial distinctions must be made between hydrogen and fuel cells, and between vehicle and building applications. While an H_2 fuel system is hindered by multiple inefficiencies, fuel cells can be important components in highly efficient systems that convert biofuels or fossil fuels to electricity. Fuel cells can operate as stationary electrical generators, potentially at significantly higher efficiencies than central power stations or other distributed generators. Emergence of a substantial fuel cell market is in no way conditioned on mass application in vehicles or development of an H_2 network.

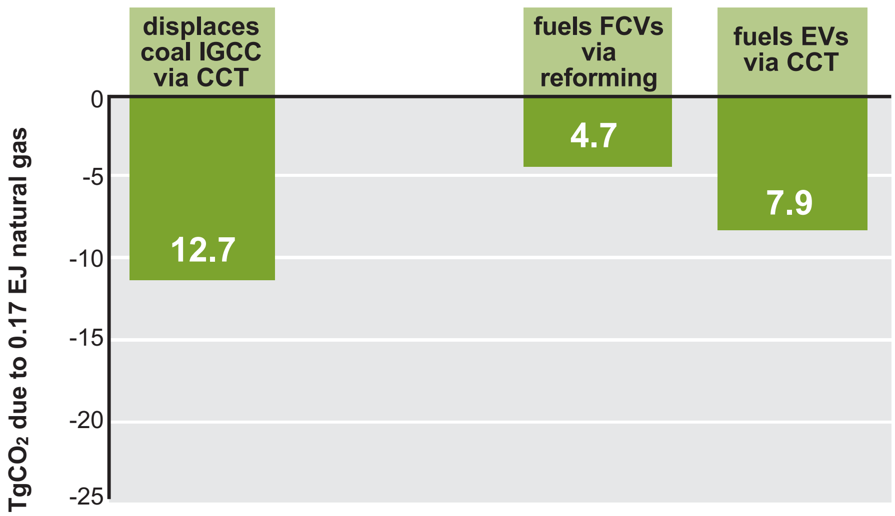
Directing Energy for Greatest Climate Benefit

The world's most authoritative body of climate scientists concludes that 55-85% reductions in greenhouse gases are necessary to stabilize atmospheric concentrations. It is crucial that renewables are utilized to greatest effect. But, as seen in the top bar graph on the back page, CO_2 reductions from applying renewable electricity to hydrogen manufacture fall far short of the CO_2 reductions from applying renewable energy in other ways.

The graph compares technology options reasonably expected to prevail within the timeframe ReH_2 might become generally available: natural gas combined cycle turbines (CCTs), integrated gasification combined cycle (IGCC) coal plants, and cars which run the equivalent of 50 miles per gallon of gasoline. Displacing coal-fired electricity with new renewables generates the greatest CO_2 reductions. Clearly, priority for renewables should be to avoid coal power generation.

Because ReH_2 faces significant economic barriers, hydrogen derived from natural gas is seen as a transition until renewable energy becomes cheap and abundant. But the bottom chart shows that natural gas could eliminate significantly more CO_2 by displacing coal





power with CCTs. Another notable result is that natural gas directed to charging EVs cuts CO_2 more than the equivalent amount used to make H_2 fuel for FCVs.

Conclusion: Finding Common Ground

In key roles envisioned for H_2 as an energy carrier - transmission of remote renewable resources, storage of intermittent renewables and vehicle fuel - electricity offers more energy efficient options that might preclude mass-scale emergence of H_2 technologies. In selecting energy pathways, the superior efficiencies of the electrical carrier medium must be taken into account when determining how our limited renewable electrical resources should be allocated. Climate stabilization demands we "get the most bang for the buck" from renewables. Even when renewable electricity becomes cheap and abundant, land use and other environmental impacts of major renewables installations will continue to exert limits.

At the same time, complementary pathways could support hydrogen and electricity. Potential common ground includes:

Rapid expansion of renewables - If ReH_2 is ever to be feasible, it will require an abundance of low-cost renewable generation.

Hybrid vehicle technology - Hybrid "big battery" systems are being developed for fuel cells as well as internal combustion. The new options all incorporate electric drive, so much complementary development is possible.

Vehicle-to-grid applications - All "big battery" cars could provide energy storage for the power grid. This will require technologies to manage large numbers of energy storage and generating devices, as well as economic models that provide car owners with incentives to participate.

Biomass - Similar feedstocks are proposed to feed production of both liquid biofuels and of hydrogen based on biological processes. Development of biomass collection and cropping is of general benefit.

The debate on hydrogen will continue, but it need not preclude broad cooperation to develop sustainable energy technologies that serve multiple agendas. The emergence of climate change represents a compelling call to undertake collaborative efforts.

Avoiding catastrophic impacts on the global atmosphere will require immense quantities of carbon-free energy. The difficulties of supplying sufficient amounts will only intensify with rising populations and standards of living. This is the essential context in which the future roles of hydrogen and electricity must be explored if humanity is to meet the critical challenges facing it this century.

The full report, with references, is available at www.ilea.org.