PERSPECTIVES FROM THE FIELD

Beyond Oil: Economic and Ecologic Options with Hydrogen-Based Energy Use and Storage

Thomas von Unwerth,
Feras Al-Saleh,
Abdelwahhab Al-Kharabsheh

What's beyond oil? This question is leading to one of the most important debates these days. Even if oil resources are only decreasing slowly (but surely), other options to power the future are essential in consideration of climate changes due to greenhouse gas emissions. An obvious solution can be found looking at the perpetual solar energy supply, especially in regions with high availability of sun irradiation. Converting this renewable energy with wind turbines or photovoltaic or solar power plants is common by now. But storing and using the electric energy generated with these technologies is quite difficult because of low energy densities obtained from current battery technologies. By contrast, hydrogen energy storage has the advantage of its higher energy density. It can be used, for example, for auxiliary power units (APUs) in combination with fuel cell systems, for powering automotive fuel cell–based drivetrains, or for local energy supply in fuel cell power plants. Additionally, hydrogen can be transported easily by trucks or pipelines even over long distances and can be distributed and sold. From the economic perspective, with hydrogen and fuel cells some interesting business models can be developed. Investing in hydrogen production and storage equipment, fuel cell systems for APUs and vehicle drivetrains, or a hydrogen infrastructure, return on invest can be seen some years ahead by selling hydrogen or fuel cell systems to national and international customers with increased ecologic responsibility. Finally, in spite of the longer energy conversion chain for hydrogen compared to pure electrical energy storage, hydrogen with the described advantages generated from renewable energies used in fuel cells is definitely an economic and ecologic chance for a greener future.

A look at historic world energy consumption reveals a trend toward increased energy demand, and the forecasts show the same or even steeper gradients of energy consumption due to growing world population and higher individual demands for prosperity, health, and safety (Figure 1). Overall seven *megatrends* could lead to immense ecologic and economic consequences:

- Climate change and climate sustainability
- Resource shortages
- Increasing mobility of the population
- Urbanization and megacities
- Globalization and individualization
- Population growth and changing social structures
- Demand for wealth, health and safety

Regarding these trends and taking into account that fossil resources are not endlessly forthcoming, the need for other energy options is growing more and more important. Furthermore carbon dioxide from combustion processes that use oil, gas, and coal (carbon-based energy carriers) impact climate conditions. Other than greenhouse gas emissions, nuclear power also entails environmental risks from radiation of its waste products.

Accordingly, solar power is the only viable option for a sustainable energy supply among wind, water, biomass, and other renewables generated by the sun. Nowadays, only very little of the available solar energy is used by conversion into other forms of energy like electricity. One reason for this is the constantly shifting amount of energy being generated, mostly available when it's not needed, leading to short operating times and uneconomic conditions for power plants. Figure 2 shows the large quantity of sun energy available and its use.

One solution is storing the energy generated from renewables in batteries. The latest generation of batteries is suitable: when

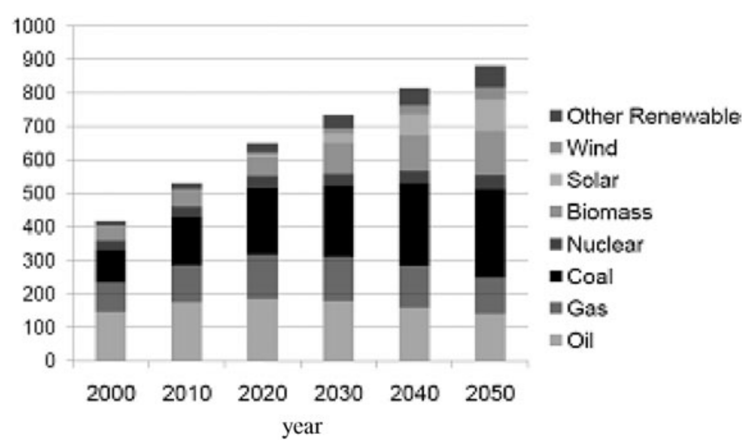

Figure 1. World primary energy input 2000–2050 (International Energy Agency, 2008).

doi:10.1017/S1466046611000536

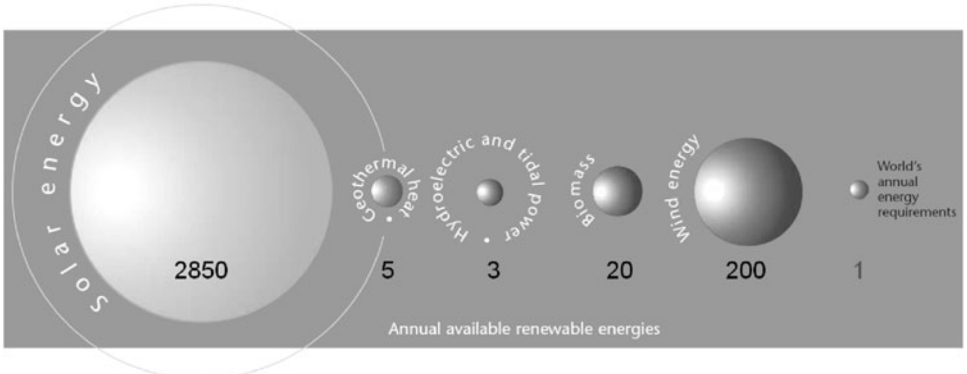

Figure 2. Annual renewable energies compared to world energy requirements (Fischedick, Langniß, and Nitsch, 2000).

placed near the power generation site or even transmitted over longer distances at high voltage levels, electricity can be stored and subsequently used with low transportation and conversion losses. Finally, from this solution is preferable an ecologic perspective.

On the other hand hand, most options for energy storage are ecologic if the energy source is renewable, as with hydrogen. Hydrogen can be produced from electricity, as well, of course, with the disadvantage of lower overall efficiency because of the additional conversion losses compared to immediate storage in batteries. But its use in combination with fuel cells also produces only water, with no harmful emission. And it offers convincing advantages: not only can hydrogen be stored at higher energy densities, it can be transported anywhere and produces water if used in a fuel cell. A brief comparison is presented in Figure 3.

Figure 3. Comparison of mass and volume for energy storage with hydrogen, batteries, and fuel (Von Helmholt and Eberle, 2007).

Using Solar and Wind Energy for Hydrogen Production

The Hashemite Kingdom of Jordan is an ideal country to invest in many strategic fields that are vital to the human life and the environment. Jordan is a safe, secure, and stable country, which is a primary issue that attracts investors and encourages them to invest their money and expertise in projects that will provide a high return on their capital. Along with its secure political and economic environment, Jordan's climate is ideal for solar, wind, and geothermal energy farms

The common and essential sources of energy nowadays are fossil fuels, which are neither renewable nor environmentally friendly and are nearing the end of their availability. Thus, many researchers looking for an alternative to fossil fuels have found that hydrogen gas is an ideal substitute that fulfills global requirements and answers most of the questions related to the issue of energy.

Why hydrogen?

Hydrogen is the first element in the periodic table and is the simplest of all chemical elements. It is a colorless, odorless, tasteless gas that burns in air to produce water. It has one of the lowest boiling points, −252.9°C (−423.2°F), and freezing points, −259.3°C (−434.7°F), of all elements. It is the most plentiful element not only on earth but in the universe, accounting for 90% of the universe by weight. However, it is not commonly found in its pure form because it readily combines with other elements, and is most commonly found in combination with oxygen in water and in organic matter, including living plants, petroleum, coal, natural gas, and other hydrocarbon compounds. The great attraction of hydrogen is that, once isolated, it is a clean-burning fuel, producing neither carbon dioxide (a greenhouse gas) nor toxic emissions, and can be used for electricity

	Wed 25-08	Thu 26-08	Fri 27-08	Sat 28-08	Sun 29-08
min	30 °C	29 °C	27 °C	27 °C	28 °C
Max	41 °C	40 °C	40 °C	41 °C	41 °C
Sun	85%	85%	90%	90%	90%

Figure 4. Example of the weather in Aqaba in August.

production, transportation, and other energy needs.

Hydrogen's net calorific value is 3.00 kWh/Nm³ = 10,8 MJ/Nm³, which is very high and feasible for energy production worldwide.

Generating hydrogen gas requires energy, and, to be totally environmentally friendly and economic, an energy source should be renewable, such as solar, wind, and geothermal energy, which returns us to the question, why Jordan? Jordan has an average of 3,800 hours of sunlight per year, with an average of 10 hours of sunlight per day, as shown see Figure 4. And this average improves in the eastern part of the country.

Hydrogen Production, Storage, and Transportation

Hydrogen is only a carrier and thus needs to be produced and applied in combination with a primary energy source. Optional sources include fossil fuels, and renewable or nuclear energy. However, in combination with nonpolluting energy sources such as water, wind, or solar power, energy generated by hydrogen is more advantageous in that consumers would soon benefit from the extraordinary contribution of an innovative combination of energy production, storage, and conversion in large-scale applications that are environmentally friendly. The use of hydrogen in homes and gas stations will become feasible.

Renewable energy sources have the disadvantage of not being perpetually sustainable, storable, or transportable. The production of energy from hydrogen, however, enables this. With the aid of fuel cells, stored hydrogen can be converted

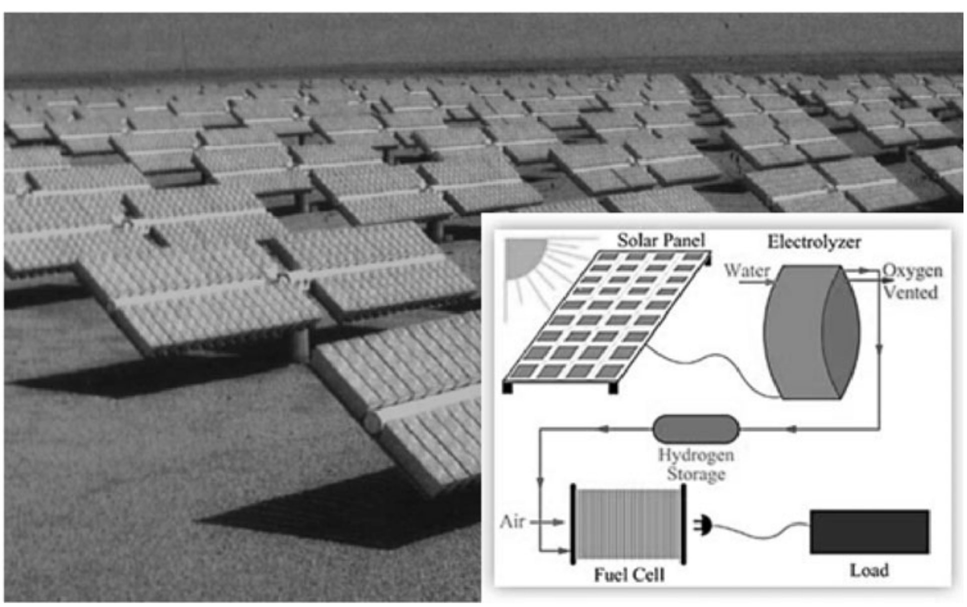

Figure 5. Photovoltaic generation of hydrogen.

https://doi.org/10.1017/S1466046611000536 Published online by Cambridge University Press

Figure 6. Transport options for hydrogen (Air Products, n.d.).

into environment-sparing electricity to meet demand.

Methods for manufacturing hydrogen vary, such as steam reforming natural gas, gasification of biomass and water, and wind or photovoltaic electrolysis. However, water electrolysis is the only worthwhile possibility for producing hydrogen commercially on a large scale in an environmentally friendly manner.

The production of hydrogen on offshore wind farms offers the possibility of applying this technology most effectively (Altmann and Stiller, 2001). By means of electrolysis, hydrogen is separated from desalinated seawater. The hydrogen can be either condensed for transmission by pipeline or liquefied for storage and transportation. In countries like Saudi Arabia and Jordan that possess enormous solar resources, solar energy can be exploited to produce storable hydrogen by means of photovoltaic-electrolysis plants (Brinner and Steeb, 2001) (Figure 5).

The transportation of hydrogen depends on the demand. Small needs are supplied mostly in gas bottles. Medium gas demands are met by means of tube trailer (Figure 6).

For larger supplies, liquid hydrogen is more advantageous. Liquid-hydrogen containers used for this purpose can be transported by truck, rail, or barge. However economic studies have proven that the most effective way to distribute hydrogen is by pipeline so that it can be either used or converted to suit different demands.

Hydrogen Applications

Like any other energy, hydrogen can be used for several applications. Most efficient is the conversion of hydrogen into electricity by use of fuel cells. There are different types of cells, suitable for different applications (Figure 7). High-temperature fuel cells are used mainly for stationary applications, whereas low-temperature fuel cells are used for portable or mobile applications.

These cells as electrochemical energy converters are not limited by the Carnot efficiency η_c like combustion engines (a comparison is shown in Figure 8). The theoretical upper limit is the thermodynamic efficiency η_{th}, according to the fuel cell type, up to more than 90%. In a fuel cell system with all its components, efficiency can still reach 60% and more.

Because of the high energy density of stored hydrogen, its conversion by use of fuel cells is most suitable for mobile applications. This means not only full electric drivetrains but also auxiliary power units. A comparison of energy density for different types of fuel is shown in Figure 9.

Fuel Cell	Electrolyte	Operating temperature	Electrical efficiency	Fuel oxydant
Alkaline Fuel Cell AFC	Potassium hydroxid (KOH) solution	Room temperature to 90°C	60 – 70 %	H_2 O_2
Proton Exchange Membrane Fuel Cell PEMFC	Proton exchange membrane	Room temperature to 80°C	40 – 60 %	H_2 O_2, Air
Direct Methanol Fuel Cell DMFC	Proton exchange membrane	Room temperature to 130 °C	20 – 30 %	CH_3OH O_2, Air
Phosphoric Acid Fuel Cell PAFC	Phosphoric acid	160 – 200°C	55 %	Natural gas, bio gas, H_2, O_2, Air
Molten Carbonate Fuel Cell MCFC	Molton mixture of alkali metal carbonates	620 – 660°C	65 %	Natural gas, bio gas, coal gas, H_2, O_2, Air
Solid Oxide Fuel Cell SOFC	Oxid ion conducting ceramic	800 – 1000°C	60 – 65 %	Natural gas, bio gas, coal gas, H_2, O_2, Air

Figure 7. Main types of fuel cells (H-TEC Systems, n.d.).

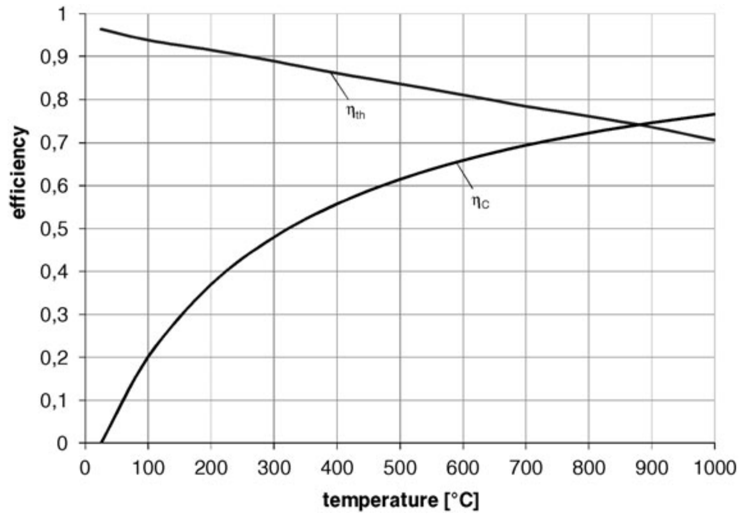

Figure 8. Thermodynamic efficiency η_{th} of a polymer electrolyte membrane (PEM) fuel cell compared to the Carnot efficiency η_c of a combustion engine (ambient temperature, 25°C).

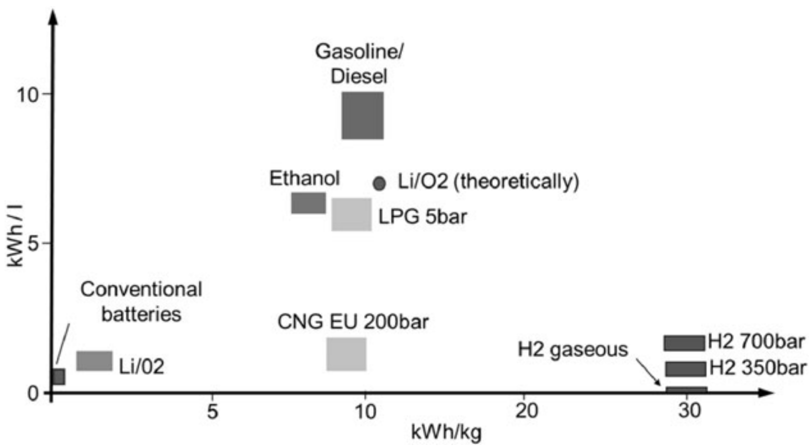

Figure 9. Gravimetric density and volumetric energy density for different types of energy storage (without a system).

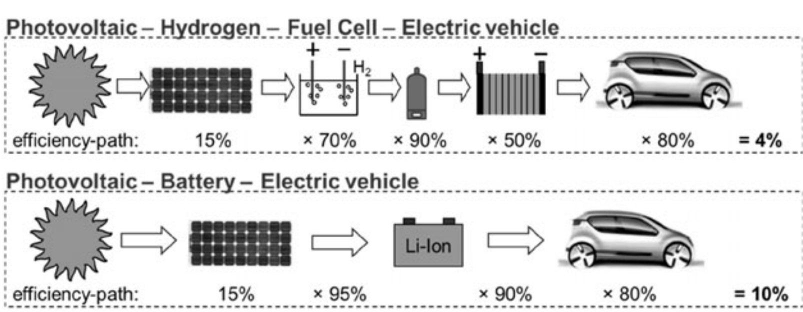

Figure 10. Well-to-wheel efficiencies for a battery and a fuel cell–powered vehicle.

Of course, a battery inside a fully electric car has the advantage of better overall well-to-wheel efficiency (Figure 10).

But hydrogen affords the possibility for driving longer distances and, even more important, the vehicle can be reloaded very quickly. Figure 11 shows that, although hydrogen filling is still not as fast and comfortable as fossil fuels, it is much faster than electric charging.

Another application can be found in auxiliary power units (APUs) or backup power units. For example, APUs are suitable for large trucks. Instead of running big combustion engines to power electric devices while idling with additional noise and emissions and very low efficiency, fuel cells can bring an ecologic and economic benefit. They run almost silently with high efficiency because of their adapted power scale, and produce only water, which could be a pleasant by-product for a driver in hot, arid regions.

Because of the high ambient temperatures in this scenario, a special fuel cell type could also be suitable: the high-temperature polymer electrolyte membrane (PEM) fuel cell. It is a derivate of the PEM fuel cell, but working at a temperature of above 160°C instead of 80°C. This is made possible with another electrolyte, based on phosphoric acid instead of water, inside the membrane. Its higher operating temperature leads to easier heat management because of the higher temperature gradient between the fuel cell and ambient. Additionally, it requires no humidification like the standard polymer electrolyte membrane PEM, which means no complicated water management.

Economic Options

Production of hydrogen from renewable sources and later back-conversion to electricity is a detour compared to immediate electricity use. But if energy is not used immediately and has to be stored, a buffer technology is needed. This could be batteries, whose current price is at around 1,000 euros (€)/kWh, to be reduced to 350 €/kWh in 2015 (SB LiMotive, n.d.). With an assumption of 10,000 life cycles, the price

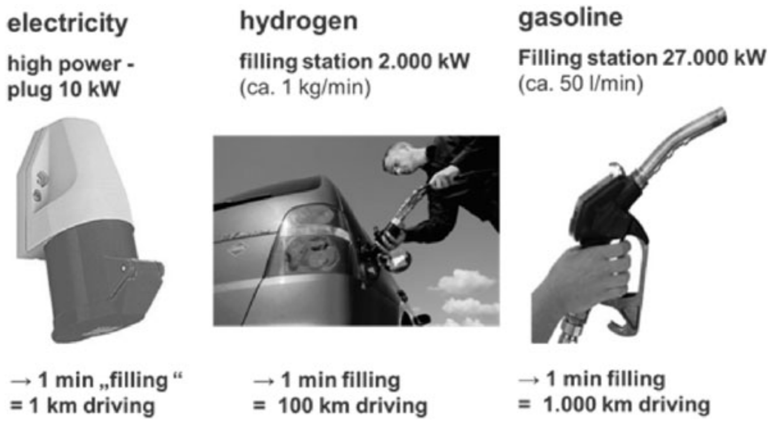

Figure 11. Filling process with electricity, hydrogen, and gasoline.

for stored electric energy is 0.1 down to 0.035 €/kWh. In comparison, hydrogen produced via electrolysis from wind turbines leads to a price of about 0.29 €/kWh (Linnemann, 2005). But in this case also improvements are under way; for example, high-pressure electrolysis, new storage materials, and innovative production processes for cheaper storage vessels.

Nowadays, countries all over the world are searching for new mobility and energy supply options. In fact, electric power combined with electric mobility is *the* future technology. Almost all car manufacturers seem to have electric vehicles on their road maps: first, battery-powered vehicles for short ranges like in megacities and then fuel cell vehicle fleets with hydrogen aboard for long-range mobility.

Everyone knows that the use of electric energy, and thus hydrogen, is the only power source that makes sense ecologically, if generated from renewables. But where will it come from? That's the opportunity available for early investors who recognize the need for hydrogen as a source of transportable, storable, fillable, and at last cheap energy.

Conclusion

When investment is considered in research for the issues discussed in this article, hydrogen infrastructure plus fuel cell technology is an economic (return on invest) and ecologic (emission free) option for a sustainable future energy supply. Hydrogen can power the future, so investment in further technological improvements in hydrogen energy is an investment in future profits.

References

Air Products. N.d. *Tiefkalte, verflüssigte Gase im Tankwagen*. Air Products and Chemicals, Bochum, Germany. http://www.airproducts.de/bulkgases/fluessiggase/index.htm.

Altmann, M., and C. Stiller. 2001. *Wasserstofferzeugung in Offshore Windparks*. Studie für GEO Gesellschaft für Energie und Oekologie. TÜV SÜD Industrie Service, Munich. Available at http://www.netinform.de/H2/Recherche/HM/HM.aspx?ID=1204.

Brinner, A., and H. Steeb. 2001. *Das Deutsch-Saudiarabische Technologie-Entwicklungsprogramm HYSOLAR*. Institute of Vehicle Concepts, Stuttgart, Germany, 13 pp. Available at http://www.dlr.de/fk/Portaldata/40/Resources/dokumente/publikationen/Hysolar_Brinner_2002.pdf.

Fischedick, M., O. Langniß, and J. Nitsch. 2000. *Nach dem Ausstieg: Zukunftskurs erneuerbare Energien*. S. Hirzel Verlag, Stuttgart, Germany, 208 pp.

H-TEC Systems. N.d. Lübeck, Germany. http://www.h-tec.com.

International Energy Agency (IEA). 2008. *World Energy Outlook 2008*. IEA, Paris, 569 pp. Available at http://www.iea.org/textbase/nppdf/free/2008/weo2008.pdf.

Linnemann, J. 2005. Kosten der H_2-Erzeugung aus Wind-Energie. In *Bunsen Kolloquium: Kosten der Wasserstofferzeugung aus Windenergie*, Colloquium of the Deutsche Bunsen-Gesellschaft für physikalische Chemie, Schwerin, Germany, June 16–17, 2005, 12 pp. Available at http://images.energieportal24.de/dateien/downloads/hydrogen/planet-h2-kosten.pdf.

SB LiMotive. N.d. Pressemitteilungen-online. SB LiMotive, Stuttgart, Germany. http://www.pressemitteilungen-online.de/.

Von Helmholt, R., and U. Eberle. 2007. Fuel Cell Vehicles: Status 2007. *Journal of Power Sources* 165:833–843.

Address correspondence to: Feras Al-Saleh, Jordanian Renewable Energy Society (JRES), Amman-Abu Nsair; (phone) 00962 6 5240095; (fax) 00962 6 5240096; (e-mail) feras.alsaleh@yahoo.de