Decentralized and direct solar hydrogen production:
Towards a hydrogen economy in MENA region

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Abstract:

As an energy carrier, hydrogen has certainly some attributes in spite of its high cost and low efficiency when compared to electricity and liquid fuel. Solar energy is an abundant, clean and renewable source of energy, currently competing with fossil fuel for water heating without subsidy. Electricity production from photovoltaic or thermal processes is about five times more expensive than conventional power generation, although it has reached the 10 GW/year of installed capacity. Photo-electrochemical, thermo-chemicals and photo-biological processes for hydrogen production processes have been demonstrated with a lot of room for improving their cost structure and efficiency in the future. These decentralised hydrogen production using solar energy do not require expensive infrastructure in the short and medium terms. Integrated desalination and hydrogen production plant is feasible in the MENA region. In the long term, synthetic fuel from CO_2 could compete with fuel cell car and petrochemistry for hydrogen utilisation. Thus, MENA region could certainly be considered a key area for a new start to a global deployment of hydrogen economy.

Keywords: Hydrogen-Solar-Decentralized-Integration

I. Introduction

In spite of the hype and significant public and private investments, it's fair to say that the hydrogen economy [1] has not fulfilled its promises [2]. Indeed production, transport, storage and re-conversion to useable power still face significant technical and economic challenges [3-5]. Furthermore, social, environmental and economical impacts of a large scale hydrogen economy deployment have not been yet properly evaluated [6].

There is no competitive and reliable long term alternative to the current petroleum based economy. This situation will likely continue to prevail in the forceable future. The hydrogen economy requires the development and maturation of numerous technologies before it could challenge petroleum and electricity as energy vectors. A transition from a petroleum (carbon) to hydrogen (carbon-less) based economy should be implemented stepwise with long term development plans for each technology. Secure sources of hydrogen, its packaging and delivery, and its practical applications remain areas of enormous attention (Fig. 1). A distributed, clean and renewable source of hydrogen as alternative to fossil fuel is critical in the short and medium terms. Fuel cell Car (FCC) utilisation is still a long term issue, requiring decades of development to challenge gasoline and battery powered cars (Fig. 1).

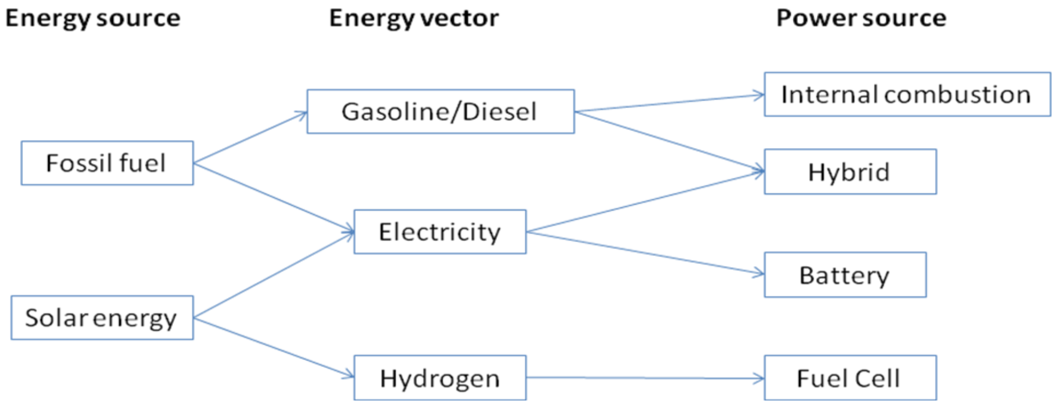

Fig. 1 Current and future energy sources for road vehicles.

Although hydrogen powered vehicles have no green house gas (GHG) emissions, a full life cycle analysis of the hydrogen production and utilisation shows that fuel cell powered car is not better than today's internal engine powered cars [7]. Furthermore, a Fuel Cell Car (FCC) is also much more expensive and less reliable than conventional cars, even when the safety factor related to the use of compressed hydrogen is discounted.

In today's era of terrorism fear, safety issues [5] is a major hurdle for any hope for an effective hydrogen economy implementation. On board production using methanol (or other liquid fuels) could potentially address this issue. In this case, we should talk more about methanol economy than a hydrogen economy [8]

With all its potential advantages as an energy vector, hydrogen has numerous issues related to its production, storage and distribution [9, 10]. First, a clean, renewable and cost effective process for hydrogen production is needed. Second, technical challenges and high cost for packaging and delivery of hydrogen will not be addressed in a short term. The last, not the least, issue is related to hydrogen conversion to electric power. Besides the cost and reliability of the PEMFC (polymer exchange membrane fuel cell), availability of Platinum catalyst remains an un-resolved issue [11].

Much attention has been paid to downstream aspects (storage and Fuel Cell) of hydrogen economy, ignoring important issues related to upstream aspects. It has been assumed that hydrogen will continue to be produced using large scale centralized natural gas reforming or electrolysis. Decentralized hydrogen production using direct solar-to-hydrogen conversion is probably the only sustainable and long term solution. Using renewable (wind) or non-renewable (nuclear) sources to produce electricity for electrolysis, is inefficient and costly in the long run.

Hydrogen is already used and will continue to be used in petrochemical industry. This is particularly true in areas with significant heavy oil reserves. There was so much focus on the environmental impact from oil powered vehicles and its replacement with low emission fuel cell powered cars, we forgot about existing applications of hydrogen. In particular, given the fact that large chemical and refineries are situated near high solar irradiation zones, it’s feasible to consider in the medium term replacing part of the fossil fuel hydrogen by solar hydrogen. Furthermore, CO_2 from these refineries and chemical plants could be transformed to a clean synthetic fuel after combining with hydrogen.

Hydrogen economy is currently envisioned within the same architecture with centralised production. Centralized production suites quite well petroleum given its high energy density. A decentralized production of hydrogen is more suitable given its lower energy density. With decentralized production of hydrogen, at least in the early deployment stages of hydrogen economy, there is no need for an expensive infrastructure for packaging and transportation of hydrogen. There are already numerous renewable technologies developed to produce hydrogen [12].

As an energy vector, hydrogen has some potential advantages over electricity [13]. With an outdate electric grid design, catastrophic blackout could occur more often in the future at the speed of electron. Hydrogen economy has complex challenges of its own related to hydrogen packaging and delivery. Hydrogen could be stored in different forms: gas, liquid or solid form. The gas phase storage in container or transported using existing natural gas pipelines. Liquid gas is stored in metal vessel at high pressures. In solid form, hydrogen is stored in metal hydrides. Today’s packaging solutions are not satisfactory.

Overall carbon footprint and energy efficiency of hydrogen value chain (production, packaging, transport, storage and transfer of elemental hydrogen) is not better than other energy carriers to warrant a near term transition [4, 14]. For long distance transportation hydrogen could offer some advantages when compared to electricity, although synthetic liquid hydrocarbons are probably better solutions. Development of a cost effective process to produce synthetic fuel from hydrogen and CO_2 could be then a viable long term solution.

Middle East and North Africa (MENA) region better known for its large but dwindling fossil fuel reserves is also endowed with one of the world highest level of solar irradiation per unit area. These two facts could help implement a smooth transition from a centralized oil-based economy to a decentralized hydrogen economy in this region. Our paper will provide a high level roadmap to support this transition. Institutional (market and political forces), academic (training), regulatory (safety, codes and standards) and financial (risk) obstacles are not discussed here. These issues are certainly very important for the hydrogen economy, but they are beyond the scoop of this paper.

II. Hydrogen production

Today, hydrogen is mostly used in refining, reforming and manufacturing of various chemicals. It’s also used as a reducing agent in metallurgy. More than 40 Million tons per year of hydrogen is consumed worldwide worth about $120 billions/year with nearly double digit yearly growth [15].

Only about 4% of hydrogen originates from water electrolysis requiring about 4kWh of electricity per m^3 of H_2. The rest is obtained from natural gas (48%), oil (30%) and coal (18%) [16]. This production process is not sustainable given the dwindling fossil fuel reserves. There are numerous alternative avenues for hydrogen production, but only few of them are potentially viable and practical [17, 18]:

- High temperature electrolysis based on an electrochemical dissociation of heated water with reduced electrical energy requirements.
- Photo-electrochemical based on photo-generated charges which will lead to an electrochemical dissociation of water at a semiconducting surface.
- High thermal water splitting: Thermal energy is used to heat and split water molecules at around 2000 °C or more.
- Thermochemical: A combined heat and chemical catalysts are used to split water at lower temperatures.

A recent technico-economic study showed that currently fossil fuel using large scale plants is the most cost effective [19]. Increased GHG emission combined with increased price of fossil fuel with declining reserves should make this option at best a short term solution. High cost of electricity is a significant hurdle for electrolysis process [19].

II.1. Hydrogen reforming

Hydrocarbon direct decomposition, partial oxidation and steam reforming remains the dominant process for hydrogen production [19-21]. These processes require high temperatures (around 1000 ^{o}C or more) and produce significantly more CO_2 as a product or by-product. Furthermore, theses hydrocarbon processes are energy and technology intensives.

Steam reforming retains the lion market share mostly for large scale production, although others technologies (electrolysis) are competing for small scale industries. Depending on raw fuel price and production process, H_2 production cost from natural gas is around $1-4/kg [19-22]. To this one should also add high delivery and packaging cost. With the total reserve estimated at 60 years at current consumption rate, natural gas reforming is certainly not the best long term solution. Hybrid processes that include heating using renewable sources could be considered as an option. Solar steam reforming allows 40% fossil fuel saving with about 20% extra expenses [23].

II.2 Electrolysis

It’s well recognized that the availability of an economical and clean platform for hydrogen production and storage will certainly provide a huge boost for the realization of the hydrogen economy dream scenario [9]. Indeed natural gas reforming is not the best long-term solution for low GHG emission hydrogen production. Hydrogen production using renewable and clean energy sources are possible alternatives. For example, electrolysis could be used to produce cleanly hydrogen at off-peak power. Hydrogen using electrolysis is about twofold more expensive than natural gas reforming [19,22].

Electrolysis could be a bridge technology for a sustainable hydrogen production. Even with electricity produced from clean and/or renewable sources such as wind [24, 25] and nuclear [26] will not address long term requirements for low cost and large scale production of hydrogen. With the resistance of local communities to larger wind towers and new nuclear power plants, it's not possible to consider expansion of wind and nuclear industries much beyond its current status. Furthermore, based on its maturity and the fact that current price structure is mostly based on high wind areas, it's unlikely to envision future cost reductions from wind power generation. The same could be said about nuclear. Indeed, the last decade we have seen a continuous increase in the cost of nuclear power generation by a factor of five or more [27].

Every kg of hydrogen necessitates around 40 kWh of electricity for a typical electrolysis setup. At a cost of 0.10/kWh, this makes the hydrogen production cost quite high ($4/kg). For example, nickel nanoparticle with an average size of 10 nm has been shown to enhance significantly hydrogen output and efficiency of hydrogen production using water electrolysis [28]. Numerous other nanonaterials have been recently developed to increase electrolysis efficiency, but their cost effectiveness and reliability are not yet demonstrated. With a current target of $2.00-3.00 per kg, including production, delivery, and dispensing of H_2, most renewable process are not economical [12]. Electrolysis of water using renewable sources requires electricity cost below 0.05/kWh to reach this target. This could be out of reach of solar, wind and nuclear power generation technologies.

Converting renewable sources to electricity and use electrolysis to produce electricity is not efficient. A penalty of around 50% is expected when on-site hydrogen power generation is considered. Indeed, the ratio of energy invested to the HHV (high heat value) of produced H_2 is about 1.5 when the hydrogen is delivered into 350 bar vehicle tank [4]. Thus even with a fuel cell efficiency of 50% and the electricity is obtained from a 40% fossil power plant, the overall well-to-tank efficiency is just about 10%.

Heat from solar and or other renewable sources could be used to improve efficiency of water electrolysis. Although possible, heat from nuclear reactor is not practical. Hydrogen production using high temperature electrolysis of water steam could reduce electricity consumption by up to 30 %, which could lead to cost reduction and GHG emission [29, 30].

II.3 Solar thermal

Five different solar thermal based routes have been explored in the past: solar thermolysis, solar thermo-chemical, solar reforming, solar cracking and solar gasification [31]. The last three options involves carbon based raw materials, will not be considered as a long term source of hydrogen.

Thermal cracking of natural gas, biomass and water using concentrated solar energy has been discussed for decades. With a global energy demand of $4x10^{20}$ J/year and hydrogen energy content of 11 GJ/m^3 H_2O, $3.6x10^{10}$ m^3 H_2O per year is needed, representing less than 0.1% of the total rainfall [32]. Thus, water is the best "raw material" for hydrogen production.

Direct splitting of water requires temperatures as high as 2500 K, difficult to implement at the industrial scale. Lower temperature water decomposition is obtained using chemical intermediaries. More than eight (over more than 20) thermo-chemical cycles have been developed and evaluated [33-34].

Sulfur-iodine is a very promising thermochemical cycle for hydrogen production. ZnO/Zn aerosol processing may provide the best example of all the thermochemical routes (Fig. 3). A two-steps thermochemical water splitting based on ZnO/Zn redox reaction has been investigated [35-37]. A first endothermic step using solar thermal produces oxygen and Zn(g) vapor following dissociation of ZnO(s) at above 2000 K. A second exothermic step produces hydrogen and ZnO(s) following a hydrolysis of Zn(l).

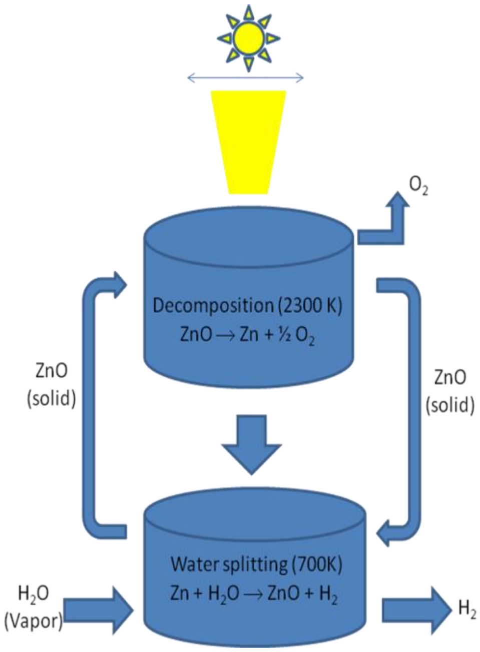

Fig. 3 Schematic representation of a two-steps process using ZnO and concentrated solar energy.

Commercial ferrites ($NiFe_2O_4$, $Ni_{0.5}Zn_{0.5}Fe_2O_4$, $ZnFe_2O_4$, $Cu_{0.5}Zn_{0.5}Fe_2O_4$ and $CuFe_2O4$) have been evaluated as alternative materials to ZnO in similar two-step thermochemical cycles [38]. A recent study comparing the economic value of solar hydrogen production using thermochemical cycles and electrolysis have been reported [39]. Hhydrogen production costs of 3.9–5.6 €/kg, 3.5–12.8 €/kg and 2.1–6.8 €/kg have been estimated for the hybrid-sulfur cycle, metal oxide based cycle and electrolysis respectively.

II.4 Photo-electrochemical

Solar photo-chemical and photo-electrochemical energy conversions is a long term option for meeting the world's future energy needs. Using solar photo-chemical and photo-electrochemical conversions, fuels, chemicals, and electricity could be produced with minimal environmental impact.

New photo-conversion systems based on nanoscale inorganic/organic assemblies (for example combination of organic dyes and zeolite A or L type, MeAlPO, ElAlPO) could help increase the overall efficiency and lower cost. Novel quantum size structures, such as hybrid semiconductor/carbon nanotube assemblies, fullerene-based linear and branched molecular arrays, and semiconductor/metal nanocomposites allow a more complete use of the solar energy spectrum. Understanding of factors controlling photo-induced long-range electron transfer, charge injection at the semiconductor/electrolyte interface, and photo-conversion in biomimetic assemblies for solar photo-catalytic water splitting is critical [40-42].

Photo-electrochemical cells (Fig. 4) is potentially the best long alternative for hydrogen production [41, 42], although this technology is currently inefficient. An efficient photo-electrochemical water splitting process using chemically modified TiO_2 has been recently reported [43], although this study is quite controversial. Numerous photocatalysts are also developed for both electrochemical and thermal water splitting [43-45].

Supported Cu_2O and CuO nanomaterials have been shown to catalyse hydrogen production when H_2O/CH_3OH solution was irradiated by UV or visible light [46]. This study also showed that UV light is an order of magnitude more efficient than visible, and CuO is about three times more photo-active.

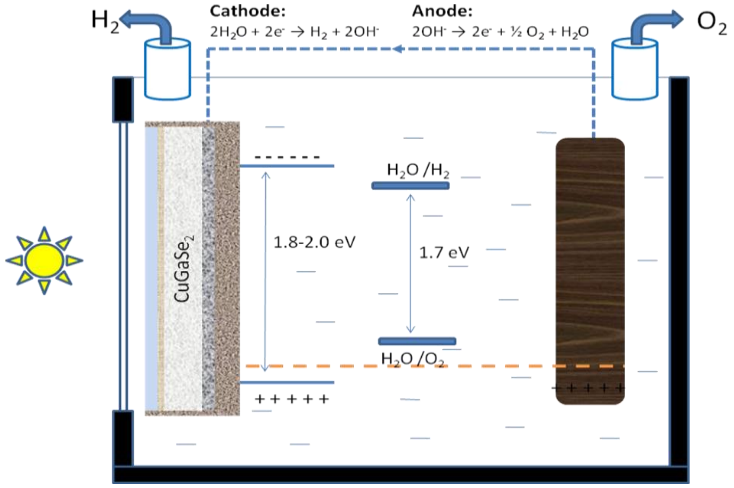

Fig. 4. Photo-cathode (alkaline electrolysis) electrochemical based Hydrogen production.

Improving efficiency and long term stability of active photo-electrodes remain the mains hurdles of photo-electrochemical based hydrogen production.

II.5 Photo-biochemical (bio-photolysis) process

This process is somehow similar to a photo-electrochemical cell. Under solar radiation, blue-green algae decompose water to form hydrogen with a potentially high efficiency up to 25%, although currently efficiency of only 2% is reached [47]. Issues related to produced oxygen during the first of the two-stage processes should be handled (Fig. 5). The overall reactor design is quite simple although a large surface area is required [47].

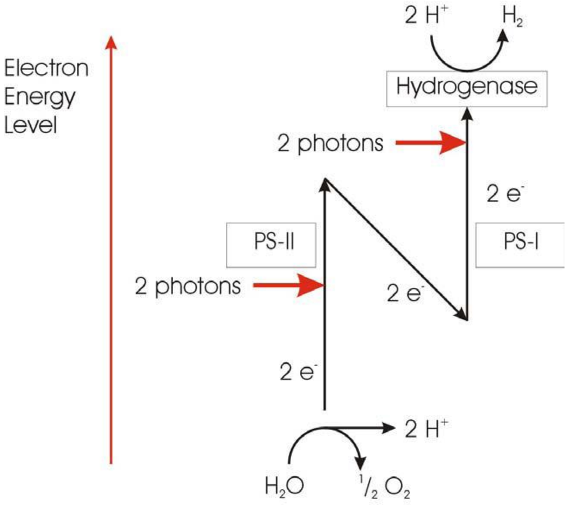

Fig. 5. Two-stage process of photobiological hydrogen production process [47]

Recent cost analysis showed that a selling price of less than \$4/kg is achievable with a reactor cost of \$10/m^2 [47].

III. Hydrogen transport, storage and dispensing

Even with a cost effective and sustainable production of hydrogen, storage and delivery present a significant hurdle with no fully satisfactory solution in sight. There are several issues that need to be addressed related to storage at the production and utilization site and transport/distribution of hydrogen. Whatever solution, safety must be a top priority.

Hydrogen distribution using pipeline is already in use within the petrochemical industry. Large scale hydrogen delivery through pipeline of hydrogen is quite equivalent to methane for distances less than 1000 km [4]. Large scale hydrogen transport by trucks, trains, ships is however highly risky and inefficient.

Hydrogen gas need to be compressed, liquefied or imbedded in hydride structures though chemical and/or physical reactions. Existing technologies are not satisfactory. There are several short and long term storage issues that need to be addressed:

- H_2 is a volatile gas with high energy content
- High storage system cost
- High weight and volume of current storage systems
- Low energy efficiency
- Inadequate durability
- Long refueling times
- Lack of standards and codes for equipments and operating procedures

As shown in Fig. 6, hydrogen packaging for fuel cell powered car is quite challenging. Compressed hydrogen tank of 700 bars with a hydrogen content in weight of about 11% is available [48]. Tank volume and safety issues could be addressed with low pressure liquefied hydrogen, although more than 1/3 of stored energy is lost during liquefaction [48].

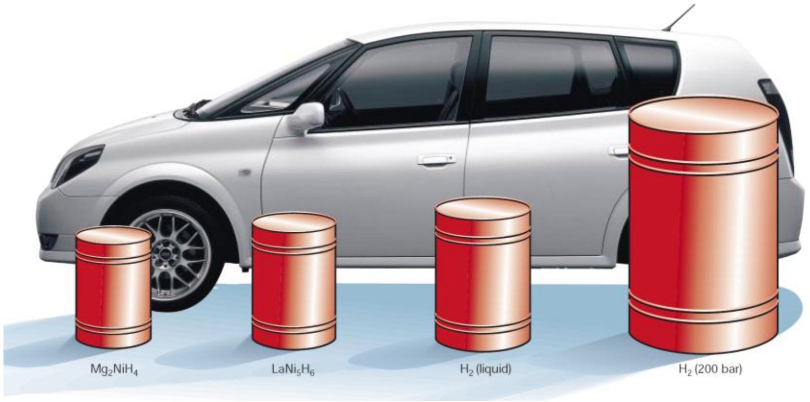

Fig. 6. Volume needed to store 4 kg of hydrogen using different technologies [49]

High heat value (HHV) of hydrogen (methane) compressed to 200 and 800 bar are estimated about 3 (8) and 10 (32) GJ/m^3 respectively [4]. For comparison, HHV of methanol, ethanol and octane in the liquid state are about 18, 23 and 34 GJ/m^3 respectively. Compressed hydrogen requires specialized pressure vessels. Up to 20% of the energy content corresponds to spent electricity. If hydrocarbon sources are used to produce such electricity at 40% efficiency, thus 50% of the energy may be lost just during the compression stage. This is even worse when hydrogen is liquefied. Volumetric density of 70 kg/m^3 or more have been obtained.

Existing hydrogen storage systems are well below the industry gravimetric and volumetric capacity targets (Fig. 7). Indeed it is suggested that a storage capacity of 6.5 wt% and 62 kg H_2/m^3 are required for the automotive and other applications. For example hydrogen storage in steel and composite material cylinders allows a maximum of about 1wt% and 3% respectively. Another drawback in using compressed gas in cylinder is space requirements even when high pressure up to 300 bars are used [50]. Storage of liquefied H_2 down to -253 °C seems a viable answer for this issue. However, around 30 % of stored energy is required for liquefaction and around 2% of hydrogen is lost every day due to evaporation

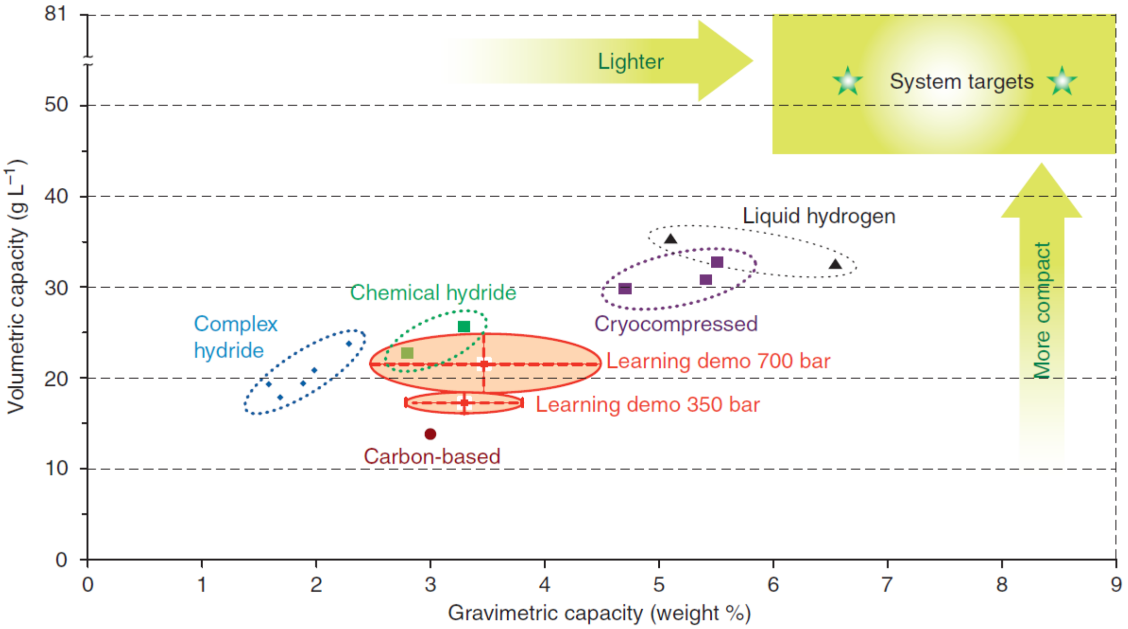

Fig. 7. Characteristics of current and future target hydrogen storage technologies [51]

Hydrides require much less energy for hydrogen packaging than compression or liquefaction. However, current hydrides technologies allow lower volumetric density. Even if we consider a H_2 storage capacity of 100 kg/m^3 and ignoring the container weight, an equivalent of 40 liters of gasoline (corresponding to 10 kg of hydrogen) requires 100 liters of hydrides.

IV.Applications and deployment of hydrogen economy vision

Hydrogen and Syngas (H_2 + CO) have been used extensively in the petrochemical industry since the early part of the 20th century [52]. Today, hydrogen is used mostly as a chemical. As an energy vector, hydrogen could be used to produce heat and or mechanical power by reacting with an oxidant such as oxygen. It could be also used to produce electricity using an electrochemical process with water as the only by-product.

To allow larger scale hydrogen deployment as an energy vector, a roadmap should be established and implemented with significant investment to address some technical and economic challenges. This roadmap should include short, mid and long terms development stages. The implementation of this roadmap is challenging, particularly if the required long lead time for technology development and maturation.

We propose a four stages development of hydrogen economy (Fig. 8) with important key challenges and milestones to be addressed at each stage. Proposed timelines is quite approximate, and meant mostly to provide guidance.

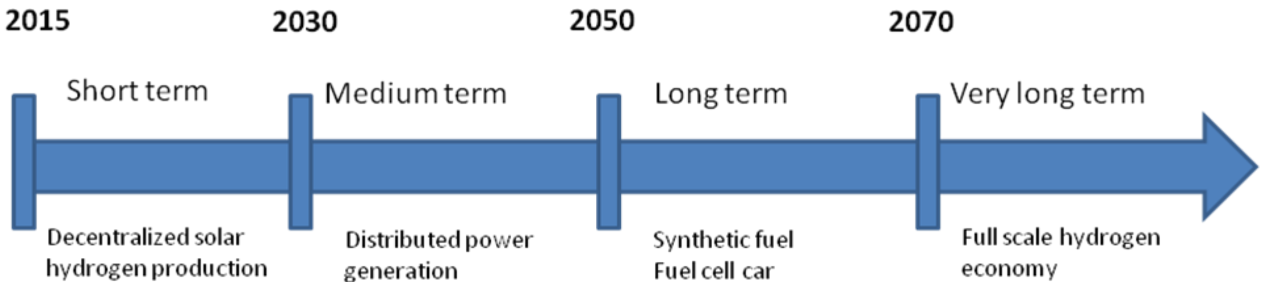

Fig. 8. Proposed steps and timeline for the hydrogen economy vision

In the long run, we believe that synthetic fuel and fuel cell are two important applications of hydrogen. In the case of Fuel cell, there are three potential areas of applications: mobile, stationary and portable devices. Although stationary applications remain the largest market, its cost disadvantages when compared to established technologies are a major drawback. Portable (computer, cell phone) and mobile (cars) applications will likely to see a larger market growth in the future.

V.1 Short term: Petro-chemistry (2015)

Currently hydrogen is used in various industrial processes. Renewable energy sources including solar will be gradually introduced to produce hydrogen used in this sector. High temperature electrolysis, photo-electrochemistry and thermochemical processes are potential candidates. These decentralized hydrogen production plants should be built near the point of use to minimize transportation and packaging requirements.

V.2 Medium term: Distributed power generation and hybrid water desalination (2030 years)

In the medium term, it will be difficult for hydrogen to compete on a large scale with renewable energy sources for the electric power. Fuel cell could certainly compete in the near future in the following niche markets:

- Portable (Up to 1 W): Micro-computers
- Mobile (Up to 1kW): as primary and auxiliary power
- Stationary (1MW): industrial and commercial CHP; secure power.

Combining clean technologies to produce water and hydrogen could be particularly important for the MENA region (Fig. 9). MENA region is well known for its water shortage. Current large scale desalination plants powered using fossil energy sources is not sustainable. Using solar energy to power an integrated water desalination and hydrogen production could be viable in the medium term (Fig. 9). At this stage of solar thermal technology development, small-to-medium scale combined desalination and hydrogen production unit is feasible.

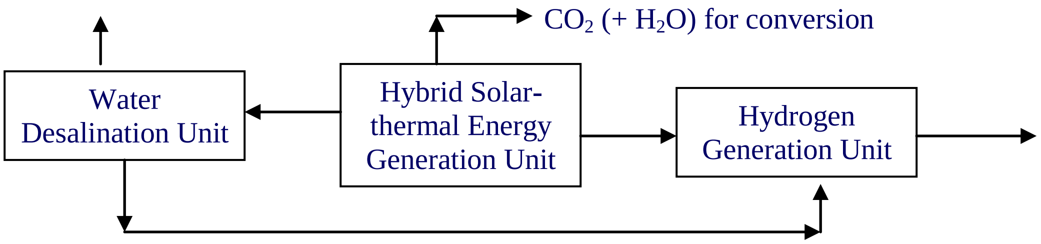

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Fig. 9 Proposed integration vision for hydrogen and energy generation

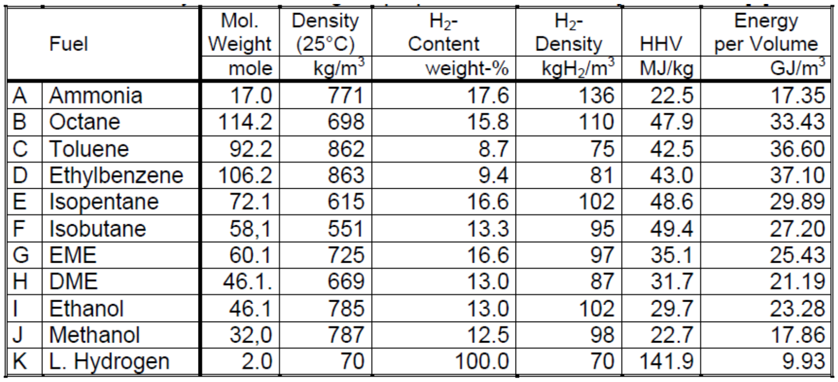
V.3 Long term: Synthetic fuel and Fuel cell powered car (2050 years)

Two viable large scale utilization of hydrogen are considered here: synthetic fuel and power generation.

Synthetic fuel

Synthetic fuels such as gas-to-liquid and coal-to-liquid (CTL) have been used for more than half a century. Their relatively high energy and capital costs combined with a low chemical efficiency are significant drawbacks. In particular SynGas (CO + H_2) process step is energy and capital intensive. Numerous synthetic fuel have been considered in the past with different characteristics (Table 1)

Table 1. Characteristics of few potential synthetics fuels [4]



	Fuel	Mol. Weight mole	Density (25°C) kg/m³	H_2-Content weight-%	H_2-Density kgH_2/m^3	HHV MJ/kg	Energy per Volume GJ/m³
A	Ammonia	17.0	771	17.6	136	22.5	17.35
B	Octane	114.2	698	15.8	110	47.9	33.43
C	Toluene	92.2	862	8.7	75	42.5	36.60
D	Ethylbenzene	106.2	863	9.4	81	43.0	37.10
E	Isopentane	72.1	615	16.6	102	48.6	29.89
F	Isobutane	58,1	551	13.3	95	49.4	27.20
G	EME	60.1	725	16.6	97	35.1	25.43
H	DME	46.1.	669	13.0	87	31.7	21.19
I	Ethanol	46.1	785	13.0	102	29.7	23.28
J	Methanol	32,0	787	12.5	98	22.7	17.86
K	L. Hydrogen	2.0	70	100.0	70	141.9	9.93

Synthesis of liquid fuel using CO_2 and H_2 gases could be the best long term fix for GHG emission mitigation (Fig. 10). Using reverse water-gas shift reaction, CO is first obtained:

$$H_2 + CO_2 \rightarrow CO + H_2O$$

Resulting CO is combined with hydrogen in the presence of appropriate catalysts to produce synthetic fuel (Fischer-Tropsch process):

$$CO + H_2 \rightarrow -CH_2 + HO_2$$

If water is used for the hydrogen production:

$$2H_2O + \text{Solar Energy} \rightarrow O_2 + 2H_2$$

thus the overall (ideal) reaction could be:

$$H_2O + CO_2 + \text{Solar Energy} \rightarrow CH_2 + O_2$$

Another alternative could be also considered. It consists of reducing CO_2 and H_2O mixture (humidified CO_2) for simultaneous electrochemical reduction of carbon dioxide and water to make syngas or C_1 products (CH_3OH, CH_4) depending on the basic process used (electron transfer process or proton exchange process, respectively).

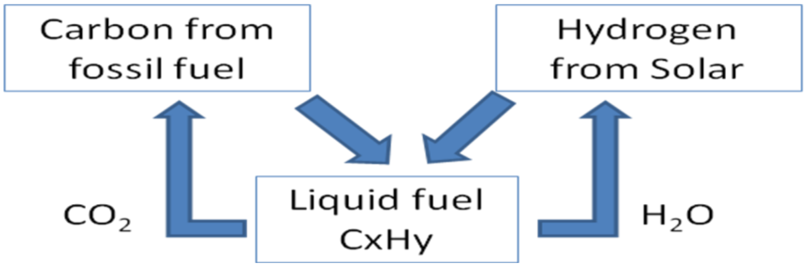


Fig. 10. Sustainability of hydrogen based synthetic fuel using hydrogen and CO_2

Other carbon sources include biomass and organic waste. This approach will reduce consumption of fossil fuel and at the same time allow carbon capture. For this, hydrogen production from non-fossil fuel is important. It has been estimated if CO_2 emission from coal power plants in USA is combined with hydrogen produced from renewable sources for synfuel production, it will meet all current hydrocarbon fuel needs for transportation [53].

Fuel Cell Car

Basically, a fuel cell is an electrochemical system consisting of an electrolyte sandwiched between two electrodes. Based on the type of fuel, working temperature, structure and composition of the electrodes and electrolyte, at least six types of fuel cells are deemed to be of interest. Two operate at high temperatures, solid oxide fuel cell or SOFC (800-1000 ^{o}C) and molten carbonate fuel cell or MCFC (550-650 ^{o}C). Other fuel cell types operating at lower temperatures have been also developed : alkaline fuel cell or AFC (60-90 ^{o}C), polymer exchange membrane fuel cell or PEMFC (60-900 ^{o}C), direct methanol fuel cell or DMFC (60-90 ^{o}C) and phosphoric acids fuel cell or PAFC (180 -220 ^{o}C). PEMFC and SOFC are currently developed for mobile and stationary applications respectively. DMFC and SOFC are probably the two most promising technologies that could reach wider use in the near future. In both cases nanomaterials development will have a different impact in lowering the cost and increase their performance.

Depending on the size and requirement, cost of today's fuel cell in the range of $10-100 per watt is quite prohibitive. Fuel cells prices are at least an order of magnitude higher than the conventional power generation. Electro-catalysts are presently considered one of the major fundamental issues hindering further development of some fuel cell technologies. Indeed with each car requiring about 20 grams of platinum, the low platinum abundance in the earth's crust will contribute to further increase in its contribution to the overall fuel cell cost [54]. Obviously, there is a need to develop alternative nanomaterials based electro-catalyst. One way to address this issue is to use nanoparticle based catalyst that allows the recovery of the spent catalyst. Furthermore, high active surface area nanoparticles will lower the amount of expensive catalyst.

Material cost used for the catalyst, membrane and bipolar plate are the main cost items. Platinum based nanoparticle catalysts are currently used in commercial PEMFC, DMFC and PAFC. The high cost of platinum (around $40 000 per kg and increasing) and platinum-group metal catalysts is the major drawback of this technology. Silica based nanocomposite are also used to improve the performance of the electrolyte membrane such water retention at high temperature. Ceramic nanopowders are also used to make more efficient solid-state electrolyte for SOFC.

V.4 Very long term: full scale hydrogen economy deployment (2070)

Until this stage, new hydrogen infrastructure will be used mostly to complement electricity grid to address increased energy demand. Large scale deployment of hydrogen as an energy vector will start to complement the electric grid. The two energy distribution networks will co-exist: One for electron and one for the hydrogen. The architecture of both energy networks will move gradually from a centralised to decentralized structure (Fig. 11).

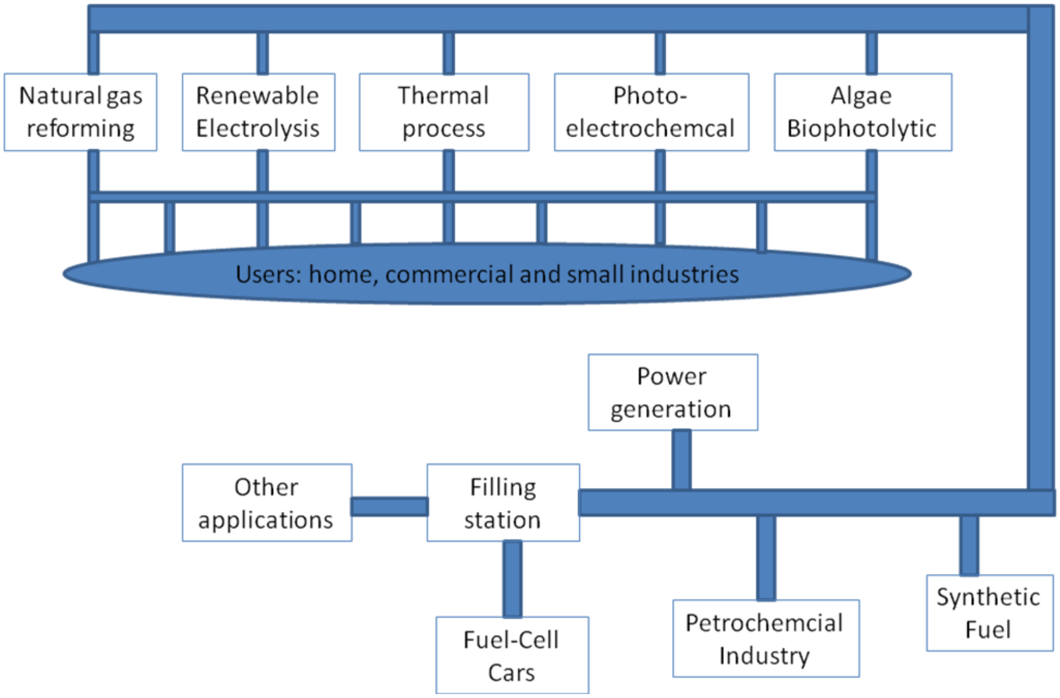


Fig. 11 Production and Delivery options of hydrogen: distributed (top) and centralized (bottom).

Using this roadmap, investment on a new hydrogen infrastructure will be used right away. Current proposed centralized hydrogen production requires a costly storage, delivery and dispensing infrastructure. This large infrastructure will be used only partially at the early stage, although it requires high maintenance and operation costs.

V. Conclusions and Perspectives

Past hydrogen economy roadmaps made three strategic errors. The first one is conditioning the deployment of hydrogen economy to funding an expensive production, storage, transport and delivery infrastructure. This infrastructure is technology and capital intensive and expensive to operate and maintains. Furthermore, this infrastructure will be used at a fraction of its capacity for at least two decades. The second mistake is to think that renewable and/or clean energy sources need to be converted to electricity first before production of hydrogen using appropriate technology. Besides the high cost of these two conversion processes, the overall efficiency of such route is quite low. Instead, we propose to use direct solar-to-hydrogen conversion as the best long term solution. Moreover, the integration of processes such as water desalination (solar energy driven), energy generation (hybrid solar-thermal) and hydrogen production (to be likely for MENA region) could lead to economically viable solution. Current hydrogen storage technologies are not suitable. Revolutionary and disruptive hydrogen packaging and delivery are required. These technologies are currently at concept levels requiring a long term development and maturation plan. Given the slow development of new technologies, reliable and cost effective technologies will probably not reach the market for several decades. We have proposed a four-stage roadmap for a global hydrogen economy fulfilment. MENA region with significant solar energy sources and an existing and/or to be developed petrochemical industry, could be ideal place to implement the early stage of our proposed roadmap.

References

1-G. Marban, T. Valfes-Solis, International Journal of Hydrogen Energy 32 (2007) 1625 – 1637
2-M. Roberts, TCE today September (2009) 22-23
3-D. Strahan, New Scientist 40 (2008) 40-44
4-U. Bossel, B. Eliasson, G. Taylor, *The Future of the Hydrogen Economy: Bright or Bleak?* http://www.efcf.com/reports/E02_Hydrogen_Economy_Report.pdf accessed January 4th 2010
5-R. Shinnar, Technology in Society 25 (2003) 455–476
6-R. S. Cherry, International Journal of Hydrogen Energy 29 (2004) 125 – 129
7-T, Grube, B. Hohlein, R. Menzer, Fuel Cell 4 (2004) 231-235
8-Beyond oil and gas: the methanol economy, George A. Olah, Alain Goeppert, and G.K. Surya Prakash, Weinheim : Wiley-VCH ; Chichester : John Wiley, 2006
9-G. Marbán, T. Valdés-Solís, International Journal of Hydrogen Energy 32 (2007) 1625 – 1637
10-S.S. Penner, Energy 31 (2006) 33–43
11-C. Sealy, Materials Today 11 (2008) 65-68
12-J. Turner, G. Sverdrup, M. K. Mann, P.-C. Maness, B. Kroposki, M. Ghirardi, R. J. Evans, D. Blake, Int. J. Energy Res. 2008; 32:379–407
13-G. Marban, T. Valfes-Solis, International Journal of Hydrogen Energy 32 (2007) 1625 – 1637
14-L. R. Sheppard and J. Nowotny, Advances in Applied Ceramics, 106 (2007) 9-20
15-J.A. Ritter, A.D. Ebner, Separation Science and Technology 42 (2007) 1123-1193
16-The Hydrogen economy: Opportunities, costs, Barriers, and R&D Needs, 2004, The National Academy Press
17-A. T-Raissi, D.L. Block, IEEE Power & Energy 2 (2004) 40-45
18-M. Momirlan, T.N. Vezirolu, Renewable and Sustainable Energy Reviews 3 (1999) 108-120
19- F. Mueller-Langer et al. / International Journal of Hydrogen Energy 32 (2007) 3797 – 3810
20-P. Ferreira-Aparicio, M.J. Benito Catalysis Reviews, 47 (2005) 491-588
21-S. Freni, G. Calogero, S. Cavallaro, J. Power sources 87 (2000) 28-38
22-K. Nath, D. Das, Journal of Scientific & Industrial Research 66 (2007) 701-709
23-S. Moller, D. Kaucic, C. Sattler, Transactions of the ASME 128 (26) 16-24
24-J. O'M. Bockris, T. N. Veziroglu, International Journal of Hydrogen Energy 32 (2007) 1605 – 1610], 25-J. Linnemann, R. Steinberger-Wilckens, International Journal of Hydrogen Energy 32 (2007) 1492 – 1499
26-M. Hori, Progress in Nuclear Energy 50 (2008) 411-416
27-The Future of Nuclear Power, An interdisciplinary MIT, 2009 update, http://web.mit.edu/nuclearpower
28-http://qsinano.com/white_papers/Water%20Electrolysis%20April%2007.pdf accessed on Jan. 4th 2007
29-S. H. Jensen, P. H. Larsen, M. Mogensen, International Journal of Hydrogen Energy 32 (2007) 3253 – 3257
30-W. J. LEE, YONG WAN KIM and JONGHWA CHANG, NUCLEAR ENGINEERING AND TECHNOLOGY, VOL.41 NO.4 MAY 2009, 413-426
31-A. Steifeld, Solar Energy 78 (2005) 603–615
32-J. Schooman, Hydrogen Production (Delft University).
33-M. A. Lewis, J. G. Masin, Interntional Journal of Hydrogen Energy34(209) 4115–24
34-M. A. Lewis, J. G. Masin, Interntional Journal of Hydrogen Energy 34 (2009) 4125 – 4135
35-A. Steinfeld, Int J Hydrogen Energy 27 (2002) 611-619
36-Rodrigo J. Weiss, Hao C. Ly, Karsten Wegner, and Sotiris E. Pratsinis, Aldo Steinfeld, AIChE Journal 51 (2005) 1966-1970
37- H. H. Funke, H. Diaz, X. Liang, C.S. Carney, A. W. Wimer, P. Li, International Journal of Hydrogen Energy 33 (2008) 1127-1134
38-F. Fresno, R. Fernandez-Saavedra, M. B. Gomez-Mancebo, A.Vidal, M. Sanchez, M. I.Rucandio, A.J. Quejido, M. Romero, Int J Hydrogen Energy 34 (2009) 2918 – 2924
39- D. Graf, N. Monnerie, M. Roeb, M. Schmitz, C. Sattler, Int J Hydrogen Energy 3 (2008) 4511 – 4519
40-Kazuhiko Maeda, Kentaro Teramura, Daling Lu, Tsuyoshi Takata, Nobuo Saito, Yasunobu Inoue & Kazunari Domen, Nature **414**, 625-627 (6 December 2001) | doi:10.1038/414625a
41-S. Licht, J. Phys. Chem.. B 105 (2001) 6281-6294
42-Oscar Khaselev and John A. Turner, Science 280 (1998) 425-428
43-Shahed U. M. Khan,* Mofareh Al-Shahry, William B. Ingler Jr, Science 297 (2002) 2243-2246
44-L. R. Sheppard and J. Nowotny, Advances in Applied Ceramics 106 (2007) 9-20
45-A. Kudo, International Journal of Hydrogen Energy 31 (2006) 197 – 202

46-Davide Barreca, Paolo Fornasiero, Alberto Gasparotto, Valentina Gombac, Chiara Maccato,Tiziano Montini, and Eugenio Tondello, ChemSusChem (2009)
47-W. A. Amos, *Updated Cost Analysis of Photobiological Hydrogen Production From Chlamydomonas reinhardtii Green Algae*, NREL Report 2003, http://www.nrel.gov/docs/fy04osti/35593.pdf accessed Jan 7th 2010
48-M. Conte, P.P. Prosini, S. Passerini, *Materials Science and Engineering B108 (2004) 2–8*
49-L. Schlapbach and A. Zuttel, Nature, 2001, 414, 353–358
50-http://www.gkss.de/Themen/W/WTP/wasserstoff/eSpeicher.html
51. M. Conte, Hydrogen Economy Energy, in Energy, 2009, 232-244, Elsevier.
52-Luca Basini, Catalysis Today 106 (2005) 34–40
53-K. Schultz, L. Bogart, G. Besenbruch, L. Brown, R. Buckingham, M. Campbell, B. Russ, B. Wong, HYDROGEN AND SYNTHETIC HYDROCARBON FUELS – A NATURAL SYNERGY, http://www.coal2nuclear.com/CO2%20and%20H2__Narration__Synfuel_poster.pdf accessed Jan 4th 2010
54-R.G. Cawthorn, South African journal of science 95 (1999) 481-489