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Resources of Fossil and Non-Fossil Hydrogen in the Middle East Can Make Fuel Cells an Attractive Choice for Transportation: A Survey Study

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1 Introduction

With substantial investments and growing interest in fuel cell technology, exciting new market opportunities are opening up for hydrogen. Nowhere is this potential more significant than in the transportation market, where numerous organizations are developing light-duty vehicles, heavy-duty transit buses, and a host of niche vehicle products powered by hydrogen fuel cells [1, 2]. Fuel cells provide the most efficient conversion device for converting hydrogen and possibly other fuels into electricity. Hydrogen and fuel cells open the way to integrated open energy and environmental challenges. A major challenge, however for the widespread use of hydrogen fuel cells is the source of hydrogen itself. In this presentation, two avenues are explored as far as the resources available in the Arab World. These are: fossil hydrogen and non fossil hydrogen.

The earth's potential energy resources are enormous; however the limitations in the access to energy are mainly caused by the uneven distribution. In general, in order to get useful information for the energy resources available in the Middle East, in particular the Arab countries, one divides the primary energy resources into two categories. They are:

(a) Fixed (stored) "capital", fossil sources.

(b) Continuous "income", non-fossil sources.

A survey of the natural gas reserves is carried out first, for potential Arab countries indicating which resources are "sweet gas" and which are "sour". Fossil hydrogen is produced next by the thermo-chemical reforming of "sulfur-free" natural gas which is the current technology employed for the production of synthesis gas (hydrogen/ carbon monoxide). Solar energy on the other hand, is regarded by many as the only ideal energy source especially for countries in the Middle East located around the so called "solar belt". Data on the surface area, solar intensity flux and sunshine hours for Arab countries are reported. Harnessing the power of the sun under these conditions would lead to a remarkable source of renewable energy to be utilized in the production of hydrogen.

2 Production of Fossil Hydrogen

2.1 Natural gas resources in the Middle East (Arab countries)

Arab countries are endowed with large reserves of hydrocarbons including oil, natural gas. The vast resources of untapped hydrocarbons mean that much development is focused there. Looking at the natural gas reserves by country, it is found that a total of 51,200 trillion cubic meters is credited to the Arab countries. It represents about 30 % of the world gas reserves [3]. If we consider Qatar as an example, we find that Qatar's offshore north field, estimated to have 25 trillion cubic meters (9.0×1014 cu ft) of gas in place.

2.2 Basis and assumptions used for fossil hydrogen production

1. The gas reserves for the selected Arab countries considered in this study, is estimated to be: 51,200 trillion cubic meters.
2. Gas reserves could last for 200 years, at optimum production levels.
3. The average total annual production of natural gas will be: 51,200 Trillion cubic meters/ 200 years = 256 trillion cubic meter/year.
4. Only 1 % of the annual production will be committed for hydrogen production using catalytic reforming for sweet natural gas; while non-catalytic partial oxidation (NCPO) is recommended for sour natural gas reserves.
5. In the steam reforming process of natural gas (represented by methane) as given by the equation: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$
   1 lb mole of methane [which occupies 359 cubic feet @ standard conditions of 32 °F & 14.7 psia] would yield 8 lb of hydrogen, at 100 % conversion. Assuming 50% conversion, the yield would be 4 lb hydrogen.
   In other words: 359 cubic feet (10.73 cubic meters) of Natural gas @ SC → 4 lb Hydrogen

2.3 Output of hydrogen production

Based on the above, 1% of the annual natural gas production would yield:

{1/100 x 256 TCM]/ 10.73 x 4 x 1/2000 = **477×10^6 Tons of Hydrogen**

2.4 Current practice for hydrogen production

Current technology employed to manufacture hydrogen or synthesis gas (hydrogen/ carbon monoxide) from natural gas is based on one of three major thermo-chemical-reforming techniques:

1. Steam reforming of methane (SRM)
2. Partial oxidation (PO)
3. Auto thermal reforming (ATR)

These are catalytic processes, which necessitates a sulfur-free feedstock of natural gas to avoid catalyst poisoning. Acidic gas removal is a pre-request step for this process, which is a costly operation involving the use of amine solvents with subsequent regeneration. Today, almost all hydrogen is produced via steam reforming of natural gas. The process referred to as steam methane reforming (SMR) is the most common method of producing commercial bulk hydrogen as well as the hydrogen used in the industrial synthesis of many chemicals. The main reactions are:

$$CH_4 + H_2O \rightarrow CO + 3\ H_2$$

This is followed by the shift reaction:

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

Thus, the final net reaction is:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

Separation of CO_2 represents the very final step in the production of hydrogen.

2.5 Novel trends in reforming sour natural gas

About a third of the world's natural gas reserves contain high concentrations of contaminants and so are termed 'sour gas' [4].The defining chemicals are often hydrogen sulphide (H_2S) and carbon dioxide (CO_2) though in some cases other sulfur compounds such as carbonyl sulfide (COS) and mercaptans are also found. All producing countries in the Middle East are stepping up their efforts to exploit sour gas, often in partnership with western energy companies, reversing the trend for hydrocarbon production in the region to concentrate on oil. Now a key target is to efficiently process sour gas to improve recovery of both liquids and natural gas. In this respect, non catalytic partial oxidation (NCPO) process is introduced for handling sour natural gas. The process was proposed by Abdel-Aal & co-workers [5, 6] as a means for the direct production of synthesis gas from **sour** natural gas. It involves the combustion of sour natural gas under partial oxidation conditions in the absence of catalysts. The following reactions are cited:

$$CH_4 + 1/2\ O_2 \rightarrow CO + 2H_2 \qquad (1)$$

$$H_2S + 3/2\ O_2 \rightarrow SO_2 + H_2O \qquad (2)$$

The NCPO process of sour natural gas is exemplified by the schematic diagrams shown in Figures 1 & 2.

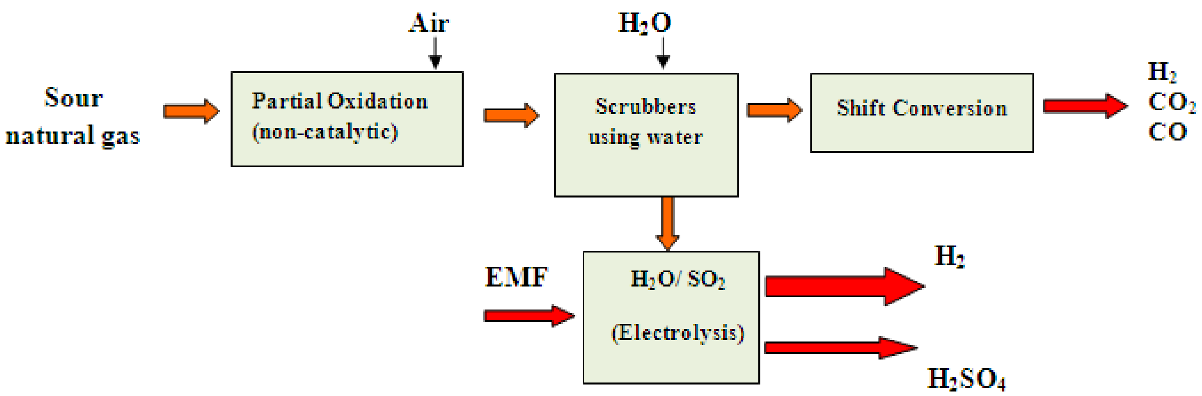

Figure1: NCPO of Sour Natural Gas producing Hydrogen and Sulfuric Acid.

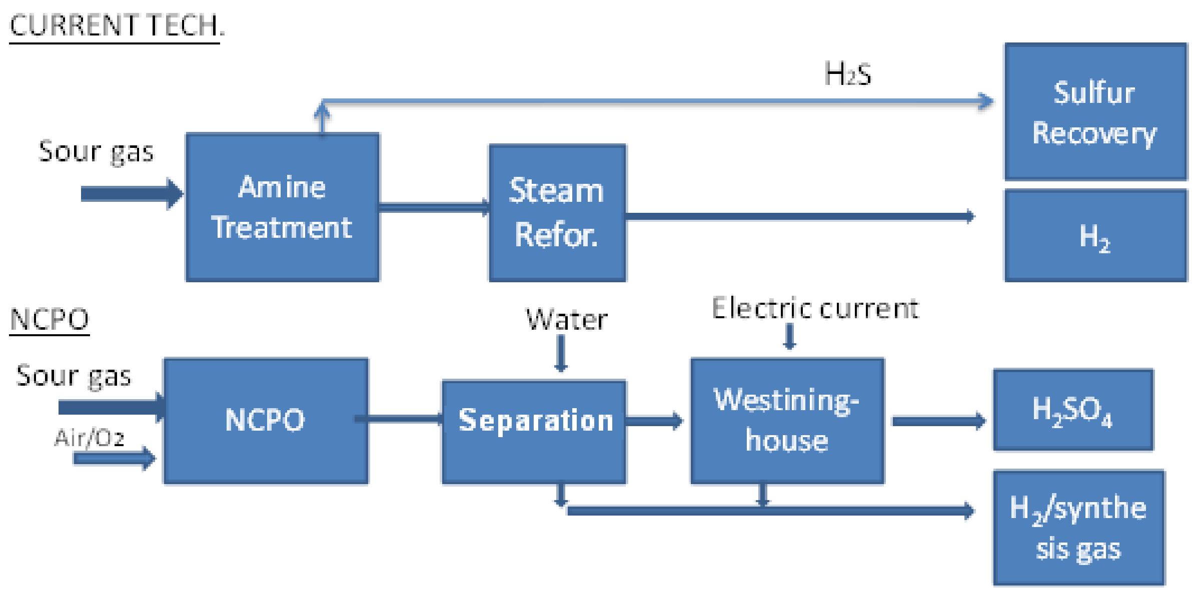

Figure 2: Current Tech. Vs NCPO for Hydrogen Production.

The merits of NCPO as compared to the SRM are as shown in table 1:

Table 1: Comparison between NCPO and STR of Sour Methane.

Parameters	**SRM**	**NCPO**
1. Treatment of raw gas to remove H_2S	Requires amine solvents	Not required
2. Recovery of S from H_2S	Claus process is applied	Not required
3. Manufacture of synthesis gas		
a) use of steam b) use of catalyst	Yes Yes	No No
4. Separation of SO_2 from synthesis gas	No	Yes
5. Production of sulfuric acid	present technology is applied: Start with S➔SO_2➔SO_3 ➔ H_2SO_4	direct production by electrolysis : H_2SO_3 (apply electric current)➔ H_2SO_4 + H_2
6. Final end products	Synthesis gas	Synthesis gas, Hydrogen and Sulfuric acid

3 Production of Non-fossil Hydrogen

3.1 The role of solar energy

Solar energy provides electricity via photovoltaic cells. Sunlight reaching the land surface of our planet can produce the equivalence of 1,600 times the total energy consumption of the world; the amount of solar energy derived from the sun's radiation on just one square kilometer is about 4,000 megawatts, enough to light a small town. Many of the Arab countries have all practical futuristic possibilities of supplying at a significant proportion of the total world energy demand of 20 TW (electric) by 2050, from their vast solar rich deserts, by erecting solar farms on them to generate power which could be used for hydrogen production. The strategic proximity of the Arab countries to many European, Asian, African and other countries would be of crucial advantage in this respect. Recently, countries such as Saudi Arabia and Qatar and organizations such as UNESCO have initiated numerous solar energy projects although the history of large-scale solar energy use dates back to the first solar power station connected to a national grid in Adrawo, Sicily. In the wake of the first Gulf War, the US Army assessed Saudi Arabia's solar energy resource potential in a classified effort to determine how oil fires had affected the region. The results were clear and surprising. In addition to being a vast petroleum repository, the desert nation was also the heart of the most potentially productive region on the planet for harvesting power from the sun. In other words, Saudi Arabia was the Saudi Arabia of solar energy. Sitting in the center of the so-called Sun Belt, the country is part of a vast, rainless region reaching from the western edge of North Africa to the eastern edge of Central Asia that boasts the best solar energy resources on Earth [7]. With the cost of oil skyrocketing, this belt is attracting the attention of a growing number of European leaders, who are embracing an ambitious proposal to harvest this solar energy for their nations.

3.2 Basis and assumptions used for non-fossil hydrogen production

(a) The average solar intensity flux = 700 Watt/m²
(b) The average sunshine hours is 3000 annually
(c) The total land area of the Arab countries considered in the survey for producing non-fossil hydrogen = 11.34 x 106 Km2 ≈ 11 x 106 Km² [8]
(d) Only 1% of total land area is utilized for solar power generation
(e) The efficiency of solar conversion is 10%
(f) The efficiency of hydrogen production is 30%
(g) One cubic meter of hydrogen produces 3 Kw.hr (thermal) [9]

3.3 Output of hydrogen production

Based on the above, the following calculations are presented:

1. The total annual Kw.hr received by one m^2 = 0.1x0.7 Kw x 3000 hr/y
   = 210 Kw.hr ≈ 200 Kw.hr
2. The total annual Kw.hr received by land area:
   $0.01 \times 200 \times 11 \times 10^6\ (Km^2) \times 10^6 (m^2/Km^2) = 22 \times 10^{12}$ Kw.hr
3. The annual hydrogen production:
   $0.3 \times 22 \times 10^{12}\ ]/3 = 22 \times 10^{11}\ m^3 = 22 \times 10^{11} \times 83.76\ (g/m^3) \times 10^{-6} (ton/g)$
   <u>= 184 x 10^6 Tons of Hydrogen</u>

4 Summary and Conclusions

In this presentation two avenues for producing hydrogen are explored as far as the resources available in the Arab world. These are:

- Fossil hydrogen, to be produced from natural gas
- Non fossil hydrogen, to be produced using solar energy as a primary energy source

A summary of the anticipated hydrogen production by both approaches is presented in Figure 3. Natural gas reserves abundant in the Arab world were cited for a number of countries. These include: Qatar, Saudi Arabia, United Arab Emirates, Algeria, Iraq, Egypt, Kuwait and Libya with a total reserve of 51,200 trillion cubic meters. This represents about 30 % of the global world reserves.

For the production of fossil hydrogen, current technology of steam reforming of natural gas along with novel trends for handling **sour** gas reserves were presented.

For non-fossil hydrogen on the other hand, harnessing the power of the sun would lead to a remarkable source of renewable energy to be utilized in the production of hydrogen. Data on the surface area, solar intensity flux and sunshine hours for Arab countries are reported.

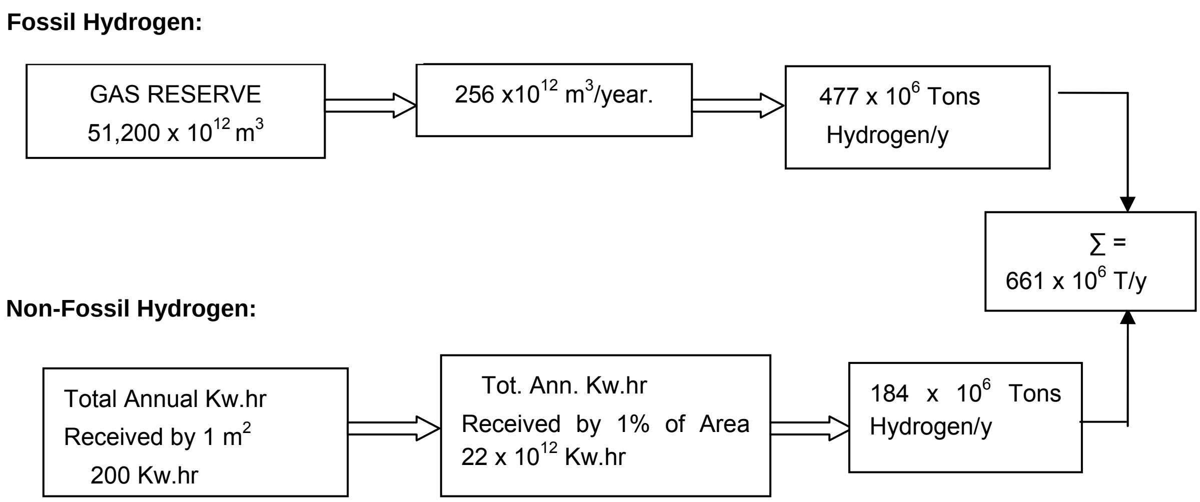

Figure 3: Summary of Hydrogen Production.

The following conclusions are most significant to be presented:

1. The Arab world could participate to supply hydrogen to the international market via the fossil and the non fossil sources. The anticipated annual production is 477 x 10^6tons plus 184 x 10^6 tons respectively to make a total of **661 x 10^6** tons.
2. As far as **sour** natural gas reserves available in the Middle east, big potential is there but technological innovation will be the key to making such reserves viable from technical and financial perspectives.
3. The **NCPO** process for producing hydrogen from sour natural gas could be a promising approach in this regard.

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