Sizing method of the photovoltaic-electrolyser system for the HCNG fuel production: HySolThane project

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***Abstract*— Transportation sector is the second largest energy consuming sector after the industrial sector with 30% of the world's total delivered energy. Hydrogen (H_2) from renewable energy sources is a clean and sustainable option as a fuel and is seen as a potential alternative to gasoline in the future. However, the use of the hydrogen in transportation sector is more known in the fuel cell electric vehicles, where have been widely investigated around the world over the past decades. These vehicles use the hydrogen as an energy carrier to power electric motors through fuel cells. Furthermore, hydrogen as fuel can be used in internal combustion engines in mixture with compressed natural gas (HCNG), which is used as a transition to hydrogen technology.**

In this context, the hydrogen enriched natural gas or HCNG fuel production process is presented with the reduction rate of the polluting exhaust gases HC, CO, CO_2 and NOx based on the hydrogen fraction in the natural gas. In addition, the current overall natural gas situation in Algeria and the potentialities of hydrogen production is reviewed. A global description of the solar fuel 'Carburant solaire' or HySolThane project is given. Based on a sizing method, simulation results of a typical stand-alone photovoltaic system for electrolytic hydrogen production used in HCNG fuel preparation is showed. These results indicate that the shift to HCNG fuel use is very promising.

Keywords- Photovoltaic hydrogen production, Hydrogen enriched Compressed Natural Gas (HCNG), HCNG fuel, Sizing method.

I. INTRODUCTION

In 2007 total world primary energy consumption was 495 quadrillion Btu and is expected to increase by 49% at 2035[1]. Unfortunately, the primary energy consumption is largely dependent on fossil fuel with a part of 86% and as these natural resources are in quick depletion, this situation is rapidly resulting in critical environmental problems and threaten the energy security.

One of the major energy consumers sector in Algeria is transportation with 6.5 million tonne of oil equivalent. According to the data published by the National Statistics Office (ONS) in 2007, gasoline is the main source of energy for 53% of vehicles and 47% run on diesel fuel [2]. Although Algeria is classified among the oil countries, it has become an importer country of diesel fuel with 2 million tonne of oil equivalent in 2012 to cope with the large demand. Thus, there is a pressing need to the use of cleaner and economically viable alternative fuels.

Hydrogen (H_2) from solar energy used in mixture with compressed natural gas (HCNG) is seen as a potential alternative to gasoline and a sweet transition to hydrogen technology. Many researches related to HCNG have been conducted during last 20 years [3], among which the solar fuel or HySolThane project at the Center of Renewable Energy Development (CDER) in Algeria. In the frame of this project, a sizing method of stand-alone photovoltaic (SAPV) system for electrolysis hydrogen production is developed [4].

II. HYSOLTHANE DESCRIPTION PROJECT

The HySolThane (Hydrogene-Solare-Methane) project has been initiated by the Development Center for Renewable Energy (CDER) and its partners SONALGAZ, SONATRACH and NAFTAL, and aims to promote the use of solar hydrogen in the transportation sector. The project expects the use of HCNG with a fraction of hydrogen at 8%/vol. Hydrogen used in the preparation of the HCNG fuel is produced by water electrolysis. The use HCNG fuel with low fraction of hydrogen into compressed natural gas can be used directly in the existing CNG technology without any modifications of the transport (pipeline), distribution (filling stations) and use (automobile fleet) sections of the fuel system. In addition, this technology will allow the mastery of the production, the distribution and the security of hydrogen technologies and allow the Algerian public to become familiar with hydrogen technology. From an environmental point of view, fuelling vehicles with compressed natural gas blended with 8%/vol of hydrogen reduces carbon emissions [5].

The main objectives of this project are:

- Learning the operational functioning of an innovative solution.
- Opening a way at the use of hydrogen in real applications.

- Understand the technical and regulatory challenges associated with the introduction of hydrogen in a gas station and a vehicles.
- Highlight a transitional solution to use hydrogen energy, with currently available technologies.
- Introduce a share of low-carbon energy and clean in today's vehicles and quantify the environmental benefits and efficiencies.
- Increasing the stability and velocity of the combustion by the significant increase of the flame speed when adding the hydrogen to CNG.
- Evaluation of the HCNG fuel Algerian potentialities.

III. Production of the HCNG Fuel

The mixture of hydrogen and methane is commonly named Hydrogen Enriched Compressed Natural Gas (HCNG), and can be produced with different hydrogen fraction for powering an internal combustion engine.

A. Hythane

Hythane® registered trademark by Brehon Energy is an enriched compressed natural gas with up to 20%Vol of hydrogen [6]. This is for allowing the use of existing transport infrastructure, gas distribution, gas boilers, cookers and water heaters.

B. Technical performance of Hythane fuel

HCNG fuel at <20%/vol of hydrogen fraction has a neighboring propriety to these of natural gas, whose risks are known and controlled. The addition of hydrogen improves engine performance with better burn and enables fast and stable combustion, while maintaining a high level of security. in Addition, introducing hydrogen in natural gas fuel reduces gas consumption because the proportion of required gas for mixture ignition decreases [7].

C. Environmental performance of Hythane fuel

According to the results in [8], the use of HCNG fuel with 20%/vol allows the NOx, CO, NMHC, CH4 emissions reduction with 51%, 36%, 60%, 47% respectively, compared to pure CNG without catalytic converter.

In addition and as research shows, by using a catalytic converter, hydrogen-enriched natural gas has the potential to achieve European IV standards.

D. HCNG fuel production technique

Fig1 illustrate the HCNG fuel production technique. As shows in the Fig1. system of the HCNG production is constituted with an hydrogen source feeding a compressor, an hydrogen Storage, a blender gas and a dispenser allowed to deliver the HCNG mixture.

TABLE I. THE COMPARISON OF 20% HCNG AND CNG[7].

Fuel type	NOx (g/kW h)	CO (g/kW h)	NMHC (g/kW h)	CH4 (g/kW h)
CNG	4.76	2.45	0.52	4
20% HCNG	2.31 (51%)	1.54 (36%)	0 21 (60%)	2.1 (47%)

IV. Potentialities of Photovoltaic-HCNG Production in Algeria

Compressed natural gas blended with hydrogen production potentialities is directly linked to the natural gas and hydrogen potentialities. In the case of Photovoltaic-HCNG fuel, hydrogen production is carried out by water electrolysis process using photovoltaic (PV) energy, which is depending on both solar and water resources.

A. Photovoltaic hydrogen potentialities

Algeria in particular are considered as one of the sunniest country in the world according to many recorded data and satellite observations. However, the distribution of the solar resource can be subdivided into three zones: *coast al* (humid climate), *atlas* (cold in winter and hot in summer), and *Saharan* (dry desert climate) with typical average values of annual daily horizontal irradiation of 4 kWh/m^2, 5 kWh/m^2, and 6 kWh/m^2, respectively[9]. The important solar potential allows to produce amount of hydrogen varying in the range of 78-112 l/m^2/day [10].

B. Natural gas potentialities

According to the Oil and Gas Journal, the proven natural gas reserves in Algeria are estimated at about 159 trillion cubic feet (Tcf) placing Algeria in the tenth rank at the world level and the second largest in Africa after Nigeria [11]. However, the recoverable reserves are much higher.

Furthermore, Algeria has an important capacity of natural gas production. In 2010, Algeria's gross natural gas production was 6.8 Tcf compared with 6.9 Tcf in 2009. Of this amount, 3.2 Tcf was reinjected for enhanced oil recovery, 3.5 Tcf was marketed, while 0.2 Tcf was vented/flared.

C. Water resources

The total conventional water resources are evaluated at 14×10^9 m^3/year with the exploitable resources being of the order of 7.9×10^9 m^3/year. These resources are fed essentially by rainfall. However, the repartition of this rainfall is characterised by its regional variability and its irregularity from year to year. Chronic drought years can be followed by wet years. Water consumption is of the order of 6.07×10^9 m^3/year which amounts to 201 m^3/capita; 65% of the water is used for irrigation, 22% for drinking and the remaining 13% for industry [10].

V. Sizing Method [4]

As part of the HCNG fuel production system, SAPV-hydrogen production sub-system (SAPV-H_{2HCNG}) is showed in Fig 2. The method developed by the author in [4] for sizing SAPV-H_{2HCNG} system is as follow

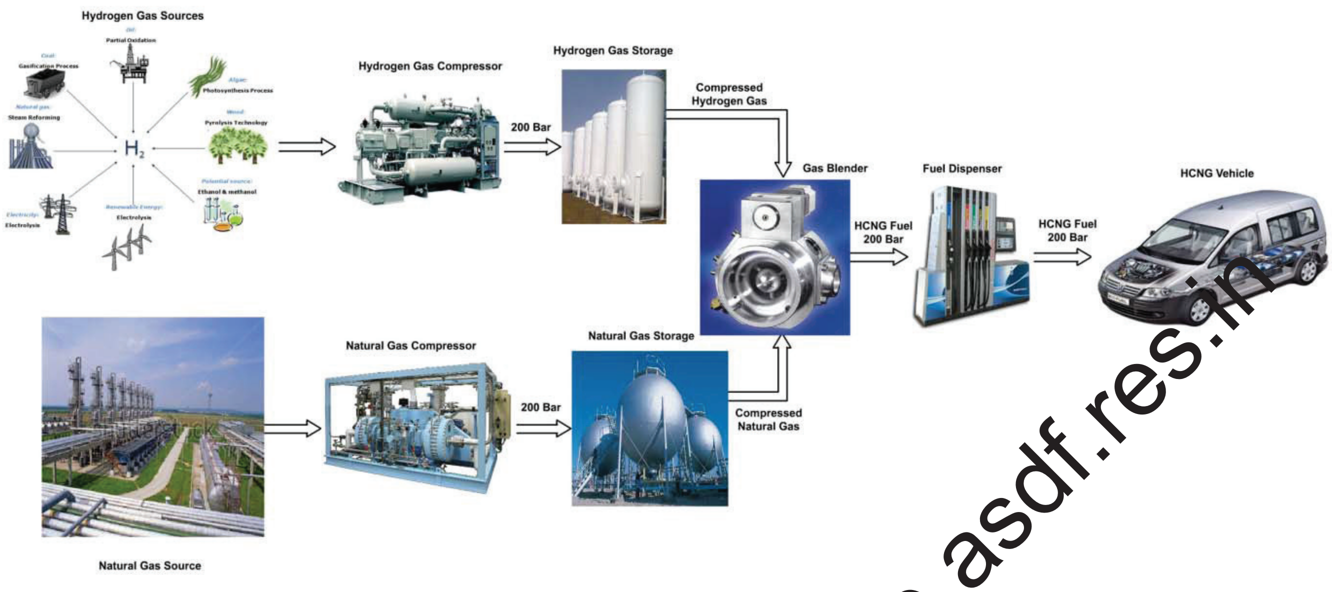

Figure. 1 HCNG Fuel Production Technique

A. Hydrogen requirement

Depending on the amount of hydrogen in the mixture of 'HCNG', daily needs of hydrogen can be quantified by:

$$m_{h_2,d} = F \rho_{h_2} V_{HCNG,d} \quad (1)$$

Where ρ_{h_2} is the hydrogen density, $V_{HCNG,d}$ is the daily HCNG requirement and F is the hydrogen fraction in the HCNG fuel.

B. PV array sizing

PV array rated power depends on the yearly average sun peak hour SPH and yearly average hydrogen requirement as:

$$P_{pv} = \frac{M_{pv} m_{h_2,y} HHV}{SPH_y \eta_{mp} \eta_{ac} \eta_{el}} \quad (2)$$

Where η_{mp}, η_{ac} and η_{el} are the MPPT regulator, DC/AC converter and electrolyser efficiency, respectively. M_{pv} is the PV array margin coefficient and HHV is the higher heating values of hydrogen.

C. Electrolyser sizing

The nominal rated capacity of the electrolyser can be calculated as:

$$P_{el} = I_{smax} A_{pv} \eta_{mp} \eta_{ac} \eta_{pv} \quad (3)$$

Where I_{smax} is the maximal value of solar irradiance during one year and A_{pv} is the PV array area.

D. Hydrogen tank sizing

Since the production and supply of hydrogen are done in parallel, the hydrogen tank capacity V_{ht} is the cumulative of surplus production during the overproduction period divided by the storage pressure value P_{ht} and is calculated by the following equation:

$$V_{ht} = \frac{M_{ht}}{P_{ht} \rho_{h_2}} \times \int_{t=d_1}^{d_2} \left(\frac{H_s A_{pv1} \eta_{pv1} \eta_{mp1} \eta_{ac1} \eta_{el}}{HHV} - m_{h_2,t} \right) dt \quad (4)$$

VI. Case Studies

To verify the relevance of the sizing method, Algiers (36.8 °N) is chosen as the location test for setting a SAPV-H_{2HCNG} to supply daily 10 vehicles with HCNG fuel. Each vehicle has a tank volume of 0.045 m^3. Fraction of hydrogen in the HCNG fuel is 8%. Fig 3 shows the hourly and monthly average collected solar irradiation data over one typical year. The maximal hourly and daily average yearly values of the recorded solar irradiation are 994.7 Wh/m^2 and 4.553 kWh/m^2. In the simulation, the PV array efficiency is η_{pv} =15%, the MPPT converter efficiency is $\eta_{mp} \approx$ 95%, the DC/AC converter efficiency is $\eta_{ac} \approx$ 95%, the alkaline electrolyser efficiency is

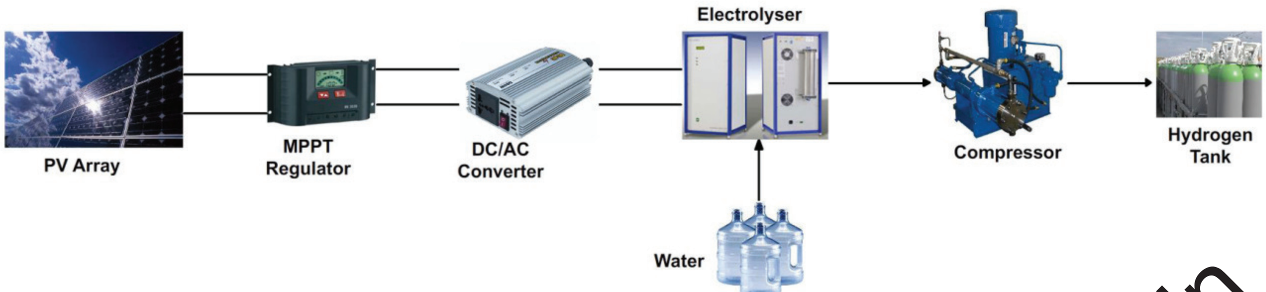

Figure. 2 Stand-alone Photovoltaic System for Electrolysis Hydrogen Production

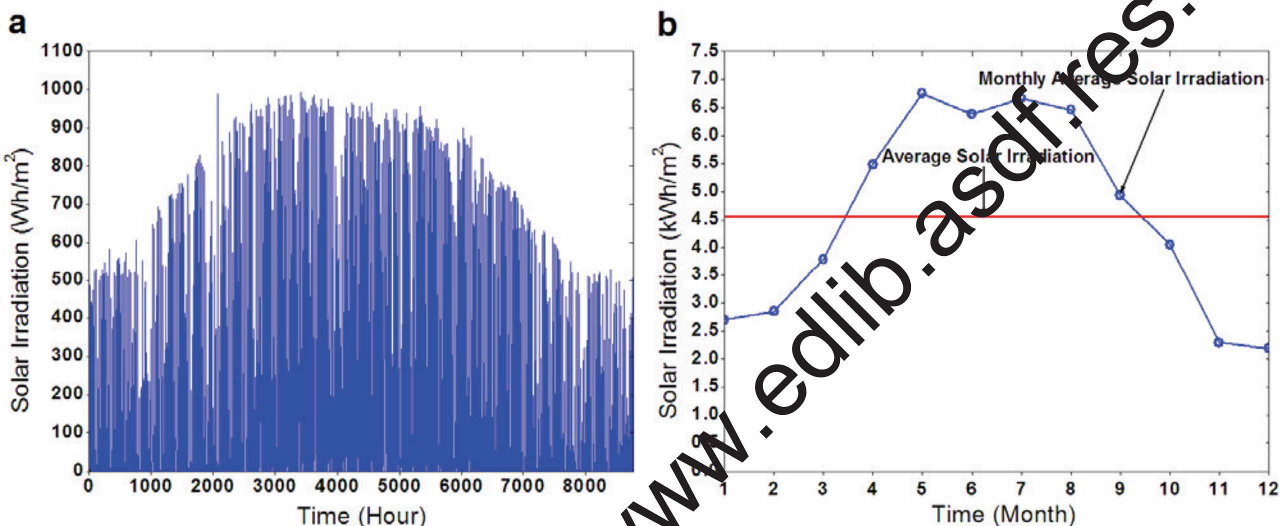

Figure. 3 Solar irradiation over one typical year: (a) hourly and (b) monthly average

TABLE 2 SYSTEM COMPONENT SIZES.

Parameter	$m_{h_2,d}$ (kg)	P_{pv} (kWp)	A_{pv} (m^2)	P_{el} (kW)
Component size	0.6473	8.8753	59.[illegible]8	8.01

$\eta_{el} \approx$ 70% and M_{pv} =1. The systems components sizes obtained using the proposed method are summarised in Table 2.

A. Simulation results

Fig. 4, Fig. 5 and Fig. 6 show the simulation results of SAPV-H_{2HCNG} system. As Fig.4 shows the PV array power production during one typical year follows the shape of the irradiance curve where the maximum PV array output is 8.83 kW.

The daily electrolysis hydrogen production varies in the gap 0.373-1.187 kg/day with an average yearly value of 0.647 kg.

Fig. 6 shows the hydrogen tank stat-of-charge (SoC) variation during the year. The initial $SoC = 0.3$ in pressurized hydrogen tank is used to cope with SoC the fluctuations and ensure the continuous operation of the system. The maximum value of the hydrogen tank SoC is 39.94% and the minimum value is 21.92%. The latest indicates that $SoC = 0.1$ is sufficient to ensure the continuous operation of the SAPV-H_{2HCNG} system.

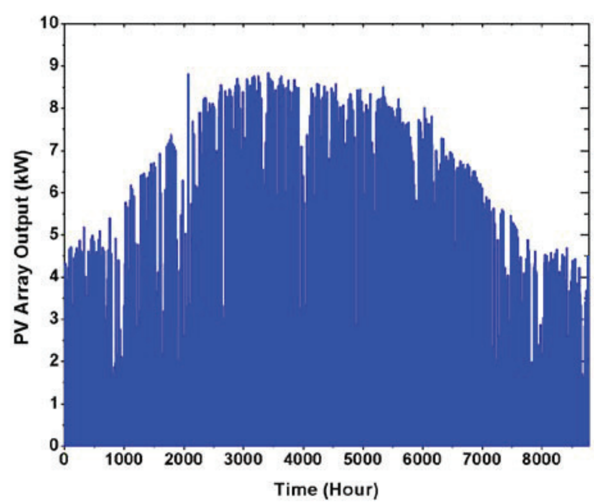

Figure. 4 PV array output during one year system operation.

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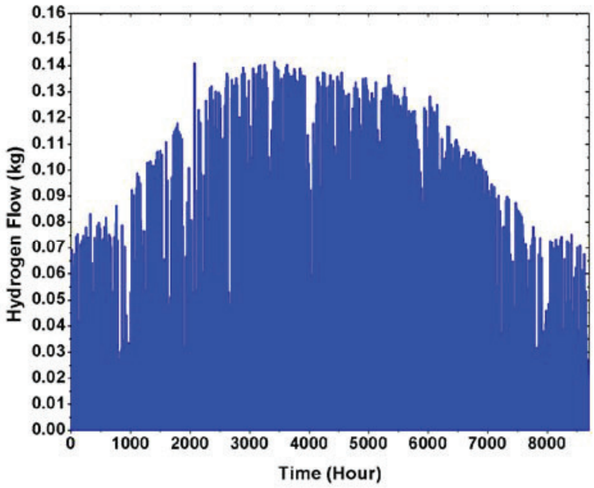

Figure. 5 Hydrogen flow during one year system operation.

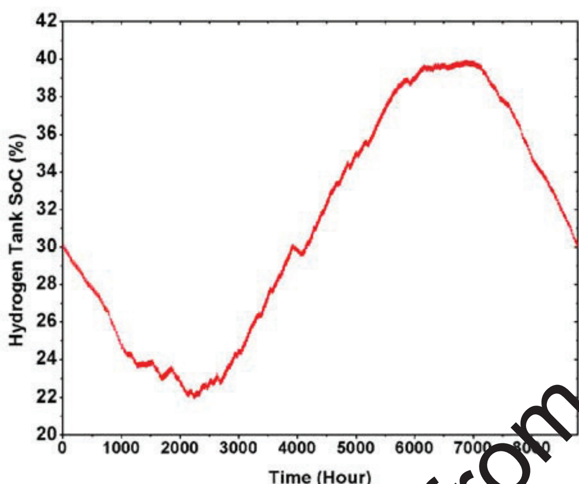

Figure. 6 Hydrogen tank stat-of-charge during one year system operation.

VII. Conclusions

Currently, clean electrolysis photovoltaic hydrogen production system sizing and optimization is a topical research topic and similarly with the study of using hydrogen possibility as a fuel. In the present work, presentation of a new fuel which combine the compressed natural gas and hydrogen HCNG with preparation technology, technical and environmental performance is given after the description of the HySolThane project. This project aims to produce the HCNG fuel with a fraction of hydrogen at 8%/vol. Algerian potentialities of the photovoltaic-HCNG fuel production is illustrated in the third time. As a part of the HySolThane project , hydrogen is produced via photovoltaic electrolysis process, and the overall system includes a stand-alone photovoltaic sub-system with electrolyser and hydrogen tank storage has been object of a sizing study. The relevance of the developed sizing method is verified by simulation of a case study.

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