Production and industrial use of “Green” hydrogen in the climatic conditions of Turkmenistan

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Abstract. The scientific article discusses the importance of using “green” hydrogen in industry through a photovoltaic solar installation in the climatic conditions of Turkmenistan, and especially examines the possibilities and features of the use of “green” hydrogen in the production of ammonia, which is a widespread product in industry. To do this, it is based on the reaction of producing ammonia, and based on this, it is calculated that to produce 1 ton of ammonia, 177 kg of hydrogen is required. The water required for the electrolyzer operating in the 2G system is proposed to be provided from natural residues, and it is determined that the installation will be able to operate 10.65 hours a day. This in turn eliminates 970 kg of CO_2 compared to the traditional method of burning natural gas to produce hydrogen. Calculations were carried out for the coordinates of the city of Mary.

1 Introduction

The main sources of energy today are fossil fuels: oil, gas, and coal. Experts confirm that the reserves of these energy sources are decreasing due to the increasing demand [1]. It is also known that the use of these energy sources releases harmful gases into the atmosphere [2], leading to climate change [3]. In this case, there is an urgent need to use a cheap and environmentally friendly energy source. Today, renewable energy sources [4] are being used as a solution. Many developed countries consider hydrogen as the energy source of the future [5].

Aim of the study:

- To compare two hydrogen production methods for industrial ammonia production.
- Evaluate the potential of "green" hydrogen production using an electrolyzer in the climatic conditions of Turkmenistan, using desalination plant wastewater.
- Analyse the environmental impact through calculations.

The object of the research is "green" hydrogen, Q.ANTUMDUO 580W photovoltaic solar panel, and an electrolyzer with a capacity of 1 MW.

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2 Materials and methods

According to [6], the world production of ammonia will be 180 million tonnes in 2020 and the demand for ammonia as an energy carrier could increase to one billion tonnes in the future. It is also seen as a convenient way to store renewable energy and transport hydrogen.

According to the known formula, the absorption of ammonia is as follows [7]:

$$N_2+3H_2=2NH_3 + Q \tag{1}$$

This reaction is exothermic and requires 3 molecules of hydrogen and 1 molecule of nitrogen to produce 2 molecules of ammonia.

The molecular mass of the substance required:

$$m = \frac{\mu}{N_A} \tag{2}$$

Where m -is the molecular mass of the substance, μ is the molar mass of the molecule of the substance, N_A - is the Avogadro constant ($N_A=6.02\cdot10^{23}$ mol^{-1}). The amount of raw material required for the industrial production of 1 tonne of ammonia can be calculated using equations (1) and (2).

From the Mendelian Periodic Table, the mass of various substances is analyzed, and based on formulae 1-2, the composition of the substances necessary for the production of ammonia is calculated based on formulae 1-2, the results of which are given in Table 1.

Table 1. Analysis results.

Substance	**Required mass, kg**	
Ammonia	$5.65\cdot10^{-26}$	1000
Hydrogen	$1\cdot10^{-26}$	177
Nitrogen	$4.65\cdot10^{-26}$	823.05

As shown in Table 1, it takes 177 kg of hydrogen to produce 1 tonne of ammonia. Hydrogen is one of the most abundant elements on Earth. However, it is not found in the usual form but in compounds. Different methods have been developed to obtain pure hydrogen [8]. Depending on these methods, it is agreed that the hydrogen obtained can be distinguished by conventional colors [9].

Until now, the hydrogen required for industrial ammonia production has been obtained by steam reforming of methane (SWR), the so-called "grey" hydrogen [10]. “Grey” hydrogen is widely used worldwide not only in ammonia production but also in oil refineries and methanol production.

According to the International Energy Agency (IEA), the contribution of natural gas to global hydrogen production will be 205 billion cubic meters in 2020 [11].

If 177 kg of hydrogen is supplied at the cost of "grey" and "green" hydrogen, it is possible to calculate how much raw material is needed and how much damage it causes to the environment. To do this, it is first necessary to look at the methodology.

2.1 Methane gas reforming

The methane reforming process consists of several stages [12], in this study we have not considered transport and storage.

2.1.1 Stage 1. Steam production furnace

For the reaction to take place, the water must be in vapor form at a very high temperature above 1500 ^{0}F. These high temperatures promote reactions between methane and water to extract as much hydrogen as possible from the process.

2.1.2 Stage 2. Reforming reaction

$$CH_4 + H_2O + Q = CO + 3H_2 \tag{3}$$

The steam from the furnace is mixed with natural gas containing methane to start the reaction. The vapor-gas mixture enters the reformer through the inlet manifold. The reformer tubes are surrounded by burners to keep the mixture temperature above 1500 ^{0}F. At these temperatures, methane (CH_4) reacts with water vapor (H_2O) to form hydrogen (H2) and carbon monoxide (CO). The efficiency of the system is ensured by the presence of a nickel catalyst. The mixture of hydrogen monoxide and carbon leaves the reformer through the cold exhaust manifold. As seen above, the carbon monoxide formed is harmful to the environment when it enters it.

2.1.3 Stage 3. Water Gas Shift Reactor (WGS Reactor)

To consume the carbon monoxide and produce more hydrogen, the carbon monoxide from the reforming reaction is fed into a water gas shift reactor. This reactor is filled with an iron-chromium catalyst that causes the water and steam (H_2O) to decompose into oxygen (O_2) and hydrogen (H_2). While the hydrogen is captured, the oxygen undergoes a reforming reaction to combine with carbon monoxide (CO) to form carbon dioxide (CO_2). Carbon dioxide is less harmful to the environment than carbon monoxide and can be reused in some useful processes.

$$CO + H_2O + Q = CO_2 + H_2 \tag{4}$$

(This reaction is endothermic and takes place at 800-1000^{0}C with the use of special catalysts.)

2.1.4 Stage 4. Gas Treatment - Pressure Swing Absorption (PSA)

The gas mixture leaving the WGS reactor is not pure hydrogen and therefore requires further purification to meet generally accepted standards. There are many ways to purify hydrogen, but the most common in industrial settings is Pressure Swing Absorption. The gas mixture enters the purifier where special absorbent materials trap the impurities under high pressure. The purified hydrogen is pumped out of the vessel. Finally, the vessel is depressurized to release the trapped contaminants. PSA is used to remove carbon dioxide, methane, carbon monoxide, and water from hydrogen.

It is important to understand that the MGR requires three 4.5 kg bottles of water to remove 1 kg of hydrogen, or both bottles of water in the process of injecting the injectables into the vessels operated in the MGR. For 1 kg of hydrogen, 6.4 – 32.2 kg of water is required. In general, however, an average of 22 kg of water is required to extract 1 kg of water from the gas [13].

https://doi.org/10.1051/e3sconf/202452401011

2.2 Electrolysis process

"Green hydrogen would be hydrogen produced by electrolysis using electricity generated from renewable energy sources (Figure 1) [14].

$$H_2O=H_2+1/2\ O_2 \tag{5}$$

(This reaction takes place when special electrolyte compounds are added to water and 4.4 kWh of electricity is used to produce 1 m^3 of hydrogen).

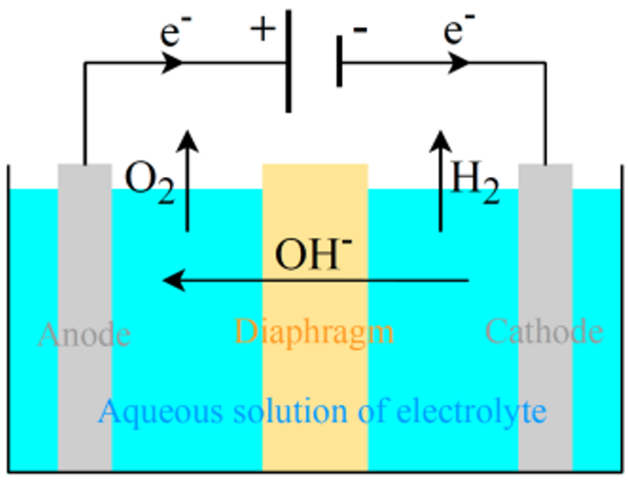

Fig. 1. Hydrogen production by electrolysis.

Anode reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ Oxygen released;

Cathode reaction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ Hydrogen is formed.

According to the international expert Herib Blanco of the portal "Energy Post", the electrolysis method requires at least 9 kg of water for 1 kg of hydrogen, or, if we take into account the phenomenon of water purification from minerals (demineralization), 1 kg requires 18-24 kg, i.e. an average of 21 kg of water for the finished fuel, if only demineralized water is suitable for electrolysis [14].

In this process, it is possible to obtain the required amount of water not only from freshwater but also from salt and seawater [15]. These waters must therefore be purified. However, this does not have a major impact on the cost.

This is because desalination accounts for less than 2% of the total cost of the electrolysis process. The use of seawater for this purpose increases the cost of water purification by a factor of 2.5 to 5 [16].

In 2050, if all hydrogen demand is met by electrolysis, water consumption will be around 25 billion cubic meters. For comparison, current water consumption is 2800 billion cubic meters in agriculture, 800 billion cubic meters in industry, 470 billion cubic meters in the urban economy, and 1,5 billion cubic meters in hydrogen production by gasification of natural gas and coal [17] (Figure 2).

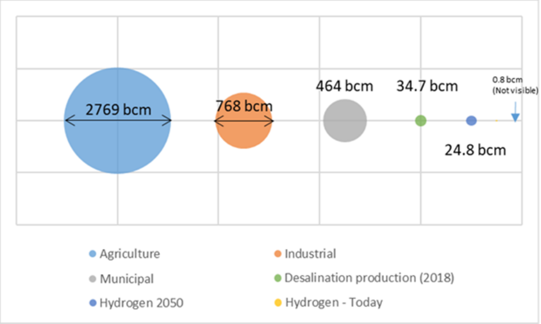

Fig. 2. Water use by economic sectors.

Based on equations (2-5) it is possible to calculate the amount of material needed to produce 177 kg of "green" and "grey" hydrogen and the amount of harmful gases released into the atmosphere as a result.

Table 2. Necessary materials to produce this hydrogen.

	Steam reforming of methane	Electrolyse
Methane mass, kg	353.1	-
Mass of water as a reagent, kg	793.85	1587.7
Average mass of total required water, kg	3894	3717
Mass of carbon dioxide produced, kg	970	-

Assuming that "Green" hydrogen is burned as fuel, 15% of the water used to produce this hydrogen is firstly recycled, i.e. recycled back into the water. This regenerated water is also suitable for hydrogen production [18].

Another way to obtain the amount of water required to produce "Green" hydrogen is to use rainwater falling on the solar panels used in its production. It can be verified by the realization of a pilot project of a "Green" hydrogen production plant located at a properly selected coordinate.

This research is based on the data (coordinates: 37o 6'north latitude and 61o 8'east longitude) obtained for the center of Mary province, Turkmenistan [19]. The calculation of the photovoltaic solar power plant was carried out using the national software "Digital System of Development of Solar Cadastre" developed at the Research and Production Centre "Renewable Energy Sources" of the State Energy Institute of Turkmenistan [20-22].

The calculations take into account the use of a 1 MW electrolyzer in the 2G system and the relevant calculations have been made using its technical specifications and the results are presented in Table 3 [21].

Table 3. Technical characteristics (features) of electrolysis installation with power of 1 MW.

Technical features	Value and measurement unit
Nominal power	1 MW
Generation of hydrogen	300 Nm3/h, 27kg/h
Control of hydrogen output	15-100%
Specific consumption of electric power	4.4 kW·h/Nm^3, 48.88 kW·h/kg
Hydrogen's outlet pressure	30-200 kgs/sm^2
Hydrogen's specific outlet	0.08988 kg/Nm^3
Lower heating power	119.96 MJ/kg (33.32 kW·h/kg or 3,00 kW·h/Nm^3)

Using Table 3, the following values can be calculated.

Maximum daily hydrogen production cost:

0.08988 kg/Nm^3 x 300 Nm^3/h = 27 kg/h or 647 kg of hydrogen produced per day (0.08988 kg/Nm^3 is the normal density of hydrogen).

The amount of electrical energy consumed per day at peak hydrogen production:

4.4 kW·h/Nm^3·300 Nm^3/h /27 kg/h = 48.9 kW·h/kg.

Using the information in Table 3, it is possible to determine the useful efficiency of the 2G system, i.e. the ratio of the internal energy produced by the hydrogen to the energy consumed to produce it:

η_{2G}= energy of hydrogen (kW·h/kg) / energy used to produce hydrogen (kW·h/kg).

If we take the minimum heat exchange capacity of the hydrogen produced and the maximum energy consumption of the electrolyzer (48.9 kW·h/kg), we can calculate the efficiency of the 2G system, i.e. the efficiency coefficient:

η_{2G} = (33.32 kWh/kg/48.9 kWh/kg) 100% = 68.1%.

The amount of electrical energy or power required to produce hydrogen at full capacity (300 Nm^3/h) of an electrolyzer in a 2G system:

$$P = 300\ \mathrm{Nm^3/h} \cdot 4.4\ \mathrm{kW{\cdot}h/Nm^3} = 1320\ \mathrm{kW} = 1.32\ \mathrm{MW} \quad (6)$$

3 Results and Discussion

Based on the above calculations, the authors of this scientific study will implement the photovoltaic solar power plant project (PV) with the help of national software, which will provide the electricity needed for the electrolyzer capable of producing at least 177 kilograms of hydrogen per day on average throughout the year. The results of this PV and the resulting electrolyzer performance are shown in Figures 3 and 4.

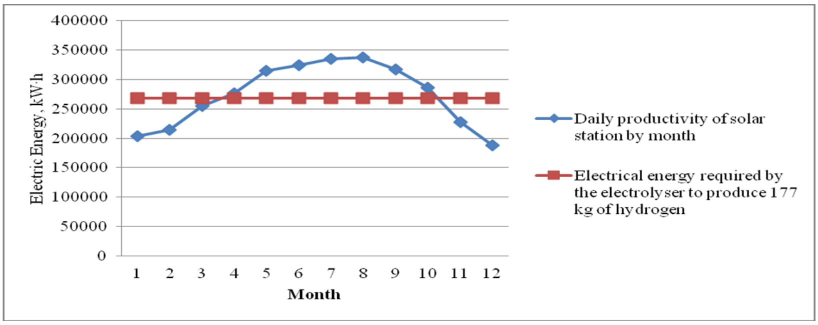

Fig. 3. Daily PV production by month and the electricity required for the electrolyzer to produce 177 kg of hydrogen.

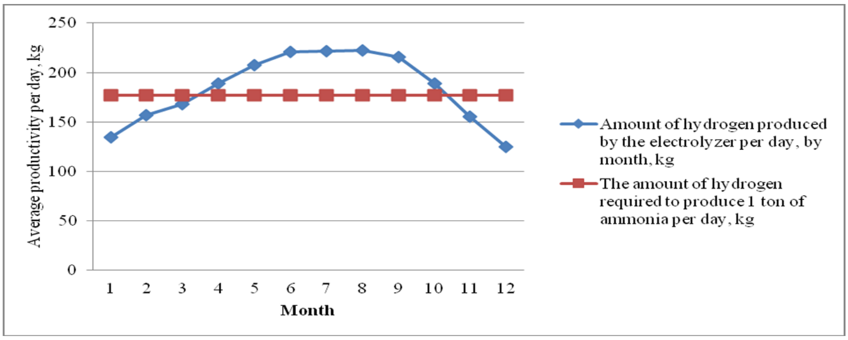

Fig. 4. The processed PV product is calculated from the hydrogen yield of the electrolyzer per month for one day and the amount of hydrogen needed to purchase 1 tonne of ammonia per day.

As can be seen from Figure 3, the productivity of the solar panels from January to March and from November to December is less than what is needed for an electrolyzer (insufficient amount of energy 250819 kW·h), but from March to October the productivity is more than what is needed (excess amount of energy (239295 kW·h), which means that the excess amount of electrical energy can be stored in hydrogen and used in the season of deficit), but it is also possible to use 11524 kW·h of electrical energy for own needs when needed.

As can be seen in Figure 4, the intensity of the productivity of the hydrogen production by the electrolyzer is directly dependent on the efficiency of the photovoltaic solar power plant, and we see that from January to March and from November to December there is a shortage of hydrogen (145.47 kg), and from March to October we see that although we do not have enough hydrogen, an excess of hydrogen is produced (227.37 kg), which we can store in special systems for use in the months when we still have excess hydrogen. Hydrogen that can be used or stored for your own needs when needed (81.9 kg).

In this scientific study, a Q.ANTUMDUO 580W solar panel with an average nominal capacity of 1.8 MW was used for 3104 seconds, which was installed at 36^0 degrees on the horizon at PV [23]. Much more than these data, PV optimizes day panels and back-cuts the metering device of one of its divisions essentially by the following formula.

$$S=a\cdot b\cdot N=2.115\text{m}\cdot 1.052\text{m}\cdot 3104=6906.34\ \text{m}^2 \tag{7}$$

During the calculations for electrolysis, it became clear that a water mass of m0 = 0.805 kg is required to produce 1 Nm^3 in the electrolyzer. On this basis, for a 2G electrolyzer, the mass of water in the zero range is given by the formula (8):

$$m_s = 300\ \text{Nm}^3/\text{h}\cdot m_0 = 300\ \text{Nm}^3/\text{h}\cdot 0.805\ \text{kg}/\text{Nm}^3 = 241.5\ \text{kg/h} \tag{8}$$

If the natural rain that will fall on the panels today is processed into the collection with the help of special tanks, it will be possible to determine the average volume of water that can be collected according to the annual rainfall at the coordinates where the calculation was made.

According to the coordinates, the average annual rainfall is given as 136 *mm* or V_{yer}=136 *l* per 1 m^2 area in the internet data [24]. Thus, the average annual precipitation falling on the total installed solar panels will be calculated as follows:

$$V_{yer}= V\cdot S=136\ \text{l/m}^2\cdot 6906.34\ \text{m}^2= 939262.24\ l \tag{9}$$

The daily amount of water for the electrolyzer can then be determined using formula (10):

$$V_g = V_{\acute{y}}/365 = 939262.24\ l/365 = 2573.32\ l \tag{10}$$

Assuming that 1 kg of pure water has a volume equal to 1 liter, m_g = 2573.32 kg of water is required for the daily operation of the electrolyzer. To find out how many hours a day this amount of water can supply the electrolyzer in the 2G system, it is sufficient to divide it by the amount of water consumed by the electrolyzer in one hour:

$$t = m_g/m_s = 2573.32\ \text{kg}/241.5\ \text{kg/hour} = 10.65\ \text{hours} \tag{11}$$

4 Conclusion

- The method of obtaining hydrogen used in the industrial production of ammonia in "grey" and "Green" forms was considered.
- If the hydrogen required for ammonia production is used in "green" form instead of "grey", 970 kg of CO_2 emitted into the atmosphere can be avoided for the production of 1 tonne of ammonia.
- The operational efficiency of the PV pilot project to supply electricity to the electrolyzer to obtain the "green" hydrogen needed to produce 1 tonne of ammonia was analyzed and it was found that the amount of electricity could be increased (11524 kW·h).
- The scientific study determined that the amount of water needed to obtain 1 tonne of “green” hydrogen at the coordinate in question can be provided by rainwater falling on the PV used in this method, and the efficiency of the electrolyzer was determined. It was found that 1 tonne of ammonia per day produced 81.9 kilograms more than the amount needed to be obtained during the year.

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