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Techno-Economic Study of the Potential for Green Hydrogen Production in Egypt

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Abstract

Green hydrogen (GH) is considered one of the best environmental alternatives fuel in the coming decades. GH is produced from natural solar energy and water resources. Although water is available in most countries, but sun is restricted in some regions along the year. Electrolysis process has a potential technology for clean and sustainable source of energy. It is also the best alternative to produce valuable hydrogen fuel (HF) from solar energy. The current study presents a theoretical analysis of designing a small-scale hydrogen generation unit containing two electrolyzers with 100 cells and 40 cm plate diameter to produce 75 kg H_2/day with consumed electric energy of 3360 kWh and 675 liter water/day, respectively. For designing a large-scale hydrogen generation plant with 280 ton/day (102,200 ton/year), the required electric power can be estimated as 618,333 kW (618.3 MW). Consequently; the electric energy consumption in MWh required can be estimated as 14,840 MWh and the required daily water consumed in m^3/day can be estimated as 2,520m^3/day. Considering the price of 1.0 kg of GH equals 3 USD, the cash flow diagram, showed that the project can recover the invested budget (2,259,390,903 USD) within 8 years and earn a remarkable profit of 5,115,728,534 USD after 25 years. This means that the investment in green hydrogen production projects is highly profitable as hydrogen can be sold as direct fuel, energy carrier or to be reacted with nitrogen to produce green ammonia where can be utilized as fertilizers and other useful industrial applications.

***Keywords**:* Green hydrogen, solar energy, electrolyzer, economic analysis, system design

Introduction

Hydrogen is an important energy carrier in the coming decades that will be produced without greenhouse's gases emissions. Steam and alkaline membrane electrolysis beside anode reactions, hybrid thermal/electrochemical cycles are improvement of existing techniques (Jens Oluf Jensen, 2017). There are three main categories to produce hydrogen; ***Electrochemical*** that uses solar electricity produced from photovoltaic (PV) panels or concentrating solar thermal systems followed by an electrolytic process; ***Photochemical/photo-biological*** that makes direct use of solar photon energy for photochemical and photo-biological processes; and ***Thermochemical*** that uses solar heat at high temperatures followed by an endothermic thermochemical process. In order to overcome the problems associated of using fossil fuels like petrol, natural gas and coal that emit a lot of pollutions to the atmosphere causing the global warming effect which negatively affect the climate conditions, three scenarios had been discussed. The first scenario is to improve the energy efficiency in industry to minimize the greenhouse gas to be exhausted to the atmosphere via capturing the oxides of carbon, nitrogen and sulfur beside methane gas, and chlorofluorocarbon's compounds. The second scenario is to increase the utilization of renewable energy (RE); the sustainable clean source of energy. This is because RE is environmentally friendly, abundant, available, and complying with the sustainability criteria. The third scenario is to produce hydrogen (H_2) as an alternative clean source of fuel. It is considered the best solution as it generates higher energy density with lower initial costs. It is abundant in the universe, the

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main challenge of using H_2 as a fuel is the methodology of extraction from its sources. It can be also produced from water, organic matters like methane and hydrocarbons. IEA, 2015 reported the current and future hydrogen production percentage from its resources as shown in Fig. 1.

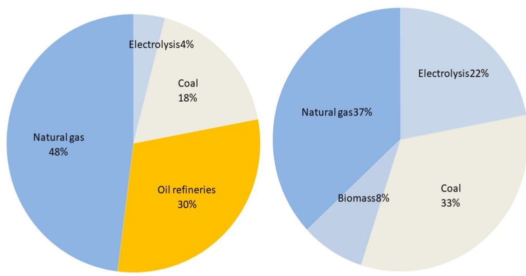

Fig. 1: Hydrogen production percentage in 2015 and 2050 from its resources (IEA, 2015)

For the water electrolysis, the total reaction equation of the hydrogen production is expressed in Equation 1. While the reactions at anode and cathode for acidic and alkaline electrolysers is shown in Table 1.

$$\mathbf{H_2O \rightarrow H_2 + \frac{1}{2} O_2} \quad (1)$$

Table 1
Reactions at anode and cathode for acidic and alkaline electrolysers

Water electrolysis	Acidic conditions	Alkaline conditions
Anode	$H_2O \rightarrow \frac{1}{2} O_2 + 2H+ + 2e^-$	$2OH^- \rightarrow \frac{1}{2} O_2 + H_2O + 2e^-$
Cathode	$2H+ + 2e^- \rightarrow H_2$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

There are several design types in commercial scales of the alkaline electrolyser's stacks but they all have same main components as shown in Fig. 2. Schematic diagram of operation of an alkaline electrolysis cell is shown in Fig. 3 Jens Oluf Jensen, (2017). H_2 categories are described by several colours depending on the energy used for its production processes. Grey hydrogen is produced from natural gas emitted with carbon dioxide (CO_2). On using such technology to remove/ store CO_2 using carbon capture and storage (CCS) or carbon capture and utilization (CCU) methods, the produced H_2 called blue hydrogen. On the other hand, black hydrogen is being produced from coal, while yellow hydrogen is produced via nuclear energy. Also, Green hydrogen (GH) can be generated from green/ renewable energy sources. Consequently, the most common methods for producing hydrogen are electrolysis and steam-methane reforming.

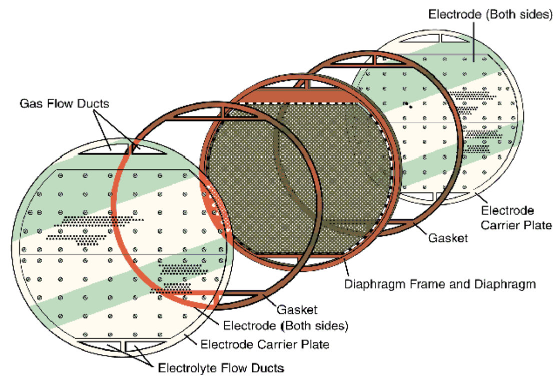

Fig. 2: Main components of the alkaline cell electrolysers stacks

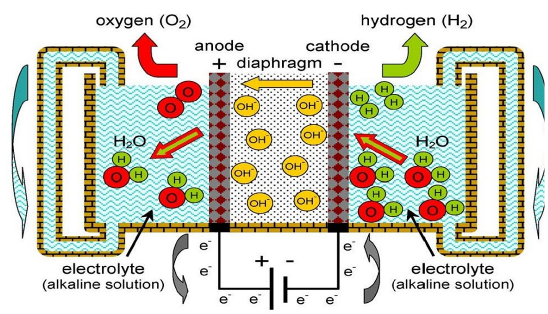

Fig. 3: Schematic diagram of operation of an alkaline electrolysis cell

$$\mathbf{2OH^- \rightarrow \frac{1}{2} O_2 + H_2O + 2e^-} \quad (2)$$

$$\mathbf{2H_2O + 2e^- \rightarrow H_2 + 2OH^-} \quad (3)$$

The Steam-methane reforming is a widely used method of commercial hydrogen production and mostly used in several countries in the world. Commercial hydrogen producers and petroleum refineries use steam-methane reforming to separate hydrogen atoms from carbon atoms in methane (CH_4). Its technology required high-temperature steam (1,300°F to 1,800°F) under 3–25 bar pressure leads to decomposition of methane in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of CO_2. On the other hand, Electrolysis is considered one of the efficient technology that splits hydrogen from water using an electric current. It does not produce any by products or emissions other than hydrogen and oxygen. The electricity for electrolysis is produced from coal, natural gas, and petroleum as a fossil fuel or biomass combustion has multi-negative effects on the environment. Added microbial-biomass/ biogas technology may be used for H_2 production. On the other side, solar and wind energies as renewable sources can generate electricity from GH via electrolysis. There are two main types of water splitting electrolyzers; Alkaline Electrolyzer Membrane (AEM) and Proton Exchange Membrane (PEM), as reported by Yujing Guo et al., (2019). The PEM electrolyzer is a kind of solid oxide hydrogen production cell, while the electrolyzed raw material is deionized water. The DC current density is $10000A/m^2$ ~$20000A/m^2$, which is about 5 times that of the AEM electrolyzer. The PEM electrolyzer, with its working temperature of 50 °C~80°C, pressure less than 5 MPa and the volume smaller than the AE, can be operated under different pressures. The structure of the PEM electrolyzer is similar to that of the AE. Pletcher, D. and Li, X., (2011) showed the main difference is the use of a thin film-electrode assembly to form a zero-pole spacing. The separator is a Nafion membrane, which is strongly acidic after being soaked in water, where the anode catalyst and the cathode catalyst are attached to both sides of the separator by electrolysis plating or hot pressing.

Solar energy is used to produce the required DC electric source to the electrolyzer. Electrolysis process can be considered a potential technology for clean and sustainable source of energy production. The utilization of water was considered the main raw material to produce valuable hydrogen fuel without any manipulation to the environment as stated by Lee et al. (2010), Afgan & Veziroghu (2010), Barton & Gammon (2010), respectively. Grani'a et al. (2007), Gomes Antunes et al. (2009), Corbo et al. (2010), Zhang & Zhou (2011), declared that the production of H_2 without traditional fuel-based processes was considered one suitable alternative solution in the coming decades.

Angelica Liponi et al., (2022) performed simulation study of hydrogen production by an alkaline electrolyser fed by a 1 MW PV plant for different electrolyser nominal powers using Matlab for a reference year. It is concluded that the increase of the electrolyser size leads to a decrease in the electrolyser capacity factor. Furthermore, the number of electrolyser shutdowns increases at higher electrolyser nominal powers leading to faster degradation. Therefore, the best choice for the electrolyser size should be the result of a trade-off between the maximization of hydrogen production and the need of limiting the number of shutdowns and of having a sufficiently high capacity factor of the electrolyser in order to keep the LCOH down.
Dash, S.K et al., 2023 presented a brief review of hydrogen production methods and their challenges. The review included the most recent developments in hydrogen production techniques using conventional and renewable energy sources, in addition to key challenges in the production of Hydrogen. Among the most potential renewable energy sources for hydrogen production are solar and wind. Water electrolysis equipment driven by off-grid solar or wind energy can also be employed in remote areas that are away from the grid. The challenges included feedstock type, conversion efficiency, and the need for the safe integration of H_2 production systems with H_2 purification and storage technologies. Because of the benefits associated with its use and the availability of carbon-free alternatives, hydrogen is gaining increasing attention as a possible fuel and a unique energy carrier option internationally.

Bairrão, D. et al, (2023) presented a study of energy transition considering green hydrogen production to identify Portugal's current state and prospects. The analysis used energy generation data, hydrogen production aspects, CO_2 emissions indicators and based costs. A comprehensive simulation estimated the total production of green hydrogen related to the ratio of renewable generation in two different scenarios. Their results suggested that the substitution of buses and trucks for H_2-based fuel implies a higher CO_2 reduction than thermoelectric plants fueled by H2. Regarding buses, the reduction represents 269% and 288%—2030 and 2050, respectively—higher than fueling thermoelectric plants.

Design of Hydrogen Unit

A small scale H_2 production unit is designed as shown in Fig. 4 using stainless steel (St.St.) iron plates in the generation cell. The AEM electrolyzer uses 30% wt. KOH solution as electrolyte. The applied DC current density is 0.5 mA/m^2 was being used at working temperatures maintained (80~90) °C, and working pressure within 3.2MPa, respectively.

The electrolytic cell consists of a permeable membrane, such as asbestos, polyphenylene sulfide, gasket, two St.St. plates, front and end (St.St.) plate as cathode and anode plates, fasteners and other components as shown in Fig. 5. In the current AE design, a circulating pump was used for recirculating the electrolyte (KOH) in and out the stack components that creating a pressure drop across the electrolyte cell. The outlet alkaline solution has to be separated from the produced gases. This to be carried out in gas-water separators that are mounted above the stack at a given height, while KOH/water flew back to the stack. The water phase has to be removed at the bottom and the gas phase from the top. The water column within the separator was also served as buffer storage for changing load specifications. The water management system regulating the gas separator filling level and water permeation via the diaphragm have to be considered. Water has to be transported to the anode side by the solvated species and charges. A mixing pipe was also installed between the anode and cathode water/gas separator to balance the OH^- charges consumed/ produced along with the electrochemical reaction. Due to the electrolyte temperature increasing, an air-cooling system was designed and installed to cool the outlet electrolyte solution of the cell, besides a cooling system designed to cool the output gas generated.

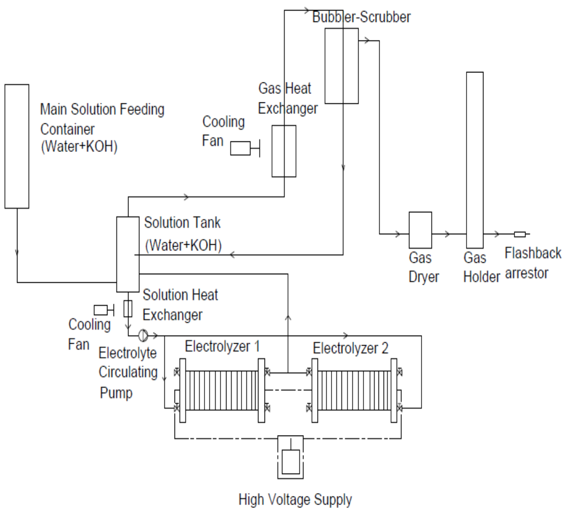

Fig. 4: Layout configuration of hydrogen production unit

The operation of the unit

The alkaline electrolyte passes to the anode and cathode regions on both sides of the membrane, and water molecules can permeate through the membrane to the other side. After connecting the electric current, the water molecules in the electrolyte combined with electrons in the cathode region to form H_2 and hydroxide ions, while in the anode region, the hydroxide ions lose electrons to generate oxygen and water. The designed unit is drawn in an isometric form as shown in Fig. 6. It consists of hydraulic system; the H_2 generation cell, main solution feeding reservoir, Solution Tank, Bubbler-Scrubber, Gas Dryer, Gas Holder, Flashback Arrestor, Solution Fan Coil Unit, Gas Fan Coil Unit, Solution Circulating Pump and Hydrogen Storage Vessel, in addition to the Piping System, Control and Measuring Devices. The electrical circuit consists of three-phase high-voltage source with an alternating current and a rectifier that converts the Alternating Current (AC) into a Direct Current (DC). The control and monitoring electric board is connected to measure the power directly, or the electric current and voltage. The voltage controlled in the two cells, the total current, and the input current has been measured for each cell. This is in addition to measuring the temperatures of the inlet and outlet solutions before and after cooling unit. It is also measuring the gas temperatures before and after cooling unit.

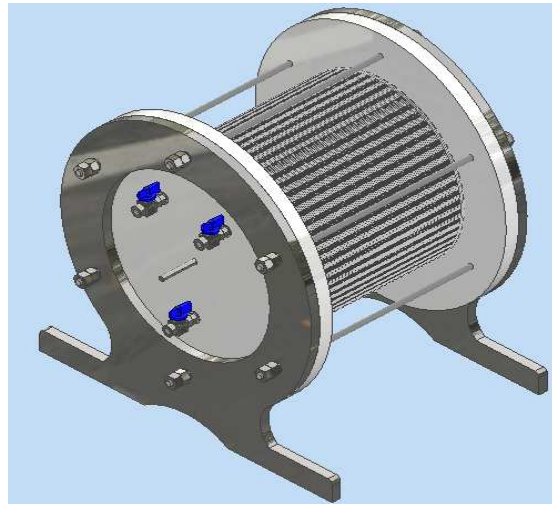

Fig. 5: H_2 generation cell

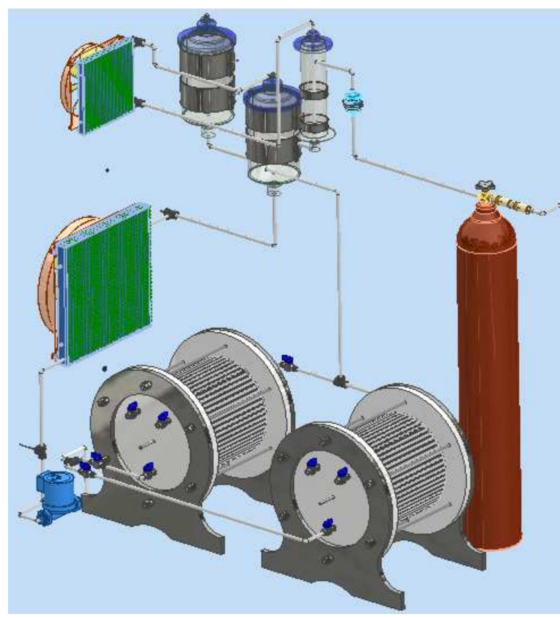

Fig. 6: Design of isometric form unit

Results and Discussion

Several parameters are affecting the performance of H_2 production in the hydrogen generation unit (HGUs), nominating: number of cells, applied voltage, electrolyte temperature, plate diameter/ surface area, electric power input, and volume of water used. The H_2 production rate may be estimated in an electrolyzer, which consists of several cells connected in series using Faraday's formula as shown in equation 4.

$$\dot{V}_{h2} = \eta_f N_{cell} \frac{I}{Z \quad F} \tag{4}$$

Where
V_{h2} = Hydrogen volume flow rate
η_f = Faraday Efficiency
N_{cell} = Number of cells
I = Electric Current
Z = number of electrons
Faraday's number = 96485.3 C /mole

The volume flow rate of hydrogen can be expressed in unit of Nm^3 /h [Alhassan Salami Tijani, 2014] as follows:

$$Q = V_{h2} \times 3600 \times HMV \tag{5}$$

Where HMV is the Hydrogen molar volume = 0.022414 m^3/mole

The effect of plate surface area on the H_2 production rate for different numbers of cells is shown in Fig. 7. It is clear that the H_2 production rate was increased with increasing the plate diameter and the number of cells. This is due to increasing the current with increasing the plate surface area and consequently the H_2 production rate is increased. The present small scale is designed with a plate diameter of 40 cm which produces 473m^3/day with a number of cells equal 100. With using two HGUs in the current design, the H_2 production rate will be 946m^3/day. For designing a large HGUs, the H_2 production rate can be estimated as 2954 m^3/day for each generation units having 100 cm diameter and 100 cells which corresponding to 70,896 m^3/day.

The effect of plate surface area on the required electric power, kW for different numbers of cells is shown in Fig. 8. It is clear that the electric power required is increased with increasing the plate diameter and the number of cells. This is due to increasing the current with increasing the plate surface area. Consequently, the electric power required has been increased. The present small scale was designed with a plate diameter of 40 cm which required 70 kW with a number of cells equals 100. With using two HGUs in the current design, the electric power required will be 140 kW. For designing large HGUs, the electric power required can be estimated as 441.56 kW for each generation units having 100 cm diameter and 100 cells.

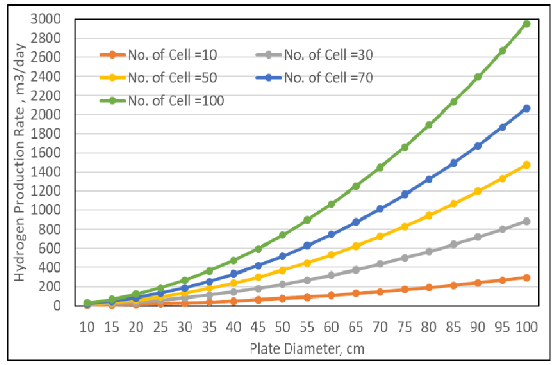

Fig. 7: Effect of plate diameter (surface area) on the hydrogen production rate for different number of cells

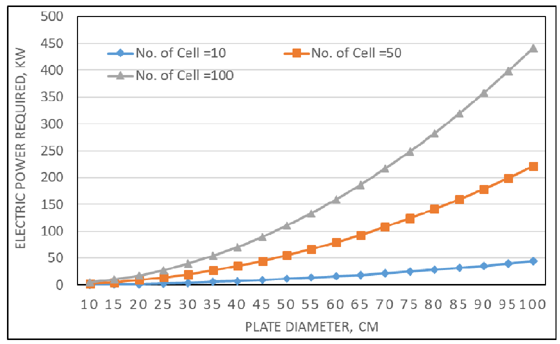

Fig. 8: Effect of plate surface area on the electric power required, kW for different number of cells

The required electric power is estimated as a function of the amount of H_2 production in ton/day is shown in Fig. 9. It is clear that the required electric power is increased with increasing the daily H_2 demand in ton/day. The present small scale is designed to produce 75 kg/day (0.075 ton/day) which required 140 kW with a number of cells equal 100. For designing a large hydrogen generation unit, to produce 280 ton/day (102,200 ton/year) the electric power required can be estimated as 618,333 kW (618.3 MW) for each generation units having 100 cm diameter and 100 cells.

The required electric energy consumption in MWh is estimated as a function of the amount of H_2 production in ton/day is shown in Fig. 10. It is clear that the electric energy consumption in MWh required is increased with increasing the daily H_2 demand in ton/day. The present small scale is designed to produce 75 kg/day (0.075 ton/day) which required 3,360 kWh with a number of cells equal 100. For designing a large H_2 generation units, to produce 280 ton/day (102,200 ton/year) the electric energy consumption in MWh required can be estimated as 14,840 MWh for each generation units having 100 cm diameter and 100 cells.

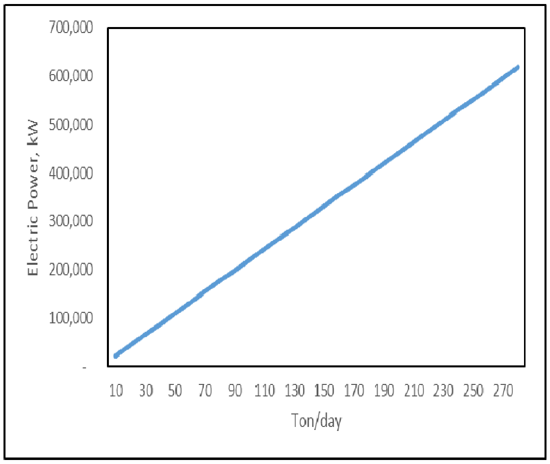

Fig. 9: The required electric power as a function of the amount of H_2 production in ton/day

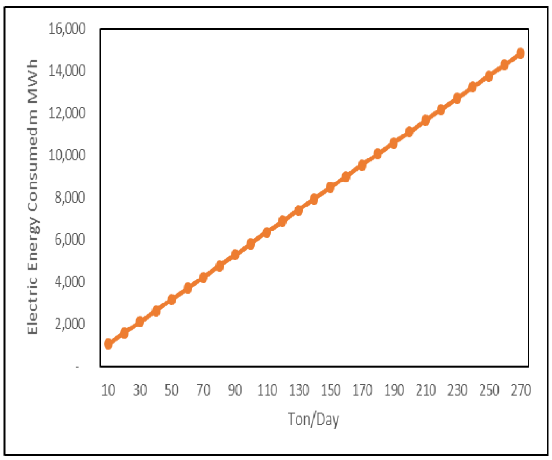

Fig. 10: Required electric energy consumption in MWh as a function of the amount of H_2 production in ton/day

To produce 1 kg of hydrogen, which is equivalent to 11,126 Nm^3 of H_2 gas it needs about 9 liters of deionized water. The required daily water consumed, m^3/day is estimated as a function of the amount of H_2 production in ton/day as shown in Fig. 11. It is clear that the required daily water consumed, m^3/day is increased with increasing the daily H_2 demand in ton/day. The current small scale is designed to produce 75 kg/day (0.075 ton/day) which required 675 liter /day with a number of cells equal 100. For designing a large H_2 generation units, to produce 280 ton/day (102,200 ton/year) the required daily water consumed, m^3/day can be estimated as 2,520 m^3/day for each generation units having 100 cm diameter and 100 cells.

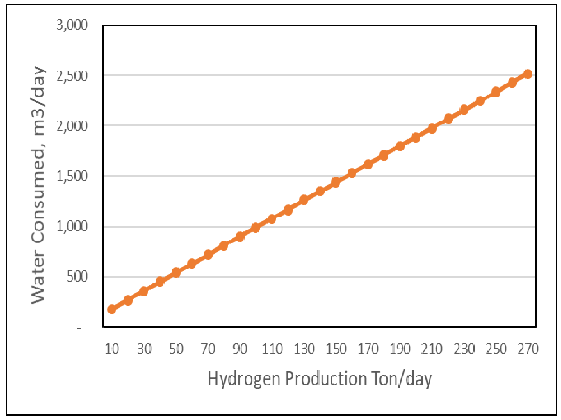

Fig. 11: The required daily water consumed, m3/day as a function of the amount of H2 production in ton/day

Economic Analysis

The economic analysis of H_2 production plant is affected by the capital cost (Capex) and operating cost (Opex). It can be estimated based on previously published research studies to identify the cost per kg of H_2 production. One of the recent studies estimated the Capex and Opex /kg of H_2 production as shown in Table 2.

Table 2
Capex and Opex /kg of H_2 production Cornelius Matis et al., (2020)

Item	USD/kg H_2
Capex Component	0.656597
Opex Components-Energy cost	1.02
Opex Components-General fixed O&M	0.155961
Opex Components-Water Cost	0.03
Opex Components-Stack Replacement Cost	0.087245
Opex Components-Leased Land Cost	0.001941
Opex Components-Decomposition and Rest Cost	0
Total	1.951744

Based on the estimated values of Table 2, a comprehensive financial study to estimate the budget required for installing a H_2 production plant with different capacities, ton/year. It is found that each kg of H_2 requires total electric energy consumption about 53 kWh. To assure durability and sustainability of the H_2 production plant, it is better to install a solar power plant to provide the electric energy needed throughout the project lifetime and to avoid the yearly inflation rates of the electricity price. The study is made to estimate the total cost (Capex +

Opex) for H_2 production of one ton/year up to 100,000 ton/year. As an example, for 25,000 ton/year, 50,000 ton/year, and 100,000 ton/year, the total cost is estimated as recorded in Table 3. As shown in Table 3, it is more economical to install solar power plant as a clean source of energy and the produced hydrogen will be green H_2. Taking the large studied plant with a capacity of 100,000 ton/year and estimating the cash flow diagram shown in Fig. 12 considering the price of one kg of green H_2 equal 3 USD. It is clear from Fig. 12 that the project can recover the invested budget (2,259,390,903 USD) within 8 years and earn a profit of 5,115,728,534 USD after 25 years. From these data, this means that the investment in green H_2 production projects is highly profitable as H_2 can be sold as fuel or energy carrier to react with nitrogen to produce green ammonia. This can be utilized as fertilizers as well as other applications.

Table 3
Total cost of H_2 production plant with/without installing solar power plant

Cost of Hydrogen Production Plant for 25 years period, USD			
	100,000 TON/YEAR	50,000 TON/YEAR	25,000 TON/YEAR
In case of installing power plant			
H2 Production plant Cost without energy	67,104,213.40	47,612,118.40	23,806,059.20
Power plant Cost, CSP 24 Electricity	2,164,166,666.67	1,236,666,666.67	618,333,333.33
operating cost	703,000,585.00	351,500,292.50	175,750,146.25
Total Cost	2,934,271,465	1,635,779,077	817,889,539
In case of using national electricity grid			
Capital cost	67,104,213.40	33,552,106.70	16,776,053.35
operating cost	3,309,100,585.00	1,654,550,292.50	827,275,146.25
Total Cost	3,376,204,798	1,688,102,399	844,051,200

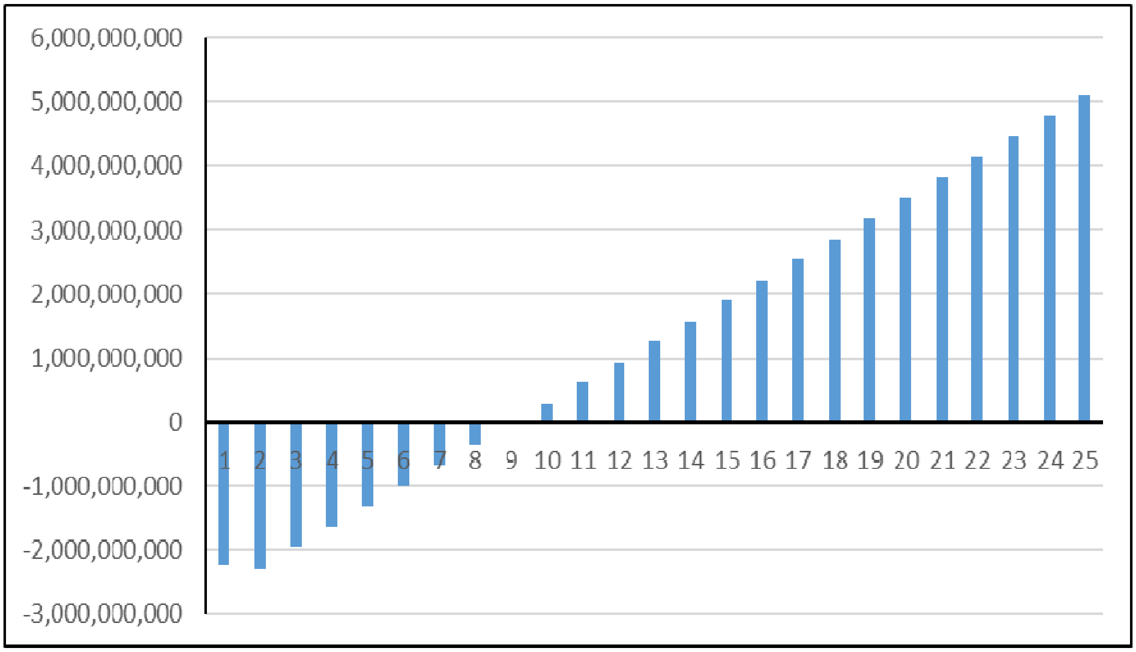

Fig. 12: Estimated cash flow diagram for 100,000 ton H_2/year

Conclusion

GH production via electrolysis process is considered one of the best alternative environmental fuels in the future. It was produced from solar energy as one of natural resources which is exist in sunny countries, clean and sustainable source of energy and water that has a potential technology. The concluded remarks are shown below, that emphasized the potential of GH production in Egypt. It has a best environment to install hydrogen industry as it has good solar energy and water resources all over the year:

1- The theoretical analysis of designing a small scale H_2 generation unit containing two electrolyzers with 100 cells and 40 cm plate diameter. It produced 75 kg/day with electric energy consumed of 3360 kWh and required 675 liter /day.
2- For designing a large H_2 generation plant, it is found that the H_2 production rate is increased with increasing the plate diameter and the number of cells. This is due to increasing the current with increasing the plate surface area and consequently the hydrogen production rate is increased.
3- The daily H_2 demand in ton/day is increased with increasing the electric power required in kW, consequently the electric energy consumption in MWh, and the required daily water consumed, m^3/day.
4- To produce 280 ton/day (102,200 ton/year) the required electric power can be estimated as 618,333 kW (618.3 MW). The electric energy consumption in MWh required can be estimated as 14,840 MWh and the required daily water consumed, m^3/day can be estimated as 2,520 m^3/day.
5- Considering the price of one kg of GH equals 3 USD. The cash flow diagram shows that the project can recover the invested budget (2,259,390,903 USD) within 8 years and earn a profit of 5,115,728,534 USD after 25 years. This means that the investment in green hydrogen production projects is highly profitable as H_2 can be sold as fuel or energy carrier to react with nitrogen to produce green ammonia which can be utilized in several applications like fertilizers and others applications.

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