

# Hydrogen Integration in a Renewable Hybrid Energy System

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## Abstract

This paper presents a technical analysis of a hybrid renewable energy system combining photovoltaic and wind energy sources with a hydrogen fuel cell for water pumping applications. The proposed system supplies electrical power to both an electrolyzer for hydrogen production and a double-star asynchronous motor driving a centrifugal pump. A detailed sizing of the different subsystems has been carried out to ensure reliable and efficient operation under varying environmental conditions. The obtained results demonstrate the effectiveness of integrating fuel cell technology into a renewable hybrid architecture, enabling clean, sustainable, and reliable energy generation for water pumping systems, particularly in remote and off-grid areas.

## Keywords

Green hydrogen; Energy storage; Electrolysis; Hybrid system; Energy transition.

## 1. Introduction

The increasing global demand for clean and sustainable energy has accelerated the development of renewable energy systems based on solar and wind resources [1]. However, the intermittent and variable nature of these renewable sources represents a major limitation for the continuity, stability, and reliability of standalone energy systems, particularly in remote and off-grid regions [2]. To overcome these challenges, energy storage technologies have become essential for ensuring energy availability and improving system autonomy [3].

Among the different storage technologies, hydrogen has emerged as a promising long-term energy carrier due to its high energy density, clean operation, and ability to store excess renewable energy for later use through fuel cells. The combination of renewable energy sources with hydrogen technologies offers an attractive solution for sustainable power generation and water pumping applications, especially in isolated areas where access to the electrical grid is limited or unavailable.

Several studies have investigated hybrid renewable systems integrating photovoltaic and wind energy sources with hydrogen production and storage technologies. These systems improve energy reliability and reduce dependence on fossil fuels. Nevertheless, the optimal integration of electrolyzers, fuel cells, and renewable sources in water pumping applications still presents important technical challenges related to system sizing, energy continuity, and overall efficiency.

In this context, this paper proposes a hybrid renewable energy system combining photovoltaic panels, wind turbines, an electrolyzer, hydrogen storage, and a fuel cell to supply a double-star asynchronous motor coupled to a centrifugal pump. The main objective is to evaluate the contribution of hydrogen integration in enhancing system reliability, energy continuity, and sustainability for water pumping applications.

The remainder of this paper is organized as follows. Section 2 presents the fundamentals of hydrogen energy and fuel cell technologies. Section 3 describes the architecture and components of the proposed hybrid pumping system. Section 4 presents the operating principles of the fuel cell. Section 5 is devoted to the pump selection and sizing procedure. The fuel cell sizing is presented in Section 6, while the quantitative analysis of the required hydrogen is discussed in Section 7. The obtained results are presented and analyzed in Section 8. Finally, Section 9 concludes the paper.

## 2. Fundamental Principles of Hydrogen

Hydrogen is a chemical element that is abundantly present in the universe, however, its extraction, whether by electrolysis, natural gas reforming, or gasification, requires the use of other energy sources.

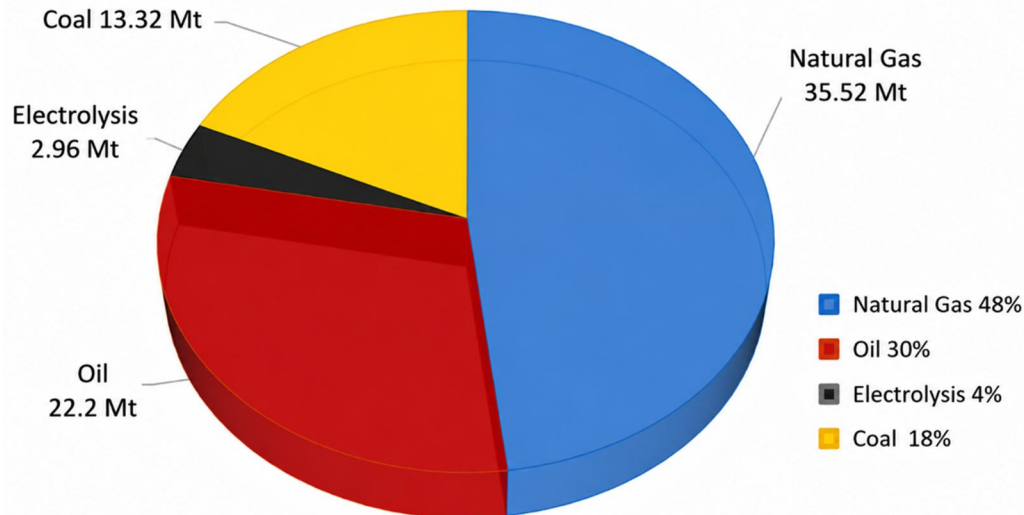


Fig. 1. Assessment of global hydrogen production in 2018 [4]

Hydrogen produced via water electrolysis powered exclusively by renewable energy is called green hydrogen (Figure 1). When obtained from nuclear energy, it is called yellow hydrogen.

Conversely, gray hydrogen is produced through thermochemical processes using fossil fuels such as coal or natural gas, and is also known as grey hydrogen. If the carbon dioxide ( $\text{CO}_2$ ) generated by these processes is captured and stored, the resulting hydrogen is termed blue hydrogen [4].

### 2.1. Hydrogen and energy

One of the main drivers behind the choice of hydrogen is undoubtedly an energy vision focused on reducing carbon dioxide emissions and promoting energy diversity, as highlighted by Johnston et al. [5] and Solomon & Banerjee [6]. Jacobson et al. [7] emphasized the potential for hydrogen to replace fossil fuels, particularly in the transportation sector, given the negative impacts of exhaust gas emissions from automobiles.

This fuel is not a primary energy source because another energy source is always required to produce hydrogen, which can then be stored as a fuel.

Pending further developments, 95% of hydrogen is produced by steam methane reforming of methane or bio methane, which remains the least expensive production technique. However, it is unreasonable to assume, in the long term, that this new energy carrier will continue to be derived from hydrocarbons [8, 9].

### 2.2. Hydrogen and the economy

Muradov and Veziroglu [10] introduced the concept of the "hydrogen economy," in which hydrogen storage is combined with electricity storage. Despite the environmental and economic benefits, as well as the absolute security of energy supply, the transition from carbon to hydrogen is progressing cautiously and gradually, intuitively following scientific, technological, and socio-economic developments. Fuel cells must be both cost-effective and safe, and reducing hydrogen production costs has become essential for the adoption of this electricity source [8].

### 2.3. Hydrogen storage and safety

Hydrogen must be stored in cylindrical steel tanks at a pressure of about 200 bar, and during its transport, the same safety conditions must be ensured. Beyond hydrogen's flammability, concerns related to high pressures or low temperatures require special handling. In the chemical industry, hydrogen is used in the production of ammonia and methanol, as well as in petrochemicals during oil refining [4]. The energy transition towards hydrogen will first involve its adoption in the industrial sector, followed by its generalization to other application areas.

### 3. Components of the Hybrid Pumping System

The proposed system includes a photovoltaic generator (PVG), a wind turbine driving a dual-star asynchronous generator (DSIG), and a fuel cell (FC) as energy sources used to supply two three-phase inverters. These inverters power the two stators windings of the DSIM, which is used to drive a centrifugal pump and an electrolyzer for hydrogen production [4, 11].

During periods of renewable energy overproduction (Figure 2), part of the electricity is used to power an electrolyzer that produces hydrogen, while the other part is dedicated to water pumping.

When renewable generation decreases, the FC takes over to supply the required energy [11, 12, 13].

Thanks to their increased reliability and absence of pollutant emissions, HES are autonomous installations, typically deployed in remote areas far from conventional power grids. This system provides a continuous energy supply over long periods thanks to its design [14].

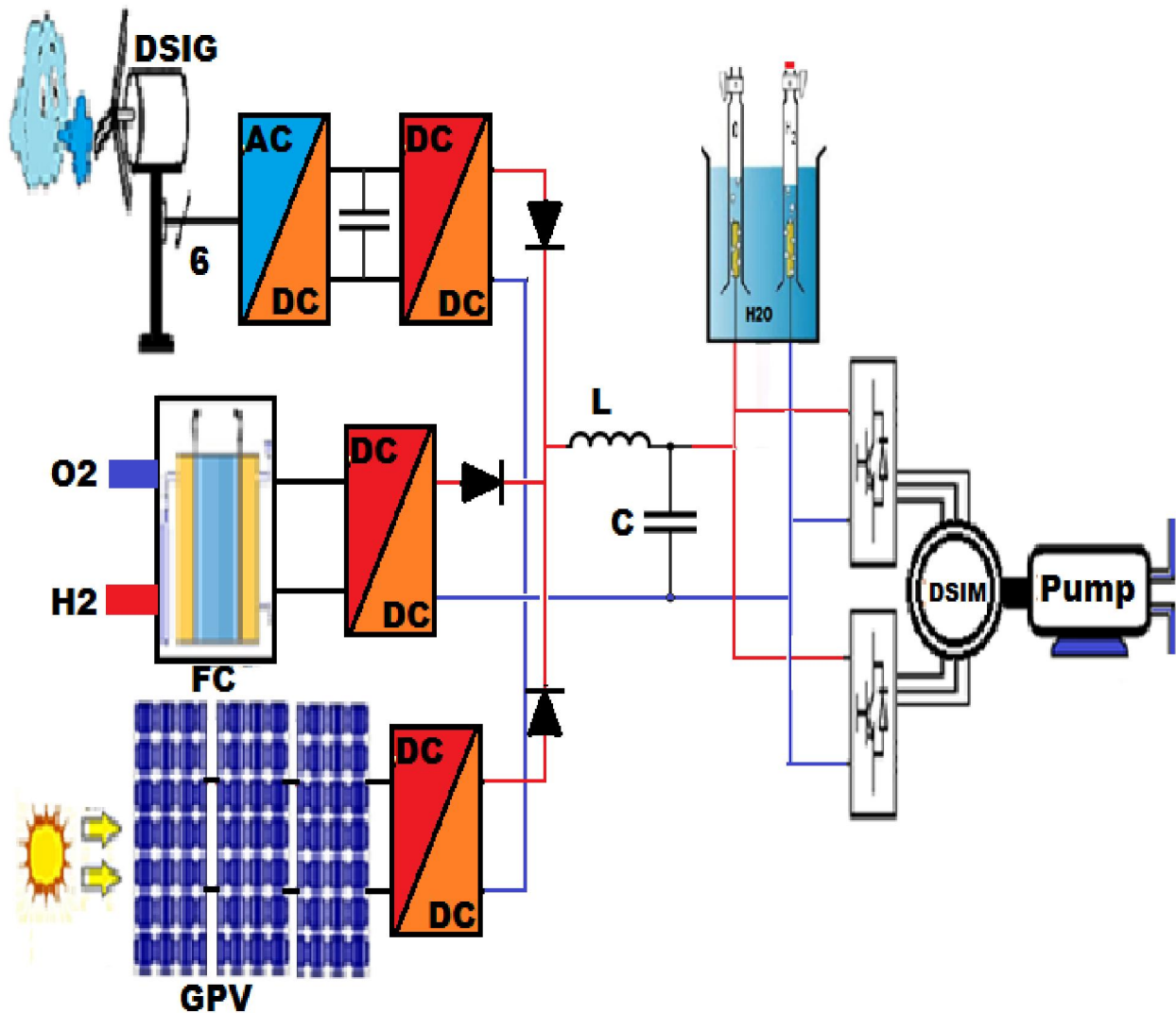


Fig. 2. Hybrid energy system (HES) [4, 11]

### 4. Fundamentals and Operational Principles of Fuel Cells

As early as the 19th century, researchers such as Davy, Grove, Langer, and Mond laid the foundations for the use of hydrogen as an energy source, leading to the development of the fuel cell, capable of producing electricity without thermal combustion.

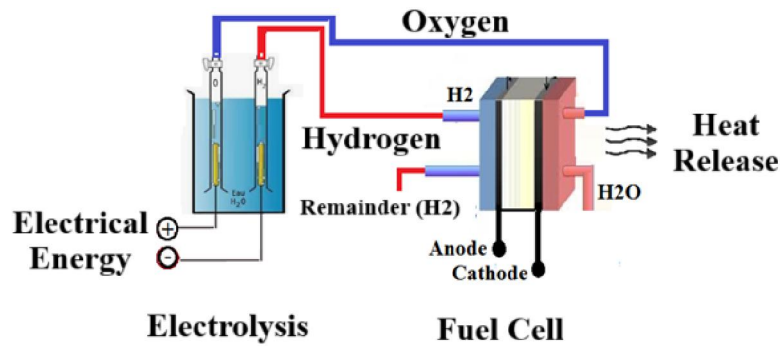


Fig. 3. Electrolysis-reverse electrolysis diagram [15]

A FC consists of an anode and a cathode separated by an electrolyte (Figure 3), which allows ions to migrate from one electrode to the other under the effect of the electric field generated. Hydrogen is the most efficient fuel due to its high electrochemical reactivity, and oxygen is the most effective oxidant thanks to its high reactivity and abundance in the air [11, 16,17].

#### 4.1. Operating principle of the fuel cell

The anode, where the oxidation reaction occurs, is supplied with a hydrogen source ( $H_2$ ,  $CH_3OH$ , etc.) as fuel.



The cathode, where the reduction reaction takes place, is supplied with oxygen as the oxidant [4, 18].



Platinum is required as a catalyst to accelerate the two half-reactions, and it is also necessary to provide channels for fluid circulation, heat and water removal, as well as water recycling for the potential conditioning of the electricity produced [4, 18].

#### 4.2. Fuel cell classifications

Apart from the polymer electrolyte membrane fuel cell (PEMFC), which is lightweight and easy to construct—and was notably used by NASA in the 1960s during the Gemini and Apollo space programs—several other types of fuel cells, summarized in Table 1, have been developed [18].

Table1. Fuel cell classifications [18].

	Low temperature				High temperature	
	Proton Exchange Membranes Fuel Cells	Direct Methanol Fuel Cells	Phosphoric Acid Fuel Cells	Alkaline Fuel Cells	Solid Oxid Fuel Cells	Molten Carbonate Fuel Cells
Temperature	70°C to 100°C	70°C to 90°C	150°C to 220°C	50°C to 250°C	700°C to 1050°C	600°C to 800°C
Electrolyte	Solid polymer membrane	Solid polymer membrane	Liquid phosphoric acid	Liquid potash KOH	Solid ceramic	Molten carbonate salt (liquid)
Available fuels	Hydrogen	Methanol	Hydrogen, Natural gas	Hydrogen	Hydrogen, Natural gas, Methanol	Hydrogen, Natural gas, Methanol
Required power range	1W to 10MW	1W to several KW	200KW to 10MW	1W to 100KW	1KW to 100MW	500KW to 10MW
Electrical efficiency	30% - 45%	30% - 45%	35% - 45% 75% In cogeneration	50% - 60%	50% - 55% 70% In cogeneration	50% - 60%

### 4.3. Fuel cell choice

The PEMFC technology is chosen for its low operating temperature, which does not exceed 100°C, its relatively fast start-up, and its efficient heat dissipation.

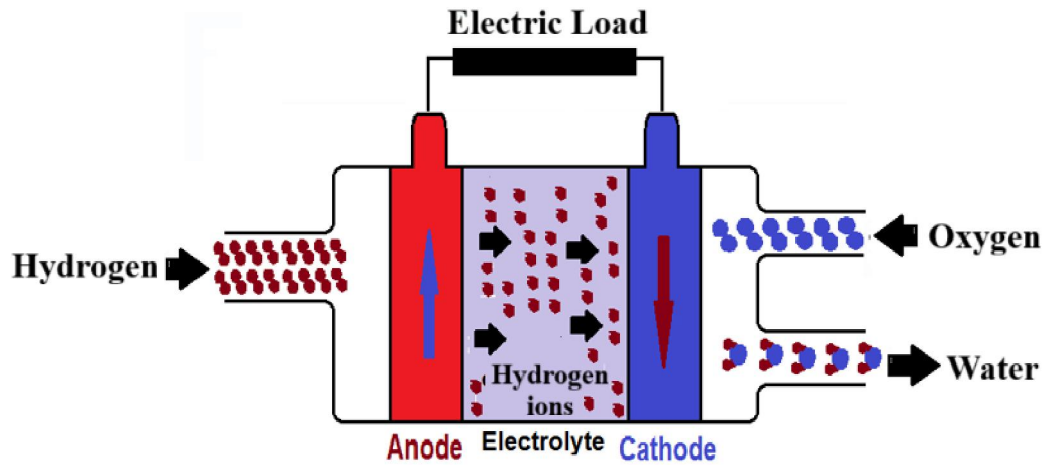


Fig. 4. Phosphoric acid and PEM fuel cells [15]

The PEMFC, or hydrogen fuel cell, uses hydrogen as fuel and oxygen as the oxidant. It is unaffected by the presence of CO<sub>2</sub> in the air and features a solid electrolyte, which ensures a longer lifespan compared to liquid-electrolyte fuel cells [19].

### 4.4. Fuel cell voltage model

Indeed, Maxwell's equations model mass transport, the Nernst equation describes thermodynamic equilibrium potentials, and the Tafel equation accounts for activation overpotentials. Internal resistance is determined using the Nernst–Planck equations. The dynamic behavior of the fuel cell (FC) can be represented by the following equivalent electrical circuit [4, 11, 15]:

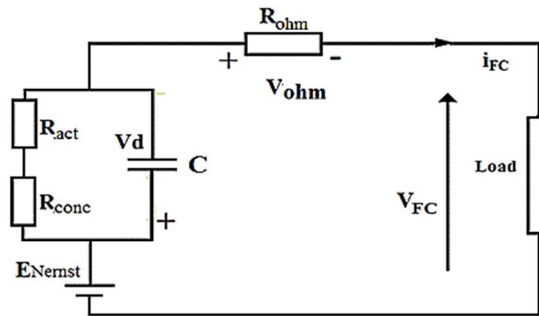


Fig. 5. Fuel cell dynamic equivalent circuit

$$E_{nernst} = 1.229 - 0.85 \cdot 10^{-3}(T - 298.15) + 4.31 \cdot 10^{-5} \cdot T \left[ \ln(PH_2) + \frac{1}{2} \ln(PO_2) \right] \quad (3)$$

The activation losses due to the initiation of chemical reactions at the electrodes of the fuel cell are described by the Tafel equation [13]:

$$V_{act} = A \times \ln \left( \frac{I_{FC} + I_n}{i_0} \right) \quad (4)$$

The voltage drop caused by ohmic losses is given by [16, 20]:

$$V_{ohm} = R_m \times (I_{FC} + I_n) \quad (5)$$

The following equation describes the concentration losses [16, 20]:

$$V_{conc} = -B \times \ln \left( 1 - \frac{I_{FC} + I_n}{I_L} \right) \quad (6)$$

According to [16, 20], the overall real potential of the PEMFC is given by:

$$U_{FC} = E_{Nernst} - V_{act} - V_{ohm} - V_{conc} \quad (7)$$

## 5. Pump Selection and Sizing

The choice of a centrifugal pump for this station is justified by the various advantages it offers. It ensures a continuous flow suitable for stable operation, and its simple design allows for easy maintenance and lower operational costs. The design of a standalone installation requires, prior to any steps and following a sequence, the understanding of several key parameters, namely [21].

### 5.1. Water demand assessment

The actual water demand of the locality to be served throughout the year must be determined in order to size the reservoir capacity and ensure system autonomy. Indeed, a reservoir with a capacity of 150 m<sup>3</sup> has been built to supply the only well originating from a borehole, where the daily water demand does not exceed this capacity even in the most unfavourable cases [17, 23, 24].

### 5.2. Pumping duration

Given the water reservoir volume  $V$  [m<sup>3</sup>], a nominal expected flow rate of  $Q_n=30$  m<sup>3</sup>/h and a total dynamic head TDH=17 m, the pumping duration is given by [4, 22]:

$$T_{pumping} = \frac{V}{Q_n} = 5 \text{ hours} \quad (8)$$

### 5.3. Calculation of the necessary hydraulic energy

The hydraulic power required for water transport between two points is given by:

$$P_H = \rho \times g \times TDH \times Q_v = 1000 \times 9,81 \times 17 \times \frac{30}{3600} \simeq 1390 \text{ W} \quad (9)$$

### 5.4. Mechanical power

The centrifugal pump, with an efficiency of 55%, requires mechanical power of:

$$P_{mec} = \frac{P_H}{\eta_{pump}} = \frac{1390}{0.55} \simeq 2527 \text{ W} \quad (10)$$

### 5.5. Electrical power

From the mechanical power and the motor efficiency, it is possible to determine the electrical power required for the motor operation.

For alternating current (AC) motors, the typical efficiency is around 85%, according to [4, 20]:

$$P_{elec} = \frac{P_{mec}}{\eta_{DSIM}} = \frac{2527}{0.85} = 2973 \text{ W} \quad (11)$$

### 5.6. Required delivered power

The actual electrical power demanded includes the consumption of static converters used in the power chain, notably inverters with an efficiency of 95% [21].

$$P_{delivered} = \frac{P_{elec}}{\eta_{inverter}} = \frac{2973}{0.95} \simeq 3130 \text{ W} \quad (12)$$

The overall efficiency of the installation can be calculated as the product of all the efficiencies of the actuators involved in the pumping chain.

It is given by:

$$\eta_{total} = \eta_{inverter} \times \eta_{DSIM} \times \eta_{pump} \quad (13)$$

$$\text{An: } \eta_{total} = 0.95 \times 0.85 \times 0.55 = 0.444$$

The electrical power demand can be calculated using Bernoulli's theorem.

To simplify these calculations as much as possible, practitioners use the following formula with a unit correction factor of 0,367.

$$P_d = \frac{Q \times TDH}{0.367 \times \eta_{total}} = \frac{30 \times 17}{0.367 \times 0.444} \simeq 3130 \text{ W} \quad (14)$$

Based on the calculated photovoltaic generator power of approximately 3912.5 W, a nominal value of 3960 W was retained for the fuel cell sizing in order to account for additional operating margins and conversion losses.

### 5.7. Required electrical energy

The electrical energy demand of the load is evaluated taking into account the daily pumping duration, as follows:

$$E_c = P_{delivered} \times T_{pumping} = 3130 \times 5 = 15650 \text{ Wh/day} \quad (15)$$

## 6. Fuel Cell Sizing

The FC is expected to provide a voltage of 630 volts to the DC bus required by the two inverters. Therefore, the electrical power to be used is 3960 W. The number of cells determines the module voltage, and the surface area of the cells determines the current. The voltage depends on the cells, which must be connected in series, knowing that each cell provides between 0 and 1.1 volts. On the other hand, the current depends on the total surface area of a cell. For an efficiency of 60%, the operating voltage is 0.63 V per cell, and the current density is 600 mA/cm<sup>2</sup>, which corresponds to nominal PEM fuel cell operating conditions [4, 15]. Therefore, the number of cells is:

$$N_{cells} = \frac{U}{U_{cell}} = \frac{630}{0.63} = 1000 \text{ cells} \quad (16)$$

Moreover, the current value will therefore be:

$$I = \frac{P}{U} = \frac{3960}{630} = 6.29 \text{ A} \quad (17)$$

The required surface area is obtained using the current density, and its value is:

$$S = \frac{I}{di} = \frac{I}{j} = \frac{6.29}{600 \cdot 10^{-3}} = 10.48 \text{ cm}^2 \quad (18)$$

Table 2 presents a summary of all the results derived from the sizing process of the fuel cell.

**Table 2.** Recapitulation of the sizing of the different sources.

Pumping system		Designation	Value
Pumping time	5 hours	Inverters efficiency	0.95
Reservoir volume	150 m <sup>3</sup>	DSIM efficiency	0.85
Flow	30 m <sup>3</sup> /h	Pump efficiency	0.55
Total dynamic head	17 m	Total efficiency	0.444
Fuel cell		Designation	Value

<b>Designation</b>	<b>Value</b>	Number of cells	1000
Current	6.29 A	Surface area	10.48 cm <sup>2</sup>
Fuel	Hydrogen	Oxidizer	Oxygen

## 7. Quantitative Study of the Required Hydrogen

This study aims to estimate the mass of hydrogen needed to operate a 4.5 kW dual-star asynchronous induction motor, intended to drive a centrifugal pump for a duration of 5 hours. The energy system considered is based on the use of a hydrogen-fed fuel cell connected to an inverter supplying power to the motor.

### 7.1. Assumptions and fundamental data

The following table summarizes the key assumptions considered for calculating the amount of hydrogen required to operate the pumping system for 5 hours. These assumptions are essential to ensure the accuracy and relevance of the estimation.

**Table3.** Assumptions and Fundamental Data.

<b>Designation</b>	<b>Value</b>	<b>Designation</b>	<b>Value</b>
DSIM power	4.5 kW	FC efficiency	50 %
Operating Time	5 hours	Inverter efficiency	95 %
Required Electrical Energy	22,5 kWh	DSIM efficiency	85 %
Lower Heating Value (LHV) of Hydrogen			33,33 kWh/kg

They include operational parameters such as motor power, system efficiency, and duration of use, as well as environmental and technical conditions. By clearly defining these assumptions, we can provide a reliable basis for the hydrogen mass calculation and ensure that the results are applicable to real-world scenarios.

### 7.2. Required hydrogen mass

The required hydrogen mass is calculated using the following equation:

$$m_{H_2} = \frac{E}{PCI \times \eta} = \frac{E}{PCI \times \eta_{Inverter} \times \eta_{DSIM} \times \eta_{FC}} \quad (19)$$

The total efficiency is calculated as:  $\eta = \eta_{Inverter} \times \eta_{DSIM} \times \eta_{FC} = 0.95 \times 0.85 \times 0.50 = 0.40375$

The hydrogen mass is given by:  $m_{H_2} = \frac{5 \times 4.5}{33.33 \times 0.40375} = 1.67 \text{ kg}$

Therefore, approximately 1.58 kg of hydrogen is required to operate the system for 5 hours, assuming the efficiencies and operating conditions described above. This estimation ensures that the fuel cell can reliably supply the necessary power throughout the entire duration.

### 7.3. Equivalent storage volume

The hydrogen storage volume depends significantly on the storage pressure, as it affects the hydrogen density. At a pressure of 700 bar, the hydrogen density is approximately 42 kg/m<sup>3</sup>. Given the required hydrogen mass of 1.67 kg, the corresponding storage volume can be calculated as follows:

$$V = \frac{m}{\rho} = \frac{1.67}{42} \approx 0.0398 \approx 37.6 \text{ liters}$$

On the other hand, at a lower pressure of 350 bar, the hydrogen density decreases to about 23 kg/m<sup>3</sup>. Using the same hydrogen mass, the storage volume is therefore larger:

$$V = \frac{m}{\rho} = \frac{1.67}{23} \approx 0.0726 \approx 72.6 \text{ liters}$$

This illustrates that doubling the storage pressure roughly halves the volume needed for the same mass of hydrogen. Therefore, selecting the appropriate storage pressure is crucial in designing a compact and efficient hydrogen storage system, balancing safety, cost, and space requirements.

## 8. Results and Discussion

Figure 6 shows the electromagnetic torque evolution during the motor start-up. The torque initially reaches a peak value of approximately 26 Nm before stabilizing near the pump resistive torque. After the transient period, the torque oscillates around the nominal value of 12 Nm with a variation of about  $\pm 2$  Nm.

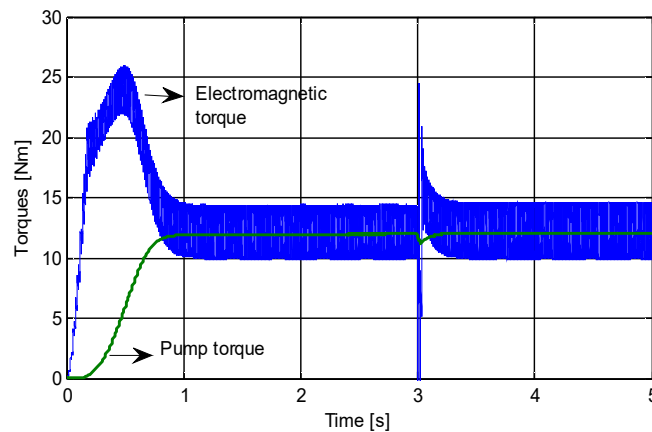


Fig. 6. Evolution of the electromagnetic torque and the resisting torque.

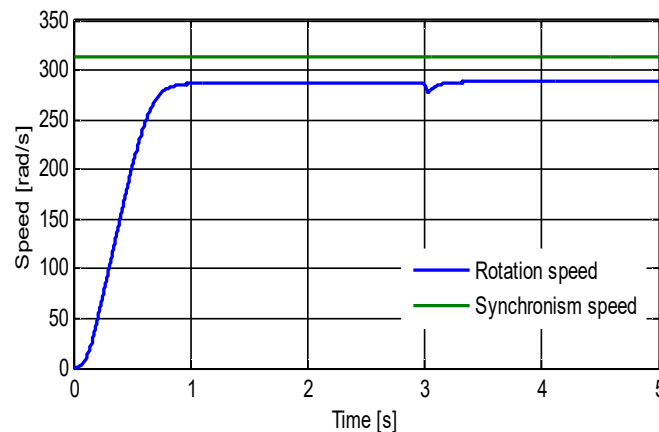


Fig. 7. Rotational speed and synchronism

Figure 7 illustrates the increase in motor speed during the starting phase until reaching its steady-state operating value. In addition, Figure 8 demonstrates that the variation of the total dynamic head (TDH) follows the same trend as the resistive torque, since both evolve proportionally to the square of the rotational speed. Finally, Figure 9 shows that the water flow rate evolves similarly to the TDH and follows the increase in rotational speed presented in Figure 7.

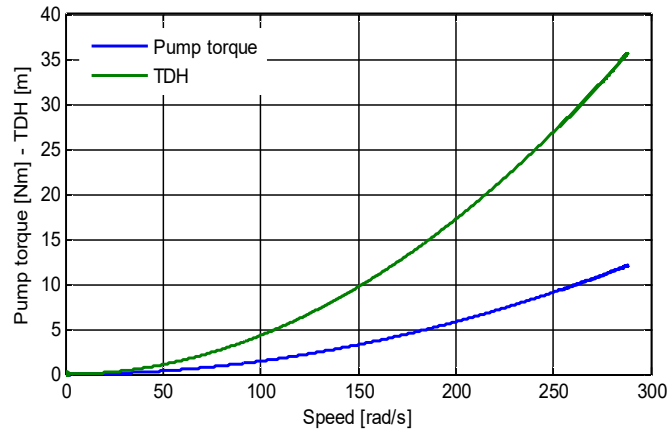


Fig. 8. Torque-speed and TDH-speed characteristics

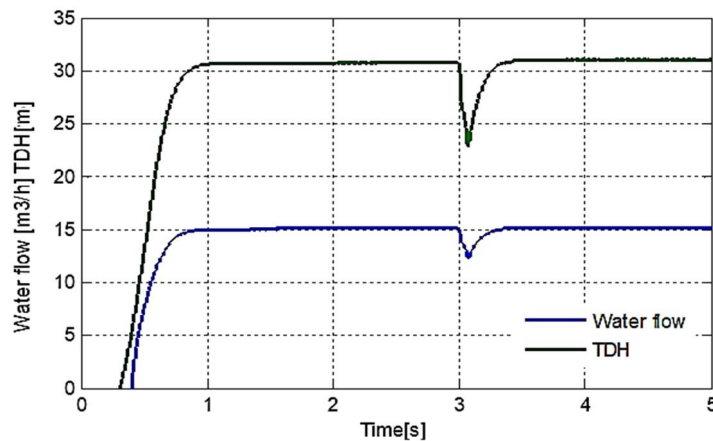


Fig. 9. Total dynamic head and flow rate characteristic curve

As part of efforts related to economic recovery and decarbonization, large-scale electrolyzer construction projects ranging from 1 GW to 10 GW are currently underway.

These installations aim to increase current hydrogen production by a factor of 100 or even 1,000, with a significant scale-up expected by 2030. Artificial intelligence could play a major role in predictive control and intelligent energy flow management [23].

Hybrid hydrogen–pumping systems are being applied in remote locations, university micro grids, and seawater desalination projects. Several pilot projects are under development in Europe and North Africa, particularly in rural and mountainous areas.

## 9. Conclusion

The hydrogen–pumping coupling appears to be a promising and practical approach and sustainable approach for rethinking energy storage and management. By combining water pumping with hydrogen production, the system offers both flexibility and improved autonomy, which makes it particularly relevant for future smart grid applications. In such configurations, water and hydrogen can be seen as complementary elements that help ensure a more continuous and reliable energy supply, under variable renewable energy conditions.

From a broader perspective, this approach contributes to reducing greenhouse gas emissions while improving the overall resilience of energy systems. The use of fuel cells helps maintain power supply under variable operating conditions, whereas electrolyzers make it possible to store surplus renewable energy in the form of hydrogen for later use.

For countries such as Algeria, which already rely heavily on conventional energy resources, hydrogen-based technologies should not be seen as a replacement in the short term, but rather as a gradual and strategic

transition. They represent an opportunity to diversify the energy mix, support long-term sustainability, and open new pathways for technological and industrial development.

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