Green Hydrogen Production by Using Recycle Aluminum Metal Without the Use of Electricity

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Abstract. Hydrogen is increasingly recognized as a clean and flexible energy carrier with significant potential to support the transition away from fossil fuels and toward renewable energy systems. Among the various methods for producing hydrogen, the reaction between aluminum and alkaline solutions stands out for its simplicity and efficiency, especially when aluminum waste is used as the source material. While aluminum recycling is widely promoted for its environmental benefits, its wider adoption is often hindered by high energy requirements, economic limitations, and operational challenges. This study explores an innovative solution that combines aluminum waste recycling with green hydrogen production, offering a dual benefit: sustainable energy generation and effective waste reduction. The experimental investigation focused on the reaction kinetics of aluminum with aqueous sodium hydroxide (NaOH), analyzing how factors such as surface area, NaOH concentration, and temperature affect hydrogen output over time. The findings demonstrated a strong correlation between the experimental data and theoretical stoichiometric predictions. Importantly, NaOH acted as a catalyst rather than being consumed, supporting continuous hydrogen production. The H_2 production rate is expected to be higher for aluminum shavings than for the aluminum cans and aluminum slabs. This approach was successfully applied to an electric scooter adapted for individuals with disabilities. Practically, one kilogram of aluminum produces 1246NLiters of hydrogen, which, with the use of PEM Fuel Cell extended the scooter's travel range about twice as much the distance achievable on a full battery charge. The results highlight the promise of this method as a sustainable and scalable technology that aligns environmental responsibility with practical energy needs.

1. Introduction

In today's global landscape, one of the most pressing challenges is finding ways to convert energy sustainably, minimizing the use of raw materials, and reducing the environmental footprint. This need has grown more urgent as the world's population continues to rise; in fact, it has more than tripled since the mid-20th century [1] and is projected to reach 9.7 billion by 2050 [2]. This increase directly translates into greater energy demand for homes, industries, and transportation. Historically, fossil fuels like coal, oil, and natural gas have met this demand, but their

environmental drawbacks, including greenhouse gas emissions, air pollution, and resource depletion, are well-documented [1, 3].

As a result, researchers are increasingly turning to cleaner and more efficient alternatives. Among these, hydrogen is a highly promising energy carrier [4, 5]. When used in energy systems, hydrogen reacts with oxygen to produce only water, which makes it a zero-emission option. This not only helps reduce carbon emissions but also improves overall energy efficiency [6]. Unlike solar or wind energy, which depends on weather conditions, hydrogen can store and deliver energy on demand, making it particularly versatile [7]. Over the past two decades, hydrogen applications have expanded significantly from stationary power systems to transportation technologies powered by fuel cells or hydrogen-fuelled engines [8-10].

However, despite its advantages, hydrogen also presents some technical challenges. It is highly flammable, can weaken certain metals, and perhaps most critically its storage and transportation can be complex and costly [11]. This has sparked growing interest in producing hydrogen in real time, directly where and when it's needed [12, 13]. Although hydrogen is the most abundant element in the universe, it doesn't exist freely in molecular form (H_2) and must be extracted from compounds like water or hydrocarbons [13]. Several methods are available to accomplish this, including steam reforming [14], partial oxidation [5], gasification [15], electrolysis, and biological approaches like fermentation [16]. In recent years, chemical reactions involving metals such as aluminum [17, 18], zinc [19], and magnesium [20] reacting with water have gained attention as a potential path for hydrogen production [21].

Among these, the aluminum–water reaction has been studied extensively for over five decades [22 - 24]. Aluminum is not only abundant and cost-effective, but also reacts quickly with water under the right conditions to produce hydrogen [25, 26]. It is safe to handle, and the by-products of the reaction are non-toxic and can be reused or disposed of easily [27]. A comprehensive life cycle assessment by Hiraki et al. [28] found that aluminum-based hydrogen production requires only about 2% of the energy and emits just 4% of the CO_2 compared to conventional steam reforming. This approach is particularly appealing for mobile applications, such as vehicles powered by hydrogen fuel cells. For example, a commercial fuel cell electric vehicle (FCEV) typically needs around 4 kg of hydrogen to travel 400 km [29], an amount that could be produced by just 36 kg of aluminum if the reaction is fully optimized [30].

The basic reaction is described by the following equation [31]:

$$(1)\ 2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2$$

Although this reaction is exothermic and theoretically spontaneous, it doesn't occur easily in practice due to the formation of a thin oxide layer on aluminum that prevents further reaction. To overcome this, researchers have explored various methods such as using oxide and salt promoters [32, 33], molten alloys with gallium or lithium [34 - 36], and hydroxide solutions like NaOH and KOH [36 - 39]. These techniques help remove the oxide layer and improve hydrogen production, often achieving yields close to 100% [24].

An alternative version of the reaction using sodium hydroxide is expressed as follows [31]:

$$(2)\ 2Al + 6H_2O + 2NaOH \rightarrow 2NaAl(OH)_4 + 3H_2$$

Importantly, the NaOH used in the reaction can be regenerated from the resulting aluminum hydroxide, which itself has practical uses in areas such as water treatment, paper manufacturing, and fire retardants [28].

Key factors influencing how fast and efficiently hydrogen is produced in this reaction include temperature, the concentration of NaOH, and the physical form of aluminum used, specifically its surface area and structure [23, 24]. Numerous studies have examined aluminum in powder form [28, 38 - 45] while others have focused on thin foils or recycled materials like aluminum cans [39]. However, side-by-side comparisons of these different aluminum forms remain limited [40]. Similarly, studies that vary NaOH concentration across a broad range are rare [34]. Temperature-based studies are more common, typically ranging between 20 °C and 80 °C [23], [24], with some extending up to 200 °C [45]. The activation energy of the reaction also varies widely in the literature, from 40 to 100 kJ/mol [45 - 48].

While numerous studies have explored the aluminum–water reaction, critical gaps remain, particularly regarding how the reaction responds to varying sodium hydroxide (NaOH) concentrations and the role of NaOH in the process. The present study was conducted as a major part of the doctoral dissertation of Demetrios Hadjipetrou [49], focuses on understanding the kinetics of hydrogen production by examining how different NaOH concentrations influence the reaction rate between aluminum and water. Furthermore, one of the primary aims is to confirm that NaOH functions as a true catalyst in the system, and it facilitates the reaction without being consumed, as it is continuously regenerated throughout the process.

By identifying these characteristics, recycled aluminum could provide the optimal higher hydrogen production efficiency depending on their use conditions and contribute not only to the scientific understanding of catalytic behavior in alkaline media, but also to practical strategies for sustainable hydrogen production using aluminum metal waste [50]. The study also presents results on the application of the described technology for the extension of the travel distance of an electric scooter for handicap people.

2. Experimental setup – Results and Discussion

The experimental setup consisted of a transparent glass container filled with a sodium hydroxide (NaOH) water solution, into which an aluminum slab was carefully placed to initiate the hydrogen production reaction. The dimensions of the aluminum were 1.5mm thickness, 9.5mm width and 5-10mm length (depends on the weight we used). The hydrogen gas produced during the reaction was directed through a connecting tube and collected using the water displacement method, as shown in Figure 1. The experiments divided in 2 sections, where in 1st section (proof that NaOH acts as a catalyst) the starting temperature was 40°C and in the 2nd section (rate of hydrogen production as a faction of NaOH concentration) was started at a temperature of 25°C. For this study, AA 6063 aluminum alloy was used as the reactive material, and its typical average composition is presented in Table 1. The resulting data were processed by calculating the average values for each condition, with all results maintaining a variation of less than 2%, thus ensuring a high degree of accuracy and consistency across the entire experimental dataset.

During the experiments, water solutions of sodium hydroxide (NaOH) with concentrations ranging from 0.5wt% to 30wt% were systematically prepared and used to investigate their influence on hydrogen production through aluminum-water reactions. For each trial, approximately 1 gram of aluminum slab was utilized as the reactive substrate. The aluminum samples were individually immersed in the prepared NaOH solutions, and the production of hydrogen gas was continuously recorded over time. The quantitative analysis of hydrogen

production as a function of time was graphically presented (see Figure 2 -5), allowing for comparative evaluation across the tested concentration spectrum.

Other experiments aiming to the investigation of the effect of NaOH, as a catalyst, various molar ratios of NaOH to aluminum (ranging from 0.25 to 2.6) were tested using 1wt% NaOH solutions. These conditions were intentionally chosen to simulate hypo-stoichiometric (0.25:1, 0.5:1, 0.75:1), stoichiometric (1:1) and hyper-stoichiometric (1.5:1, 2.6:1) NaOH availability, according to the reaction (2).

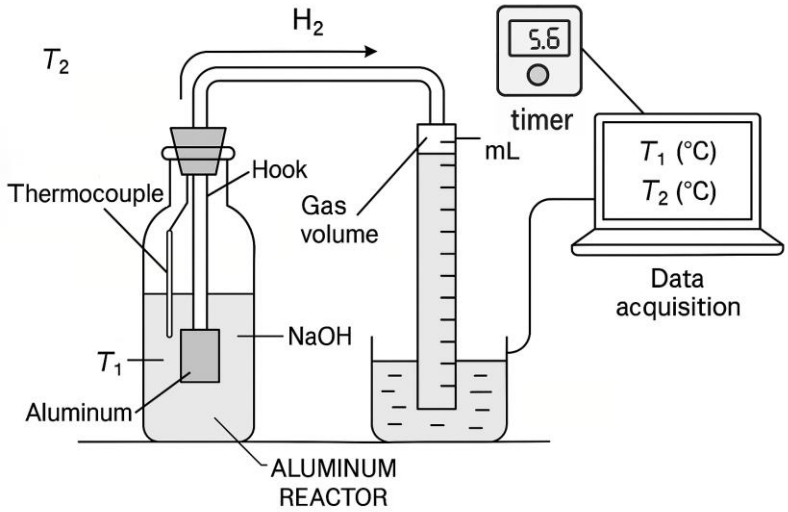

Figure 1. Experimental setup of measurement of hydrogen production from aluminum with the method of water displacement.

Table 1. Aluminum Alloy 6063 standards.

Constituent Element	Minimum (% by weight)	Maximum (% by weight)
Aluminum (Al)	97.5	99.35
Magnesium (Mg)	0.45	0.9
Silicon (Si)	0.2	0.6
Iron (Fe)	0	0.35
Chromium (Cr)	0	0.1
Copper (Cu)	0	0.1
Manganese (Mn)	0	0.1
Titanium (Ti)	0	0.1
Zinc (Zn)	0	0.1
Others	0	0.15 total
		(0.05 each)

2.1 Proof that NaOH acts as a catalyst in the reaction with aluminum to produce hydrogen

The catalytic behavior of sodium hydroxide (NaOH) in the reaction between aluminum and water was further substantiated through experiments conducted at varying aluminum-to-NaOH molar ratios and concentrations. In particular, the clearest results for the proof, were obtained using a 1 wt% NaOH solution across a wide range of molar ratios, ranging from 0.25 to 2.5 (mol/mol). At the onset of the reaction, all curves on the plotted data followed a similar trajectory, indicating that the aluminum was initially exposed to an identical alkaline environment namely, the 1 wt% NaOH solution. This uniformity in early-stage behavior demonstrated that the NaOH concentration was sufficient to initiate hydrogen production across all tested ratios.

However, as the reaction progressed, a divergence in behavior was observed, especially for ratios 0.25 - 0.75. This shift can be attributed to the gradual transformation of sodium hydroxide into sodium aluminate ($NaAlO_2$) as the aluminum dissolved. While NaOH was not consumed in the traditional sense, the concentration began to decrease due to its incorporation into sodium aluminate complexes. Consequently, the rate of hydrogen production started to decline, particularly in systems with lower initial NaOH quantities. Despite this depletion, the reaction still proceeded to completion, even at the lowest tested molar ratio of 0.25, which was significantly below the theoretical stoichiometric requirement.

This outcome strongly supports the catalytic role of NaOH. In the lower-ratio experiments, the initial NaOH concentration was insufficient to sustain the entire reaction if NaOH were acting as a stoichiometric reactant. Yet, the reaction continued, suggesting that sodium aluminate underwent hydrolysis, regenerating NaOH in situ. This regeneration maintains the evolution of hydrogen, allowing the system to proceed without requiring a proportional increase in the original NaOH dosage.

In all cases, even in the hypo-stoichiometric conditions, all Aluminum metal was dissolved and produced the expected theoretical amount of $_{H2}$ (1246NLiters/kg_{Al}) within the experimental error of 5%. Therefore, NaOH behaves as a catalyst rather than a consumable reactant.

Therefore, the ability of the reaction to proceed under sub-stoichiometric conditions, combined with the observable decline in reaction rate due to temporary NaOH depletion followed by continued hydrogen production, confirms that NaOH functions not as a consumed reactant, but as a catalyst. It facilitates the dissolution of aluminum by continuously providing hydroxide ions through hydrolysis cycles, maintaining the alkaline environment essential for hydrogen evolution.

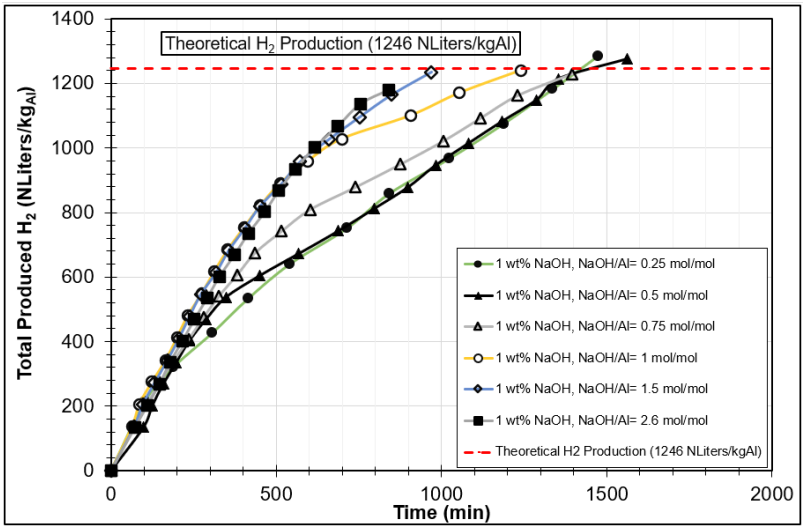

Figure 2. Hydrogen production as a function of time with 1wt% NaOH concentration and different initial NaOH / Aluminum (mol/mol) ratios.

2.2 The rate of the production of hydrogen as a faction of NaOH water concentrations

The results (Figure 3) demonstrated a clear correlation: as the concentration of NaOH increased between 5 - 30%wt NaOH, the rate and total volume of hydrogen production also increased significantly. These findings support the theory that higher alkaline concentrations facilitate more rapid and complete aluminum activation, through enhancing the efficiency of the hydrogen production reaction.

In all the experiments, the total volume of hydrogen produced was converted to Normal Liters (NL), which means the amount of gas under standard conditions (0 °C and 1 atm). This step was taken to allow consistent comparison between different test conditions. After the conversion, most of the results showed that hydrogen production was close to theoretical at almost all sodium hydroxide concentrations. It's worth noting, however, that this calculation might include some small errors within ± 5% of the theoretical, due to temperature errors and aluminum purity.

All tests in this section of experiments were performed at an initial temperature of around 25 °C, and although the reaction is exothermic, the solution temperature didn't rise much. This was because we used a large amount of liquid, which helped to absorb and spread the heat evenly throughout the solution. Additionally, since the setup wasn't insulated, a portion of the heat was lost to the surroundings, keeping the temperature stable within a range of about 25 ± 3 °C.

From a practical point of view, especially considering cost, safety, and ease of handling, it makes sense to keep the NaOH concentration as low as possible, provided it still supports a good rate of hydrogen production. Even 2wt% NaOH gave promising results. And if one considers a real reactor, where more aluminum is used and the volume of liquid is smaller, the temperature inside the reactor would likely rise significantly. That kind of temperature boost would naturally speed up the reaction, suggesting that even lower concentrations like 0.5 or 1wt% NaOH could work well in those conditions.

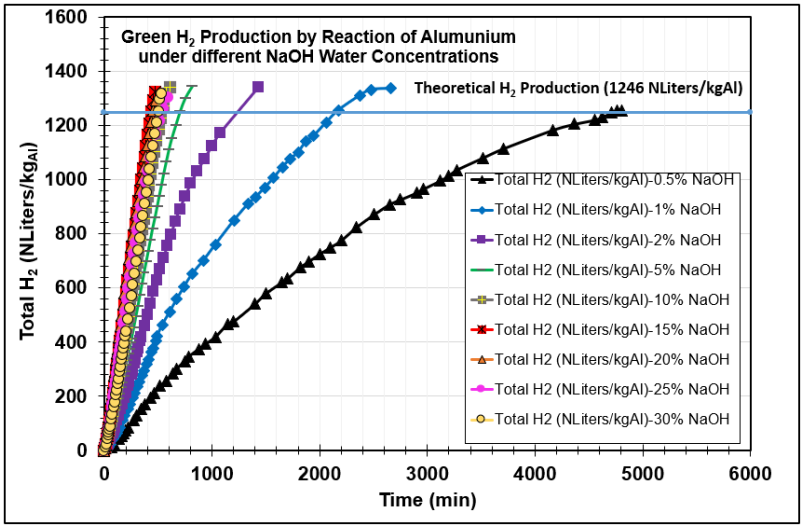

Figure 3. Hydrogen production of aluminum Slabs as a function of wt% NaOH concentrations.

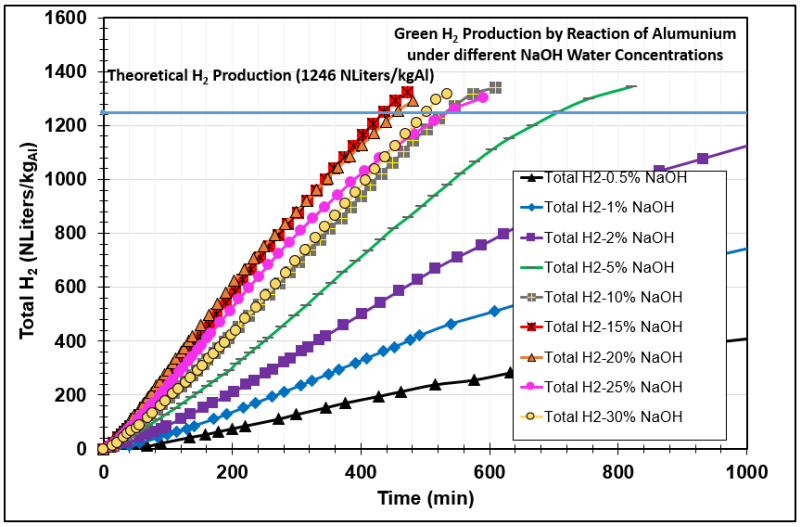

Figure 4. Hydrogen production of aluminum Slabs as a function of wt% NaOH concentrations (0-1000 min).

In addition to total hydrogen output, the initial reaction kinetics were also investigated by analyzing the initial slope of the hydrogen production curves across different NaOH concentrations (0.5–30 wt%). This analysis, depicted in Figure 5, provides insight into the immediate reactivity of the system before any substantial thermal or chemical equilibrium effects could alter the reaction environment. The initial rate of hydrogen evolution was evaluated as a direct function of NaOH concentration and was found to increase proportionally with higher NaOH content. Notably, from 5 wt% NaOH and above, the initial reaction rate reached considerably elevated levels.

However, at concentrations exceeding 20 wt%, a slight decline in the initial rate was observed, especially at 25 wt% and 30 wt%. This reduction is not due to a decline in chemical reactivity, but rather a result of stagnant conditions in the solution. At these higher concentrations, sodium aluminate forms very quickly and dissolves easily, accumulating around the aluminum surface making the rection kinetics diffusion-limited rather than to NaOH concentration-limited. This accumulation creates a localized zone where fresh NaOH cannot easily reach the metal surface. As a result, the reaction slows down not because it has stopped, but because the diffusion of reactants and products is now the limiting factor. In simpler terms, what begins as a reaction-limited process which is controlled by how fast NaOH catalyses and reacts with aluminum metal, gradually shifts into a diffusion-limited process, where the rate depends on how fast sodium aluminate can diffuse away from the reaction site and how quickly new NaOH can replace it.

This shift becomes more pronounced at 30 wt% NaOH, where sodium aluminate remains dissolved around the Aluminum metal and does not allow the regenerated NaOH to fast reach the Al surface. Instead, it needs to diffuse away to make room for new NaOH milecules to come in and keep the reaction going. However, in such concentrated solutions, diffusion becomes significantly slower, further limiting the reaction rate.

It's important to highlight that these effects are primarily due to the lack of agitating. If the system were continuously agitated, the sodium aluminate would be dispersed more efficiently, allowing NaOH to reach the aluminum surface more freely. In that case, the reaction rate would likely remain high, even at concentrations above 20 wt%. This finding confirms that at high NaOH concentrations, the rate-limiting step is not the reaction itself, but the ability of the system to transport elements in and out of the reaction zone.

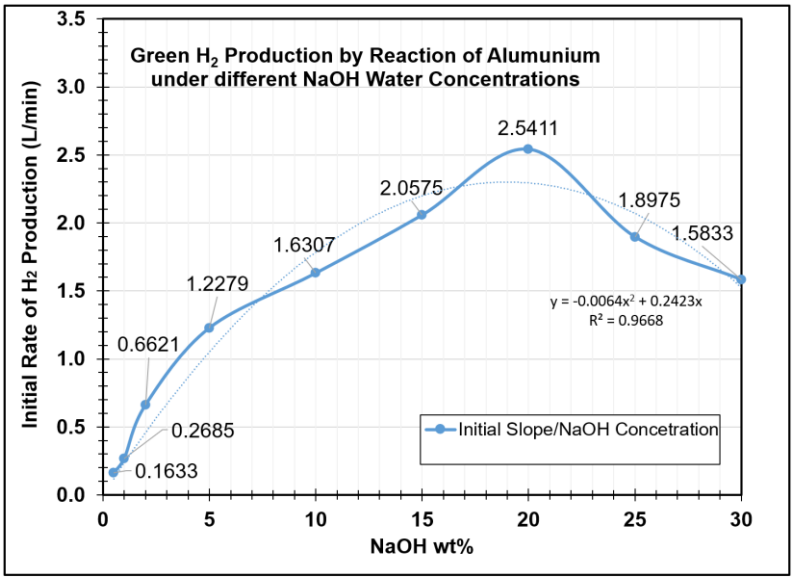

Figure 5. The initial rate of hydrogen production as a function of the weight percentage of the NaOH water solution

Based on the experimental observations, the hydrogen production rate seems to be proportional to the specific surface (m^2/kg) area of the recycle aluminum metal. Materials possessing a higher specific surface provide more active contact area for the reaction to occur, thereby enhancing the overall reaction kinetics. Consequently, recycled aluminum in the form of fine shavings is expected to exhibit significantly higher hydrogen production rate compared to aluminum cans, while both are anticipated to outperform bulkier aluminum slabs, as described in the detailed study by Christina Ch. Christodoulou et. al., [51]. This trend underscores the critical role of exposed reacting aluminum surface in influencing the efficiency of the aluminum–alkaline water reaction for hydrogen production.

2.3 Application of the green hydrogen production from aluminum on an electric scooter

The developed technology was practically implemented to produce green hydrogen through a 200watt proton exchange membrane (PEM) fuel cell system. This hydrogen was produced via the catalytic reaction of recycled aluminum with 5wt% NaOH water solution. The energy contribution of hydrogen produced from recycled aluminum was quantitatively assessed in terms of its ability to extend the travel distance of an electric scooter specifically designed for handicapped people.

The specific scooter exhibits a 24VX33Ah=792Wh energy battery to cover a specific distance. The installed H2/Fuel Cell system exhibited a 200W Fuel Cell and an Aluminum plastic reactor containing a 5wt% NaOH water solution. The respective Fuel Cell produces 1.333Wh/NliterH2. Based on the presented results, one kg of recycle Aluminum produces about 1246NlitersH2 equivalent to 1.333X1246=1660.9Wh, and therefore, could theoretically extent the traveling distance of the scooter by 1661/792=2.1 times.

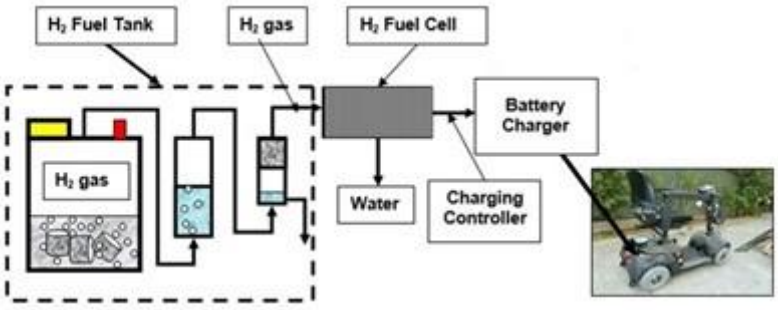

Figure 6. Application of the green hydrogen production from aluminum on an electric scooter for handicapped people

Remarkably, the actual findings demonstrated that the use of one kilogram of recycled aluminum effectively enhanced the scooter's travel range by a factor of 2.0 compared to its standard distance achievable on a fully charged battery alone, which is very close to the expected theoretical value. This significant improvement underscores the potential of aluminum-based hydrogen production as a sustainable and efficient alternative for augmenting electric mobility solutions.

3. Conclusion

The production of green hydrogen through the reaction of recycled aluminum materials, such as aluminum shavings, aluminum chunks or aluminum cans, with aqueous sodium hydroxide (NaOH) has been demonstrated as a viable and sustainable approach. Specifically, this reaction yields approximately 1246 NLiters of hydrogen per kilogram of recycled aluminum when conducted in solutions with NaOH concentrations preferably exceeding 5wt%. Importantly, NaOH functions as a catalytic agent in this process, and facilitates the reaction without being consumed, thus allowing the system to operate with water as the primary reactant.

The integration of this hydrogen production method with fuel cell technology presents a promising solution for extending the travel distance of electric scooters designed for handicapped people. By producing hydrogen on demand from recycled aluminum, the system offers extended travel autonomy without reliance on grid-based recharging infrastructure, thus supporting clean energy goals and improving the quality of life for users through greater independence and sustainability.

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