

GREEN HYDROGEN GENERATION APPLIED IN FIELD MOBILE ROBOTS

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Abstract

This article explores the application of green hydrogen technology in field mobile robots for remote and off-grid operational scenarios. Traditional battery systems present limitations in endurance and downtime, prompting the integration of renewable-energy-powered hydrogen production systems as an efficient alternative. The proposed design utilizes solar energy to generate green hydrogen on-site using a PEM electrolyser, storing it safely in metal hydride canisters for future use. Hydrogen fuel cells are utilized to power mobile robots, significantly extending operational duration and minimizing downtime. The system's architecture of a robot charging station encompasses a solar panel array, MPPT controller, buffer battery, inverter, electrolyser, and metal hydride storage, creating a self-sufficient, renewable, and emission-free infrastructure.

Practical service robot implementations demonstrate the feasibility and benefits of this technology, notably in applications such as agricultural patrol and logistics transportation. While green hydrogen offers distinct advantages, such as fast refuelling, eco-friendly fuel generation, off-grid independence, and scalability, several challenges remain. Issues include lower overall energy efficiency compared to battery systems, complex system integration and management, safety considerations, and higher initial costs. Addressing these barriers through technological advancements and strategic design improvements is crucial for broader adoption.

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Introduction. Field mobile robots – ranging from agriculture, patrol, and transport robots – are increasingly used in remote or off-grid environments where access to the electrical grid may be limited. Traditionally, these robots rely on batteries that require frequent recharging, leading to downtime and logistical challenges in the field. Green hydrogen provides a promising solution to extend robot operation with minimal environmental impact. By generating hydrogen fuel on-site using renewable energy (such as solar power) and powering robots via hydrogen fuel cells, it is possible to achieve long-duration and zero-emission operation for mobile robots. This article presents a design of a green hydrogen production in a small-scale solar-powered charging station and the application of hydrogen fuel cell power in field robots.

What is green hydrogen? According to the GH2 organization, the Green Hydrogen Standard is H_2 produced through the electrolysis of water with 100% or nearly 100% renewable energy with close to zero greenhouse gas emissions [1]. Unlike “grey” hydrogen (produced from the steam reforming of natural gas, which emits CO_2) or “blue” hydrogen (produced from fossil fuels with carbon capture), green hydrogen production generates no carbon emissions apart from water vapour. Green hydrogen offers a clean energy carrier that can be stored and later used in a fuel cell to produce electricity on demand, emitting only water and heat as exhaust.

Green hydrogen powered robots. Using hydrogen as an energy source for robots is appealing because it has a very high specific energy, or energy per unit mass. In fact, hydrogen gas contains approximately 33 kWh of energy per kilogram, far surpassing typical lithium battery chemistries. When used in a hydrogen fuel cell, this energy can be converted to electricity to drive electric motors and power the onboard electronics. Modern PEM (Proton Exchange Membrane) fuel cells achieve efficiencies of around 40%, meaning that approximately 13.2 kWh of usable electricity can be generated per kilogram of hydrogen. This gravimetric energy density is still several times greater than that of batteries, allowing for longer operation with the same weight. Moreover, hydrogen fuel cells sustain power output as long as fuel is supplied, unlike batteries, which gradually deplete and require lengthy recharging. These traits make green hydrogen an attractive option for off-grid, long-endurance robotic missions where replacing or recharging batteries is impractical.

Green hydrogen generation – designing a solar-powered robot charging station. Components. To apply green hydrogen in the field, a small robot charging station was designed. It produces hydrogen on-site using solar power. This autonomous station integrates several key components working

together to generate, supply and store hydrogen fuel:

Monocrystalline solar panel. A single high-efficiency solar photovoltaic panel (monocrystalline silicon) serves as the primary power source. Monocrystalline panels are known for their efficiency of $\sim 20\text{--}22\%$, and we have chosen a 470 W (peak) solar module that can produce a significant amount of energy in sunny conditions, keeping the whole system relatively compact. The panel's output is DC electricity that fluctuates with sunlight intensity. Using the panel manufacturer's specifications and solar radiation values for Sofia, Bulgaria, we have calculated a mean (year round) electricity production of 1.6 kWh per day. This estimation is in agreement with the actual performance of similar-sized photovoltaic systems in the same geographic location, as reported online [2].

MPPT solar charge controller. The station utilizes a Maximum Power Point Tracking (MPPT) controller to ensure that the solar panel operates at its optimal voltage and current balance for maximum power output. The MPPT controller actively adjusts the electrical load on the panel to draw the maximum power possible as conditions change (sun angle, cloud cover, temperature, power consumption). This maximizes the energy harvested from the panel, which is critical for efficiently running the downstream electrolyser and charging the buffer battery.

Buffer battery pack. A buffer battery with a capacity of 2000 Wh is used to store excess solar energy and provide a stable power supply to the electrolyser and other devices. The solar energy is intermittent (nighttime or cloudy periods yield little power), so the battery smooths out power delivery and allows hydrogen production to continue (or robots to charge) even when solar input dips. The battery system will provide the high startup currents and steady voltage needed by the electrolyser.

Solar inverter. The Victron Phoenix C12 1200W pure sine wave inverter is used in the charge station. It is engineered to deliver stable, high-quality AC power (220 V@50 Hz) from a 12V DC source. The system produces stable pure sine wave output, ensuring optimal electrochemical reactions within the electrolyser cells and facilitating consistent and efficient hydrogen production while minimizing stress and degradation of the electrolytic components. The inverter's efficiency is 92–94%.

Water electrolyser (PEM type). At the core of the station is a PEM electrolyser that produces hydrogen gas from water using the electricity supplied by the solar panel and battery. PEM (Proton Exchange Membrane) electrolysers are well-suited for variable renewable power sources because they can quickly ramp up or down production and produce high-purity hydrogen. The electrolyser in our system is a compact unit (Heliocentris HG series) capable of producing on the order of 0.5–1.2 L/min of H_2 at output pressures up to 16 bar. The device consists of a stack of cells, where water is split into oxygen (O_2) at the anode and hydrogen (H_2) at the cathode. The PEM membrane allows protons to pass while keeping gases separate, resulting in a very pure hydrogen gas ($> 99.999\%$ typically)

[3]. The system also includes a gas drying/purification stage – a maintenance-free pressure swing adsorption (PSA) system – to ensure dry hydrogen output suitable for storage and fuel cells. As the electrolyser operates, the oxygen by-product is safely vented, and the hydrogen is stored. The electrolyser's efficiency is approximately 60–70%, meaning that some of electrical energy will be lost as heat during electrolysis [4]. When the sun is strong or the battery has surplus energy, the electrolyser can operate continuously, generating green hydrogen throughout the daylight hours.

Hydrogen storage in metal hydride canisters. Rather than compressing hydrogen to very high pressure in gas cylinders, the charge station uses metal hydride storage (MHS) canisters to store the produced hydrogen safely at low to moderate pressure. Metal hydride canisters contain special AB₂ Ti-Mg-based alloys that absorb hydrogen gas into their metal lattice when cooled and under pressure, and release hydrogen when heated. According to the specification, Heliocentris metal hydride storage (MHS) canisters operate at 10–30 bar – much lower pressure than standard gas tanks, and they can hold a substantial amount of hydrogen relative to their volume.

The hydrogen essentially bonds with the metal matrix, forming a stable hydride. In the charging station, the hydrogen from the electrolyser at a pressure of 16 bar flows into the metal hydride canister. As the alloy absorbs H₂ exothermically, the canister may warm up; therefore, cooling is applied to enhance absorption. Once “charged” with hydrogen, the canister safely stores it at a low pressure (e.g., ~ 25 bar max) until needed. To refuel a robot or generate electricity, the hydride is heated (even ambient temperature may suffice if the pressure drops) to release H₂ gas. The storage capacity of these canisters is typically given in normal liters (Nl) of H₂. The MHS-800 canister can hold 800 Nl (~ 0.072 kg) at 25 bar, with a total width and weight of about 7.3 kg when filled [5]. The hydride tanks enable compact, safe storage at low pressure, although they add weight and necessitate thermal management for optimal charging and discharging. Compared to high-pressure cylinders, metal hydrides significantly reduce the explosion risk and simplify the refuelling interface – a quick-connect fitting can be used to transfer hydrogen without handling extremely high pressures. For a field robot scenario, the station can store hydrogen in one or multiple canisters during the day.

Hydrogen fuelling interface. The station uses a quick-connect coupling system that mates with the hydrogen canister input valve. Because the generation and the storage are at moderate pressure (≤ 16 bar), refuelling is relatively safe and straightforward compared to the liquid fuelling than high-pressure gas transfers. The entire metal hydride canister is removable, so the robot's depleted canister can be swapped for a full one from the station. In a future design, tank swapping may be automated with a specially designed electromechanical system. Also, the station can directly transfer hydrogen into the robot's tank until the required amount is reached.

Control module. To ensure charge station control and monitoring, an ESP32 MCU-based controller is used. It allows for very low power operation and supports WiFi, enabling remote access and telemetry data transmission. It connects to the station components using a serial interface.

Charging station operation. The solar-hydrogen station generates hydrogen during sunny periods and stores it in the buffer battery and hydride canisters, effectively storing solar energy in chemical form. When a robot needs to recharge, it can either dock at the station and refill its hydrogen supply or swap its empty hydride cartridge for a full one. The buffer battery and smart controls ensure that the electrolyser runs efficiently. For instance, the MPPT directs surplus solar power to the electrolyser when available, and the battery covers transient loads and allows hydrogen production to continue briefly under a passing cloud. At night or in bad weather, hydrogen production will pause once the battery is depleted, but the stored hydrogen can still be used by robots. This concept enables a degree of energy independence in the field: as long as there is sunlight (and water for electrolysis), the system can create its fuel and keep robots running without external fuel or grid input. Essentially, it is a renewable hydrogen refuelling station on a small scale. A block diagram of the station is shown in Fig. 1.

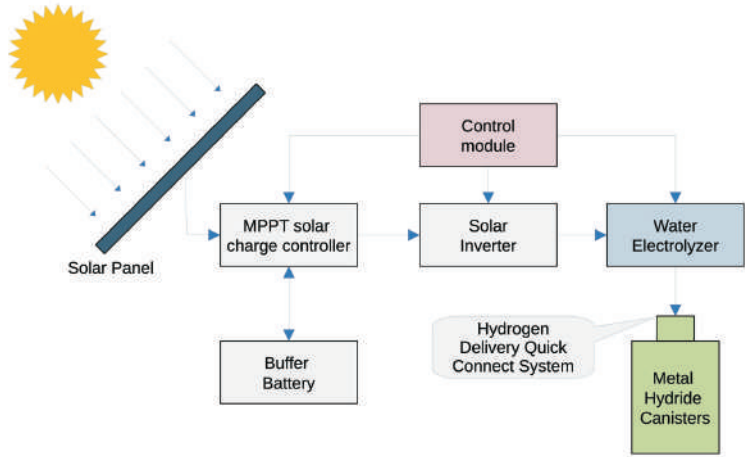


Fig. 1. Block diagram of the green hydrogen robot charging station

Hydrogen power technology in field robots. We utilize two service robots for initial design calculations and to estimate how green hydrogen power can be applied in real-world scenarios. These are examples of how our current robots could benefit from a solar-hydrogen energy system.

Athena 2 mobile robot with UFACTORY xArm 7 manipulator. The Athena 2.0 is a general-purpose wheeled robot platform developed by Slamtec. The base Athena 2 robot has a footprint of roughly 0.4 m by 0.4 m and a height of

about 0.6 m, weighing around 22–30 kg with its batteries. It supports autonomous navigation via LiDAR and can carry payloads of about 40–60 kg. Our robot is outfitted with a UFACTORY xArm 7 robotic arm – a 7-degree-of-freedom robot arm mounted on top of the mobile base [6].



Fig. 2. Robot Athena 2 with robotic arm and gripper

The xArm 7 itself weighs 14 kg and can handle a payload up to 3.5 kg, making the combined robot a mobile manipulator capable of performing various remote field tasks (Fig. 2). Such a robot could be deployed in outdoor environments or large industrial facilities for inspection, maintenance, or material handling tasks that require both mobility and dexterous manipulation. Originally, the Athena 2 is powered by a rechargeable 480 Wh LiFePO₄ battery. It enables the robot to operate for several hours on a single charge. By integrating a hydrogen fuel cell power system, the robot will vastly extend its operating time and work truly off-grid.

In terms of usage, Athena 2 can patrol a solar farm or an agricultural field and perform inspections using its robotic arm. Equipped with a hydrogen power system, the robot can operate all day, recharge or refuel quickly at midday, and continue into the evening, covering far more ground than a battery-limited robot.

The weight of a small fuel cell system and full hydride canister might be on the order of 10–15 kg, which Athena can accommodate given its payload ability. The result is a mobile manipulator robot that is self-sufficient, requiring only sunlight and water at its support station to operate continuously in remote areas.

Spartacus transport and logistics service robot. The Spartacus robot is a robust and reliable service robot designed for transportation and logistics, developed at the National Robotics and AI laboratory, part of the Institute of Robotics (BAS). This service robot features a 4 × 4 drive system with hub motors, allowing it to navigate challenging terrains easily (Fig. 3). With a lifting capacity of up to 240 kg, Spartacus can transport standard loads packed in EuroBox containers.



Fig. 3. Spartacus mobile robot

It operates under the ROS (Robot Operating System). Adding hydrogen power will extend both the operating time and the area of coverage of the robot.

Discussion. The benefits of using of green hydrogen generation for field mobile robots are clear:

- **Off-grid renewable operation.** The concept of a solar-powered hydrogen station enables the deployment of robots in remote locations, eliminating dependency on grid electricity or fossil fuels. As long as sunlight (or another renewable source) and water are available, the system can produce its own hydrogen fuel on-site. This is ideal for field robots in agriculture, environmental monitoring, disaster response, or military operations where logistic supply lines are limited. It provides energy autonomy – a form of “energy harvesting” to sustain the robots indefinitely

- **Eco-friendly fuel generation.** Green hydrogen production represents a significant advancement in eco-friendly fuel generation, offering a completely emission-free alternative to conventional fossil fuels. By harnessing renewable energy sources to electrolyze water, green hydrogen is produced without generating greenhouse gases or harmful pollutants. This clean, sustainable fuel provides a perfect solution for decarbonizing industries, transportation, and power generation, thereby playing a critical role in the global efforts to mitigate climate change and promote environmental sustainability.

- **Reduced infrastructure for charging.** In multi-robot deployments, battery-powered systems often require numerous charging stations or battery swap infrastructure to maintain operation, as well as grid upgrades to supply high charging power. With hydrogen, a single solar-hydrogen station could refuel

many robots and avoid drawing large electrical power from the grid at peak times (since solar energy is harvested and stored as hydrogen). This can simplify the infrastructure – a refuelling post instead of multiple electrical charge points – and can be scaled by just adding more solar panels or a larger electrolyser without reworking electrical distribution as much.

Scalability and modularity. A hydrogen-based power system can be scaled by adjusting the tank size and fuel cell capacity independently. If a mission needs more endurance, one can add extra hydride canisters or higher H₂ storage, without necessarily doubling the fuel cell (as long as extended time at lower power is the goal). Conversely, one can upgrade the fuel cell for increased power (to carry heavier loads or travel faster) while refuelling more frequently if needed. This decoupling of energy capacity and power (unlike a battery, where both are linked) gives designers flexibility. Additionally, hydrogen can be shared – one central production facility can refuel multiple units, which is particularly efficient in multi-robot setups.

As with every new technology, there are several disadvantages. It is important to recognize these to assess where the technology is viable and what areas need improvement:

- **Overall energy efficiency.** Perhaps the biggest drawback of the hydrogen route currently is its lower efficiency compared to direct battery use. Converting solar electricity to hydrogen and back to electricity entails multiple energy losses – in the electrolyser ($\sim 30\text{--}40\%$ lost as heat), compression/storage, and then in the fuel cell ($\sim 40\text{--}50\%$ lost). By the time power reaches the robot, only about 30% of the original solar energy may be utilized [7]. In contrast, using solar to charge a battery and then run a motor can be $\sim 80\%$ efficient overall. In other words, a battery system might use renewable electricity almost three times more efficiently than a hydrogen fuel cell system for the same task. This inefficiency means that much larger solar panels would be needed or more input energy to accomplish the same work, which can drive up cost and weight. For a given solar array size, a hydrogen system will provide fewer robot-hours of operation than a direct solar-to-battery system (though it gains in other areas like refuelling speed). Improving electrolyser and fuel cell efficiency, or using waste heat effectively, will be key to mitigating this disadvantage.

- **System complexity.** A hydrogen-based power solution involves many components – solar panels, charge controllers, batteries, electrolyser, storage tanks, fuel cells, regulators – which make the system more complex than a simple battery and charger. More components mean more potential points of failure. The robot itself needs additional subsystems (fuel cell management, hydrogen sensors, etc.) that increase the design complexity. Maintenance of a fuel cell system (e.g., keeping the fuel cell membrane humidified, replacing filters, checking for leaks) can be more involved than maintaining batteries. Technicians will require training in hydrogen safety and fuel cell operation, which is a new area for many robotics

teams. The complexity can also result in higher upfront costs to build the system, as well as increased maintenance costs throughout the robot's lifespan.

• **Hydrogen generation rate.** The solar-powered electrolyser station described has a limited rate of hydrogen production (proportional to solar input and electrolyser capacity). With a 470 W panel and a small electrolyser, one might produce on the order of 0.5 cubic meters (500 Nl) of H₂ per sunny day (roughly 40–50 g of hydrogen per day, given realistic efficiencies). This amount contains about 5.6 kWh of thermal energy (and would yield ~ 2.8 kWh of electricity via fuel cell at 50% efficiency). While this is enough to extend a robot's operation significantly, it is not a huge amount of energy by industrial standards. If multiple robots rely on the station, or if a single robot has high power demands, the station may not be able to keep up supply with consumption. The bottleneck is that solar collection is low-density, and electrolysis takes substantial energy. The solution is to scale up the whole system if the application is demanding this.

• **Cost and economics.** Fuel cell technology and electrolyser equipment are still relatively expensive, especially at small scales. Even a small PEM electrolyser system and fuel cell adds substantial cost to the system. Metal hydride canisters and specialized components also add to the cost. By comparison, batteries have benefited from mass production and have much lower upfront costs for a given energy capacity. In a cost-sensitive application, hydrogen may be difficult to justify unless the operational need (such as long endurance or fast turnaround) strongly warrants it. However, with growing investment in the hydrogen economy, costs are gradually coming down. A careful cost-benefit analysis is needed for each use case to determine if hydrogen power provides a net gain.

• **Safety considerations.** Hydrogen is a highly flammable gas, and while the volumes in small robot applications are not enormous, any gas handling requires care. The station and robots must be designed to prevent leaks and to quickly dissipate hydrogen in case of a leak to avoid accumulation. Ignition sources near the refuelling area must be controlled. In many industries (e.g., forklift operations with hydrogen fuel cells), safe practices have already been established that can be adopted. Additionally, in cold weather, hydrides require heating to release hydrogen, and in hot weather, they need cooling to charge. Improper handling of these thermal needs could lead to underperformance or, in extreme cases, pressure buildup. All these safety systems add more complexity and must be planned carefully and thoroughly.

Conclusion. In summary, green hydrogen power for robots is a highly promising energy solution for field robots, providing clean and longer-lasting power that can keep up with the 24/7 demands of modern automation. These benefits can translate to lower operational costs in the long run and greater capabilities for robots to take on challenging tasks. Of course, the solution is not a silver bullet – it trades efficiency and simplicity for endurance and rapid turnaround. For specific applications – especially those requiring long, continuous operation or

where the grid is unavailable – this trade-off can be advantageous. However, the future hydrogen power systems must address the challenges of efficiency, manage the added complexity, and ensure robust safety and reliability measures are in place.

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