

WHITE PAPER

POWERPASTE FOR OFF-GRID POWER SUPPLY

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POWERPASTE is a novel hydrogen storage substance invented by Fraunhofer IFAM with an exceptionally high specific energy and energy density as well as many other advantages. On contact with water, POWERPASTE releases gaseous hydrogen in a controlled way in a hydrogen generator. This hydrogen can be converted to electricity by means of a PEM fuel cell.



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Contents

Executive summary	2
Introduction	2
Comparison of POWERPASTE with state-of-the-art technologies	4
POWERPASTE for off-grid power supply	6
Commercial uses of POWERPASTE-based power systems	8
Technology offer	10
About Fraunhofer IFAM	11
List of figures and tables	11

Executive summary

POWERPASTE is an ultra-high capacity hydrogen storage substance for PEM fuel cell applications invented and developed by Fraunhofer IFAM.

POWERPASTE releases hydrogen on contact with water. It has a hydrogen capacity of about 10 mass-% (i.e. 10 kg POWERPASTE → 1 kg hydrogen). This is a specific energy of 1.6 kWh_e/kg and an energy density of 1.9 kWh/liter, or about 10 times the capacity of Li-Ion batteries.

The award-winning POWERPASTE technology is patented (EU, US) and offers many advantages over other energy storage technologies, in particular in the power range from 100 W to 10 kW.



Figure 1: POWERPASTE (left); POWERPASTE cartridge (middle); portable 100 W power supply unit (right).

Introduction

High-energy materials, mainly in the form of fossil fuels, have advanced human progress over the last centuries. However, as fossil fuels become increasingly scarce and global warming is a detrimental side effect of burning fossil fuels, which has tremendous economic implications. Alternatives are required more than ever.

POWERPASTE is a novel hydrogen storage substance invented by Fraunhofer IFAM with an exceptionally high specific energy and energy density as well as many other advantages.

On contact with water, POWERPASTE releases gaseous hydrogen in a controlled way in a hydrogen generator. This hydrogen is then converted to electricity by means of a PEM fuel cell.

A schematic representation of the operation principle of a POWERPASTE-based electrical power supply is displayed in the following diagram:

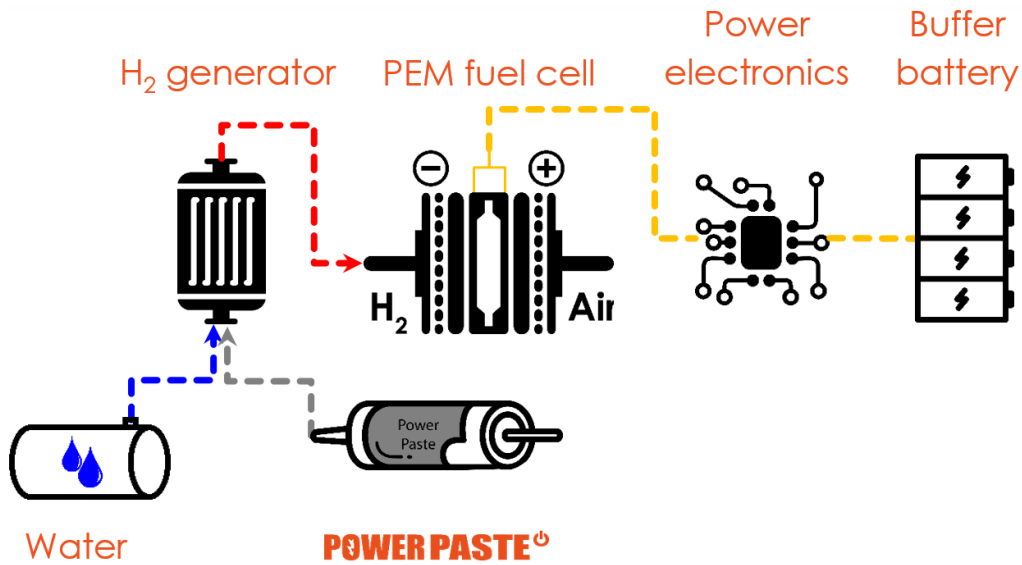


Figure 2: Schematic representation of a POWERPASTE-based power system.

Unlike batteries, POWERPASTE-based power systems are grid-independent and can be recharged quickly within seconds (switching cartridges). Moreover, POWERPASTE is highly durable and does not suffer from self-discharge. Furthermore, CAPEX costs per installed kWh and/or TCO of POWERPASTE-based power systems are economically compatible, in particular, in the power range from 100 W to 10 kW, for example for UAVs with long flying times or cars with extended range, but also for various stationary applications such as back-up power generators.

The main ingredient of POWERPASTE is a non-toxic substance called magnesium hydride, MgH_2 , in which hydrogen is stored in a safe form. From a materials perspective, the concept of generating hydrogen with POWERPASTE can be represented by the following reaction diagram:

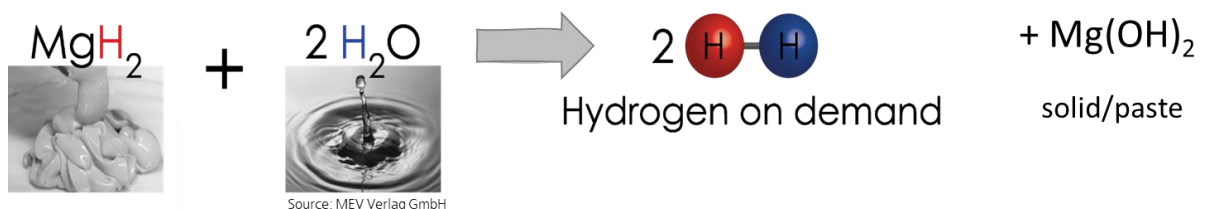


Figure 3: Reaction scheme to generate hydrogen.

Fraunhofer IFAM has demonstrate the use of POWERPASTE in a real portable power supply unit (TRL 5) built for the German military (cf. Figure 1).

Comparison of POWERPASTE with state-of-the-art technologies

Fuel cell-based power systems have emerged as promising alternatives over batteries but they have been economically successful only in niche markets so far.¹ This is mainly due to the lack of fuel and fuel infrastructure for fuel cells. Most fuel cells need hydrogen in some form at their anode, which can then react inside the fuel cell with oxygen (ambient air) from the cathode to generate electrical power. The general operation principle of a fuel cell is depicted in the next figure:

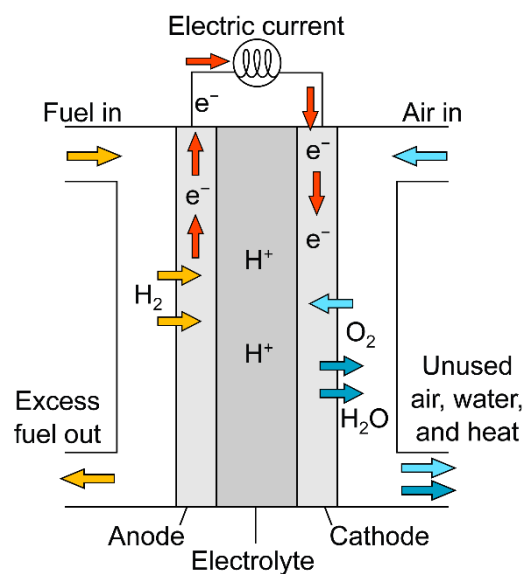


Figure 4: General working principle of a fuel cell.

As hydrogen is a gas, which is not readily available, hard to store and problematic to refuel, there are four main approaches to provide hydrogen for fuel cell-based power systems:

1. Provide gaseous hydrogen directly to the fuel cell. Here, hydrogen is stored in special gas cylinders (made from high-strength materials such as carbon fiber composites) at a pressure of many hundred bars. Downscaling of high-pressure hydrogen storage tanks is limited due to mandatory safety components. Moreover, a dense network of hydrogen fueling stations is needed.
2. Generate hydrogen in a reformer connected to the anode side of the fuel cell. At high temperature, the reformer converts conventional fuels (hydrocarbons, such as diesel, LPG or methanol) into hydrogen and carbon dioxide (CO₂).
3. Generate hydrogen from special fuels directly in the fuel cell. To date, this is only viable with methanol in so-called direct methanol fuel cells (DMFCs) which emit CO₂, too. A special methanol-water mixture needs to be supplied.

¹ E4tech, The fuel cell industry review 2017.

4. Generate hydrogen at near-ambient pressure through a chemical reaction of a hydrogen carrier substance with water, a so-called hydrolysis reaction that does not emit any CO₂. The hydrogen carrier needs to be supplied in cartridges. POWERPASTE is an example for this type of fueling.

A comparative overview of the most relevant energy storage and power supply technologies in the power range from 100 W to 10 kW is given in the following table:

Key performance indicator	POWERPASTE-based PEM fuel cell	Gasoline, diesel (ICE+generator)	Direct methanol fuel cell	Li-ion battery
Specific energy	+	+	+	-
Energy density	++	+	+	-
Power range	++	++	-	0
Grid independence	+	0	+	-
Recharging time	++	+	++	--
Self discharge	++	++	++	-
Durability	+	++	+	0
Toxicity	++	-	--	+
Noise	++	--	++	++
Emissions	++	--	0	++
Safety on impact	+	0	0	-
Temperature range	+	++	-	--
System complexity	0	0	0	+
Maintenance	++	-	++	++

Table 1: Key performance indicators of state-of-the-art power supply technologies.

It is worth to look into two of the most important properties in more detail – their specific energy and energy density. In the following diagram, an overview of a range of high energy fuels is provided comparing these properties as fuels are used to generate electricity under realistic conditions (in real systems including all conversion losses):

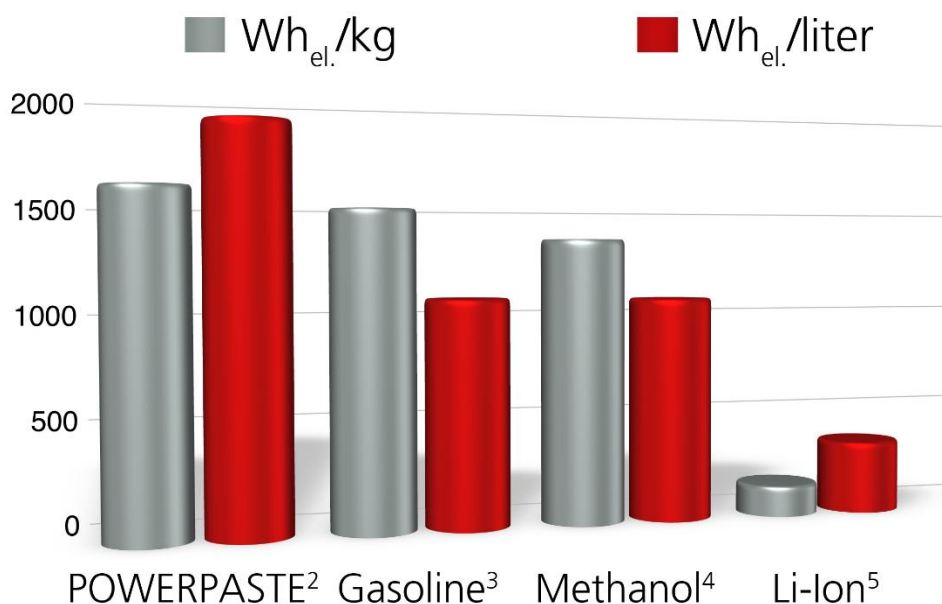


Figure 5: Specific energies and energy densities of selected high-energy fuels.

This chart impressively shows the huge potential of POWERPASTE-based power systems for lightweight applications in comparison with other technologies. POWERPASTE has a hydrogen content of nearly 9 % (9 kg POWERPASTE releases 1 kg hydrogen). This is a specific energy of 1.6 kWh_{el.} per kg and energy density of 1.9 kWh_{el.} per liter, or about 10 times the capacity of Li-ion batteries.

POWERPASTE for off-grid power supply

There have been numerous attempts to effectively deliver hydrogen to a fuel cell by means of a chemical reaction because this circumvents the necessity of high pressures and special infrastructure (hydrogen fuel stations). Chemical hydrogen carriers (solids or liquids) can be transported and refilled easily. The reactions of sodium borohydride (NaBH₄) or other reducing agents with water (so-called hydrolysis reactions) have been proposed as a possible solution for some time. Although sodium borohydride is promising from a chemical perspective, both its toxicity⁶ and a market price of more than 15 EUR/kg on a large scale⁷ limit its use.

² At an efficiency of ~ 0.50. Conversion with a PEM fuel cell of a 1 kW system under realistic load changes.

³ At an efficiency of ~ 0.17. Conversion with an internal combustion engine of a 1 kW system under realistic load changes.

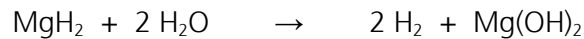
⁴ At an efficiency of ~ 0.25. Conversion with a DMFC fuel of a 1 kW system under realistic load changes.

⁵ At an efficiency of ~ 0.95. Conversion under optimal conditions.

⁶ <https://echa.europa.eu/de/substance-information/-/substanceinfo/100.037.262>

⁷ Derived from import data from the year 2016 from zauba.com for an import quantity of > 10 t.

On the other hand, there have been many attempts to enable the potentially much cheaper⁸ and non-toxic magnesium hydride for an efficient and controlled reaction with water.^{9,10,11} One notable peculiarity of the hydrolysis reaction of magnesium hydride is a magnesium hydride to hydrogen ratio of one-to-two which means half of the produced hydrogen originates from the water:



Yet, previous attempts to generate hydrogen from the reaction of magnesium hydride and water in a highly dynamic and simple fashion while controlling the reaction to a degree, that an instantaneous start/stop and complete load following of the fuel cell becomes possible, have been unsuccessful. One of the reasons is the formation of passivation layers on magnesium hydride on contact with water. As Fraunhofer IFAM demonstrated, the addition of certain metal salts to magnesium hydride can, however, effectively reduce the formation of these passivation layers.¹²

Another reason is that – unlike NaBH_4 – magnesium hydride cannot form metastable aqueous solutions, which makes a highly controlled reaction more difficult. Only through the invention of the semi-solid formulation POWERPASTE, which contains magnesium hydride and the above-mentioned metal salts as well as a non-toxic ester, Fraunhofer IFAM was able to create a fuel with the following unique combination of properties:

- Very high energy density of up to 1.9 kWh_e/liter
- Highly dynamic reaction with water for an instantaneous fuel cell start/stop
- Orientation-independent dosing possible (up to +/- 90° tilt in all directions)
- Non-toxic and safe formulation
- Easily disposable or recyclable
- Long shelf life (up to 5 years)
- Low manufacturing costs (estimated down to ~ 2 EUR/kg POWERPASTE)

⁸ Magnesium prices are typically below 2 EUR/kg on a large scale.

⁹ H. Uesugi, T. Sugiyama, and I. Nakatsugawa, *Production of Hydrogen Storage Material MgH₂ and its Applications*, BIOCOKE Lab. Ltd., Japan, **2009**, http://www.biocokelab.com/dcms_media/other/paper_20090719.pdf

¹⁰ A. W. McClaine, S. Tullmann, K. Brown, *Chemical Hydride Slurry for Hydrogen Production and Storage*, Safe Hydrogen, LLC, **2004**, http://www.hydrogen.energy.gov/pdfs/progress04/iiib3_mcclaine.pdf.

¹¹ A. W. McClaine, K. Brown, *Chemical Hydride Slurry for Hydrogen Production and Storage*, Safe Hydrogen, LLC, **2008**, http://www.hydrogen.energy.gov/pdfs/progress08/iv_b_3_mcclaine.pdf.

¹² M. Tegel, S. Schöne, B. Kieback, L. Röntzsch, *Advanced hydrolysis of MgH₂ for on-demand hydrogen generation*, International Journal of Hydrogen Energy **2017**, 42, 2167-2176 (<https://doi.org/10.1016/j.ijhydene.2016.09.084>).

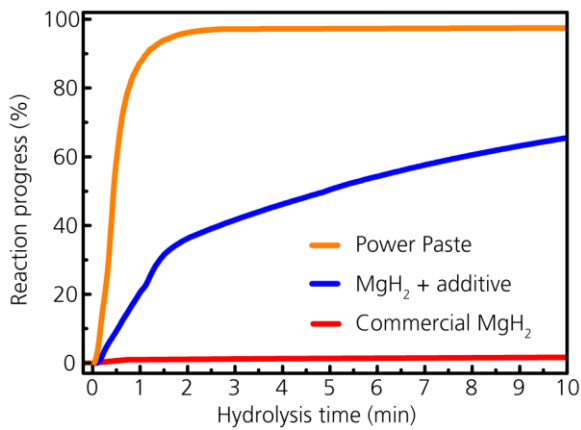


Figure 6: Reaction dynamics of pure magnesium hydride, magnesium hydride + metal salt additive and POWERPASTE (left); POWERPASTE (right).

To produce hydrogen with POWERPASTE, no special water is required. The reaction takes place with a variety of different water qualities (i.e. hardness) and works even with sea water.

Commercial uses of POWERPASTE-based power systems

The main components of a POWERPASTE power supply system are: A POWERPASTE cartridge, a water pouch or tank, a hydrogen generator, a PEM fuel cell, actuators, electronics and a buffer/backup battery. A general outline of such an energy supply can be seen in the following diagram:

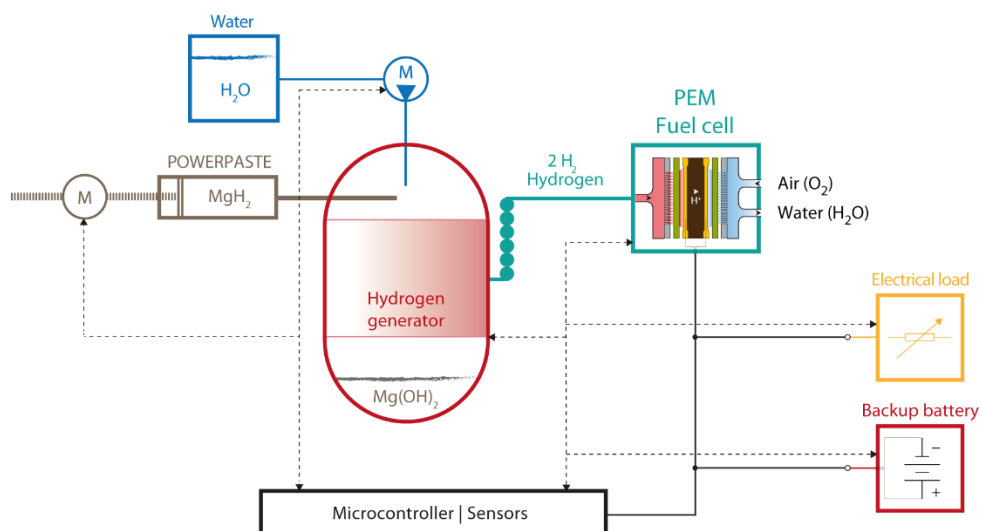


Figure 7: General outline of a POWERPASTE-based energy supply.

Through dosing exact amounts of POWERPASTE and water, the reaction within the hydrogen generator is controlled so that the amount of hydrogen produced coincides exactly with the

hydrogen consumption of the fuel cell, allowing low system pressures and, thus, light systems. Refueling just means to swap cartridges, which makes refueling extremely fast.

According to our calculations, lightweight power supplies can be built with about *three times the specific energy* of lithium-ion batteries at the system level, making these power supplies interesting for various high-energy applications:

- Unmanned aerial vehicles (UAVs) / drones
- Autonomous water / underwater vehicles
- Light electric vehicles and electric bicycles
- Medical devices
- Camping / outdoor equipment

A proposed outline of a light power system for UAVs is shown in the following diagram as an example:

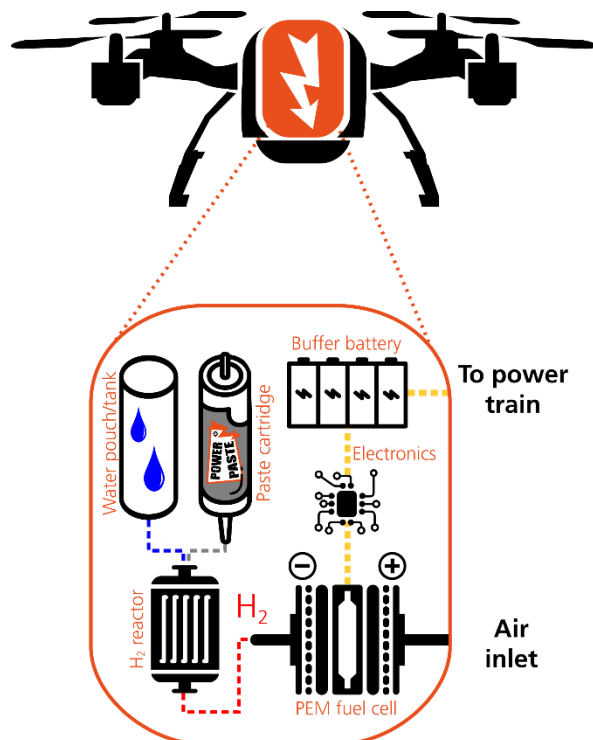


Figure 8: Outline of a POWERPASTE energy supply for UAVs.

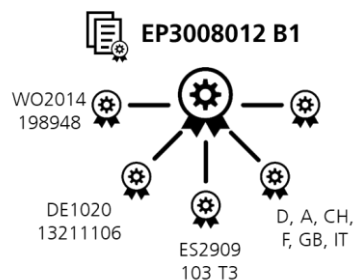
However, the high energy density as well as no self-discharge, long shelf life and low maintenance requirements make POWERPASTE-based power systems also predestined for certain portable and stationary applications such as

- Power supplies for construction sites
- Personal power generators
- Surveillance and security applications
- Back-up power generators

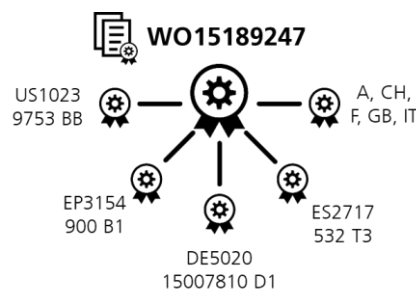
Technology offer

Fraunhofer IFAM offers research and development services ranging from materials synthesis to complete **POWERPASTE-based power systems**, including detailed case studies for specific energy applications, materials up-scaling and development, mechanical and electronics engineering as well as software development. Please, contact us to discuss your development goals personally. **Please contact us for more details.**

Fraunhofer IFAM's POWERPASTE technology is patented in two main patent families.



“Device and method for the hydrolytic production of hydrogen, device for producing electrical energy and possibilities for usage”. Patents granted.



“Composite material for hydrolytically generating hydrogen, device for hydrolytically generating hydrogen, method for generating hydrogen, device for generating electric energy, and possible applications”. European patent granted. US patent granted.

About Fraunhofer IFAM

With more than 600 employees, working in 20 departments, Fraunhofer IFAM is devoted to the development of advanced functional materials and manufacturing processes. We put our central principles into practice: scientific excellence, a focus on the application of technology, measurable utility for customers and ensuring the highest quality.

Most of the products, processes, and technologies are developed for industrial sectors where sustainability is particularly important, namely for the aviation industry, automotive sector, energy and environment, medical technology and life sciences, maritime technologies. The solutions developed at Fraunhofer IFAM are, however, also used in various other branches of industry including machinery and plant construction, electronics and electrical engineering, shipbuilding, rail vehicle manufacture, the packaging industry, and the construction sector.

Since 2012, an interdisciplinary team of engineers, physicists and chemists has been working on POWERPASTE and POWERPASTE-based power systems.

List of figures and tables

List of figures

Figure 1: POWERPASTE (left); POWERPASTE cartridge (middle); portable 100 W power supply unit (right).	2
Figure 2: Schematic representation of a POWERPASTE-based power system.	3
Figure 3: Reaction scheme to generate hydrogen.	3
Figure 4: General working principle of a fuel cell.	4
Figure 5: Specific energies and energy densities of selected high-energy fuels.	6
Figure 6: Reaction dynamics of pure magnesium hydride, magnesium hydride + metal salt additive and POWERPASTE (left); POWERPASTE (right).	8
Figure 7: General outline of a POWERPASTE-based energy supply.	8
Figure 8: Outline of a POWERPASTE energy supply for UAVs.	9

List of tables

Table 1: Key performance indicators of state-of-the-art power supply technologies.	5
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