PROJECT FINAL REPORT

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Project acronym: HYPER

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1 Executive summary

The HYPER project (2012-2015) was funded by the 2011 FCH JU call within the Early Markets topic ‘Research, development and demonstration of new portable Fuel Cell systems’. The project’s main aims were to develop and demonstrate a market ready, portable power pack comprising an integrated and cost effective modular fuel cell and hydrogen storage system, readily customised for application across multiple low power markets.

Early (*alpha*) 100 W_e prototypes of the ‘HYPER System’ have been developed and demonstrated in two specific applications: as a power pack for remote applications (specifically for the emergency services) and as a field battery charger. The system consists of:

- A lightweight planar PEM fuel cell, based on a modular design in which 20 W_e modules can be assembled to provide a range of power outputs
- A common interface (control electronics) to use with alternative hydrogen supply
- Two types of interchangeable hydrogen storage: lightweight compressed gas cylinders (300 and 700 bar) and low temperature solid state (based on metal hydrides).

The next (*beta*) prototype design is underway. This will incorporate a number of technical improvements around thermal management and system efficiency, as well as safety features required for CE marking, and a bespoke housing designed for cost effective manufacture (with proportionate cost reduction at power outputs <100 W_e).

The other principal aim of the project was development of advanced solid state H_2 storage. Significant contribution has been made to the scientific understanding of potential solid state storage materials. A great many materials were synthesised and tested during the project, providing insights into the behaviour of nanostructured hydrides (and resulting in three peer-reviewed publications) and culminating in development of an innovative advanced storage material (nanostructured ammonia borane confined within a carbon matrix). With a gravimetric capacity >>6 wt%, and no unwanted by-products detected (mass spectrometry sensitivity of 100 ppb), this offers a potentially step-changing improvement over competing technologies.

Alongside the technical work stream, development of the HYPER Commercialisation Strategy has confirmed strong evidence of market demand for the HYPER System, in particular for emerging low power, long run-time applications (such as remote monitoring) that are not currently served by other fuel cell, battery, solar power or hybrid solutions. The next steps required to progress towards commercialisation, including identification of appropriate partners have also been defined. Talks with a number of third parties interested in demonstrating the *beta* prototype are underway.

Experience gained during the project can contribute to the development of an appropriate RCS framework for small scale hydrogen fuel cell systems. In particular, insights into the challenges associated with filling portable hydrogen cylinders (mainly due to incompatibility between fittings) and the uncertainty over requirements for risk assessment and product certification for pre commercial demonstration, have been defined.

Throughout the HYPER project, the Consortium has actively engaged with academia, the market and relevant stakeholders to both share experiences and the project outcomes, but also to validate the market opportunity and inform the product development pathways in support of subsequent commercialisation. This has resulted in the establishment of new academic, technical and commercial relationships that will contribute to the continued development of the European fuel cell and hydrogen supply chain.

2 Project context and objectives

The Fuel Cells and Hydrogen Joint Technology Initiative was established with the primary aim of accelerating the market introduction of hydrogen and fuel cell technologies. Within the 2011 Implementation Plan, the Early Markets theme was focused on the demonstration of near and ready to market products. The HYPER project was funded within the specific topic ‘Research, development and demonstration of new portable Fuel Cell systems’. The primary aims of this were to

- Develop application specific prototypes ready to be used by specified end users, and demonstrating performance and operational improvements
- Incorporate design for manufacture that reduces costs
- Provide recommendations for an effective RCS framework.

There are significant market opportunities for portable power packs (20 W_e to 500 W_e scale) across a wide range of applications, such as power tool charging, emergency lighting, security and remote monitoring, that are truly portable in nature and/or remote from the grid. The incumbent products used in these applications are batteries, for example, lithium ion, battery/solar hybrids and small gensets. Fuel cells must offer increased performance such as higher energy density (>150 Wh/kg), more convenient re-fuelling/re-charging, or greater reliability, all at a competitive price, in order to successfully displace the use of these technologies.

The three-year HYPER project (September 2012-2015) aimed to develop and demonstrate a market ready, portable power pack comprising an integrated and cost effective modular fuel cell and hydrogen storage system, readily customised for application across multiple low power markets.

The key elements of the proposed HYPER System were as follows:

- A core fuel cell, based on a 50 W_e module which could be assembled to provide an electrical output of up to 500 W_e. The chosen fuel cell was a simple planar, air-breathing design, based on low temperature PEM technology, and designed to be robust, reliable and amenable to low-cost, volume manufacturing.
- A common interface (hydrogen supply and control electronics) to use with alternative hydrogen supply modules to meet the needs of a range of end user applications.
- A lightweight, protective casing incorporating user control and display panels, as appropriate.

Two generic types of (interchangeable) hydrogen storage module:

- A bespoke, gaseous hydrogen storage module, designed and fabricated to build on recent advances and know-how in the development of composite cylinders which have been driven by needs of the fuel cell powered vehicles.
- A solid-state hydrogen storage module based on innovative technology which improves the kinetics of hydrogen storage and incorporates novel nanostructured hydrogen storage materials with enhanced performance.

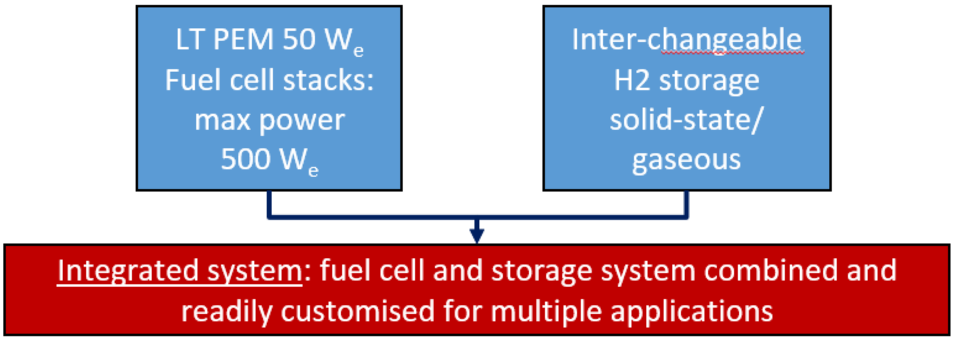

Figure 1: Schematic of proposed HYPER system

The FCH JU call also specified the following more detailed technical targets:

- Proof of concept systems containing stacks, all balance of plant components and fuel supply meeting application specifications
- System operation with electrical efficiencies of 30%+
- 1,000 h lifetime including 100 start-stop cycles and specific size and weight of less than 35 kg/kW and 50 l/kW
- System validation through systematic and widely agreed testing protocols/activities, demonstrating a cost prediction for mass production of less than 5,000 €/kW
- Operating temp -20 °C to 60 °C.

The target specifications of the HYPER fuel cell modules were as follows:

Fuel cell system output (W_e)	**100**	**500**
Weight (kg)	1.5	5
Volume (litres)	2	6
Fuel efficiency (H2 fuel)	>50%	>50%
Operating temperature (°C)	-20 to 60	-20 to 60

It was expected that one or both of the proposed hydrogen storage options would achieve a gravimetric energy density of >3 wt%. On this basis, the outline specification of the hydrogen storage module was:

Hydrogen storage module	
Weight (kg)	5
Volume (litres)	4
Chemical energy stored (Wh)	4,957

Consequently the target specification for the final integrated HYPER systems was:

HYPER system output[1] (W_e)	**100[2]**	**500**
Weight (kg)	6.5	10
Volume (litres)	6	10
Electrical energy produced, net (Wh)	2,478	2,478
Runtime (hrs)	25	5
System specific energy (Wh/kg)	381	247

The core of the proposed technical programme comprised six research-based work packages concerned with the development and testing of fuel cell modules and systems, solid-state hydrogen storage materials and modules, gaseous hydrogen storage modules, and integration of the final 100 W_e and 500 W_e HYPER prototype systems. The project also adopted a systems engineering approach to provide a unified framework for the technical research and to ensure that the requirements for end user applications remained at the heart of the project.

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[1] Assuming zero parasitic electrical load.

[2] It was acknowledged in the proposal that the target size and weight for the 100 W_e system could only be met by reducing the runtime of the hydrogen storage module to ~10 hours

The principle research aims (moving beyond the state of the art) were to:

- Fuel cell: optimise the electrochemical performance of the planar fuel cell in order to increase the overall power density and enable scale up of the basic module from 10 W_e to 50 W_e; address thermal and water management following assembly of the basic modules into larger systems, and develop appropriate control electronics.
- Solid state storage:
    a) Characterise and test of a variety of potential solid state storage materials with a focus on the effectiveness of nanostructuring advanced hydrides to couple optimum capacity with optimum refuelling kinetics; and prioritising readily available, cheaply-produced or waste materials.
    b) Design a lightweight storage tank to accommodate the advanced materials, focused on improving kinetics and heat management, and supported by thermal modelling to determine the optimum trade-off between H_2 storage capacity of a material, its requirement for heat management, and the parasitic load on the fuel cell.
- Gaseous storage: source and customise a small, lightweight cylinder (made with the latest composite materials) that is readily integrated into the final system, ensuring ease of exchange and refilling.
- Integrate all components into a robust system, readily customised for different applications with different priorities (e.g. power output, fuelling mode, runtime or cost).

Subsequent demonstration of the HYPER system was planned in three user specific applications:

- A 100 W_e portable power pack for remote applications (specifically for the emergency services), to be conducted by an independent end user.
- A 100 W_e field battery charger unit, to be undertaken by partner Airbus Group Innovations (AGI).
- A 500 W_e range extender for a civilian unmanned aerial vehicle (UAV), with multiple applications, such as crop inspection and spraying, also to be undertaken by AGI.

These were selected to demonstrate system flexibility, whilst addressing early market opportunities.

In parallel, the project also included a work package focused exclusively on the development of a commercialisation strategy. This involved analysis and validation of manufacturing cost projections, market testing and intelligence gathering, and the development of a commercialisation plan for target markets. The principle relationships between work packages are illustrated in Figure 2.

The HYPER project consortium consisted of 7 partners with complementary skills and expertise (Figure 3).

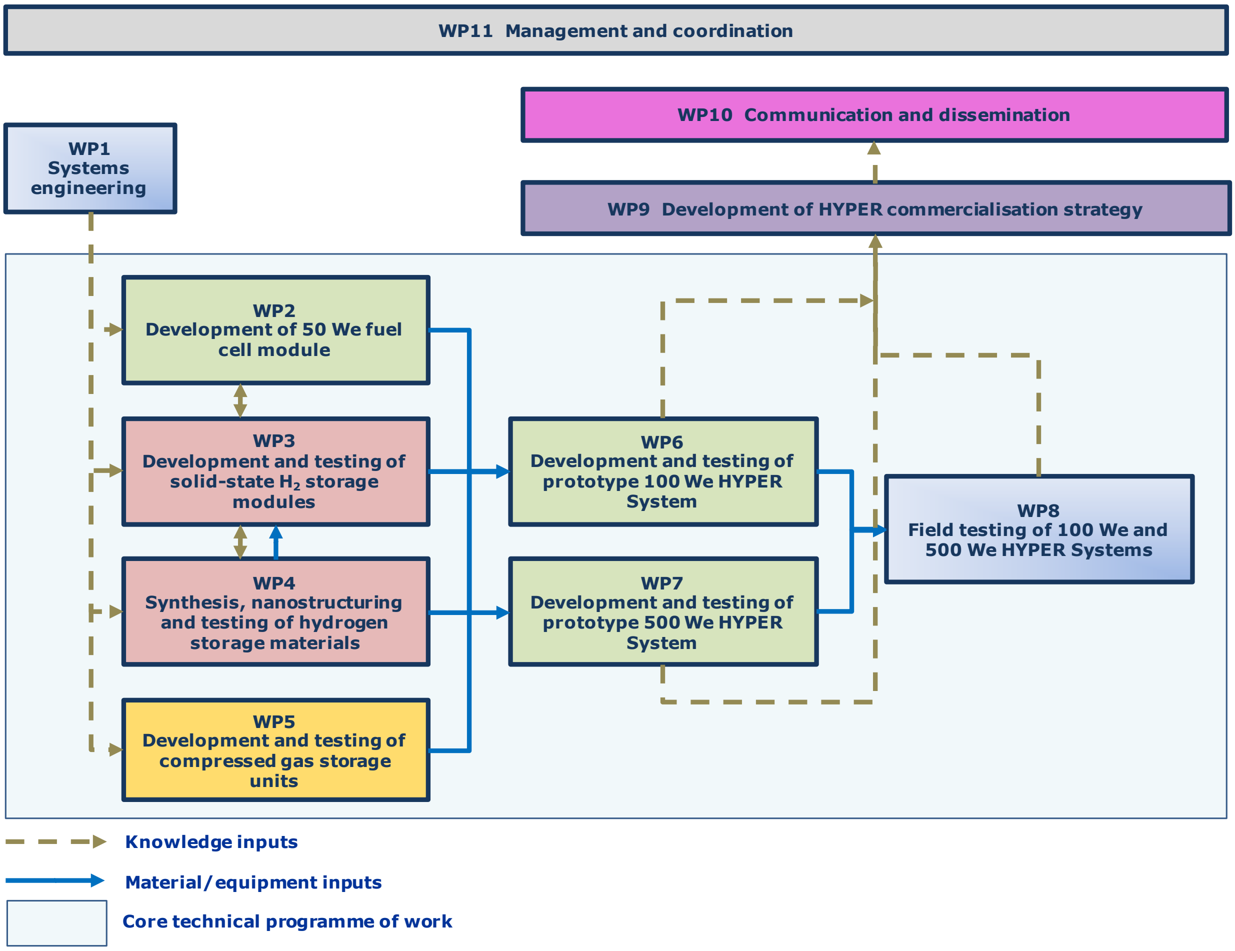

Figure 2: HYPER project organisation chart

- Orion Innovations (UK) Ltd – UK (Coordinator)
  - *Commercialisation of emerging technologies in the cleantech sector*
- PaxiTech SAS – France
  - *Development of air breathing fuel cells for portable applications*
- University of Glasgow – UK
  Fabrication and testing of advanced hydrogen storage materials
- McPhy Energy SA – France
  - *Solid-state hydrogen storage as metal hydrides*
- Institute of Power Engineering – Poland
  - *Modelling of heat and mass exchange during thermal processes*
- Airbus Group Innovation – Germany
  - *Development and demonstration of fuel cell applications*
- Joint Research Centre – Belgium
  - *Reference laboratory for EC and FCH JU projects*

Figure 3: Consortium partners

3 Results

In order to ensure that project developments remained in line with the requirements of the proposed HYPER system applications, the technical work was supported by an early systems engineering work stream which involved definition of customer requirements, sub-systems and interfaces, and performance and cost targets.This provided the overarching framework for subsequent component and system development.

3.1 Solid state storage

Development of the solid-state storage material and tank was a significant research element of the project. The materials work was primarily undertaken by Glasgow University, supported by the JRC. Tank development was led by McPhy, supported by IEn with thermal modelling and tank simulation.

Early system engineering work enabled the following targets to be determined for the hydrogen storage material, prior to incorporation into a storage tank, in order to meet the requirements of the final lightweight applications.

- Capacity of ideally over 6 wt%
- H_2 kinetics desorption of under 30 minutes
- H_2 desorption temperature ideally below 250 ^{o}C
- Low enthalpy of reaction
- A surface temperature, not exceeding 80 ^{o}C in order to not damage the PEM fuel cell
- Hydrogen to be delivered to the fuel cell at a temperature of 10-30 ^{o}C.

3.1.1 Stand-alone materials

Four ‘stand-alone’ materials were initially selected as promising candidates.

- MgH_2, to be used as a performance benchmark, and to explore whether chemical nanostructuring of the material resulted in a reduction in desorption enthalpy and/or desorption temperature compared with high energy ball milling.
- Li-N-H system as an advanced hydride system with high reversible gravimetric capacity and dehydrogenation, achievable at a viable working temperatures.
- $LiOH(H_2O)$ + LiH and NaOH + NaH as a high capacity cheap “single shot” materials which can be regenerated off board and used in recyclable hydrogen storage modules.

Nanostructured material was synthesized using high energy ball milling, and materials were characterised and tested at Glasgow University and JRC. This was accompanied by testing in a benchtop tank at McPhy and a comparative analysis (IEn) of the potential energy sources that could be used to reach dehydrogenation temperatures.

After more than 10 months of extensive testing, it became clear that none of these materials could meet the consortium targets, primarily because the kinetics of desorption was too slow and the dehydrogenation temperatures remained too high. The system would therefore require considerable energy to initiate and complete dehydrogenation, and sufficient electrical or combustion energy sources would, in turn, significantly increase the weight and volume of the solid state tank. Nevertheless, use of chemical energy to heat up the storage materials was identified as a potential solution.

3.1.2 Composite filler/matrix concept

A new concept was therefore devised for a composite material in which an exothermic component is embedded within a matrix of magnesium hydride. Reaction of the exothermic filler heats up the endothermic matrix and reduces the external energy source required to reach the onset temperature for dehydrogenation. Such a reaction is characteristic of one-shot materials, and the material would therefore need to be regenerated off-board before it can be used again.

The exothermic filler material itself would be a hydrogen storage material, thereby both providing the energy to initialise dehydrogenation of the MgH_2 matrix and also increasing the hydrogen capacity.

A number of potential tank designs were modelled at IEn. The best option involved uniform distribution of the exothermic material within the MgH_2 matrix (Figure 4). Such a solution increases the heat exchange area between materials and therefore avoids potential runaway temperature increases. Each portion of the exothermal filler could be separately initialised by a glow-plug[3] which would also potentially enable adjustment of the hydrogen flux.

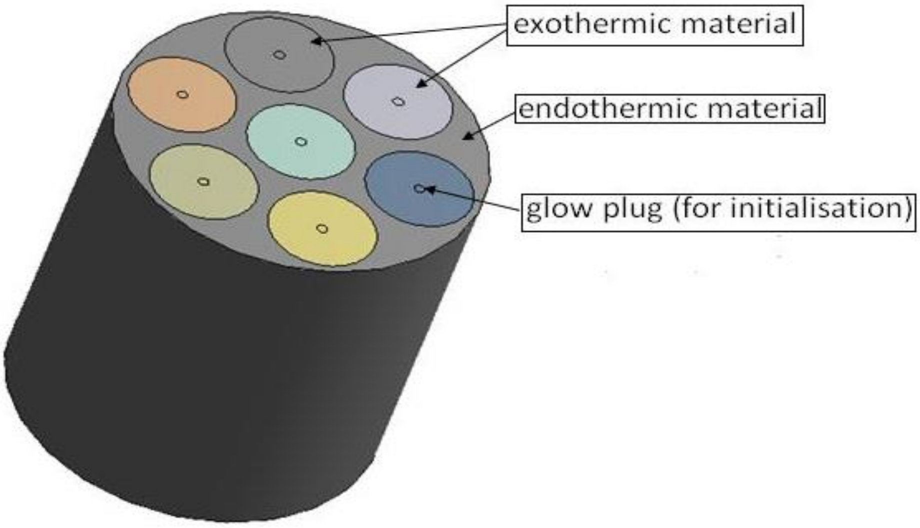

Figure 4: Matrix and filler, proposed tanks design

Following kinetic modelling at IEn, $Mg(OH)_2$ + MgH_2 was selected as the most promising material, with a theoretical low dehydrogenation temperature (80 °C), fast reaction rate, easy regeneration and low cost. Ball milled $Mg(OH)_2$, ball milled MgH_2 and chemically nanostructured $Mg(OH)_2$ (Figure 5) were successfully synthesised and tested at Glasgow and JRC, together with McPhy's own MgH_2 + catalyst material.

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[3] Glow plugs are small devices, able to reach very high temperature (~1000 °C) within few minutes.

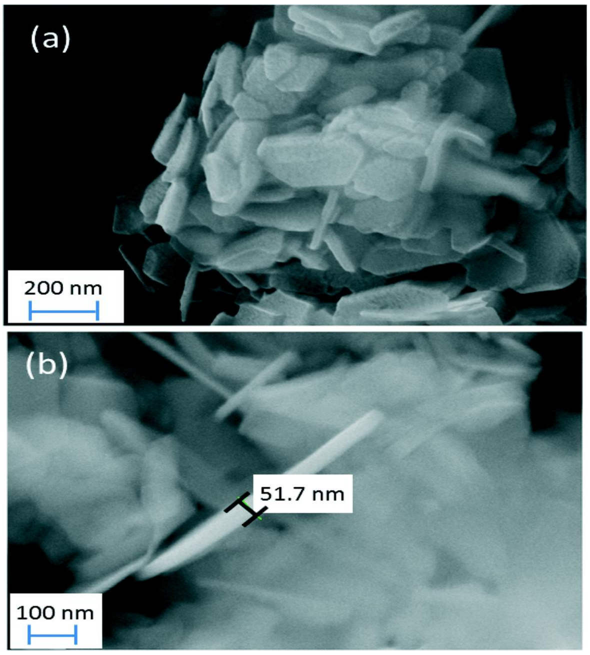

Figure 5: High resolution SEM images of nanostructured $Mg(OH)_2$

Results from the $Mg(OH)_2$ + MgH_2 system confirmed some advantages as an exothermic ‘filler’ material. The starting materials are relatively cheap and the end products, Mg and MgO can be regenerated. The mixture is also stable at the ‘rest’ temperature of 65 ^{o}C.

However, a number of drawbacks were also identified:

- The mixing process of the system is inefficient, since a reaction occurs between $Mg(OH)_2$ and MgH_2 during ball milling.
- Even though the first stage of the reaction in the system is exothermic, theoretical calculations performed at IEn suggested that the energy produced by the system would not be sufficient to initialise dehydrogenation from the MgH_2 matrix.
- The kinetics of H_2 release is too slow as determined by tests at McPhy and JRC, and the incorporation of additives did not prove successful in improving dehydrogenation kinetics.

As a result two additional systems were tested:

- $LiOH(H_2O)$ + MgH_2 – with low onset temperature and high gravimetric capacity.
- $Mg(OH)_2$ + LiH – with low onset temperature and high gravimetric capacity but potentially more complex to recycle.

The $LiOH.H_2O$ + MgH_2 system resulted in improved dehydrogenation properties compared to the $Mg(OH)_2$ + MgH_2 system. However, the release of H_2O in the system, especially at room temperature was problematic from an engineering viewpoint, and would dilute the quality of the fuel. The system was also not ‘stable’ at idle temperature (65 ^{o}C).

The $Mg(OH)_2$ + LiH system showed significant improvements over the first two exothermic fillers studies:

- The hydrogen release temperatures of this system were very encouraging with the kinetics showing an improvement over other hydroxide systems.
- There were no issues with the stability of the system at 65 °C and the system does not require high energy ball milling to be performed.
- The starting materials are relatively cheap and the MgO end product can be recycled ($MgO + H_2O \rightarrow Mg(OH)_2$), although recycling the the Li_2O to LiH is harder to achieve.

However, a number of issues were still identified:

- The components would need to be in ‘indirect’ contact (i.e. separated by a physical barrier) due to possible issues with reactivity during regeneration of the MgH_2 matrix and replacement of the filler material.
- The system is limited by the slow kinetics of H_2 release, which appears to be constrained by the formation of core shell hydroxide/hydride particles.

Results from this work are of significant scientific interest and three papers[4] have been published during the lifetime of the project. However, it was decided that the composite filler/matrix material would not meet the original project targets, and a new approach was sought.

3.1.3 Ammonia-borane-carbon composite

In September 2014, a new concept was therefore devised involving ammonia borane (AB) and carbon based materials. AB has an extremely high hydrogen gravimetric capacity of 19.6 wt%, but when heated releases by-products such as ammonia, borazine and diborane, which can be toxic for a PEM fuel cell. Recent evidence had suggested that nanoconfining AB into an inert mesoporous host, such as carbon, could successfully suppress this gas release, and this approach was the subject of research during the final 10 months of the project.

Following an extensive literature and patent search, it was decided to focus attention on ammonia borane and carbon based composites. A number of carbon based composite materials (incorporating graphene, AX-21 or activated carbon (AC)) were prepared by ball milling (to form nanocomposites) or in solution (to enable nanoconfinement) and tested. The carbon is dried overnight under vacuum at 400 ^{o}C to ensure the pores are free of air/moisture prior to the synthesis of the AB composites.

The results have been extremely positive in terms of onset temperature, release of H_2 and suppression of by-products. The most promising solution consists of activated carbon, which provides a high surface area and good porosity, combined with confinement via wet impregnation. This allowed the toxic gases to be reduced to a minimum, but nevertheless a small external filter was considered necessary to protect the fuel cell from any risk of poisoning. Key highlights are as follows:

- A novel AB-carbon composite that can store >>6 wt% H_2 has been developed, with an optimal dehydrogenation temperature of 96 °C.
- When synthesised using the solution impregnation method, this composite entirely suppresses borazine release.
- An accompanying downstream filtration system based on $NiCl_2$ has also been developed which absorbs ammonia from the AB and decreases the concentration of other unwanted by-products such as diborane to <100 ppb.

These results have been endorsed by early simulations by IEn in which the reaction rate and the hydrogen flux was found to be almost constant as the temperature front moved along the tank.

Scale up and benchtop testing has not been possible within the timeframe of this project, since the Consortium do not possess the necessary expertise to perform the solution impregnation methodology at scale without significant investment. However, successful discussions around support for scale up (to ~50g) have already been conducted with a third party (a company with particular expertise in carbon composites). This company also provided the opportunity to test alternative host carbon materials which are both mesoporous and microporous in nature, potentially enabling a greater content of AB to be loaded on the carbon, and are available in the form of beads which may make regeneration of the spent AB easier and cheaper. Good early results have been achieved with these carbons, but more work is needed to select the optimum size and structure before beginning scale up.

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[4] J. M. Hanlon, L. Bravo Diaz, G. Balducci et al., Rapid surfactant-free synthesis of $Mg(OH)_2$ nanoplates and pseudomorphic dehydration to MgO, Crys.Eng.Comm, 17, 5672-5679, 2015; J. Mao, Q. Gu, D. Gregory, Revisiting the Hydrogen Storage Behavior of the Na-O-H System, Materials, 8, 2191-2203, 2015; J. Mao, Recent advances in the use of sodium borohydride as a solid state hydrogen store, Energies, 8, 430-453, 2015.

Due to insufficient material, it was also not possible to test the released H_2 with a PEM fuel cell. Nevertheless, based on the mass spectrometer results obtained from the composite, in which no by-products were detected with an MS sensitivity of 100 ppb, the purity of the H_2 gas is considered extremely likely to meet the requirements of the fuel cell (99.99%).

3.1.4 Alternative low temperature solid state storage tank

Following the decision to focus materials research on the new AB composite, it was agreed that development of a suitable storage tank would not be ready for integration into the planned field trials.

The Consortium therefore decided to introduce development of an alternative, solid-state storage tank, which would not meet the ambitious performance targets set by the DOW, but would enable the project to demonstrate the interoperability of the HYPER system (interchange of two types of storage system). The partners compared a number of commercially available state of the art solid state storage tanks with an ‘in house’ low-temperature hydride tank proposed by project partner McPhy Energy. It was subsequently decided that it would be preferable to go with McPhy’s solution for the following reasons:

- McPhy were confident that they could produce prototype tanks suitable for both 100 W_e and 500 W_e applications in time for field trials, since both the material and the tank itself were based on existing technology development at the company.
- The tank was expected to be comparable in performance to commercially available alternatives.
- This route reduced the risk of introducing unknown sub-contractors or suppliers into the project.

After testing three families of metal hydride, an AB_2-type alloy based on $TiMn_2$ was selected, with a storage capacity at working pressures and temperatures of ~1.15 wt% between 10 and 1.5 barA at 20 °C. Tanks were equipped with an integrated pressure regulator (for connection with the fuel cell, which requires a maximum inlet pressure equal to 5 barG), an inlet for filling the system with hydrogen, an outlet for the hydrogen supply to the fuel cell, and a safety valve to protect the tank from over-pressure. A protective collar enabled the tanks to be easily handled and transported and protected the safety valve, the pressure regulator, the check valve and the connectors from mechanical damage (Figure 6).

The 100 W_e tank is CE-marked and compliant to the Pressure Equipment Directive (PED). It was designed, as far as possible, to meet future TPED homologation requirements and has been manufactured according to standard practices required by ADR and ISO 16111 for transportable gas storage devices.

The prototype for the 500 W_e system was made with a smaller design in order to conform to the weight and volume requirements of AGI’s UAV application. A simple change of scale, keeping the same diameter as the previous 100 W_e prototype was not feasible, so it was necessary to change the diameter as well. In order to optimize the design conception and to reduce the final cost, the tank was designed to be manufactured using machining processes without welds and their weld-controls. Tank specifications are shown in Table 1.

	100 W_e system	**500 We system**
Weight (kg)	7.3	1.3
Total volume (l)	2.36	0.45
Hydrogen content	40 g / 450 Nl	10 g / 111 NL
Energy (Wh)	1347	332

Table 1: Tank specifications for 100 W_e and 500 W_e (UAV) applications

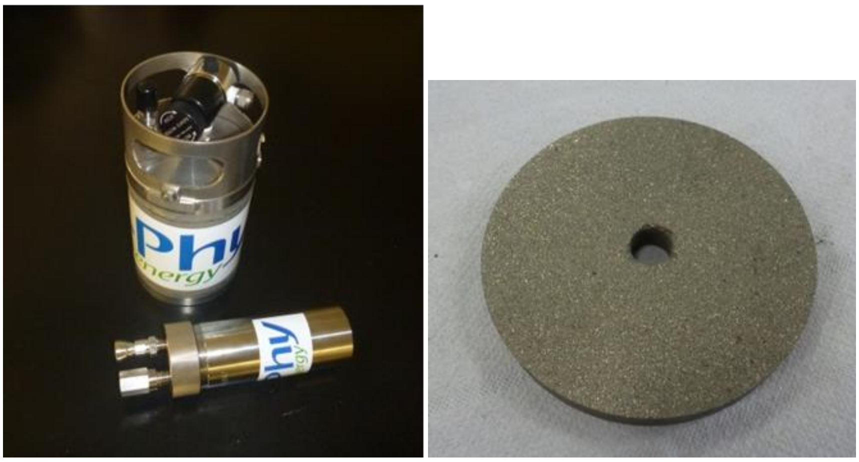

Figure 6: Left – tanks for 100 W_e (vertical) and 500 W_e (horizontal) applications; right - compacted pellet

Both prototype tanks showed good reproducibility with repeated testing, but some limitation of performance at higher flow rates, due to poor heat transfer.

One 100 W_e and two 500 W_e units were delivered to Airbus Group Innovations facilities (January and June 2015) for integration with the fuel cell module and then field testing.

In parallel to the development of the two solid-state storage tank prototypes, optimisation of the tanks was continued in order to achieve increased storage capacities and better thermal transfer. Compaction studies were carried out on a closely related AB-type alloy, which was easier to handle (non-pyrophoric). Most compacts have a tendency to fragment during cycling tests. Treatment with a polymer, which 'glued' particles together, was carried out, and compaction tests were performed in order to optimize the binder content.

This was highly successful and resulted in compacts that keep their shape during cycling tests with hydrogen.

The compacts were then tested in the HYPER benchtop tank, and subsequently a specifically designed prototype tank that can hold up to 15 compacts of 10 mm in thickness. More than 300 cycles were successfully completed on the compacted hydride, in a repeatable manner, using the small tank containing 15 compacts (Figure 7).

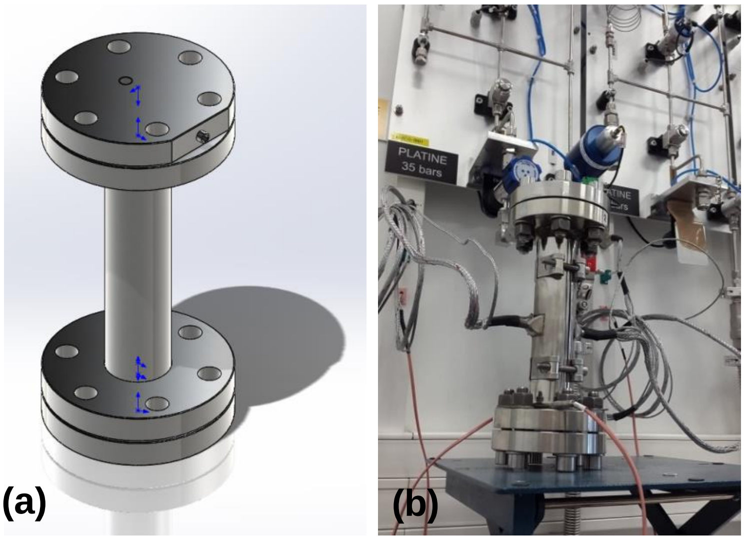

Figure 7: Multi-compacts small tank developed at McPhy Energy, (a) conception design and (b) connected to gas panel for cycling tests

These showed a significant increase in flow rate, as a result of enhanced heat transfer. Expected performance in future development of the HYPER hydride, extrapolated from the results with the AB-type allow, suggest storage capacity could be doubled and maximum flow rate multiplied by 17 using the compaction process. For the 100 W_e tank, this would give 80 g of H_2 (1 wt%); for the 500 W_e tank, 20 g of H_2 (1.5 wt%).

The compaction test cycles also demonstrated continued integrity of the tank, in spite of potential large strains applied to the wall of the tank by the successive volume expansion and contraction of the compacts during absorption and desorption respectively. Research to quantify and determine the exact nature of these strains is ongoing.

3.2 Gaseous storage

HYPER had a high level goal of selecting and sourcing a lightweight gaseous hydrogen storage module with a gravimetric energy density of 3 wt%. After contacting numerous suppliers, it became evident that small (<5 litre) hydrogen cylinders and compatible valves and regulators are available on a commercial basis at 350 bar pressure or below. However cylinders at the next pressure node of 700 bar, which is required to achieve the 3 wt% target, are rare at this scale.

Significant effort was expended in:

- Identifying cylinders that had undergone the certification process for use with high pressure hydrogen.
- Sourcing compatible valves and regulators, including testing material components with hydrogen gas.

Eventually it became clear that there was no single cylinder that met the target wt%, and the Consortium selected two cylinders which provided alternative sizes and pressures (Table 2, Figure 8 and Figure 9), and enabled the project to trial cylinders at the working pressure and volume set in the performance requirements of the 100 W_e and 500 W_e HYPER systems. Moreover this dual approach provided opportunities to increase knowledge of the operation of gaseous storage technology in portable applications.

	Pressure (bar)	**Volume (l)**	**Gross energy content (Wh)**	**Cylinder wt (kg)**	**Valve + regulator wt (kg)**	**System wt (kg)**	**Wt%**
Dynetek cylinder + GHR valve and regulator	700	2.0	2,643.35	3.1	2.0	5.1	1.6
Luxfer cylinder + VTI valve + regulator	300	4.7	3,261.67	2.8	0.97	3.8	2.6

Table 2: Selected compressed H_2 cylinders

Figure 8: GHR valve/regulator and Dynetek cylinder (700 bar)

Figure 9: VTI valve/regulator and Luxfer cylinder (300 bar)

It was originally intended to test both cylinder tanks prior to integration with the fuel cell system and as part of both 100 W_e application field trials (in Grenoble and in Ottobrunn). However, numerous challenges were encountered in filling the cylinders.

- Initially three industrial gases companies were contacted, but there was a reluctance to be involved in a small scale project because of the small volume hydrogen requirements. There were also concerns about transportation of filled cylinders to partner premises, particularly in relation to 700 bar filling and across national borders.
- Two filling stations were eventually selected: ET Energie Technologie (ET) near Ottobrunn and Symbio FCell in Grenoble. Both stations were able to supply hydrogen to >99.995% purity and to 700 bar. However, soon after engaging with Symbio FCell, the company reported difficulties in connecting both the 300 and 700 bar cylinders for filling. On-going problems with connecting cylinders for filling led to the decision for PaxiTech to focus on testing with the 300 bar cylinders alone and for AGI to test both 300 bar and 700 bar cylinders (with filling at ET).

- ET were familiar with the fitting on the VTI valve (K44-60.0-S1) for the 300 bar cylinder, which conformed to ISO5145. However it turned out that the company were not able to make a connection to the 700 bar cylinder as the Staubli plug was 'non-standard'. ET offered to fill the 700 bar cylinders if AGI were able to provide 'an adapter with an interface for the test stand as per NovaSwiss standard ¼" high pressure tube 20,000 psi'. After many discussions between Staubli, GHR, ET, ORION and AGI, it transpired that the 'common' standard for gaseous hydrogen land vehicle refuelling is ISO 17268 (and SAE J2600). GHR had originally used a quick-release filling connector manufactured by WEH which conformed to this standard. However the company had decided that the standard profiles were too large and so commissioned Staubli to design and manufacture a custom 'plug' and 'nozzle'.
- In order to make a connection between ET's filling station and the 700 bar cylinders, it was therefore necessary to purchase the counterpart nozzle from Staubli and a custom fabricated adapter from Nova-Swiss' UK agent, SeaSpray Systems Limited. This adapter was described as a '¼ BSP Female to suit Staubli CHV02 Coupling, ¼ HPCT High pressure Female to suit Nova Swiss ¼ High Pressure Tubing'.
- For 300 bar cylinder filling by Symbio FCell, it was realised that, although the VTI valve conformed to standard ISO 17268, this design was different to that specified by relevant French standards that had been adopted by the company. Fortunately, VTI was able to propose two possible adapters to overcome this problem. After consultation with Symbio FCell, PaxiTech selected and purchased an adapter from VTI.

In summary, both 300 and 700 bar cylinders were eventually filled with high purity hydrogen. However, it proved very difficult to identify local filling stations willing to fill low numbers of small cylinders. Moreover significant effort was expended in resolving problems associated with making connection to the cylinders for filling due to incompatibility between fittings. In the case of the 300 bar cylinders, this was due to a difference in ISO and French national standards. For the 700 bar cylinders, a smaller plug and socket connection had been developed specifically for portable applications but this was not compatible with the common automotive standard for hydrogen filling. Improved guidance from manufacturers and hydrogen filling stations would help to resolve this barrier to the development and market adoption of fuel cells and hydrogen for portable power applications.

The 300 bar and 700 bar cylinders were subsequently used in field trials (section 3.5).

3.3 Fuel cell module

The HYPER core fuel cell was based on a modular design in which a basic 50 W_e module could be readily assembled to provide power outputs of up to 500 W_e. Research and development of this core module was primarily undertaken by PaxiTech and consisted of the following steps:

- Selection and optimization of fuel cell components, and initial build of the 50 W_e module.
- Redesign of the basic module to decrease weight and volume, reduce potential for hydrogen leakage and ensure cost of manufacture was kept to a minimum.
- Validation of a prototype 6 W_e version of the new design, followed by scale up to 20 W_e module. This module became the basic fuel cell building block of the 100 W_e HYPER system (see Section 2.4).

Initial component analysis consisted of evaluation and selection of the catalysts, the gas diffusion layer (GDL), the electrolyte membrane and the connecting materials, in order to integrate them in to the planar modules.

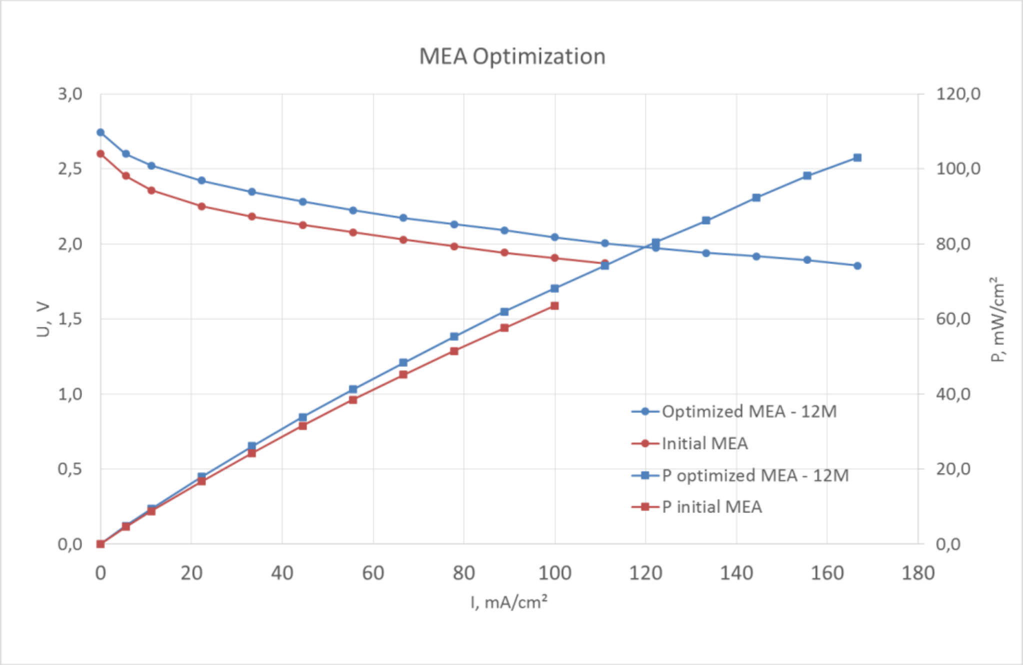

Figure 10: Polarization curve (U and P vs. I) of an optimized MEA compared to the initial performance

This resulted in an MEA with significant performance improvements (Figure 10) and target power densities for this type of planar cell achieved (>100 mW/cm²).

However, evaluation of the first 50 W_e module revealed issues with the mechanical design (primarily use of nuts and bolts for cell clamping). A new design was undertaken which resulted in a smaller and lighter 'screwless' module, easier to assemble both in series and in parallel, with reduced risk of H_2 leakage and compatible with fully automated and cost effective manufacture and assembly. After a number of design iterations, a 6 W_e prototype was validated and scaled up to form a basic 20 W_e module (Figure 11).

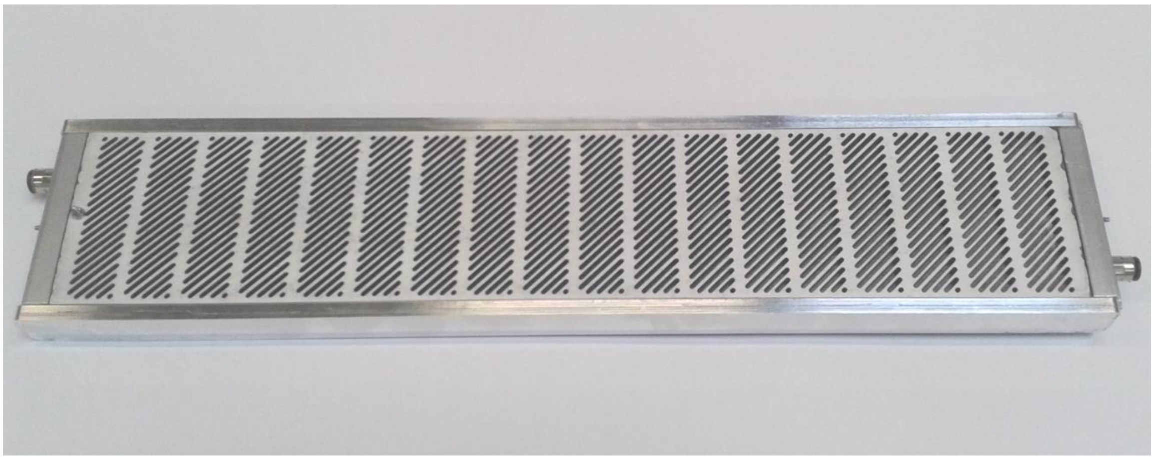

Figure 11: Basic 20 W_e FC module

Validation of this module showed that performances obtained at 6 W_e and 20 W_e levels were consistent, and equivalent to that anticipated from the performance and selection of the electrochemical components. Lifetime testing (572 hours) was undertaken using 2 x 20 W_e modules, and subsequently extended on one of the 20 W_e modules within a climatic chamber, in order to evaluate the impact of temperature and time on the fuel cell performance (total >1000 hours).

The lifetime evaluation confirmed successful operation of the fuel cell for >1000 hours, but also revealed some issues with thermal management. Figure 12 represents the performance of the 2 x 20 W_e modules as a function of time, for two levels of power/voltage.

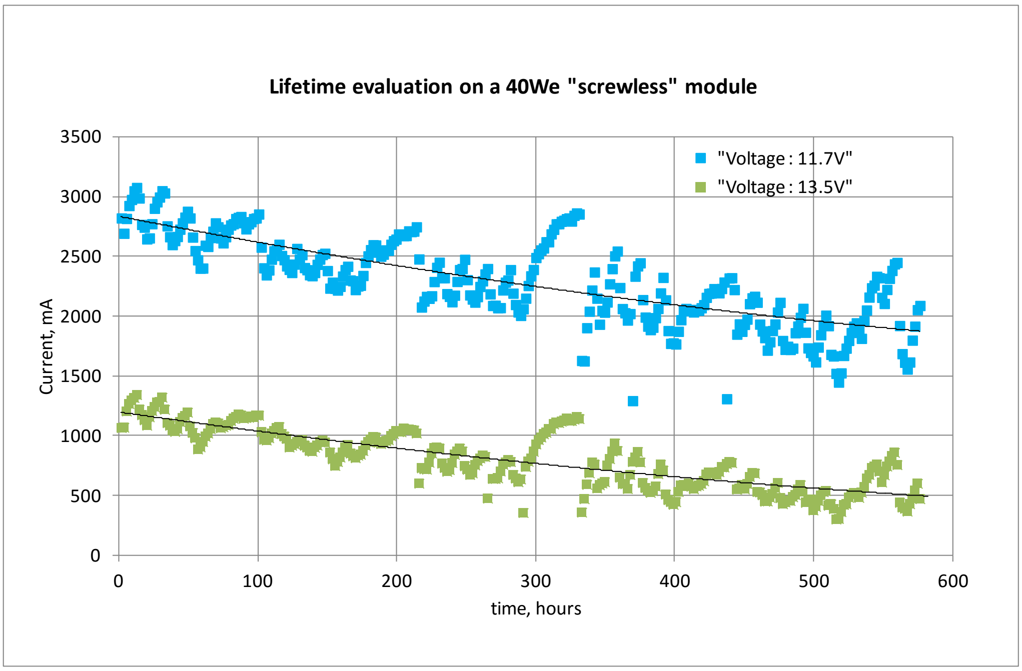

Figure 12: Lifetime evaluation of a 2 x 20 W_e module. Evolution of the current as a function of time for two different levels of voltage/power.[5]

The curves show some degradation of the fuel cell performance with time, but it can be seen that the degradation is also reversible. Two main reasons are believed to be the cause of degradation in performance:

- Internal temperature increases caused by use of an inappropriate power profile, in which power peaks exposed the fuel cell to high currents. This was avoided within the integrated (100 W_e) system by hybridisation with a battery (eliminating power peaks).
- The insulating nature of the cover material preventing efficient heat dissipation and rendering the fuel cell over-sensitive to ambient temperature. This was confirmed by the controlled testing in the climatic chamber in which performance during 200 hours maintained at 0 °C was extremely stable. A reduction in the thickness of the cover was incorporated into the next design iteration, and used for modules integrated into the 100 W_e system. This also reduced the weight of the 20 W_e module from 450 g to 310 g.

3.4 System integration

Development of the 100 W_e HYPER prototype for demonstration in specific applications involved assembly of multiple 20 W_e FC modules with the required balance of plant (BoP) into an appropriate lightweight and robust housing. This followed a three-step process:

- Integration into an existing housing for intial evaluation (*alpha* 1 prototype) followed by assembly of two new systems (*alpha* 2 prototypes) for validation during field trials.
- A risk analysis process and evaluation of *alpha* 1, leading to the definition of a pre-industrial version of the system (*beta* prototype), incorporating CE marking requirements.

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[5] For each “cycle” there were two different steps, one at 11.7 V, the other at 13.5 V.

- Design engineering of a bespoke lightweight housing that could incorporate all necessary safety features and controls, and analysed the optimum trade off between performance and low cost of manufacturing.

Alpha **prototype development**

The integrated system was designed to have a simple start up and shut down routine, to ensure good management the fuel cell stack so that it stayed within the required operating parameters and to provide end user feedback on performance.

The main BoP components are:

- Controller, which monitors all of the integrated sensors, controls the system components, and enables display of all the relevant parameters for the system user. The priority of the controller is to ensure that the stack voltage stays above 20 V, and that the battery voltage does not exceed 12.5 V. The current is regulated to ensure that these to criteria are satisfied. If either of these voltages is exceeded, the system enters a standby condition.
- Electrical BoP, consisting of a DC/DC converter and battery, transforms the unregulated electrical voltage output of the fuel cell stack so that it is compatible with the requirements of the end user. The power provided to the end user and internal battery is restricted by a current limit set by the controller (Figure 13).
- Mechanical BoP, which consists of cooling fans, an internal fuel isolation valve and internal stack purge valve. The fuel and purge valves are switched on and off according to a preconfigured schedule during start up, and shut down. The fan is proportionally controlled via an asynchronous integrating controller.

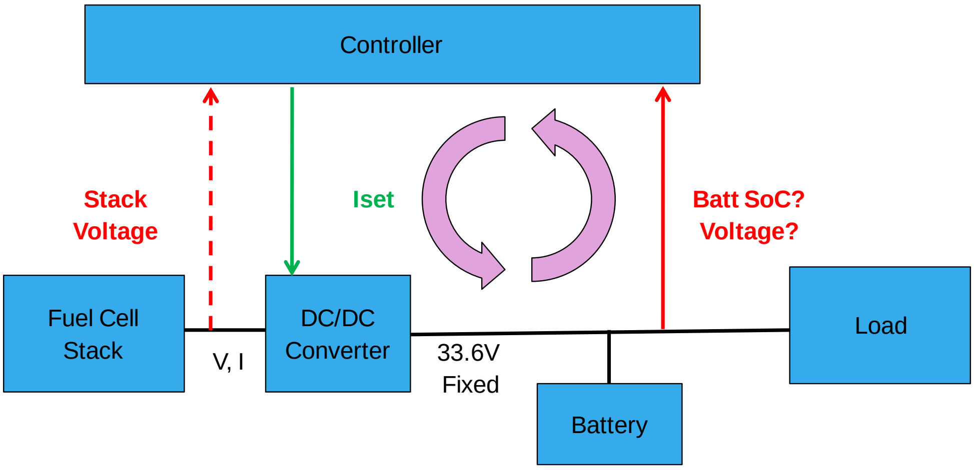

Figure 13: Electrical BoP major components

The control and electrical interface parts of the *alpha* 1 system performed well. However, there were some thermal issues surrounding the positioning of the fuel cell modules (due to the difference in size between the fuel cell stack originally used in the housing, and the planar fuel cell modules developed in the project), and the placement of the cooling fans relative to the modules caused some inconsistent performance. A Computational Fluid Dynamics (CFD) analysis was therefore conducted in order to determine the best layout of the fuel cell modules in the housing for optimal thermal performance. Results suggested that the best scenario was to set the modules in 3 or 4 double rows (mounted one on top of the other).

As a result, a decision was taken to design and develop the *alpha* 2 prototype, which would incorporate this configuration, and also include a new stack temperature sensor with proportional control of the cooling fans, plus minor modifications of the turn on and shut down sequence. The fuel and purge valves and interface card were also added at this point.

Two *alpha* 2 prototypes were assembled (in preparation for field testing in Grenoble and Ottobrunn). The first already showed significantly improved performance over *alpha* 1, but was found to be slightly underpowered with six 20 W_e FC modules (primarily because the parasitic loads of the DC/DC converter, fans, controller and display required some additional power). The second *alpha* 2 prototype therefore had eight 20 W_e FC modules giving a theoretical maximum power of 140 W. It also had a more robust wiring loom, and the valves (which were causing some electromagnetic compatibility (ECM) issues) were changed.

In total, approximately 600 hours of testing were completed on these two *alpha* prototypes. Insights will be taken forward to inform the continued development of the *beta* prototype, in particular:

- Addition of diagnostics tools (via an automatic datalogger)
- Addition of a short circuit device for lifetime improvement and fuel cell humidification
- Better thermal management (specifically increasing the number of thermocouples for improved temperature control)
- Optimisation of the parasitic loss of the system
- Optimisation of the electronic control and circuit boards:
    - A smaller/more efficient DC/DC converter
    - Integrating the 3 printed circuit (PC) boards into one.

It was also noticed that shipping the housings (via aeroplane or road) could lead to some loose electric and hydrogen connections. Stronger connectors, and better fixing of the fuel cell modules within the housing is therefore needed for the final version.

The two 100 W_e *alpha* prototypes were subsequently used in the field trials at PaxiTech and AGI.

Risk analysis

The risk assessment was a critical element to ensure safe use of HYPER fuel cells plus hydrogen storage in field trials. Moreover, as the objective is to launch commercial products soon after the end of the project, it was essential to consider any necessary safety features required to achieve appropriate product certification.

The process to determine an appropriate and proportionate risk analysis procedure was not as straightforward as originally envisaged (see Figure 14), and it became evident that there was no readily available, formal guidance on this issue from the EU regulating bodies.

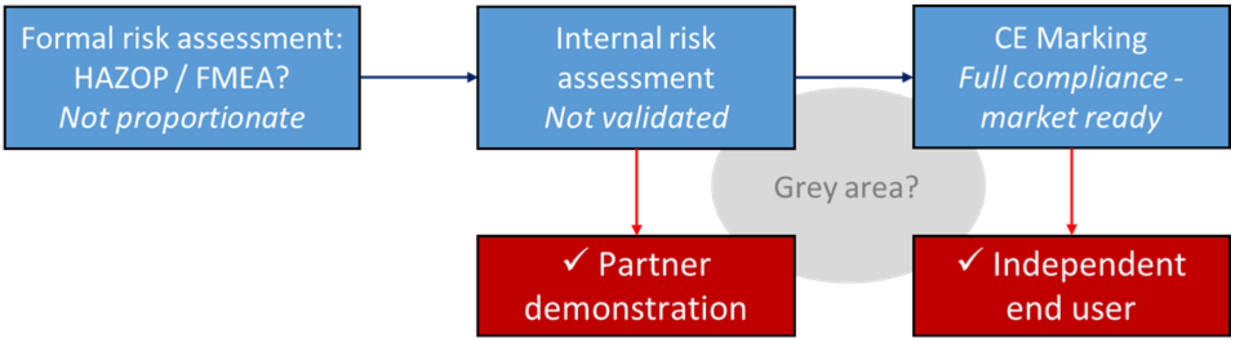

Figure 14: Schematic of risk assessment process

Initially two structured risk assessment procedures were considered, based on previous experience of partners within the HYPER consortium: Hazard and Operability Analysis (HAZOP) and Failure Modes, Effects and Criticality Analysis (FMECA). Initial research, however, suggested that both procedures were too complex for a risk assessment of the relatively small scale and simple HYPER system.

The standard EN 62282-5-1:2012 ‘Portable fuel cell power systems – Safety’ was subsequently identified as the most relevant to the HYPER system, but again the document is extremely detailed and it was not immediately clear which elements it would be appropriate (and cost-effective) to comply with for the demonstration phase.

Contact was then made with commercial manufacturers of fuel cell systems and other energy products to understand what their requirements would be for new technologies. It was clear that it is mandatory for products ‘placed on the market’ in Europe to be CE marked, by which a manufacturer declares conformity with EU safety, health or environmental requirements and compliance with EU legislation. Whether or not pre-commercial prototypes require CE marking if used for field trials by end-users (i.e. non-consortium partners), and the relationship between CE marking and the portable fuel cell standard, was again less clear.

The CE marking process requires significant development and testing time and resources, and expert support. Nevertheless, the Consortium decided that would be prudent to achieve CE marking before placing the HYPER prototype within the hands of independent end users.

The standard EN 62282-5-1:2012 ‘Portable fuel cell power systems – Safety’[6] references EU Directives that may apply to the product, potentially including the Machinery, Electromagnetic Compatibility, Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) Directives.

All aspects of the ‘Design and construction requirements’ set out in Section 4 of EN 62282-5-1:2012 were considered in two HYPER project team workshops, the second involving an external expert on CE marking. The standard states that the manufacturer shall ensure that:

- All foreseeable hazards, hazardous situations and events associated with the portable fuel cell power system throughout their anticipated lifetime have been identified.
- The risk for each of these hazards has been estimated from the combination of probability of occurrence of the hazard and of its foreseeable severity.
- These two factors which determine each one of the estimated risks (probability and severity) have been eliminated or reduced as far as possible through design (inherently safe design and construction).

The risk assessment of the fuel cell system identified design modifications required to achieve CE marking, including the incorporation of pressure relief valves, hydrogen detection and adequate case ventilation, and a re-design of control circuitry. Some of these modifications were already addressed in the *alpha* 2 prototypes. The remainder will be incorporated into the *beta* prototypes prior to field testing by end-users. The CE marking process also involves the production of an operating manual, product labelling, and both type and routine testing.

McPhy took responsibility for certification of the alternative low temperature solid-state storage tanks. The solid-state prototype for 100 W_e applications was itself CE marked, specifically to verify compliance with the Pressure Equipment Directive (PED), with no insurmountable difficulties. However, transportation of hydrogen filled tanks requires compliance with International Road Transport Agreement (ADR). Homologation according to the ADR is time consuming and expensive, and therefore not proportionate for an early prototype. McPhy applied to the national authority for a derogation but later decided to fill the tanks on site at AGI to obviate the need for this. Risk assessment of the gaseous storage cylinders was not required since these were certified by the manufacturers.

It was originally intended that the *beta* prototype would be completed for delivery to an independent end user by the end of the project, and work was undertaken on a bespoke housing design that would contain the required safety features and optimum module configuration, as well as enable cost-effective volume manufacture. However, the challenges encountered with system integration of the *alpha* system meant that physical build of the *beta* prototype did not take place during the project

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[6] Fuel cell technologies, Part 5-1: Portable fuel cell power systems - BS EN 62282-5-1:2012, ISBN 978 0 580 60957 2.

itself. Despite this, the consortium is convinced that the CE marking approach was the right one, ensuring that the first build of the *beta* prototype will follow the optimum design pathway, leading to reduced development time and costs.

Beta prototype housing – design for manufacture

Work was undertaken on design of a rugged, lightweight and low cost housing for the *beta* prototype. Effective design for manufacture assesses and optimises the materials and processes employed to balance strength and functional aspects with the relative costs of the different materials available.

Assumptions included:

- Production volumes in batch sizes of max 1000 units (for the next stage of product development)
- Manufacture would be conducted by a third party
- Set up/tooling costs would need to be met, as well as unit production costs.

Three processes were considered:

- Injection moulding (plastic) – offers high volume (10,000 to 250,000 units), requires high initial investment, but produces low cost, lightweight plastic parts, which are very flexible in terms of appearance and shapes. Future changes cannot be adopted easily.
- Sheet metal – offers low to high volumes (10 to 10000). Low volumes have low initial setup and tooling costs. Heavier than plastic, although careful design can help minimise the extra weight, and good flexibility in terms of part design, and the opportunity to incorporate future modifications.
- Die cast metal – has similar benefits to injection moulding with high initial investment and low part costs. Again, there is a weight penalty and future changes cannot be easily incorporated.

The final design consists of a mix of processes that optimizes cost and performance: plastic parts reduce weight, enable complex parts to be included and improve appearance and feel, whilst sheet metal components (using minimal material thickness) improve robustness and retain flexibility (Figure 15).

Figure 15: _Beta_ housing design for 100 W_e system

Externally the case is constructed via a central core of aluminium outer parts, with plastic moulded end pieces, handle and control panel area. Each end piece maximises the opportunity to create inlet and outlet vents, with mounting points for the incoming and outgoing connections (electric and H_2).

The hydrogen supply bottle is housed in a retractable cage that holds the bottle during operation. When not in use the bottle can be separated and cage retracted, reducing the overall size for transportation. The control panel area is made from two mouldings, an inner panel which provides the interface between the outer case, switches and LCD display, and a transparent hinged cover plate to protect the controls from accidental operation and/or damage. The moulded carry handle provides an ergonomic grip to transport the unit.

Internally the construction is made up of a number of two main chassis compartments:

- The fuel cell compartment: a sealed container with from 2 to 8 fuel cell modules and associated fans.
- The electrics compartment: a mounting for all the electrical control components providing support for the incoming and outgoing connections and controls. This represents a constant design element for all the various power size options.

The two compartments join together internally to form a rigid structure, and that structure is then secured to the outer metal shell. This arrangement enables pre-assembled fuel cell and electronics modules to be tested separately prior to final assembly in the outer case parts.

The design of the HYPER system, based on a modular fuel cell, was always intended to provide maximum flexibility, enabling ready scaling both down to 20 W_e and up to >200 W_e. As a result, it is anticipated that the cost of low powered HYPER systems (<100 W_e) would be proportionately less, not only because fewer modules would be employed, but also because BoP and housing requirements would be simplified. The *beta* housing study confirmed this with an estimate for the housing part costs of a 40-60 W_e system (two to four modules) at about 15% less than for the 100 W_e system, and tooling costs at just 25% (on the assumption that the housing would be about one third of the volume).

3.5 100 W_e Field trials

Two field trial applications were undertaken for the HYPER 100 W_e system, using the *alpha* 2 prototypes.

1. Field lighting for emergency services (at PaxiTech's facilities)
2. Field battery charger for military and civilian use (at AGI's facilities).

These aimed to prove the performance of the system in the field, and demonstrate the flexibility of the 'platform' with the ability to serve a variety of applications and work with multiple hydrogen storage systems.

In line with the market identification and validation work described above, the applications represent two of the priority early markets (emergency services and portable battery charger for tools and equipment), and as such serve as concrete stepping stones towards commercialisation. Since it was not possible to complete the trials with independent end users, the duty cycles were designed to simulate use of each application as realistically as possible.

The two HYPER *alpha* systems used in the trials were equivalent in terms of specification and functionality,[7] but demonstrated with different demand profiles and fuelling modules. The final specifications are shown in Table 3.

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[7] There were very slight differences in specification between the two *alpha* HYPER systems, with one containing six FC modules, and the other eight modules.

Fuel cell system		
Voltage output	Nominal 12V DC	
Power output	60 - 80 W (nominal, continuous)	
	100 W (peak)	
Current output	5 - 8 amp	
	10 amp (max)	
FC system weight	310g per 20 W module = 1.86kg	
FC system dimensions	454 x 324 x 171 mm	
FC efficiency	50%	
Operating temperature range	-10°C to 40°C	
Gaseous storage	**300 bar compressed**	**700 bar compressed**
Weight	3.8kg	5.1kg
Volume	4.7l	2l
Gross energy content	3262 Wh	2643 Wh
Dimensions (with pressure regulator)	(h) 565 x (d) 150 mm	(h) 575 (d) 116
H_2 purity	99.999%	99.999%
Max H_2 flow rate	n/a	3-4 l/min
Outlet pressure (bar)	4.5	2 to 10 adjustable
Solid state storage	**For 100 W_e applications**	**For 500 W_e UAV**
Weight	7.7kg	1.3kg
Volume	2.36 l	0.45 l
Hydrogen capacity	40 g	10 g
Gross energy content	1347 Wh	332 Wh
Max H_2 flow rate	1.2 l/min	1.2 l/min

Table 3: HYPER 100 W_e system specification

Principle objectives for these field trials were as follows:

- *Proof of concept*: validation that the integrated product can perform in line with the application requirements, and with general expectations of overall technology
- *Technical performance data*: generation of key operational performance data to validate performance targets and inform future product development and costings
- *Ease of use*: to gain an understanding of remaining improvements required to produce a market-ready system
- *Partnership development*: to demonstrate that the Consortium Partners can work together in an effective and cooperative manner
- *Define the product package:* to gain insights into requirements for logistical support and provision of an integrated package to the end user.

3.5.1 Methodology

Testing took place at PaxiTech's facility (Grenoble) between July 21st and July 30th. Although the system was therefore located indoors, it was subjected to both fluctuations in and extremes of temperature and humidity.

The system was connected twice a day for three hours to a lighting balloon (Figure 16). The system was fuelled by the Luxfer 4.7 litre, 300 bar compressed gas cylinders.

Figure 16: View of the fuel cell system powering a lighting balloon

Testing took place at Airbus Group Innovations (Ottobrunn) between August 4th and 26th. The system was installed in a ventilated container (Figure 17) that mimicked the conditions that can be found at a typical field camp.

Figure 17: Ventilated container containing HYPER system

The system was set up to charge a field battery for 4 hours per day (after which the battery was disconnected and discharged), and used to continuously power a Toughbook computer, which also stored data from an automatic data logger. Three types of fuel module were used:

- Luxfer 300 bar composite cylinders, with valve and regulator from VTI
- Dynetek 700 bar cylinders, with valve and regulator from GHR
- McPhy low temperature solid state storage tank.

In both experimental set ups, fuel cell voltage, battery voltage, fuel cell current output and environmental conditions were measured either manually (every 15 minutes), or automatically via a data logger.

The Hyper *alpha 2* prototypes consisted of a hybrid system comprising a pack of six or eight fuel cell modules and a battery (see Figure 18).

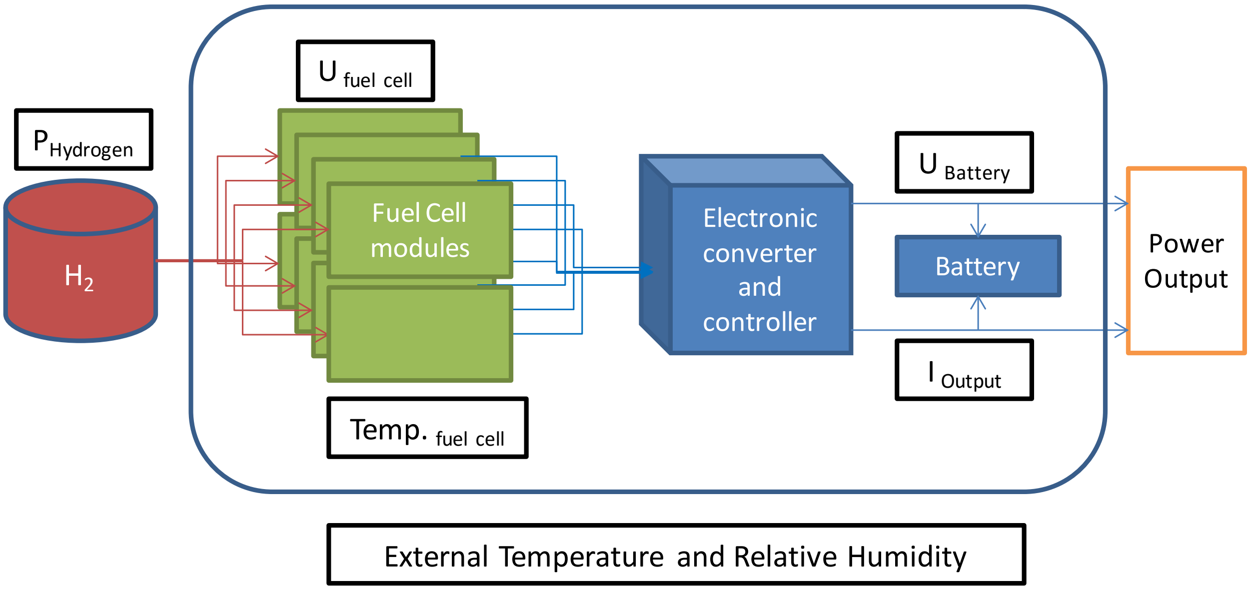

Figure 18: Fuel cell system architecture

3.5.2 *Results and conclusions*

The HYPER system was used successfully to power both installations at both sites, and this confirmed the suitability of the system in terms of power production, simplicity and design concept for these types of applications.

At PaxiTech, the HYPER system provided continuous power to the lighting balloon (maximum demand 60 W) for all 16, 3-hour experimental periods. At AGI, the system worked well during the second day of testing, with stable behaviour and the delivery of the nominal power required for the battery charger and Toughbook computer (60 W).

The relationship between the fuel cell and battery (i.e. the hybrid design) was shown to work effectively in both systems, with the battery providing energy only when the fuel cell voltage dipped below about 20 V (expected nominal voltage for the FC was 24 V).

However, the results from both field trials also revealed a number of issues that need resolving, in particular around response to temperature and humidity, system efficiency, and hydrogen leakage.

Temperature and humidity

Air-breathing PEM fuel cells, by their nature, respond to changes in environmental temperature and humidity. Environmental temperatures during the two test periods were high: typically between 30 °C and 36 °C, and fluctuated significantly (by more than 10 °C on many days). Humidity, on the other hand was typically between 30% and 45% and reached as low as 22%.

During both sets of trials, fuel cell performance (voltage) was closely tied to environmental conditions, dropping with increasing temperature and decreasing humidity. However, the performance generally recovered quickly as conditions improved, showing rapid recovery of the MEA after drying out. See for example, Figure 19 which shows the influence of surrounding temperature on the performance/voltage of the fuel cell during the first 4 days of testing at PaxiTech.

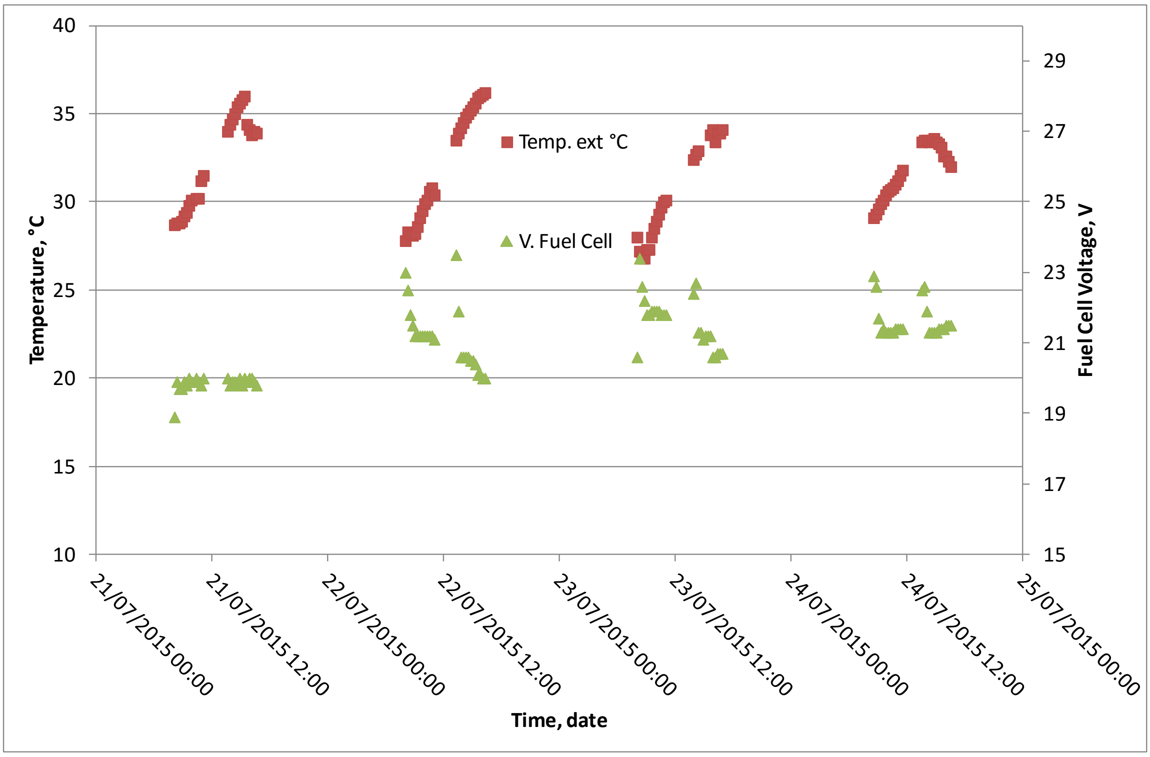

Figure 19: Evolution of temperature and the fuel cell performance vs. time, during the first four days of the trial

Unfortunately, displacement of a thermocouple caused a dramatic temperature increase within the system at AGI, which is believed to have damaged two fuel cell modules. This prevented the second week of testing from taking place and impacted negatively on the results during the first week.

Although small responses in behaviour of the HYPER fuel cell system with environmental conditions is to be expected, improvement in the thermal management of the system is required. This is anticipated to be readily achieved by changing the nature of the material covering the FC cathodes. PaxiTech have already experimented with a thinning the covering, but although light and strong, the original material acts as an insulator, creating problems with heat dissipation. Tests are now underway at PaxiTech to evaluate new plastics loaded with glass fibres. These have the potential both to improve heat dissipation and to decrease module weight still further.

Balance of plant efficiency

Overall system efficiency is a product of the fuel cell, system (balance of plant, BoP) and hydrogen efficiencies. Fuel cell efficiency can be obtained from voltage outputs. BoP efficiencies can be estimated by comparing the polarization and power curves obtained with the fuel cell modules on the test bench before integrating them into the system, with the actual power output of the fuel cell in the system. Hydrogen consumption can be back-calculated and plotted as a function of time, using the measurement of the output current and the estimated efficiency of the balance of plant. Table 4 compares obtained values with expected values.

	Expected (%)	**Obtained (%)**
Fuel cell	55	44-45 (at 0+/-0.5V)
Balance of plant	90	61
Hydrogen	100	40-65
Overall	50	13-24

Table 4: Expected versus actual efficiencies

Poor BoP efficiency is believed to be the result of the following issues:

- Relatively high parasitic consumption from the three cooling fans, the two electric valves, the screen, and the switches
- Use of an ‘off-the-shelf’ (inefficient) development DC/DC converter
- An increase in contact resistance with ageing of the FC module.

Improvement to the thermal management, described above (primarily via a new cover material), would have a correspondingly positive effect on BoP efficiency by reducing the cooling requirements (fans). Increased rigidity of the cover materials would also help to prevent the increase in contact resistance over time. Lastly, a bespoke controller and smaller/more efficient DC/DC converter, designed specifically for the HYPER system, is expected to provide significant efficiency improvements.

Hydrogen leakage

Hydrogen consumption at both trial sites was significantly higher than expected, and at AGI, this led to a considerable reduction in the number of hours that the trial was able to run. In addition to the high parasitic loads described above, excess consumption is believed to be associated with leakage from three potential areas:

- Leakage around the hose connecting the regulator to the FC housing.
- The high number of gas connectors between the pressure regulator and the FC module (including numerous 3 way T-junctions on the inlet and outlet manifolds), as well as 2 way electric valves and two manual valves.
- Gas tightness of the FC module itself.

The next iteration of the *beta* design will therefore include a bespoke manifold design that reduces the number of H_2 connectors required, as well as incorporating improvements to the gas tightness of the module (for example via fine-tuning the size of the O-ring or the thickness of the membrane) and the connecting hose from the cylinder regulator to the fuel cell.

3.5.3 Fuel options

Three different fuel options were tested at AGI: 300 and 700 bar compressed gas cylinders and McPhy’s solid state storage tank. All modules were successfully attached to the system, but H_2 leakages and eventually damage to the FC itself (due to internal temperature increases, described above), meant that the different options could not be fully tested as originally planned. Key insights are as follows:

- The 300 bar cylinder was readily filled, but some issues were encountered with leakages from the hose used to connect the regulator with the fuel cell.
- Hydrogen was used up from the 700 bar cylinder much more quickly than expected. Although it is likely that the same leakages were occurring as with the 300 bar cylinder, it should be noted that the 700 bar cylinder was not equipped with a manometer, so it was not possible to verify that the cylinder was completely full at the start of the experiment.

Nevertheless, the flexibility of the system design has been demonstrated, with a range of hydrogen storage options used, although more testing is clearly needed to evaluate the 700 bar and solid state tanks fully.

The project has also demonstrated that high pressure gaseous storage is a viable alternative to solid state storage at a gravimetric energy density of >2.5 wt%. The 300 bar composite cylinders appear to offer the most attractive gaseous storage option currently available. The energy density is higher than for 700 bar cylinders due to lighter cylinder construction and use of simpler, lightweight valves/regulator assemblies. The number of suppliers of 300 bar cylinders is also increasing and there may be the potential to use ultra-lightweight titanium regulators.

3.5.4 Conclusions and future work

Early (*alpha*) 100 W_e prototypes of the 'HYPER System' have been developed and demonstrated in two specific applications: as a power pack for remote power (specifically emergency lighting) and as a field battery charger.

The next (*beta*) prototype design is underway. This will incorporate a number of technical improvements around thermal management and system efficiency, as well as safety features required for CE marking, and a bespoke housing, designed for cost effective manufacture (with proportionate cost reduction at power outputs <100 W_e).

Call targets have been met to a significant degree for the 100 W_e system (Table 5).

Call target	100 W_e system	Comment
Weight and volume <35 kg/kW and 50 l/kW	100 W_e system, 85 kg/kW and 250 l/kW	Higher than anticipated weight and volume are largely due to balance of plant (BoP) requirements, use of off-the-shelf casing, need to incorporate fans to meet safety regulations and spacing of FC modules to ensure cooling by natural convection. However, call weight and volume targets are expected to be met at lower powers where BoP and need for cooling reduced (<40 W).
System efficiency >30%	FC efficiency >50% achieved	FC efficiency >50 % achieved with individual modules and system efficiency >50% is expected for the *beta* prototypes
Lifetime: 1000h, 100 start stop cycles	20 W_e module: 1000 h and >360 cycles	Targets for lifetime and start stop cycles have been for the 20 W_e FC module. The 100 W_e module has been tested for 600 h in the laboratory and for 90 hours with 30 cycles during demonstration in specific applications.
Final system cost <5,000 €/kW	Cost forecasts are confidential but are not expected to meet the target	However, cost per kW rises significantly for small FC systems. Composed of compact 20 W_e modules with limited BoP, the HYPER system is expected to be extremely competitive at small scales (<100 W).
Operating temp -20 °C to 60 °C	-20 °C to 40 °C	The FC has been shown to work at -20 °C. 40 °C is a maximum operating temperature, and temperatures of 41 °C trigger an automatic cooling system in the 100 W_e system.

Table 5: HYPER 100 W_e results in relation to call targets

Many of the required design improvements are already being incorporated into the next iteration of the *beta* design which will combine:

- The cost effective and user friendly industrial design of the *beta* prototype housing;
- Design modifications required to achieve CE marking, including the incorporation of pressure relief valves, hydrogen detection and adequate case ventilation, and a re-design of control circuitry, as well as the necessary documentation and guidance needed to demonstrate the system with independent end users;

With

- Technical improvements to solve the remaining issues identified during system integration and demonstration, most importantly heat dissipation, system efficiency and H_2 supply.

The next steps towards commercialisation have been clearly identified in the HYPER Commercialisation Strategy (see Section 4).

3.6 500 W_e field trials

The original HYPER proposal included development of a 500 W_e system for use as a range extender for a mini UAV. However, for a variety of reasons, development was not concluded during the lifetime of the project.

- Although results from the ammonia-borane based solid state storage material are extremely promising, research into this material started too late in the project to be able to develop a prototype advanced solid state storage tank.
- A lightweight (2 kg) low temperature (LT) solid state storage tank was delivered to AGI in June 2015 but this was able to maintain the required flow to power 500 W_e (4.64 Nl/min) for only 10 minutes.
- System integration at the 100 W_e scale was more challenging that anticipated, in particular relating to the complexity of the control electronics as well as electrical balancing and thermal control of the fuel cells. Delays that had occurred with the new design of the fuel cell module were exacerbated by this and it became clear that it would not be possible to supply a 500 W_e fuel cell system in time for integration into the UAV.
- As an alternative, it was suggested that the fuel cell and storage options could be used within a realistic flight simulation (the ‘iron bird’), which would mimic the power requirements of the UAV (as determined within the systems engineering activity).
- However, continued development of the working 100 W_e system prototypes revealed that the projected weight and volume of the 500 W_e fuel cell system was likely to be considerably higher than expected (primarily due to requirements for balance of plant and thermal cooling).
- In addition, it became clear that technical issues with system integration, although solved at the 100 W_e scale, would not be resolved at the 500 W_e scale within the timeframe of the project. It was therefore no longer possible to use a HYPER 500 W_e fuel cell for the laboratory simulation.
- The possibility of using a smaller (but still scaled up fuel cell) (e.g. 200 W_e) and/or trialling the 500 W_e storage tank with an alternative fuel cell were also discussed. However, from the perspective of AGI as a potential end user of the HYPER system as a UAV range extender it became evident that running such an Iron Bird test would not generate sufficient data of relevance for the proposed application at this time. Therefore, it was agreed that there was no merit in investing resources in doing so.
- Finally, it was also agreed that the 500 W_e LT solid state tank could be tested equally effectively with the 100 W_e system.

The decision was therefore taken by the Consortium (July 2015) to stop further work on the 500 W_e system and to concentrate the remaining time and resources on the 100 W_e system field tests.

4 Impact

4.1 Overview

As anticipated in the DOW, the HYPER project has achieved wide ranging and positive impacts on the overall commercial development of the hydrogen and fuel cell sector. Directly, as a result of the nature of the work undertaken, the project demonstrated significant impact in terms of science and technology by catalysing and facilitating related and follow-on R&D, and also in terms of environment and climate change by accelerating the market translation of the HYPER fuel cell system.

Throughout the HYPER project, the Consortium has actively engaged with academia, the market and relevant stakeholders to both share experiences and the project outcomes, but also to validate the market opportunity and inform the product development pathways in support of subsequent commercialisation. This has resulted in the establishment of new academic, technical and commercial relationships that will contribute to the continued development of the European fuel cell and hydrogen supply chain. It has also provided opportunities for a wide audience to access information and evidence relating to the performance of the HYPER system components.

Most importantly, HYPER has sought to overcome the technical and economic barriers that have limited the market uptake of low power fuel cell systems. The Consortium has always been committed to taking the next steps towards subsequent commercialisation via early routes to market developed during the course of the project. This is described in more detail below.

4.2 Impacts with respect to early markets

A key objective of the HYPER project has been to develop an effective and appropriate commercialisation strategy and plan to facilitate the market diffusion of the HYPER system after the completion of the project. The HYPER Commercialisation Strategy therefore includes plans for the future market translation of HYPER system, as appropriate for the individual contributory elements as follows:

1. Advanced solid state hydrogen storage materials developed and tested – led by GU
2. Solid state storage system using current ‘best in class’ low temperature hydrogen storage materials – led by McPhy
3. High pressure gaseous storage tanks procured from commercial third parties for the purposes of this project and adapted to meet the requirements of the HYPER system – led by Orion
4. 20 W_e PEM fuel cell modules and sub systems – developed and tested by PaxiTech
5. Integrated 100 W_e fuel cell system with hydrogen storage – developed and tested by PaxiTech and AGI.

The Consortium has worked effectively together on this project for the last three years and the individual Partners now wish to pursue the further commercial development of various elements of the HYPER system listed above in line with an appropriate ‘go to market’ strategy.

4.2.1 Priority markets

The HYPER project generated insights and evidence to inform the identification of suitable and attractive near terms markets for the 100 W_e unit and the future potential for a 500 W_e unit.

The screening process prioritised the seven applications, listed in Table 6 below, as representing the best near term commercial fit with the target HYPER 100 W_e System. The applications fall into two main segments: industrial applications and remote power.

Segment	Applications
Industrial	1. Small generator replacement 2. Portable battery charger for tools and equipment 3. Industrial lighting 4. Security cameras
Remote power	5. Remote Monitoring and Control 6. Emergency services 7. Outdoor leisure

Table 6: Short list of best fit applications for the HYPER System

Many of the potential target applications are converging, and new markets are continually emerging. Technical advancements in low power appliances, e.g. LED lighting and wireless communications, are actively opening up new market opportunities in a much broader range of low power applications at <100 W. For example, one market commentator has forecast that the emerging market for remote sensing systems based on renewable and alternative energy alone will grow to between 27,000 and 40,000 units per annum by 2020[8].

A key part of commercialisation is engagement with end users in order to ensure that anticipated demand for the product is real and to gain a clear understanding of the characteristics of the product that are most valued, be it performance, price, convenience, or environmental credentials. It also provides an essential understanding of the way in which customers expect / are able to purchase and use the system. This information was important in the development of a robust value proposition and appropriate business model within our commercialisation strategy.

A broad range of individuals were consulted, having been selected to provide a spectrum of views from across the priority market sectors. In particular, we were keen to ensure that we had insights from more than one respondent for each target market. We were also keen to engage with organisations that are based in, or operate in different parts of the world.

Without exception, there was significant interest in a potential low-power, grid independent power source. The scale of interest reflected the interviewees’ low level of satisfaction with their incumbent power solutions, and the perceived benefits of a future potential HYPER System. Several respondents had multiple potential applications of relevance to the HYPER System.

This market validation and testing exercise confirmed that all the short listed priority markets offer prospects for the commercialisation of a future HYPER System. Remote monitoring and control applications in both Europe and the rest of the world offer particularly attractive near-term market opportunities for the commercialisation of a HYPER System, which can offer a reliable low power (<20 W), grid-independent power source that can be left unattended for lengthy periods of time.

Fuel cells have the potential to challenge ICEs and batteries for provision of power in civilian UAVs (in particular if forecasts for sharp increases in specific power (kW/kg) to 2020 and beyond are realised), with the advantage that energy and power capability can be decoupled from each and operational range can be increased. As such, it was originally identified as a potentially attractive market for the HYPER system.

However, the commercial attractiveness of fuel cells for UAVs is strongly dependent on the specific application, dimensions/size and design of the system, the boundary conditions, and (re)fuelling infrastructure. Fuel cell systems are likely to fit most readily into the Mini UAV scale, and will compete best with batteries for longer missions and lower than average power demands.[9]

A few competitors are leading the way with FC miniaturisation (primarily Horizon Fuel Cells and EnergyOR), achieving very high energy densities of 400 – 650 Wh/kg), and representing the current

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[8] Navigant Research, Off Grid Power for Remote Sensing Applications, Feb, 2013.

[9] Fuel cells for UAV applications, Argumosa, M. P., Instituto Nacional de Tecnica Aerospacial, Spain, 2014.

benchmarks for these systems. Some advances are also being made in advanced (solid state) H_2 storage (Horizon Fuel Cells). None of these systems have yet been widely tested in commercial applications and, in practice, concerns remain over their reliability and lifetime performance[10].

4.2.2 Basis for competitive advantage

The HYPER System is looking to displace incumbent power generation technology in the majority of its target markets. Specifically these include gensets (petrol and diesel), batteries (lead acid and Li Ion), and hybridised systems (increasingly including solar and wind). Our market research has also shown that a number of potential clients in these markets have knowledge of fuel cells systems, have trialled them, or indeed currently deploy them. The HYPER System will therefore increasingly compete with other fuel cell systems.

On-going improvements in all of these technologies means that the competitive performance targets for the HYPER System are continually evolving.

Our market research has shown significant demand for low power (<40 W) long run-time power solutions, offering a significant commercial opportunity for a HYPER system. This has been corroborated by subsequent discussions with potential commercialisation partners and trial customers for the HYPER fuel cell system.

Running off compressed hydrogen, the HYPER system offers specific advantages in terms of reliability and operating temperature range over existing methanol-based fuel cell solutions, and has the potential to satisfy a niche market at <40 W scale that is not currently served by other hydrogen fuel cell solutions. Specifically the 20 W_e basic module has inherent weight advantages relating to its design for mass manufacture (e.g. the planned roll-to-roll production of MEAs at PaxiTech) and for operation with minimum balance of plant that offer the potential for cost advantages relative to other fuel cell systems.

Fuel cell solutions are also of potential relevance to lightweight portable (e.g. hand tools) or aerospace (e.g. UAV) applications, although the advantages of fuel cells relative to incumbent and emerging battery technologies is less clear cut. Fuel cell solutions, including the HYPER system, are not currently significantly more attractive on a volumetric or weight density basis than incumbent battery only solutions, and some are considered unreliable.

In particular the HYPER system, in common with other fuel cell systems, does not yet achieve the energy densities of greater than 400Wh/kg needed for UAV deployment.

The hydrogen storage technology (e.g. compressed hydrogen or solid state hydrogen) and associated fuel logistics is an important factor in this equation. The forecast energy density of emergent solid state hydrogen storage solutions, including those under investigation within the HYPER project, are predicted to deliver a step change improvement over incumbent battery power solutions as well as compressed gas-based fuel cell solutions.

It became evident during the course of the HYPER project that, while solid state technologies under investigation have the potential to offer significant advances in hydrogen storage densities, these would not be realised during the course of the project. Once these materials are proven, this will open up future opportunities for fuel cells in both portable and UAV type applications.

4.3 Next Steps

4.3.1 Solid state hydrogen storage

The results from development and testing of the AB composite are very promising in terms of gravimetric density, desorption onset temperature and hydrogen purity. The material is considered to have the potential to form a one-shot solid state storage system that will readily compete with the state of the art (pre-commercial) advanced storage in terms of weight and volume, as well as reliability and safety, and be significantly superior in performance to existing, off-the-shelf metal hydride solid H_2

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[10] Active industry player, pers. comm.

storage. This would represent a step change improvement over incumbent battery power solutions as well as compressed gas-based fuel cell solutions, and would open up weight-sensitive applications, including lightweight portable (e.g. hand tools) or motive (e.g. UAV) applications to the HYPER system. Nevertheless more work needs to be done to optimise the structure of the carbon host and the ratio of AB to carbon, and to investigate options for efficient scale up.

A particularly important factor in successful commercialisation will be reduction in the cost of raw materials. Although these are currently extremely high, theoretical work suggests that the potential exists for sufficient cost reduction at mass production scale to enable the material to compete with compressed H_2 as a fuel. This needs to be explored further, alongside a clearer understanding of where patents may exist in this field. Further research on the potential for regeneration (including recycling of expensive reactants) may also reveal additional opportunities for cost reduction.

Glasgow University are now actively seeking appropriate funding and commercial partners to take this forward.

4.3.2 Low temperature solid state storage system

The low temperature hydride tanks that were designed and manufactured during the project were first prototypes, with the goal of demonstrating technical feasibility. Results from the laboratory testing are promising, in particular if improved density can be transferred from McPhy's closely related hydride. However, a much longer period of field testing is needed before the product will be market ready.

Overall, with some improvement in performance, the tanks are anticipated to be competitive for low power (<50 W) stationary applications, such as off grid monitoring devices and small LED lighting solutions, in particular where low weight is not a priority. The tank is expected to be comparable to existing state of the art solutions, with a gravimetric density >1 wt%, and weight of 4-5 kg for 500 NL. Although the gravimetric density of these early solid state storage tanks is not yet superior to compressed gas cylinders, they are believed to have an important transitionary role in the deployment of fuel cells + solid state storage and offer alternative options to the market, in terms of re-fuelling and fuel handling.

4.3.3 High pressure gaseous storage technology

300 bar composite cylinders appear to offer the most attractive gaseous storage option currently available. The energy density is higher than for 700 bar cylinders due to lighter cylinder construction and use of simpler, lightweight valves/regulator assemblies. The number of suppliers of 300 bar cylinders is increasing and there may be the potential to use ultra-lightweight titanium regulators. Furthermore, filling stations for 300 bar cylinders are more widely available than for 700 bar filling, and there are fewer concerns about transportation and handling.

Prices for cylinders and associated valves and regulators depend strongly on purchase quantities. Current market prices could reduce as more suppliers enter the market.

The HYPER project has highlighted the barriers to the commercialisation presented by lack of widespread adoption of standard connections for portable hydrogen cylinders and lack of interest from larger gas suppliers in filling small numbers of tanks for demonstration purposes. There would be benefit in producing guidelines to support potential manufacturers, users such as filling stations and end-users of valves and regulators.

4.3.4 100 W_e HYPER fuel cell system

The 20 W_e basic fuel cell modules developed in this project have proven to perform well and to be on track to be competitive in terms of performance and cost (in particular at power outputs <100 W). Whilst some issues were identified during the field trials, these primarily related to the module cover material and to system integration and are expected to be addressed during the delivery of the *beta* units, alongside incorporation of the recommendations from the CE marking process and the industrial design study.

In the near term PaxiTech will seek to exploit emerging opportunities for early market deployment of stand-alone fuel cells systems (specifically in the power range of <40 W_e) to prove the value of their product and attract appropriate strategic partners to realise future volume deployment. The focus on low power applications will not only meet the identified niche market demand, but will also capitalise on the system's modularity, and the resultant ability to offer reduced cost and increased simplicity (BoP) with decreasing numbers of 20 W_e modules.

In this regard, PaxiTech is progressing discussions with a number of potential partner organisations for the commercialisation of its technology. These include anchor customers, systems integrators, industrial gas suppliers, and synergistic technology companies.

Specifically, introductions and facilitated discussions have been held with a number of UK-based organisations that are interested in trialling fuel cells systems and partnering in their commercialisation.

The next step is to finalise the *beta* design and showcase the fuel cell system in real-world installations in order to gather insights and knowledge needed to develop a market ready product or series of products.This process will also be used as a means of developing the necessary relationships needed in order to take the technology to market.

4.3.5 500 W_e HYPER fuel cell system

The original HYPER proposal included development of a 500 W_e system for use as a range extender for a mini UAV. However, as discussed, for a variety of reasons development was not concluded during the lifetime of the project.

Nevertheless, AGI believes that battery/fuel cell hybridisation is an essential route forward for improved energy provision for UAVs and will continue to investigate FC power for its UAV portfolio, including the mini UAVs (~500 W_e) and the larger 150 kg 'vertical take-off and landing' VTOL UAV. However, the company will be looking for a system that can improve on the current market leaders and HYPER is not on a pathway to reach equivalent power densities at present. This would require a change of design incompatible with exploitation of the near term market opportunity in low powered applications and is therefore not an immediate priority for PaxiTech.

H_2 storage continues to be a major barrier to the use of fuel cells in flight applications. Experience with compressed gas confirms that the handling requirements and energy densities remain less than optimal and there is continued interest in developing a high gravimetric density, low pressure advanced solid state storage system. In addition to the UAV applications, this could be applied to use with a fuel cell system to power civilian aircraft galleys. Current turbine efficiencies (~40%) and electrical heating inefficiencies mean that there is a desire to take galleys out of the primary aircraft electrical circuits.

AGI are therefore interested in future opportunities to continue development of advanced solid-state storage (>4 wt%). A number of options are being explored to collaborate on further development of the AB composite material at Glasgow University.

4.4 Summary conclusions

The HYPER project has realised considerable progress in advancing the state of technical development for low power hydrogen fuel cell systems, and sub elements of system are now ready for pre commercial demonstration with potential early adopters. In addition, strong evidence of market demand has been established, as has the modular flexibility of the HYPER system to address a range of low power applications. In this process, the profile of fuel cell solutions has been raised within the target markets.

Significant contribution has also been made to the scientific understanding of potential solid state storage materials. A great many materials were synthesised and tested during the project, providing insights into the behaviour of nanostructured hydrides (and resulting in three peer-reviewed publications) and culminating in development of a potentially step-changing advanced solid state H_2 storage material (nanoconfined ammonia borane within a carbon matrix).

However, the development of the HYPER system as a fully integrated product including interchangeable, and 'best in class' solid state hydrogen storage has not been achieved within the timing of the current project. In addition, several of the specific target specifications have not been met, most notably volumetric and gravimetric densities of the integrated system.

Nevertheless, analysis of target markets and competing solutions has defined a basis for competitive advantage for the HYPER system, in particular in early markets at a scale of <40 W based on compressed hydrogen (currently at 300 bar) in specific remote power and industrial applications.

Specifically the 20 W_e module has inherent weight advantages relating to its design for mass manufacture (e.g. the planned roll-to-roll production of MEAs at PaxiTech) and for operation with minimum balance of plant that offers the potential for cost advantages relative to other fuel cell systems. Third party organisations have expressed an interesting in trialling the *beta* system immediately after the conclusion of this project.

There is also active interest amongst the relevant partners to continue development of the advanced AB storage material and associated tanks, as well as the low temperature storage tanks. Longer term, the development of high density solid state hydrogen storage materials will open up potential for wider market opportunities at larger scale – including UAVs, a key priority for AGI, whilst the low temperature solid state tanks have an important transitionary role in the deployment of fuel cells + solid state storage and offer alternative options to the market, in terms of re-fuelling and fuel handling.

However, some key challenges remain in the early commercialisation of the HYPER system and its component parts:

1. **Cost reduction and validation** – to get each element of the system to a cost competitive position relative to incumbent solutions and also to demonstrate cost advantage based on whole life costing.
2. **Proof of performance** – specifically via 'real world' field deployment at sufficient volume to provide early adopters with confidence in the product and to further refine the business model.
3. **Access to hydrogen supply, infrastructure and know-how,** specifically relating to compressed gas in the short to medium term.
4. Provision of **field support, product certification and warranties** for early adopters.

Currently, not all of these skills and resources are available within the Consortium and identification of appropriate development and strategic partners to support commercialisation is underway.

Future investment in the commercialisation of the various component parts is now the responsibility of the individual partners, rather than the Consortium as a whole. Each partner has its own strategic objectives and commercial imperatives that influence their decision making. Discussions with each of the Partners, and then together as a Consortium, has defined aspirations for future involvement in the commercialisation of the project outputs and these have been documented with the HYPER Commercialisation Strategy. Various bi/multilateral collaborations have already been instigated to progress the next stages of product development and commercialisation.

In summary, it is believed that, to a large extent, the high level aims of the FCH JU call have been met, with proof of concept of application specific HYPER systems and manufacturing cost considerations embedded within the development of each of the component parts. The project has also highlighted key factors that present potential barriers to the commercialisation of low power hydrogen fuel cell systems across Europe and which are not within the direct control of the Consortium Partners. These have been presented within the 'Recommendations for an appropriate RCS framework', and include:

- A lack of widespread adoption of standard connections for portable hydrogen cylinders. There would be benefit in the availability of guidelines to support potential manufacturers, users such as filling stations and end-users of valves and regulators.
- Lack of clear guidance relating to the requirements for risk assessments and product certification, particularly for pre commercial demonstration.

4.5 Dissemination of project results

At the start of the project, a press release for the project was prepared and distributed via partner websites. In line with the project proposal, the consortium then prepared a Communications Plan. This included development of the public facing website (www.hyperportablepower.com) and project dissemination material (such as flyers, postcards) as well as presentations and posters at a variety of academic and industry conferences, organization of two workshops with other FCH JU projects, and a final dissemination event.

These are listed in Table 7 below. It can be seen that HYPER project partners have been active in attending a wide range of events, and in ensuring that the project itself and the role of the FCH JU have been well publicized to different target audiences (academia, industrial end users and supply chain in particular).

The materials research has been disseminated via a number of high profile academic conferences. The research was well received at all events and generated considerable interest. Key impacts include:

- Discussions with several academic groups in Saudi Arabia, Qatar and UAE re, collaboration towards developing new hydorgen storage systems and links to photoelectrochemical hydrogen generation.
- Discussions with Boeing comparing experiences and best practices with respect to on board solid-state hydrogen storage for autonomous flight applications.
- Initiating a collaboration with Element Energy, a UK SME for a proposed future project in small scale hydrogen storage systems for low power, portable applications.
- Specific discussion with a researcher from University of Bath on potential improvements to the $Mg(OH)_2$-MgH_2 system.
- Specific discussion around the MgH_2 core shell (matrix) including suggestions for a neutron experiment.
- New contact with researcher from University of Valladolid studying enhanced properties of ammonia borane nanoparticles confined in microparticles of silica gel. Future exchange of information will be useful in the next stages of HYPER AB research.
- Discussions with Dr Marc Stanton, Commercial/Marketing Director, Clean Power Solutions Ltd regarding potential collaboration with Glasgow University.

Attendance at more industry focused events (e.g. All Energy 2015, Glasgow UK) was also very important, and used to validate interest in the system for our priority market applications as well as to make introductions to potential early adopters and end users interested in supporting prototype demonstrations.

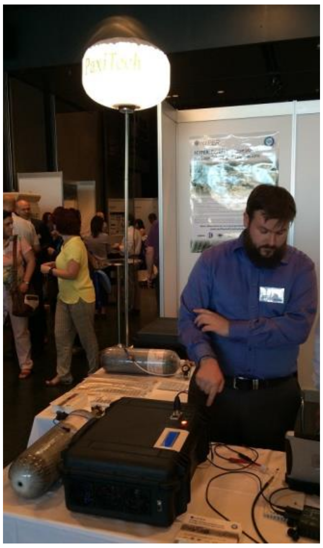
Of particular interest were the two workshops:

- FCH JU Projects on Hydrogen Storage: Joint Workshop with SH2S, EDEN and BOR4STORE. This was a large workshop between four projects working on solid state hydrogen storage and incorporated a lively poster session for students and four breakout discussions on challenges associated with each key part of the value chain (materials, tank, integration, end users).
- Critical aspects in planning for field trials, was a smaller workshop that aimed to share learning associated with early technology demonstration in the FC&H sector. Invited experts and projects at different stages of technology development discussed the pitfalls associated with field trials and ways in which planning for demonstration could be improved.

Finally, the 5th European Fuel Cell Forum Annual Conference and Exhibition, held in Lucerne, June 30th to July 3rd was chosen as the location for the HYPER ‘final event’. This offered a large audience from within the fuel cell sector, not only academic researchers, but also industry specialists and policy makers.

The project demonstrated two working 100 W_e alpha prototype systems at the exhibition, used to power a 60 W outdoor balloon light (for events etc.) and a battery charger for a portable computer. Fuel was provided by lightweight 300 bar composite H_2 cylinders (Figure 20). An animation of the Beta prototype was also displayed (Figure 15) above.

Figure 20: HYPER system at the EFCF exhibition stand



During a drinks reception to showcase project achievements, Noel Botha (Orion Innovations) introduced the project within the context of the developing fuel cell market and in particular in the light of strongly growing interest in portable fuel cells for small scale applications, such as remote monitoring and outdoor temporary lighting. Renaut Mosdale demonstrated the system and discussed the development of the fuel cell itself. Duncan Gregory spoke about the work done within the project on advanced solid state storage, and the recent highly promising results we have obtained with an ammonia borane-based composite. Finally Alexander Ohnesorge explained the interest that our corporate partner Airbus has in developing fuel cell systems at a range of scales, and the significant learnings that have been provided by the project.

The HYPER stand was also selected as part of the ‘VIP walk round’, during the second day of the conference.

HYPER also gave two oral presentations at the formal conference: James Hanlon, 'Solid State Approaches for Portable H_2 Applications' and Renaut Mosdale, 'FCH JU Hyper – results from the 100 W_e Hyper system field testing and risk assessment analysis'.

The prototypes attracted an excellent level of interest over the four days of the exhibition, with specific contacts being made with Swiss, Spanish, Croatian and Rumanian companies to directly use, integrate, or commercially distribute this type of products for construction applications (generators in buildings) or mobile applications (generators in camping cars or sailing boats). These companies or organizations have all requested updates about the HYPER system.

These types of exhibitions (Cherbourg – France, Luzern – Switzerland) proved very useful in demonstrating the new technology, and informing potential users about the readiness of such generators. As an example, the conference in Cherbourg attracted many local political decision makers from all over France who expressed particular interested in hydrogen energy, including low power generators such as the HYPER system. Most of the applications they discussed involved safety crews (firemen) or power for small scale solutions in remote, off grid locations.

Work undertaken in development of the HYPER Commercialisation Strategy was also particularly effective in fostering new collaborations and potential commercialization partners. This included a ‘market validation exercise’ in which individuals from more than twenty separate organisations were consulted on their interest in and requirements for fuel cell and hydrogen powered applications (20-500 W_e range); and identification strategic partners to provide opportunities for demonstration and/or resources not currently available to Consortium partners. Several individuals expressed interest in hearing more about the system as it develops, and a number requested one to one meetings to explore options for future collaboration.

Lastly, three peer reviewed publications resulting from the materials research carried out for HYPER have been published within the project lifetime and a fourth on the ammonia borane solid state storage concept is in preparation. In addition, two ‘non-peer’ reviewed publications will be included within the Proceedings of the 5th European PEFC and H_2 Forum (Table 8).

Date	Type of activity	Event Title	Presenter	Presentation Title	Place
Nov 2012	Press release	HYPER, Integrated hydrogen power packs for portable and other autonomous applications	N/A	A Consortium of European Partners has launched a three year project to develop unique, flexible and fully integrated fuel cell and storage systems for portable power applications	Partner websites
Jan 2013	Website	HYPER Integrated hydrogen power packs	N/A	www.hyperportablepower.com	N/A
Mar 2013	Flyers	HYPER Integrated hydrogen power packs	N/A		N/A
Mar 2013	Oral Presentation	Hydrogen and Storage, 9th International Conference	Geoffroy Ville, McPhy	HYPER, Integrated hydrogen power packs for portable and other autonomous applications	NEC, Birmingham
May 2013	Oral Presentation	E-MRS Spring Meeting	D.H. Gregory, Glasgow University	Tailoring nitride-based multi-anionic energy materials	Strasbourg
May 2013	Poster Presentation	2nd Adel International Workshop	Ismael Aso, McPhy	ADvanced ELectrolyser for Hydrogen Production with Renewable Energy Sources	Corsica
Jul 2013	Poster Presentation	4th European PEFC and H_2 Forum	Agata Godula-Jopek, AGI	HYPER Project: Integrated Hydrogen Power Packs for Portable and Other Autonomous Applications	Lucerne
Aug 2013	Networking with industry	SHFCA meeting	D.H. Gregory, Glasgow University	N/A	Strathclyde University
Oct 2013	Joint workshop	FCH JU Projects on hydrogen storage: joint workshop with SH2S, EDEN and BOR4STORE	J. Kauffmann, Orion Innovations	HYPER, Integrated hydrogen power packs for portable and other autonomous applications	
			R. Mosdale, PaxiTech	Portable fuel cell systems	
			N. Tapia Ruiz, Glasgow University	Candidate storage materials for portable hydrogen power packs	
			N. Tapia Ruiz, Glasgow University	Poster - HYPER project: potential solid-state materials to be used in the H_2 storage module	
			J. Mao, Glasgow University	Poster - Reversible hydrogen storage in the Na-O-H system	
			I. Aso, McPhy Energy	McPhy Energy: hydrogen storage solutions	
Dec 2013	Symposium	RSC Gulf Symposium Series ‘Materials and Chemistry for New Energy Technologies’	D.H. Gregory, Glasgow University	New Dimensions in Energy Materials	Masdar, UAE[11]
Feb 2014	Oral Presentation	SHFCA Members Meeting, ‘UAV Opportunities: Fuel Cells for Flight & Environmental Mapping’	D.H. Gregory, Glasgow University	Hydrogen Storage for UAVs; the HYPER project	Edinburgh

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[11] Presentation also given at King Saud University, Saudi Arabia and Qatar University, Qatar.

June 2014	Oral Presentation	European Technical School on Hydrogen and Fuel Cells 2014	L. Bravo Diaz, Glasgow/JRC	The MgH$_2$-Mg(OH)$_2$ system as a cheap, pioneering hydrogen store	Crete
Dec 2014	Oral presentation	Inorganic Seminar Series- School of Chemistry	J. M. Hanlon, Glasgow University	Modular Solid State Solutions for Portable H$_2$ Applications	University of Glasgow
Dec 2014	Oral presentation	Hydrogen & Fuel Cell SUPERGEN Researchers Conference	J. M. Hanlon, Glasgow University	Modular Solid State Solutions for Portable H$_2$ Applications	University of Birmingham
Dec 2014	Poster presentation	Hydrogen & Fuel Cell SUPERGEN Researchers Conference	L. Bravo Diaz, Glasgow/JRC	Thermodynamic and Kinetic Characterisation of Novel Solid State H$_2$ Solid State Materials for Portable Power Applications	University of Birmingham
Feb 2015	Workshop	Critical aspects in planning for field trials: joint workshop with FC Powered RBS, SUAV and H$_2$Trust	J. Kauffmann, Orion Innovations	Experiences from the HYPER project	Barcelona
			N. Botha, Orion Innovations	Facilitation of group discussions on specific issues highlighted by project presentations	
Feb 2015	Exhibition stand	FC Expo 2015	R. Mosdale, A. Ronez, PaxiTech	Demonstration of two *alpha* Hyper fuel cell prototypes powering a lighting balloon and battery charger	Tokyo
March 2015	Poster presentation	Hydrogen Days	A. Milewska, IEn	Numerical simulations for portable hydrogen applications	Prague
May 2015	Networking with end users and supply chain	All Energy 2015 Exhibition & Conference	J. Kauffmann, A. Cavey, Orion Innovations	N/A	Glasgow
July 2015	Poster presentation	1st Chemistry in Energy Conference organised by Energy Sector of the Royal Society of Chemistry.	L. Bravo Diaz, Glasgow/JRC	Nanostructures optimisation in novel solid-state H$_2$ storage materials for portable power applications	Heriot-Watt University, Edinburgh
June 2015	Exhibition stand	Hydrogène dans les Territoires	R. Mosdale, PaxiTech	Demonstration of two working *alpha* fuel cell systems.	Cherbourg, France
July 2015	Exhibition stand	5th European PEFC & H2 Forum	All partners	Demonstration of two working HYPER prototype systems with a lighting balloon and portable computer	Lucerne, Switzerland
	Oral presentation		J. M. Hanlon	Solid State Approaches for Portable H$_2$ Applications	
	Oral presentation		R. Mosdale	FCH JU HYPER – results from the 100 W$_e$ HYPER system field testing and risk assessment analysis	
Sept 2015[12]	Oral presentation	E-MRS Fall Meeting	L. Bravo Diaz, Glasgow/JRC	Novel solid state H$_2$ storage materials for portable power applications	Warsaw University of Technology, Pl
Sept 2015[11]	Oral Presentation	Scottish Hydrogen and Fuel Cell Association meeting	D. Gregory, Glasgow University	Innovation with Hydrogen and Fuel Cells	HW University, Edinburgh

Table 7: List of dissemination activities

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[12] These presentations were given just after the end of the project, and were not eligible costs. Nevertheless they were directly related to the HYPER project and are included for completeness.

No.	Title	Main author	Title of periodical or series	Number (Vol), date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers	Open access?
Peer reviewed										
1	Rapid surfactant-free synthesis of $Mg(OH)_2$ nanoplates and pseudomorphic dehydration to MgO	J. M. Hanlon	Crys.Eng.Comm	17, June 2015	Royal Society of Cambridge	Cambridge, UK	2015	5672-5679	DOI:10.1039/C5CE00595G	Yes
2	Revisiting the hydrogen storage behavior of the Na-O-H system	J. Mao	Materials	8, April 2015	MDPI	Basel, Switzerland	2015	2191-2203	DOI:10.3390/ma8052191	Yes
3	Recent advances in the use of sodium borohydride as a solid state hydrogen store	J. Mao	Energies	8, Jan 2015	MDPI	Basel, Switzerland	2015	430-453	DOI: 10.3390/en8010430	Yes
Non peer reviewed										
4	Solid-state approaches for portable H_2 applications	J. M. Hanlon	Proceedings of the 5th European PEFC and H_2 Forum*	July 2015	EFCF	Lucerne, Switzerland	2015	tbc	tbc	Yes
5	HYPER Results from the 100 W_e HYPER system field testing and risk assessment analysis	R. Mosdale	Proceedings of the 5th European PEFC and H_2 Forum*	July 2015	EFCF	Lucerne, Switzerland	2015	tbc	tbc	Yes

Table 8: List of publications

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