PROJECT FINAL REPORT

Grant Agreement number: **303418**

Project acronym: **PHAEDRUS**

Project title: **High Pressure Hydrogen All Electrochemical Decentralized RefUeling Station**

Funding Scheme:

Period covered: **1 November 2012 - 31 October 2015**

Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:
dr. ir. P.J. Bouwman, Chief Technology Officer, HyET

Tel: **+31 (0) 26 36 23 944 / +31 (0) 62 36 95 897**

Fax: **+31 (0) 26 36 23 945**

E-mail: **peter.bouwman@hyet.nl**

Project website**Error! Bookmark not defined.** address: **www.phaedrus-project.eu**

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

1. *Executive summary*

The main objective of the PHAEDRUS project was to Research and Develop the feasibility of a scalable Hydrogen Refuelling Station (HRS) station by bringing to the table component based on new technologies. These dedicated components were delivered by select project partners in our consortium having the necessary specific expertise, having their design and performance capability validated for realising a safe and efficient Hydrogen Refuelling Station at a scale of 200 kg/day:

- Electrolyser: APEM and PEM → higher pressure output, smart operation & system design
- Compression: Electrochemical Hydrogen Compression → Isothermic compression principle, No moving parts, silent operation and similar dynamic capability as the Electrolyser.
- Dispensing: Cost Reduction → Effective Pre-cooling, Compact system, Control strategy
- Hydrogen cost: Production, Compression, Refuelling < 10€/kg → Delivering capacity matching demand, taking into account electricity tariffs and cost variations
- Safety and compliance: SAE J2601, SAE 2799, PED, CEN/ISO

The figure below presents the schematic 2D layout of the HRS components, as resulted by the PHAEDRUS project. However, the detailed configuration, component dimensioning and system scaling are influenced significantly by anticipated operating conditions, the local situation and expected customer demand as shown by the outcome of the generated mathematical models. This model, predicting the most energy efficient method for generating, compressing and dispensing hydrogen at 70MPa, will be made available to enable stakeholders to optimise the HRS beforehand.

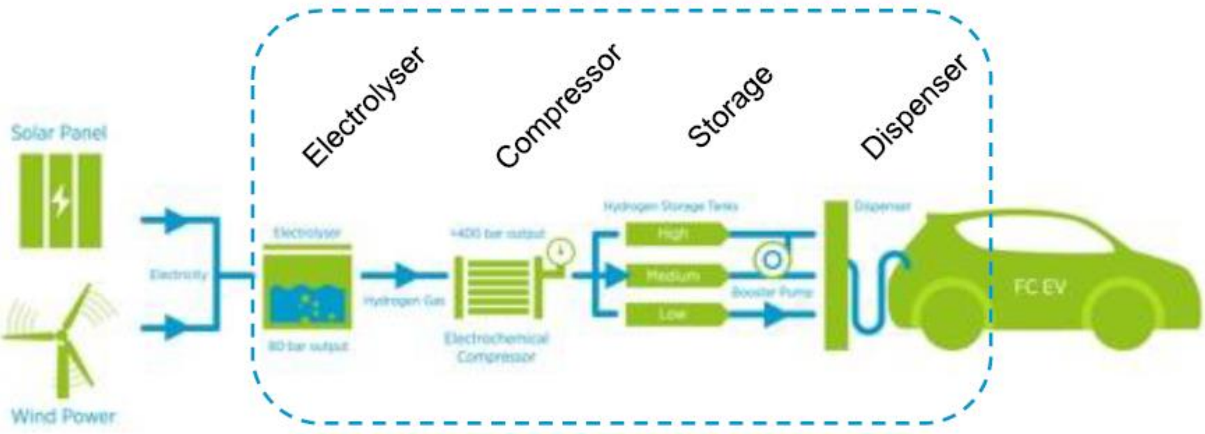


Figure 1 – Schematic diagram of the general HRS component configuration considered in PHAEDRUS

PHAEDRUS has been a successful project that has created impact by directly addressing current HRS issues and showing how and where new technology can make a clear difference. Our approach was justified according to the completed technology comparison and cost projections based on the world's premier integration and strong cost-down potential, projecting in 2020 the targeted investment costs of < 10 k€/kg and hydrogen sales costs < 10 €/kg are deemed feasible.

More technical information will be discussed further in this report and in the Periodic Report.

2. Summary description of project context and objectives.

Project Context

One of the biggest challenges to the wide-spread introduction of fuel cell electric vehicles is the lack of a cost and performance effective hydrogen fuelling infrastructure. The European Union and the major car manufacturers are aiming towards making hydrogen cars commercially available together with an adequate hydrogen fuelling infrastructure. However, investment cost associated with building and operating hydrogen refuelling stations (HRS) during the early market penetration years of hydrogen vehicles is perceived as a primary obstacle. Currently hydrogen is mainly produced (90%) from fossil fuels via for instance steam reforming. Several decentralized hydrogen production routes exist (e.g. natural gas reformer technology, alkaline/PEM water electrolysis technology). Light house projects with fuel cell electric vehicles and centralized fuelling stations have been initiated (Clean Energy Partnership, H2MOVES Scandinavia and CHIC[2]) and consequently experience has been gained on 'real world' user patterns. Crucial factors for a successful operation are: reduced capital and operational costs, reliability, instant availability of hydrogen, the retail price of the hydrogen and safety. Integrated facilities with footprints small enough to be deployed into established refuelling infrastructures need to be designed and implemented.

The automotive sector has targeted 70 MPa hydrogen storage technologies for application in fuel cell electric vehicles in the passenger car segment. Therefore, Hydrogen Refuelling Stations (HRS) need to supply hydrogen at pressures over 70 MPa. Today, hydrogen is compressed using rather inefficient and unreliable mechanical compressors. It has been acknowledged that the compression of hydrogen remains a challenge on reliability and energy efficiency in the well to wheel chain of fuel cell electric vehicles.

Project Objectives

The objective of the project is to develop and validate a new concept for 70 MPa hydrogen refuelling retail stations enabling self-sustained infrastructure roll-out for early vehicle deployment volumes, showing the applicability of the electrochemical hydrogen compression technology in combination with a PEM electrolyser, storage units and dispensing system. The use of electrochemical hydrogen compression technology is expected to provide a step change in both the efficiency and cost of ownership of an integrated hydrogen refuelling system. The applicability will be demonstrated in a system producing 5 kg hydrogen per day, while a design is made for a fuelling system capable of producing 200 kg hydrogen per day. This is typical for the need of fleet owners and early markets.
Another objective is to analyse and validate the safety aspects, efficiency and economic viability of the system. Important factors influencing cost and efficiency are the absolute and relative sizes of the individual building blocks. The business case for the final refuelling system will be done by a reliable assessment of the cost and energy efficiency of the H_2 compression and refuelling cost as a function of the production size (in size and in (production) number of stations) in comparison to systems based on mechanical compression.

The project aimed at developing HRS infrastructure with a modular dispensing capacity in the range of 50-200 kg per day. If higher capacities are needed, several modules can be combined. Higher capacities, *e.g.* 1,000 kg/day, would theoretically improve the OPEX as the CAPEX cost in relation to the capacity would be lower. However the project targeted the early HRS network roll-out from 2015 onwards to 2020. As expected, during this period number of FCEV's has been low and not enough to support larger HRS's.

[2] Clean Energy Partnership http://www.cleanenergypartnership.de/, H2MOVES Scandinavia www.h2moves.eu and CHIC http://chic-project.eu

Nevertheless, the produced concept system enables a small footprint, low CAPEX and OPEX refuelling system, complying with the relevant standards: SAE J2601 and SAE J2799.

The relationships between efficiency/current density and output pressure has be analysed and an optimal (OPEX/CAPEX) system has been developed within these boundaries to maximise the commercial suitability of the electrolyser system.
It should be noted that for OPEX, the electricity price is the most important cost driver. At €0.05/kWh the OPEX is targeted to be €2.5/kg. It is therefore important to ensure the electrolyser is able to operate preferentially during periods of low electricity price (off-peak tariffs, overnight, during times of renewable curtailments). It is also anticipated that demand load management will play an important role in electrolyser based hydrogen fuelling, helping to offset electricity costs. The ability of the electrolyser to respond quickly to access availability payments for grid balancing services is a key benefit to PEM electrolysis in the longer term. It is expected that the requirement for demand side balancing services will grow in step with deployment of renewable generation assets.

The Electrochemical Compression technology introduced in this project has the potential to be more energy efficient than the incumbent mechanical compression, because it is based on an quasi-isothermal process, rather than an adiabatic process. However, the most convincing advantage is that the responsiveness of the EHC is equal to the electrolyser and is able to follow the anticipated dynamic hydrogen production and provide maximum savings on operational costs. Note the compression efficiency is influenced by the compression rate: slow compression is most efficient, while fast compression dissipates more heat according to Ohm's law, but may be a rational option in periods of increased demand or supply. EHC stack modules can accommodate a range of compression rate and pressure capabilities and can be placed in parallel to multiply the output of the system, and also guarantee operational availability.

In the FCH-JU MAIP (update draft version July 2011), reported in the DoW, the overall targets for hydrogen refuelling systems are suggested, and summarized below. The R&D efforts within the project on the various building blocks and technologies focused on these overall targets.

Table 1 - Suggested cost targets for Refuelling Stations, H2 production and H2 price.

Targets suggested by the FCH-JU MAIP (update draft version July 2011)				
	HRS size	**2010 State-of-the-art**	**2015 target**	**2020 target**
HRS CAPEX	50-80kg/day	<1 M€	<0,6 M€	-
	200 kg/day	<1,5 M€	<1 M€	<0,6 M€
H2P CAPEX	Price per Nm^3/hour	€4.100	€3.500	€2.500
EU market volume (no. of stations)		<75	<300	>2,000
Hydrogen price*		€15-20/kg	€10-15/kg	€5-10/kg

H2P = Hydrogen production

Table 2 - Report on PHAEDRUS's results in comparison to the MAIP/AIP targets

Programme objective/target	Project objective/target	Project achievements to-date	Expected final achievement
MAIP			
HRS Capex 2015 target <1M€	Cascade system configuration simplified using new technology	HRS model is available as tool for optimal design before realisation	CAPEX Cost per daily dispensed H2 around 10,000 €/kg is feasible!
H2P CAPEX 2015 target: €3500 per Nm^3 /hr	Modular unit system, low membrane costs and low Pt catalyst loadings	Components were validated, membranes and low catalyst loading evaluation complete	Scalable unit validated at 5 kg/day, model shows large costs down potential with optimisation

Programme objective/target	Project objective/target	Project achievements to-date	Expected final achievement
AIP 2012			
Optimisation of compression & storage systems with respect to cost, efficiency and capacity	Balance component specifications in final system configuration	Components sized using model based on component test results and realistic costs	Configuration relates impact of costly high pressure storage tanks and component limits given specific demand profile
Compliancy	standardised compliance verification and BAM evaluation		H2 Logic applies refuelling control system adapted to new SAEJ2601
Hydrogen Price	2015: 10-15 €/kg	<2015: 13. 7 €/kg	>2015: 10.6 €/kg

3. Description of the main S&T results/foregrounds

General main results and achievements

As mentioned in the introduction, the PHAEDRUS's concept consists in optimizing and bringing together three main components of a hydrogen refuelling station:

1. The electrolyser
2. The electrochemical compressor
3. The storage and station self

The main goal was to provide customers with a new concept of HRS, since the current status is that Hydrogen refuelling station are present, however their number in Europe is quite limited, utilisation is quite low while OPEX is significantly highly, as last (but not less important) there is no clear standard configuration. The PHAEDRUS project searched for an answer for all these points and, at the end, proposed an optimised HRS configuration considering a specific situation. The artist impression of the HRS innovation process is shown in Figure 2, where the existing, operational HRS in Holstebro (Denmark) is shown on top and most supporting systems are hidden from view by a blue screen, versus the outlook of a single integrated dispenser/container that is easily scaled to demand.

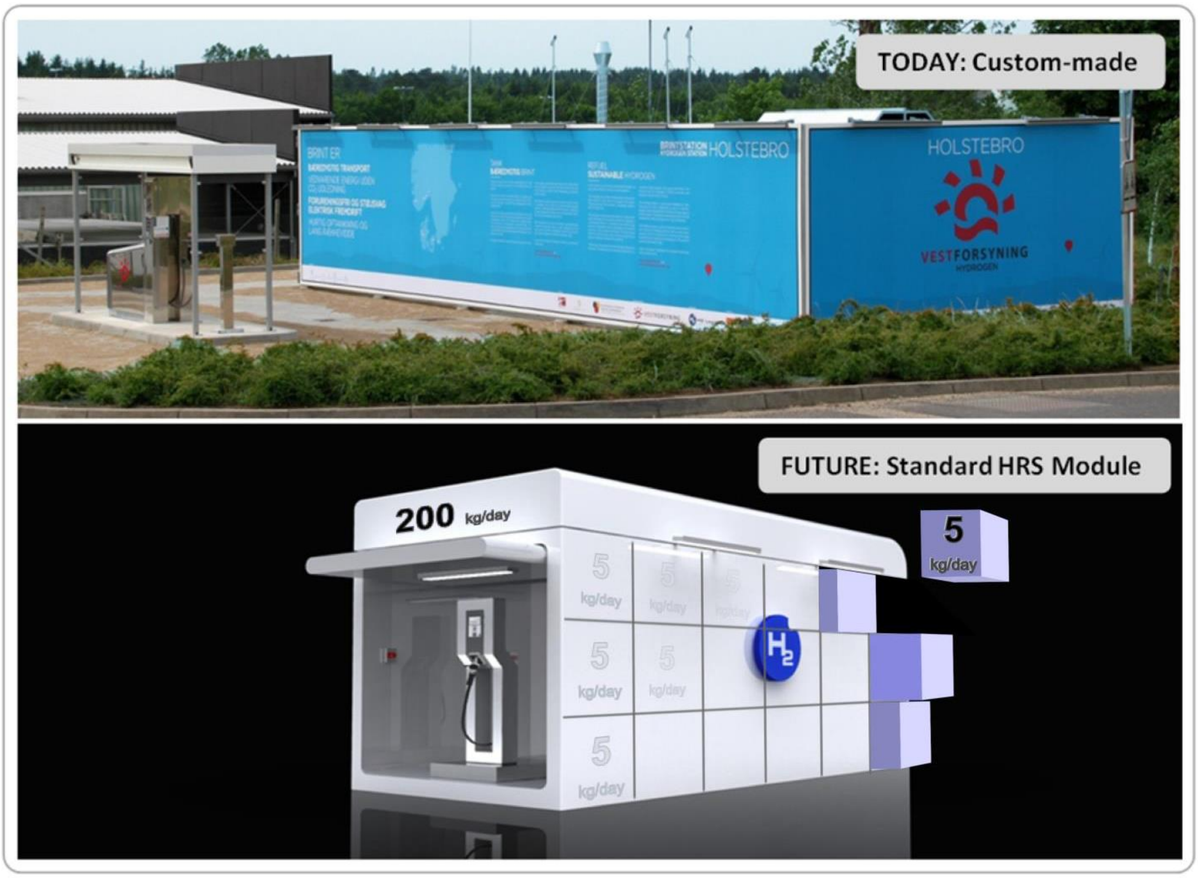


Figure 2 – Picture showing the existing 70 MPa Hydrogen Refuelling Station in Holstebro (Denmark), with a rendering of a futuristic design, building on the concept of a modular and scalable approach.

The challenges and deliverables targeted in the PHAEDRUS project have been:

- **For the electrolyser**
  - Optimisation of membranes for high pressure and small scale test cell
  - Development of a prototype electrolyser with 5kg/day stack
  - Preparation of a design of electrolyser with capacity of 200 kg/day

- **For the compressor**
  - MEAs optimisation towards a pressure ratio of 40
  - Endurance tests of the newly developed materials.
  - Development of a prototype compressor with capacity of 5 kg/day
  - Preparation of a design of compressor with capacity of 200 kg/day

- **For the HRS**
  - Finalizing the selection of technologies and sub-system configurations
  - Completion of R&D of HRS components and selected laboratory tests
  - Preparing the virtual integration with the electrolyser and the compressor
  - R&D of a modularised HRS integration skid with reduced costs and footprint

- **For the market analysis**
  - Focus on the report on assessment of costs and WTW analysis
  - Prepare the market comparison and potential of the technology

ITM, in particular, has developed high pressure and high current density electrolysis technology and ancillary systems for use in commercial electrolysis machines based on the PEM electrolyser concepts. This included, initially in the first period, the use of APEM membranes to reduce cost. ITM then produced a PEM high current density plant, with high pressure hardware, produced accelerated stress tests to screen catalysts, and, significantly, optimised its heat exchange strategy within its stack. ITM also demonstrated the integration of all electrochemical hydrogen generation and compression equipment – the technologically challenging core principle of a highly efficient and silent refuelling station.

The integration of components (HyET/ITM, compressor and electrolyser) was planned and executed in the last few months of the project, form the data obtained (and reported in D5.5) it is clear that a valuable solution has been found. The data have been used by H2Logic in order to finalize the virtual integration of the components in the new HRS skid model.

The technological bases for the optimisation of future HRS have been set by the PHAEDRUS project, partners are committed to continue in this direction to reach the demonstration phase. However, the entire community of hydrogen fuel cell should “do more” and support these results and help putting them on the field by installing more HRS, scalable on demand; optimising configuration using latest technologies and including on-site H_2 production.

4. *Main results per WP*

WP1: Work Package 1 aims to analyse the three overall system configurations and select the most cost and energy efficient one. This is done by taking into account the technical abilities of the electrolyser, compressor and storage in terms of cost, efficiency, capacity and inlet/outlet pressures. The selection will enable the R&D activities in later work packages to commence. In parallel, an analytic system modelling tool is to be developed that enables further fine-tuning of the system architecture and sizing.

The overriding objectives of this WP can be described as follow:

- To determine fuelling system requirements and set targets for CAPEX and OPEX as a function of station size and deployment volumes to assess competitiveness against other technologies.
- To select the optimal system architecture & sizing with respect to cost and efficiency
- To develop an analytic system simulation model for fine-tuning of architecture & sizing

This work consolidates the knowhow of consortia members, filling gaps with data from existing studies and external sources and to create common understanding between the partners regarding the challenges and opportunities. Thus, this work aims to translate this understanding into functional and cost targets for the fuelling system that can be used to define the system architecture in further task objectives.

WP2: Hydrogen is an excellent fuel, but as a gas it does not fit easily into the framework of a conventional filling station as we have in everywhere today. This means that getting the necessary test certificates, approvals and other papers you need before you can start operating a hydrogen refilling station may be even more complicated and difficult than it is anyway for a normal station. Neither test bodies nor the relevant authorities are acquainted with such a type of filling station. This work provides a summary of the legal framework in which such a station must fit.

This WP focussed on the HRS, it was performed and completed during the first project period. The main results, as reported in the deliverables are the full optimised system design for the HRS and the related safety and legal analysis. The aim is to have a system design and control strategy for the entire Hydrogen Refuelling Station (HRS) and onsite hydrogen production.

The complete HRS from H2 Logic to be developed in the PHAEDRUS project is to include a compressor system from HyET and is to be connected to an electrolyser from ITM through standardized interfaces. This requires development of a joint system design and control strategy so that the various sub-systems can be integrated and work together through passive and active systems. During the final integration in WP5, this information proves valuable.

WP3: ITM, has developed high pressure and high current density electrolysis technology and ancillary systems for use in commercial electrolysis machines based on the PEM electrolyser concepts. This included, initially in the first period, the use of APEM membranes to reduce cost. ITM then produced a PEM high current density plant, with high pressure hardware, produced accelerated stress tests to screen catalysts, and, significantly, optimised its heat exchange strategy within its stack. ITM also demonstrated the integration of an all electrochemical hydrogen generation and compression equipment – the technologically challenging core principle of a highly efficient and silent refuelling station.

Hydrogen costing less than €7/kg inclusive of CAPEX and OPEX has been shown possible for an electrolyser rated to produce 200kg of hydrogen per day at a pressure of 80 bar. Electricity consumption was shown to be the largest portion of the overall hydrogen cost, which was calculated using 10c/kWhr. The hydrogen cost dropped to €2.32/kg at 2c/kWhr, demonstrating the sensitivity. The nominal current density in the system design was 1.32A/cm^2.

An accelerated stress test was developed for the catalysis to simulate 9.6 years of operation. High pressure cell hardware was developed with burst pressure in excess of 200 bars. The longevity of a small PEM electrolyser set to constant current mode at 3A/cm^2 was demonstrated with over 18,000 hrs accrued and significantly, a very low degradation rate <2.5µV/hr.

In the first period, an 80 bar differential pressure across an APEM membrane showed remarkably low hydrogen permeation being undetectable with available equipment. Finally the development of a non-precious metal catalyst electrode for the APEM system and its testing saw short term alkaline electrolysis performed at above 3A/cm^2.

An 80 bar working pressure, 1.5 A/cm^2, 5kg H_2/day PEM electrolyser system was demonstrated in the project as shown in Figure 3. This was integrated with the electrochemical compressor at ITM's facilities.

Figure 3 - *5kg H_2/day, 80 bar PEM electrolyser achieving assessment criteria of 1.5 A/cm^2*

WP4: In this project HyET demonstrated a record compression value of 100 MPa single stage, proving the principle of electrochemical compression is applicable across a wide range of pressures and could be considered for numerous applications, the most challenging being automotive refuelling.

Significant development was conducted in this project on the Membrane Electrode Assembly (MEA), which is the functional pumping 'heart' of the compressor. New catalyst materials were prepared by partner Armines based on aerogel support structures, integrated in the MEA design and tested. Membranes with enhanced properties were realised and integrated in the final stack design, improving overall energy efficiency by reducing electrical resistance and gaseous hydrogen back diffusion. Sealing high pressure hydrogen is always challenging, and HyET managed to integrate solutions enabling a significant reduction of the cell-to-cell pitch in the stack hardware.

Several iterations of the stack hardware were developed to improve performance through enhanced control over operating conditions and to reduce weight for cost saving. The final stack prototype was successfully operated in the field, validating the technical combination with the electrolyser system.

HyET has dedicated significant attention to the development of the Balance-Of-Plant system to maintain the operation conditions of the Electrochemical Compressor. Past experiences with customers have learned that the stack may be the pumping heart, it will not perform optimally over longer periods of time, if we do not integrate some degree of 'intelligence' in the controls, pre-empting the stack behavior and gas, thermal and water management requirements. Continuous feedback and control is imperative to guarantee safe operation and gain experience in the field.

During the course of the project, HyET has translated knowhow and experience on operating procedures and diagnostic testing in the laboratory, towards building an excellent piece of kit to conduct Research and Development at high standards in the field. This transfer to the mobile "MoHyTO" platform as shown in Figure 4 was a key step in the development progress of the electrochemical hydrogen compressor, as the Technology Readiness Level (TRL) is to be increased further beyond stage 5 by conducting demonstration field testing as part of full HRS systems.

Figure 4 – Picture showing the developed mobile EHC test platform dubbed " MoHyTO".

WP5: As a completing task of the WP5 efforts on HRS component development a design for a HRS skid has been developed. In addition, an assessment has been conducted on assessing a relevant scaling and integration of the electrolyser and compressor with the HRS at full scale capacity, meaning a station with 200kg/day capacity. The field validation test of the SAE J2601 was conducted as part of PHAEDRUS, thus helping both to validate the SAE J2601 as well as the new refueling control system developed in PHADRUS.

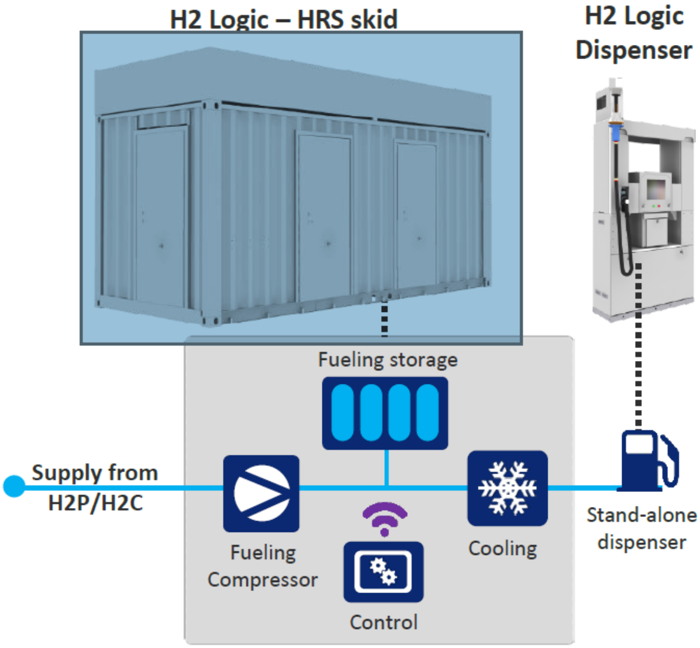


Figure 5 – Schematic diagram showing HRS components for storage and dispensing tested at H2Logic

The validation of the novel technology integration at small scale was conducted at ITM in Sheffield, while the review and assessment of other HRS components was conducted at H2Logic in Denmark. As shown in Figure 6, two separate systems were physically connected and operated simultaneously, thus successfully completing the critical step of the integration validation and generating important data that was used in the model predicting the operational performance and HRS expenses at scale.

Figure 6 – Picture showing world's first integration and validation of the PEM Electrolyser and the Electrochemical Hydrogen Compressor (MoHyTO) in the field at ITM laboratory in Sheffield.

WP6: This WP offered a market comparison and potential of the PHAEDRUS's technology, continuing from the reports D1.2 "Initial system architecture and sizing" and D1.3 "System simulation model and report on final system architecture". First capital expenses and operational expenses of the full scale fuelling station have been assessed to next complete the report on "Well to wheel analysis".

The main goal of the PHAEDRUS project is to develop and validate a new concept for 100 MPa hydrogen refueling retail stations enabling self-sustained infrastructure roll-out for early vehicle deployment volumes, showing the applicability of the electrochemical hydrogen compression technology in combination with an onsite electrolyser, storage units and dispensing system in the most optimum configuration considering circumstances.

This report evaluates the different architectures and the recommended architecture is to add a mechanical booster compressor, which allows the electrochemical hydrogen compressor (EHC) to compress hydrogen up to 50 MPa instead of 100 MPa and reduces the size of the high pressure storage tank significantly (see HRS6 in Figure 7). The system is developed in MATLAB/Simulink and the components are simulated and sized to achieve target efficiency.

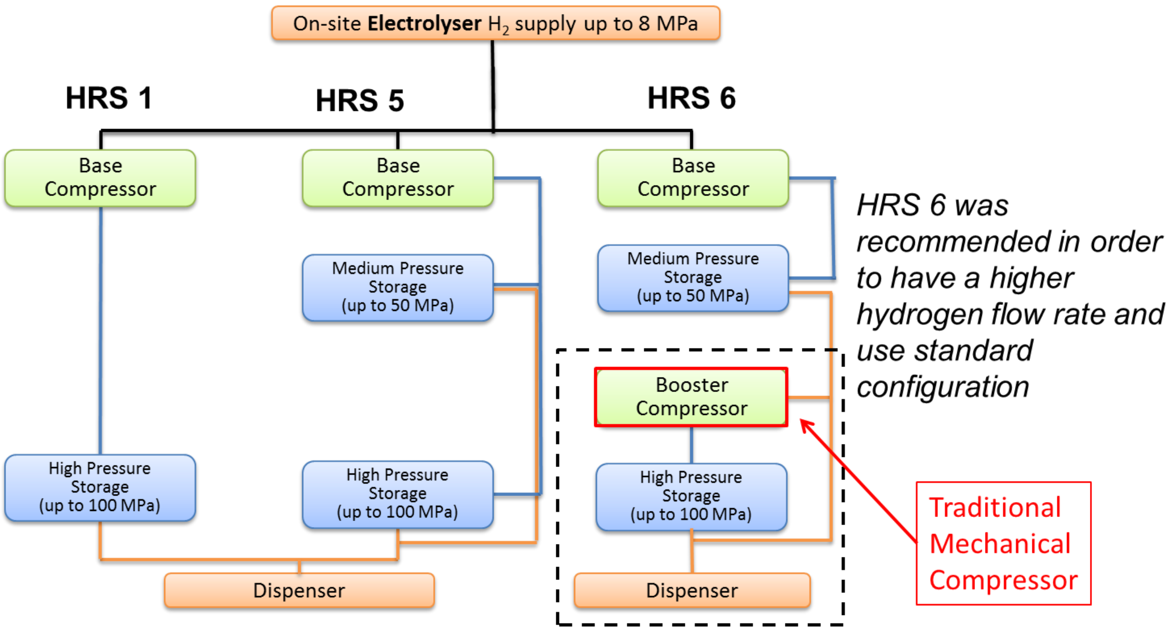


Figure 7 – Overview of select configurations considered in the modelling of the HRS CAPEX/OPEX analysis, where configuration HRS 6 proved an interesting combination with existing compression technology to combine mutual benefits.

PEM electrolysers and the EHC compressor are still new technologies, with a high improvement potential. Within the calculation and evaluation of the cost structure, current and future values are taken into consideration. Therefore the improvement of the utilized components is projected. Compared to 2015, the year 2020 predicts mainly cost reduction of the EHC base compressor reducing hydrogen provision cost to 10.61 €/ kg H_2.

After a significant reduction regarding the CAPEX and OPEX as well as the energy consumption, on-site HRS are a good possibility to supply the future FCEV fleet with sustainable produced hydrogen.

To satisfy the environmental awareness of the society, a low environmental impact of FCEV is essential. Under ecological aspects the electricity supply via renewable energies offers the benefit of low GHG emissions.

WP7: The project progress has been monitored and reported on the project website during the entire project duration, announcing and tracking key dissemination events in the public domain. Frequent highlights and periodic newsletters were updated and uploaded to keep audience posted.

official website: http://www.phaedrus-project.eu

Dissemination highlights have been most frequent in the last six months of the project lifetime, since more obtained results could be disclosed and placed in context. The final dissemination activities were a dissemination video and a final oral presentation at an international conference / exhibition event: "World of Energy Solutions" in Stuttgart, (see Figure 8 and Figure 9) which was attended by many stakeholders in the automotive (refuelling) industry. Also the timing, 12-14th of October 2015, coincided well with the closing of the project.

The video was shown continuously for three days to passers-by on the wide screen television shown on the right hand side of Figure 8, and is also available as link on the official website. This video combines a 2D animation to explain the HRS component configuration briefly, and incorporates footage taken on two consecutive occasions: the first being the technical validation of the electrolyser and the compressor at ITM, and secondly the gathering during the final General Assembly at the Hydrogen Refuelling Station in Sheffield. The editing was completed in one week in order to make it on time for the dissemination event and conference.

Figure 8 – Picture of the exposition area at the "World of Energy Solutions" conference/exhibition event where the project coordinator HyET displayed and disseminated the PHAEDRUS results to the audience.

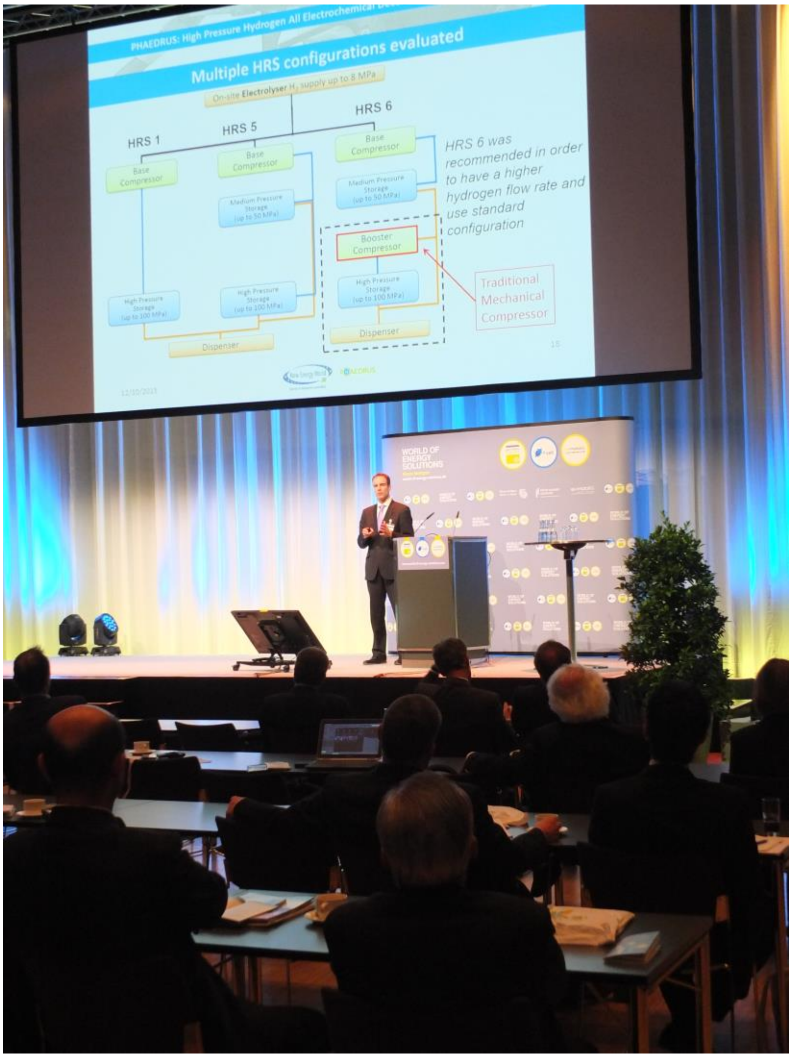


Figure 9 – Picture taken by partner BAM (courtesy of Ulrich Schmidtchen) during the oral presentation of the PHAEDRUS project results during the plenary conference session of the "World of Energy Solutions" event on 12th October 2015.

Other Achievements

In short, the PHAEDRUS project successfully managed:

1. Communication with the Advisory Board via email and telephone conference, which included members from ECN (NL), Element Energy (UK), ZSW (DE).
2. Final review by the Advisory Board achieved
3. Newsletters distributed and published on the website at regular intervals
4. Continuous update of mailing list for the newsletter and project information
5. Study and recommendation for market deployment completed
6. Preparation of dissemination video available online showing successful integration and statements from partners in the consortium.
7. Dissemination activities: presentations at conferences (more details provided further in the report)

5. Potential impact, main dissemination activities and exploitation of results

Based on the project plan, as described in the DoW, the technology roadmap and plan towards reaching commercial targets for the proposed HRS infrastructure are summarised here.
Estimates on the total accumulated market potential for 2020 range from 2,500 – 3,000 HRS stations with a 200 kg/day equivalent capacity, *i.e.* the capacity needed to serve 1,000,000 - FCEVs. In HRS infrastructure investments, this corresponds with € 1.35 to € 3.3 billion based on the assumption that the costs for a hydrogen distribution and retail infrastructure are 5% of the overall costs of FCEVs (€ 1,000 – 2,000 per car).

The figures below gives preliminary estimates in market volumes of HRS systems in terms of 200 kg capacity per day up to 2020 and 2025. These numbers fit within the roll out scenario's presented in the *Global context for FCEVs and hydrogen infrastructure* and with the figures suggested in the draft MAIP 2011.
Altogether, it represents a more than healthy business case for all industrial stakeholders, *i.e.* cumulated turnover over € 0.5 billion. The companies involved: HyET, H2L, ITM, HEX, Daimler and Shell will pursue this market each from their own perspective.

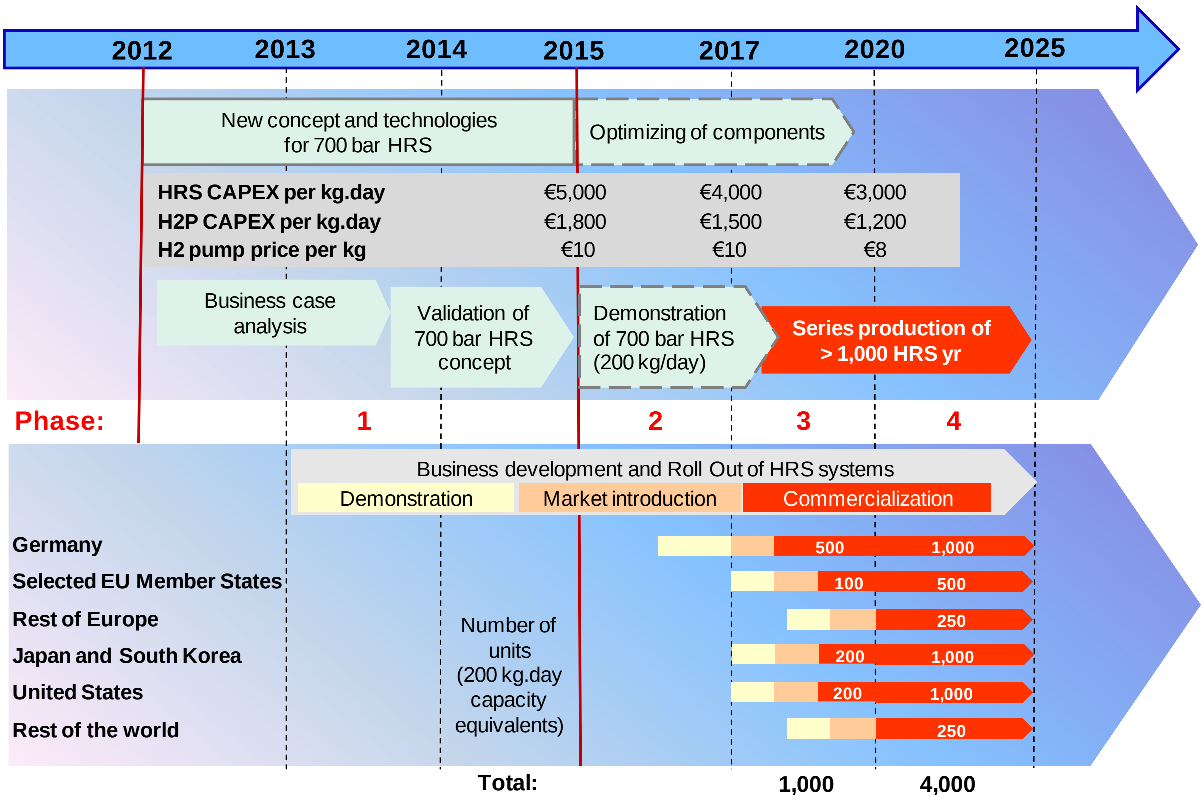


Figure 10 - Technology roadmap and plan towards reaching commercial targets. The phases (or steps) correspond with the phases listed in the table below.

Table 3 - Plan towards reaching commercial targets

Phase	Activities	Timing
1	- **Development and validation** of an electrochemical technology based 70 MPa HRS concept in accordance with FCH-JU MAIP targets and relevant SAE standards; - Connection (information exchange and coordination) to various European and international efforts such as the working groups of SAE J2601, SAE J2799 by H2, Shell and Daimler, CSA TIR 4.3 by H2L, ISO TC 58/SC3 and ISO TC197 (WG15) by HEX and ITM; - Connection (information exchange and coordination) to other international public private partnerships in Japan, Korea and the US through the Advisory Board and individual consortium partners; - Connection (information exchange and coordination) to H2Mobility by Daimler and Shell that are founding partners of this initiative; - Consider the drafting of a joint business development plan by H2L, HyET, ITM and HEX.	2012-2014
2	- **Demonstration** of the developed technologies and 70 MPa HRS concept by laboratory test of full-size systems and later building and operation of several 50-200 kg/day stations in selected European regions where FCEV's are market introduced; - Optimizing of technologies and components; - Preparing for series production of components and subsystems; - Connection (information exchange and coordination) to H2 Mobility and international public private partnerships in JP, KR and the US.	2015-2016
3	- **Market introduction and roll out** of the developed technologies and 70 MPa HRS systems by building and operation of several hundred stations in selected European regions where FCEV's are market introduced; - Optimizing series production of subsystems and HRS modules; - Demonstration of several 200 kg/day HRS modules in other European Member States, JP, KR and the US; - Connection (information exchange and coordination) to international public private partnerships in the rest of the world.	2017-2020
4	- **Full commercial roll out** in Europe, Japan, Korea, United States and the rest of the world.	2020-2025

PHAEDRUS Phase 2

The project was scheduled for 3 years and can be regarded as phase one of a two-step development. In the first phase technology was developed and validated on a 5 kg/day scale. And, a complete Hydrogen Refuelling System design is made for 200 kg/day capacity. Subsequently in phase two the technology will be demonstrated as a laboratory full-size prototype in a scalable 200 kg/day Hydrogen Refuelling System. There are currently consultations ongoing among the partners about how to structure and when to plan phase two.

The main project impact, after more than 36 months of work, can be summarised as follows:

- Development of a model for the most energy efficient method of generating, compressing and dispensing hydrogen at 70MPa
- Development of high pressure, high current density **electrolyser** stack & BoP
- Optimisation of an **electrochemical compressor** and mobile MoHyTO system
- Extensive **durability** data for developed components and systems
- Successful **integration** and operation of a high pressure, high current density electrolyser module with an electrochemical compressor
- Technology **cost comparison** and projection undertaken with Daimler
- Validation of a n**ew approach** and required technology for decentralised H2 generation & refuelling
- Electrochemical compressor needs to achieve higher TRL level but potential benefit and **cost –down potential** justifies continued its pursuit
- Hydrogen cost target of €10/kg for 2020 assuming EHC achieves projected cost savings
- Further **collaboration** between partners outside of the Phaedrus Project

Possible societal impact

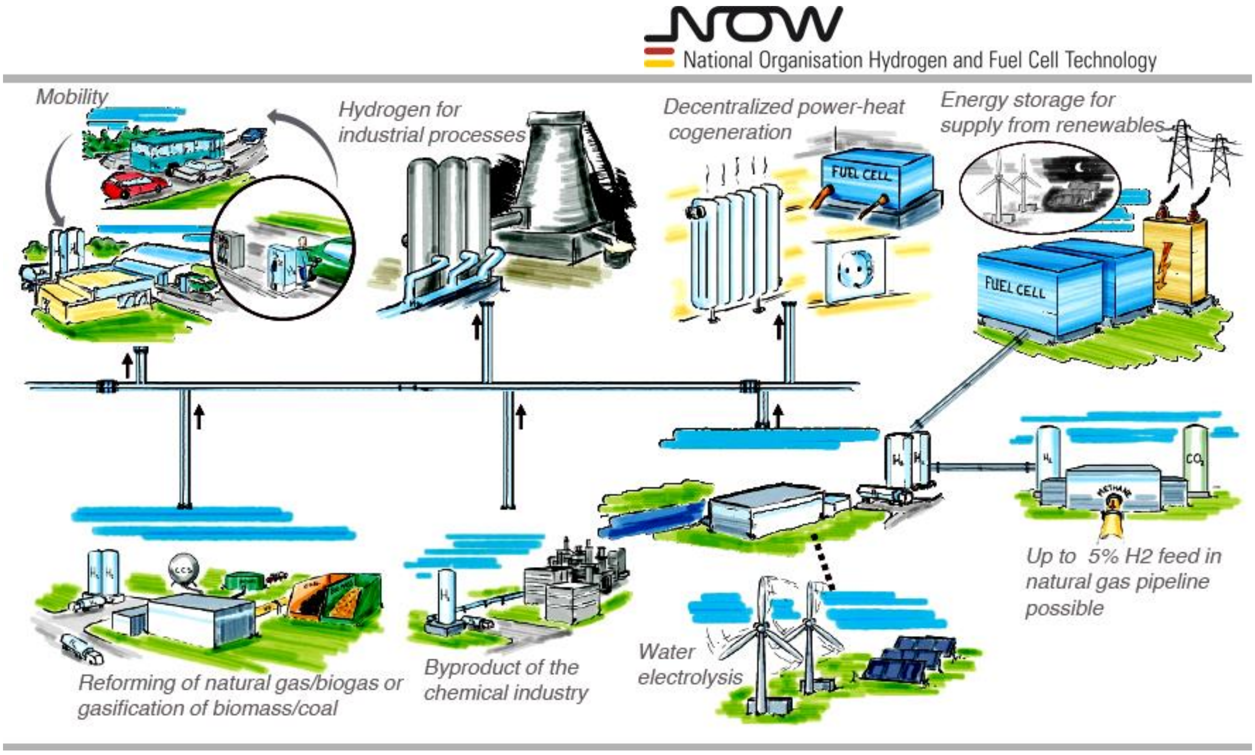
The technological development is by no means finished, and could in some cases still be classed as immature, but PHAEDRUS shows that we are on the cusp of reaching the tipping point where its roll-out becomes commercially feasible. The timing is essential, particularly since we are now facing the chicken-egg stalemate issue that is keeping consumers from making the transition to commercially available hydrogen electric vehicles.

On a technological and scientific level the small scale validation showed a proof of concept and opened the way to realise more demonstration projects and tackle observed technical barriers. For example, the 5kg H_2/day PEM electrolyser proved a fully featured instrumented research platform which has now been upgraded with a power supply capable of 7A/cm^2. High current density will be investigated in this plant to verify the efficacy of the stack optimised heat management solution.

All partners involved, subscribe with ITM's aim to create many jobs with the adoption of applications requiring hydrogen gathering momentum and becoming increasingly understood. Green and pure hydrogen can be produced at high pressure with ever increasing amounts of cheaper green electricity, but which is available intermittently and at varying cost even during the course of a day.

This greater availability of green electricity has meant electricity prices have fallen in Germany for the last 5 consecutive years - down to less than 30€/MWh on the wholesale market. This is not emphasised enough and the EU wide picture is not the same. This is used and pro-actively reflected in ITM cost models (Germany being a prime market) -as well as efficiency projections- in response to this new economic environment and, in turn, offers an advantage in pre-sales efforts to win orders and ultimately deploy more systems. A consequence of lower electricity prices is that the proportion of OPEX in the cost of a kilogram of hydrogen has reduced and the justification and support for developing CAPEX efficient components feels more relevant as a result.

PHAEDRUS has validated a new on-site approach and required technology to produce compress and dispense hydrogen fuel satisfying local customer demand. This achievement could have significant impact on mobility in general, spilling over from the automotive sector considered here. Given the opportunity and the technical ability to store energy as fuel, people are likely to become more self-conscious, more considerate about their consumer behaviour and perhaps even self-sustaining on a local level. This will truly change the nature of economic interactions and deliver a sustainable change for the better to the greater society in years to come, if support properly.



Main dissemination activities and possible exploitation

In the three years project lifetime different dissemination activities have been performed (newsletters, presentation at conferences, papers submitted, and video).
Each partner has been promoting its work as well as the team effort at different levels, communication and dissemination was in the beginning, mostly, at national level or for a dedicated target group. However, the addressed issues are encountered everywhere and there is strong international interest to resolve these in a cost-effective manner.

Now, after the final results have been analyzed and presented in the last final deliverables, the message of our achievements can be spread with a broader range. In particular for market growth, the final outcome (and what partners are trying to obtain) is:

- Hydrogen made available to the customer at the same or lower cost as conventional fuels.
- Fuelling stations able to sell hydrogen for this comparable cost.
- Cost of production, compression and dispensing needs to be below the sales level to break even, but this is deemed feasible given the strong cost-down potential and smart operation
- Urban environment dictates: footprint requirements, noise reduction, high safety standards.
- CAPEX/OPEX balance: serious CAPEX for installation now, but you need to look at the OPEX to make the business case work.

During the period of Phaedrus, ITM has trebled its current density and increased its stack pressure by more than 5 times. This 'goes with the grain' of the company's development strategy, helping to reduce equipment costs. Phaedrus has helped support activities which allow these benefits to be integrated in ITM's product offering. ITM continues to build on this in many ways including efforts directed at development of a larger PEM stack platform (part funded by the FCH-JU under project name MegaStack).

In addition to hydrogen for clean fuel and energy storage applications, the higher pressure operation helps ITM to access various chemical applications, including synthesis of more complex substances (which often require higher pressure hydrogen) and de-pollution of diesel car emissions (where the 80 bar is considered an adequate pressure to dispense hydrogen to a small on-vehicle store). Both applications are potentially very large and ITM's ability to interact with them in enhanced as a result of the Phaedrus project.

6. Public website address (if applicable), as well as relevant contact details.

Project website:
www.phaedrus-project.eu

Main contacts:
Peter Bouwman (HyET), project coordinator
E-mail: Peter.Bouwman@HyET.nl
Tel: +31 26 362 3944
Mob: +31 62 36 95 897

Anna Molinari (UNR), project manager
E-mail: a.molinari@uniresearch.com
Tel: +31 15 275 4000
Mob: +31 6 2117 2319

Consortium primary contacts:

Partner Number	Partner Short Name	Title	First Name	Last Name	E-mail
1	HyET B.V.	Dr	Peter	Bouwman	peter.bouwman@hyet.nl
		Mr	Derek	Zwiersen	derek.zwiersen@hyet.nl
2	ITM	Dr	Rachel	Smith	rls@itm-power.com
		Dr	Simon	Bourne	sjb@itm-power.com
		Mr	Frederic	Marchal	FALM@itm-power.com
3	H2 Logic A/S	Mr	Mikael	Sloth	ms@h2logic.com
4	Raufoss / HEX	Mr	Per Sigurd	Heggem	per.heggem@hexagonraufoss.com
5	Daimler	Dr	Jörg	Wind	joerg.wind@daimler.com
6	Shell	Mr	Jurgen	Louis	jurgen.j.louis@Shell.com
		Dr	Andrew	Murphy	Andrew.Murphy@shell.com
7	BAM	Mr	Ulrich	Schmidtchen	Ulrich.schmidtchen@bam.de
8	ARMINES	Dr	Rudolf	Metkemeijer	rudolf.metkemeijer@mines-paristech.fr
		Dr	Sandrine	Berthon-Fabry	sandrine.berthon-fabry@mines-paristech.fr
		Dr	Christian	Beauger	christian.beauger@mines-paristech.fr
9	UASE	Prof	Ferdinand	Panik	fpanik@t-online.de
		Mr	Hisham	Al Ashkar	Hisham.Al-Ashkar@hs-esslingen.de
10	Uniresearch	Dr	Jaap	Struijk	j.struijk@uniresearch.nl
		Dr	Anna	Molinari	a.molinari@uniresearch.nl

Figure 11 – PHAEDRUS consortium partners posing at the HRS in Sheffield at the project conclusion

7. *Acknowledgement*

This project is co-funded by the 7th FP (Seventh Framework Programme) – Fuel Cells and Hydrogen Joint Undertaking

http://www.fch-ju.eu/

http://ec.europa.eu

Disclaimer

The FP7 project has been made possible by a financial contribution by the European Commission under Framework Programme 7. The Publication as provided reflects only the author's view.

Every effort has been made to ensure complete and accurate information concerning this document. However, the author(s) and members of the consortium cannot be held legally responsible for any mistake in printing or faulty instructions. The authors and consortium members retrieve the right not to be responsible for the topicality, correctness, completeness or quality of the information provided. Liability claims regarding damage caused by the use of any information provided, including any kind of information that is incomplete or incorrect, will therefore be rejected. The information contained on this website is based on author's experience and on information received from the project partners.