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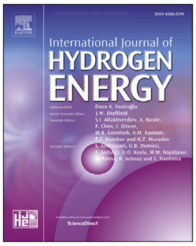

HYDRIDE4MOBILITY: An EU HORIZON 2020 project on hydrogen powered fuel cell utility vehicles using metal hydrides in hydrogen storage and refuelling systems

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HIGHLIGHTS

- Advanced metal hydrides for H storage and compression were proposed.
- MH containers with improved H charge-discharge dynamic performance.
- Integrated with PEM fuel cell hydrogen energy system was developed.
- EU Horizon 2020 RISE project 778307 project HYDRIDE4MOBILITY.
- Hydrogen powered forklift uses MH based H storage and PEM fuel cell.

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ABSTRACT

The goal of the EU Horizon 2020 RISE project 778307 “Hydrogen fuelled utility vehicles and their support systems utilising metal hydrides” (HYDRIDE4MOBILITY), is in addressing critical issues towards a commercial implementation of hydrogen powered forklifts using metal hydride (MH) based hydrogen storage and PEM fuel cells, together with the systems for their refuelling at industrial customers facilities. For these applications, high specific weight of the metallic hydrides has an added value, as it allows counterbalancing of a vehicle with no extra cost. Improving the rates of H_2 charge/discharge in MH on the

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materials and system level, simplification of the design and reducing the system cost, together with improvement of the efficiency of system “MH store-FC”, is in the focus of this work as a joint effort of consortium uniting academic teams and industrial partners from two EU and associated countries Member States (Norway, Germany, Croatia), and two partner countries (South Africa and Indonesia).

The work within the project is focused on the validation of various efficient and cost-competitive solutions including (i) advanced MH materials for hydrogen storage and compression, (ii) advanced MH containers characterised by improved charge-discharge dynamic performance and ability to be mass produced, (iii) integrated hydrogen storage and compression/refuelling systems which are developed and tested together with PEM fuel cells during the collaborative efforts of the consortium.

This article gives an overview of HYDRIDE4MOBILITY project focused on the results generated during its first phase (2017–2019).

Introduction

Necessity of radical changes in stationary and mobile power generating technologies towards shortening the consumption of conventional hydrocarbon energy carriers (fossil fuels) is a significant challenge. Fossil fuels are the major contributor in the balance of primary energy sources with a global share exceeding 84%. Of the total energy consumption, 33% is attributed to the use of oil, about 65% of which is consumed in transportation[1] [1–3]. Aside from the global problems of energy security, mitigation of climate change and environmental pollution, the use of fossil fuels in transportation is the origin of direct health hazards associated with harmful emissions, particularly from utility vehicles which operate in a confined space.

The general solution to the specified problem is the transition from combustion-based power trains to electricity-driven ones, including those utilising hydrogen as a clean non-polluting fuel. The main problem to be addressed for the implementation of this approach is in finding a suitable energy storage method. Currently, two technologies for the mobile applications are under consideration [4,5]:

(i) Direct storage of electric energy in rechargeable batteries and supercapacitors;
(ii) Chemical energy storage in the form of hydrogen via the electrochemical conversion of H_2 into electricity using hydrogen driven fuel cells (HFC).

The HFC technologies offer maximum energy storage densities varying from 0.33 to 0.51 kWh/L, depending on the hydrogen storage method, while the highest value achieved for rechargeable Li-ion batteries does not exceed 0.14 kWh/L [6]. HFC's, particularly low-temperature proton exchange membrane fuel cells (LT PEMFC), possess a number of attractive advantages, including; high efficiency, low operating temperature, high power density, fast start-up times and response to fluctuating load changes, positive environment impact, simplicity in design and long life. Subsequently, the utilization of LT PEMFC's is an ideal solution for a number of stationary and vehicular applications [7].

The use of hydrogen fuel cells in heavy duty utility vehicles, including material handling units/forklifts, has a number of advantages over similar battery-driven vehicles. It is a promising niche application, closest to early market penetration [8]. Hydrogen-powered forklifts offer refuelling in minutes, increased performance, and zero emissions for use within warehouses and buildings. More than 20,000 hydrogen fuel cell forklifts are operating now in warehouses, stores, and/or manufacturing facilities throughout the United States [9]. Number of similar units deployed outside USA is significantly lower, about 500 in Europe [10] and 100 in Japan [11]. As a rule, hydrogen fuelled forklifts utilise hybrid power train when fuel cell delivers average power, and the peak power is provided by batteries [12]. Most of the fuel cell power systems for forklifts demonstrated so far have utilised compressed hydrogen, stored on-board in gas cylinders at pressures up to 350 bar [13].

Hydrogen storage is a key enabling technology for the advancement of HFC power systems in transportation, stationary, and portable applications. The main challenge is in finding an efficient way to deliver hydrogen to the consumer because at normal conditions H_2 is a low density gas (0.09 kg/m^3), thus requiring a densification by physical (compression or liquefaction) or chemical methods [14].

Even at high pressures, the density of compressed hydrogen remains too low, about 0.02 kg/L at $P = 350$ bar and $T = 25$ °C. Accordingly, the volume of pressure cylinders for storage of necessary amount of hydrogen becomes too big that is critical for mobile applications characterised by strict space constrains. As an example, typical capacities of hydrogen storage tanks in commercial forklift fuel cell power modules of various sizes vary from 0.7 to 3.4 kg that corresponds to the tank volume 35–170 L, or 10–20% of the space occupied by the power module itself [13]. Disadvantages of hydrogen storage as a cryogenic liquid include very high energy consumption (above 30% of the heating value) and boil-off losses resulting

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[1] Including aviation, shipping and speciality vehicles.

in the high costs and limited storage time. Thus chemical (e.g., in metal hydrides, MH) storage methods are of a special interest [14].

MH's offer a number of technical advantages to hydrogen storage systems, with the selection of optimal alloys composition being largely dependent on the target end-use application [15]. One promising application for MH based hydrogen supply systems, which provides hydrogen to PEM FC's is in emission-free heavy-duty applications, such as forklifts, mining vehicles, and marine applications. Proper weight balancing of these vehicles requires the use of additional ballast which can be provided by the use of interstitial MH's with hydrogen storage capacities typically between 1.5 and 2 wt% H (i.e. storage of 1 kg H requires more than 50 kg of the MH material when gravimetric efficiency is 2 wt% H), and the low weight capacity of intermetallic hydrides, which is usually considered as the major disadvantage to their use in passenger vehicular applications, becomes an advantage in the aforementioned heavy duty utility vehicles. Importantly, hydrogen absorption and desorption are associated with the release/absorption of large amounts of heat. Thus, thermal integration of “low temperature” MH's operating with a FC is crucial and enables the utilization of up to 40–45% of the heat produced during operation of the FC stack improving the overall system efficiency [16,17].

Main advantage of hydrogen storage systems utilising MH is in a lower hydrogen storage pressure as compared to compressed hydrogen gas storage option. According to the estimations [18], the replacement of compressed gas hydrogen storage tank with MH one on-board fuel cell vehicle allows to achieve 36.5–38.7% reduction of the refuelling costs due to significant reduction of the costs for hydrogen compression.

The goal of the EU Horizon 2020 RISE project 778307 “Hydrogen fuelled utility vehicles and their support systems utilising metal hydrides” (HYDRIDE4MOBILITY) presented in this article, is in addressing critical issues towards a commercial implementation of hydrogen powered forklifts using metal hydride based hydrogen storage and PEM fuel cells, together with the systems for their refuelling at industrial customers facilities.

Project description

Objectives and general concept

To achieve the stated goal, solutions for several technical challenges associated with the following areas of activities are required:

- Compact and efficient on-board storage of hydrogen fuel and its uninterrupted supply at the required pressures and flow rates.
- Fast refuelling; safe, reliable and inexpensive hydrogen refuelling infrastructure.
- Optimisation of the efficiency of Balance-of-Plant (BoP) and integration of the on-board power modules comprising MH hydrogen storage and fuel cells.

Success in overcoming these challenges requires a multidisciplinary approach which involves competence in several different fields including materials and systems for hydrogen storage, manufacturing and integration of the fuel cell power modules, manufacturing of the utility vehicles, as well as identifying the customers of the hydrogen fuelled utility vehicles and refining their specifications to the systems. These specialists belong to different academic and non-academic institutions located both inside and outside the EU, and it is envisaged that the strengthening of existing links and establishing new collaborative links between the different institutions will be crucial for the success. Accordingly, the specific objectives of the project include:

1. To promote international and inter-sector collaboration and sharing knowledge in the following fields:
   a. Development of utility vehicles for various applications in chemical, metallurgical and mining industries;
   b. Hydrogen fuelled fuel cell power systems for these utility vehicles;
   c. Hydrogen refuelling systems for these utility vehicles;
   d. Metal hydride based system components;
   e. Advanced metal hydride materials for the application.
2. To foster a shared approach of research, development and innovation focused on the promising application of metal hydrides for hydrogen storage and refuelling of the utility vehicles utilised by industry.
3. To develop and implement advanced engineering solutions for:
   a. Advanced fuel cell powered utility vehicles for industrial applications;
   b. Volume- and cost-efficient hydrogen storage on-board of these utility vehicles;
   c. Low-pressure refuelling of the utility vehicles characterised by low costs without significant increase of the refuelling time;
   d. Development of advanced metal hydride materials for hydrogen storage and compression and their integration in the hydrogen storage and refuelling systems characterised by improved hydrogen charge/discharge dynamics.

A general system concept previously suggested by UWC and implemented by UWC, FESB and TFD at Implats plant in fuel cell powered forklift with on-board MH hydrogen storage and on-site refuelling by hydrogen gas [16,19] is shown in Fig. 1. The system consists of a forklift (1) utilising hybrid (fuel cell + battery) power module (2) with an integrated metal hydride hydrogen storage system. The stationary hydrogen refuelling system (3) consists of a low-pressure hydrogen supply and a MH hydrogen compressor, which provides periodic refuelling of the on-board hydrogen storage system in the power module (2).

The main feature of the on-board hydrogen storage is a combination of compressed gas cylinder(s) (CGH2) and MH in an original “distributed hybrid” system developed by UWC and FESB for Implats [20] and consisting of individual MH and CGH2 tanks with a common gas manifold, and a thermal management system in which the MH tank is integrated with

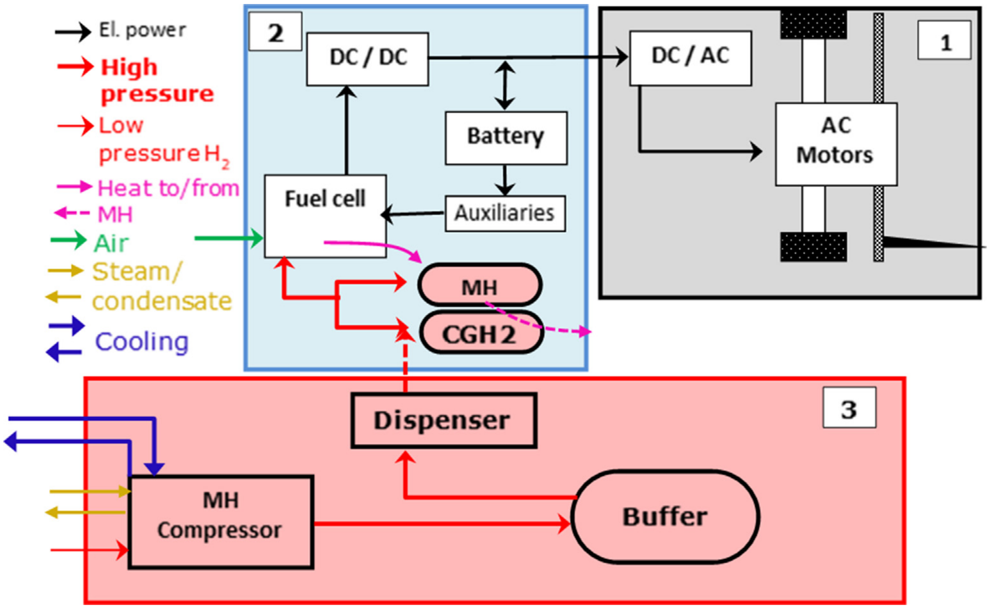


Fig. 1 – General system concept being implemented within HYDRIDE4MOBILITY project.

the cooling system of the low-temperature PEMFC BoP. This solution allows for; (i) an increase in the hydrogen storage capacity of the whole gas storage system, while reducing the H_2 charge pressure; (ii) shorter charging times in the refuelling mode and smoother peaks of H_2 consumption during its supply to the fuel cell stack; (iii) the use of standard hydrogen infrastructure parts with a simple layout and with lower costs; and (iv) adding flexibility in the layout and placement of the components of the hydrogen storage and supply system. Fast H_2 charge-discharge of the MH tank is also provided by optimisation of the MH containers for improved heat transfer performance [21].

Hydrogen refuelling (system 3) is charged by a thermally driven metal hydride hydrogen compressor which compresses low pressure H_2 available at a customer site (below 50 bar H_2) to a high pressure (200 bar) in a buffer tank (standard gas cylinder pack). Hydrogen is further dispensed to the H_2 storage system on-board the vehicle at pressures between 150 and 190 bar, which is significantly lower than the $\geq$350 bar supply pressure necessary for the refuelling of the standard CGH2 system alone. Hydrogen compression is thermally-driven, achieved by the use of low-grade steam (120–140 °C) and circulating cooling water (15–25 °C), both available at the site of the industrial customer and utilised “for free”.

The proposed approach was validated by South African and Croatian project participants [16,19] as an extension of CGH2 storage (composite cylinder) in a commercial GenDrive PEMFC power module from Plug Power Inc. The power module with the MH extension tank was integrated into a STILL electric forklift, together with the development of a refuelling station with integrated MH compressor. Both systems have demonstrated excellent performance, which has been highly appreciated by the industrial customer. Particularly, hydrogen refuelling of the forklift at dispensing pressures of 150–185 bar takes no longer than 15 min. The 15 min-long refuelling cycle allows the user to achieve a useable hydrogen storage capacity (CGH2+MH system) of about 1.83 kg H_2. This is higher than the useable capacity of the standard CGH2 tank in the commercial power module (1.69 kg H_2) at the standard refuelling pressure of 350 bar. Shortening the refuelling time to 6 min allows for 1.52 kg of H_2 to be dispensed into the CGH2 + MH system, which corresponds to 83% of its maximum useable hydrogen storage capacity.

Nevertheless, the development of the forklift and the refuelling station and their operation in the industrial environment has highlighted a number of challenges to be addressed within the present project aimed at improved efficiency of the hydrogen energy system in total:

- Necessity to further increase the useable hydrogen storage capacity and to further shorten the refuelling time using a lower refuelling pressure;
- High cost of the MH extension tank, mainly due to the high cost of the individual MH container and, to a lesser extent, the high cost and restricted availability of the MH materials;
- Necessity to improve the hydrogen refuelling system, first of all, by improving the MH hydrogen compressor resulting in a decrease of the input pressure and heating temperature, as well as increase of the hydrogen supply productivity at a required level of H_2 pressure and H_2 supply rate, and system reliability.

Consortium members

The problems specified above are being addressed by a collective effort of project consortium which includes academic teams and industrial partners from two EU Member States (Germany, Croatia), one associated country (Norway) and two third countries (South Africa, Indonesia).

Institute for Energy Technology (IFE), Norway, academic

IFE (https://ife.no) is Norway's national centre for energy and nuclear technologies. The focus of the IFE's R&D activities is in the area of renewable energy technologies integrated with use of hydrogen and electricity as energy carriers and on the petroleum sector. The IFE team involved in HYDRIDE4MOBIITY project and supervised by its coordinator (VY) has a strong background in the development and characterisation of metal hydride materials [22–25], their use for hydrogen storage and supply in the fuel cell applications [17,26], as well as thermally driven metal hydride hydrogen compressors [27,28].

Along with general management and coordination of this project, IFE is involved in the research activities focused on the development, synthesis and characterisation of advanced MH materials for hydrogen storage and compression.

Helmholtz-zentrum geesthacht zentrum für material-und küstenforschung GmbH (HZG), Germany, academic

The expertise of the HZG (https://www.hzg.de/) project team covers materials optimisation and evaluation, as well as the study, development and tests of MH containers for H_2 storage systems for FC vehicles [29,30], and hydrogen compressors integrated in their refuelling systems. In this second aspect, too, the attention to the volume efficiency and to the cost effectiveness when designing dynamic systems for on board storage or thermally driven compression is crucial. For example, the hybrid approach is often suggested to exploit at best the characteristics of intermetallic alloys [31]. The experiments on MH containers do not involve only testing the performances of the material, but also the thermal management, coupling the storages with fuel cell systems, as PEM or SOFC [32]. While the latter works in a temperature range that is more suitable for complex hydrides, the former can be coupled with intermetallic alloys and currently both computer simulations and laboratory investigations of a storage system integrated with a PEMFC are ongoing at HZG.

Within HYDRIDE4MOBILITY, the HZG team is involved in works on the advanced characterisation of MH materials (in situ phase development, characterisation at elevated pressures), as well as the specification, simulation and general layout of MH containers for H storage. The team also focuses its efforts in the framework of international and intersectorial collaborations on the development and characterisation of advanced materials for hydrogen storage and compression.

University of Split, via Faculty of electrical engineering, mechanical engineering and naval architecture (FESB), Croatia, academic

The Faculty (https://www.fesb.unist.hr/) belongs to the University of Split. The fundamental activities are R&D in the fields of Technical Sciences including Electrical Engineering, Mechanical Engineering, Computing and Fundamental Technical and Natural Sciences. FESB is the largest technical faculty outside of Zagreb, capital of Croatia.

FESB team is included in the HYDRIDE4MOBILITY project via Laboratory for New Energy Technologies. Its expertise includes fuel cell systems integration/engineering, BoP components of fuel cell systems and heat and mass transfer in PEM fuel cells. Along with the general activities related to fuel cells [7,33,34,66], the team was also involved in their integration with metal hydride hydrogen storage and supply components [17] including BoP of forklift fuel cell power modules [16,19,20] that is directly related to the scope of the present project. Accordingly, within HYDRIDE4MOBILITY, the team activities are focused on the R&D related to the integration of MH H storage systems in BoP of FC power modules for utility vehicles. The team is closely collaborating with the South African project partners (UWC and Implats) in system design and its optimisation, as well as in engineering solutions related to efficient utilization of waste heat for hydrogen desorption from MH storage by means of advanced CFD modelling. FESB is also involved in the related mechanical engineering studies including vehicle vibration analysis in real industry environment.

HYSTORSYS AS, Norway, industrial partner

HYSTORSYS AS (http://www.hystorsys.no/) is a Norwegian SMB providing hydrogen systems based on metal hydrides. The company was established in 2005. During the last years, the company has focused development of thermal metal hydride based hydrogen compressor systems. The company has built and operated for about 5000 h two proof-of-concept compressor systems, completed a cost-reduction program and developed a new improved compressor design (TRL: 8–9). Some background results have been published in Refs. [27,35,36].

Within HYDRIDE4MOBILITY, HYSTORSYS is involved in the development of MH systems for H_2 compression, including addressing thermal management issues at the system level.

University of the Western Cape (UWC), via HySA Systems Centre of Competence, South Africa, academic

UWC (https://www.uwc.ac.za) is one of the biggest South African universities. UWC participates in HYDRIDE4MOBILITY via HySA Systems Centre of Competence hosted by South African Institute for Advanced Materials Chemistry (SAIAMC) at UWC. HySA Systems is one of three Centres of Competence established by the Department of Science and Innovation (DSI) in South Africa. HySA Systems performs technology validation and system integration in several key programmes related to hydrogen and fuel cell technologies.

MH related activities at the SAIAMC have started since 2004. After the establishment of HySA Systems in 2008, R&D activities focussing on MH materials and technologies have continued within the HySA Systems' projects. At present, the SAIAMC and HySA Systems MH-related activities include: (i) Poisoning-tolerant surface modified MH materials and MH systems for H_2 separation and purification [37], (ii) preparation routes and characterisation hydride materials on the basis of Ti [38] and Mg [22], (iv) MH hydrogen storage and supply systems for fuel cell applications [17,21], (v) thermally-driven MH H_2 compressors [27,28,39] and (vi) MH hydrogen storage and refuelling systems for utility vehicles [16,19,20]. UWC, with the participation of TFD and FESB, has developed a number of engineering solutions on metal hydride and fuel cell materials and technologies including the ones directly related to the implementation of HYDRIDE4MOBILITY project [40–43].

Within the project, the UWC team is involved in the activities on (i) integration of advanced MH materials in hydrogen storage and compression systems and (ii) outlining general system layouts, as well as collaboration with European project partners in (iii) optimisation of compositions of MH materials and their upscaled manufacturing, (iv) outlining optimal system solutions for advanced MH hydrogen storage systems and compressors, and (v) integration of MH based system components in fuel cell power modules for mobile applications.

Institut Teknologi Sepuluh Nopember, Surabaya (ITS), Indonesia, academic

ITS is ranked the second amongst the best technological and science universities in Indonesia. Department of Mechanical Engineering (DoM) at ITS (https://www.its.ac.id/) has about 800 students in the undergraduate, master, and doctoral program and 47 faculty members. DoM ITS focuses on R&D on energy conversation and energy materials including automotive applications (multipurpose and electric vehicles), heat transfer and thermodynamics, failure analysis, fluid mechanics, manufacture and material. The ITS team participating in HYDRIDE4MOBILITY has a solid background in the characterisation of metal hydride materials [24,44,45] and is involved in the project activities related to (i) characterisation of MH materials for H storage & compression, (ii) system integration of MH containers on their basis and (iii) improvement of the cycle stability of the metal hydride alloys as related to the conditions of long term tests – hydrogen pressure, temperature and amount and type of impurities of the active gases present.

TF Design (pty) Ltd. (TFD), South Africa, industrial partner

TFD (https://www.tfdesign.co.za) is a South African company specialising in the fields of heat transfer and fluid dynamics. TFD develops products and projects in these fields with a strong emphasis on prototyping and experimental validation of products. TFD also produces in-house control systems and automation solutions to complement the products and thus delivers complete turnkey solutions. TFD, in collaboration with UWC, made a significant contribution in the background of HYDRIDE4MOBILITY project [19,21,39,42] laid into the general concept of the systems to be developed (Fig. 1).

Within the project, TFD is involved in in-depth development and manufacturing of prototype MH H storage tanks and H_2 refuelling systems, as well as collaboration with European project partners in optimising engineering solutions related to the design and technology for manufacturing of advanced MH containers.

Impala Platinum Ltd. (Implats), South Africa, industrial partner

Implats (https://www.implats.co.za/) is one of the world's foremost producers of platinum and associated platinum group metals (PGM). The group of companies managed by Implats produces just under a quarter of the world's supply of primary platinum. Impala Platinum is structured around five main operations including Impala, Zimplats, Marula, Mimosa and Two Rivers, with headquarters in Johannesburg. The Group's operations are also located on the Bushveld Complex in South Africa and the Great Dyke in Zimbabwe, the two most significant PGM bearing ore bodies in the world.

As an important player on the market of PGM which are in a great demand for hydrogen and fuel cell technologies addressing the global decarbonisation challenge, Implats has a strong motivation in promoting commercialisation of HFC and the related technologies. By 2019, Implats has invested around R25 million (~US$1.8 million) in targeted fuel cell development in South Africa in collaboration with government and academic institutions [46]. Special attention in these activities is paid to the validation of hydrogen transportation solutions in the mining sector [47] including the above-mentioned development of the prototype fuel cell forklift and hydrogen refuelling station integrating MH technologies in 2012–2015 [48].

As industrial customer of HYDRIDE4MOBILITY project outputs, Implats monitors the operation of the prototype units in real working environment. Within available budget for the implementation of HFC technologies, Implats will order, according customised specification, a trial series of the utility vehicles developed within this project for their use in core operations of the company.

Project activities

The R&D activities within HYDRIDE4MOBILITY are scheduled for five years (started on December 01, 2017) and split into five work packages, see Table 1.

The work package 1 is aimed at the development of advanced metal hydride materials for hydrogen storage and compression and has the following objectives:

- To promote international and inter-sector collaboration and sharing of knowledge in advanced metal hydride materials for hydrogen storage systems on-board fuel cell utility vehicles and thermally driven hydrogen compressors integrated in their refuelling systems;
- To develop and implement advanced metal hydride materials characterised by high volumetric hydrogen storage densities, suitable for the applications thermodynamics of reversible interaction with H2 gas, fast hydrogenation/dehydrogenation kinetics, as well as minimised labour efforts and costs for their industrial-scale manufacturing and further processing.

The work package 2 is aimed at the development of advanced metal hydride containers for hydrogen storage and compression, with the following objectives:

- To promote international and inter-sector collaboration and sharing of knowledge in metal hydride based system components (MH containers) for hydrogen storage systems on-board fuel cell utility vehicles and thermally driven hydrogen compressors integrated in their refuelling systems;
- To develop and implement dynamic-, volume-, and cost-efficient containment for hydrogen storage on-board of the

Table 1 – R&D activities within HYDRIDE4MOBILITY project.

Work package number	Title	Months		Lead	Other participants
		Start	End		
WP1	Development and characterisation of advanced MH materials for hydrogen storage and compression	1	48	IFE	HZG, ITS, UWC
WP2	Development of cost efficient MH containers with a focus on their mass production	4	54	HZG	UWC, IFE, HYSTORSYS, TFD
WP3	Integration of MH containers comprising advanced MH materials	7	54	HYSTORSYS	HZG, UWC, TFD, ITS
WP4	System integration	6	60	FESB	UWC, Implats
WP5	Implementation of the developed materials and systems	8	60	FESB	Implats, UWC, HYSTORSYS

Table 2 – Fitting parameters from the regression analysis (Eq. (1)).

i	Element	A_i ($Y = \mathrm{Ln}(P_0)$)		
		T = 300 K	T = 400 K	T = 500 K
0 (Y_0)	–	11.1152	7.9510	6.0524
1	Ti	−12.6756	−3.8907	1.3801
2	Zr	−40.8471	−26.0452	−17.1641
3	Fe	8.5362	9.4937	10.0682
4	Mn	−4.0428	−0.8274	1.1018
5	Cr	−7.4938	−2.7346	0.1209
6	V	−23.5277	−14.5238	−9.1215
7	Ni	7.6365	8.6366	9.2367

utility vehicles, as well as hydrogen compression for the refuelling systems.

The objectives of work package 3 aimed at the development of advanced solutions for system integration of metal hydride containers for hydrogen storage and compression include:

- Promotion of collaboration and share of knowledge between consortium partners in field of integration of advanced MH containers in on-board hydrogen storage systems and MH compressors;
- Development of efficient (both system and cost) and reliable hydrogen storage tanks for utility vehicles, as well as thermally-driven MH compressors for their refuelling stations.

The work package 4 is aimed at the development of advanced solutions for the system integration of hydrogen storage systems developed within WP3 in Balance-of-Plant (BoP) of fuel cell power modules for utility vehicles and hydrogen refuelling stations for their refuelling. The work package objectives are the following:

- To promote collaboration and share of knowledge between consortium partners in field of integration of fuel cells and its BoP components for powering utility vehicles;
- To develop efficient (both system and cost) and reliable fuel cell systems for powering utility vehicles.

Finally, the work package 5 includes activities towards implementation and pre-commercialisations of the systems (fuel cell utility vehicles and their refuelling systems comprising metal hydride components) developed within WP4. The work package has the following objectives:

- To foster a shared approach of research, development and innovation focused on implementation of metal hydride systems for hydrogen storage and refuelling of the utility vehicles used by industrial customers;
- To establish international supply – demand chain for the fuel cell utility vehicles and their support infrastructure utilising metal hydrides.

In addition, separate work packages are focused on project management and IPR issues (WP6), as well as communication and dissemination (WP7) and ethics (WP8).

Results generated during the first phase of the project (2017–2019)

During the first phase of the project (months 1–24), the project consortium contributed in all work packages listed in Table 1 above. The works were carried out both in the consortium member institutions, as well as during secondments of their staff members to the project partners. A brief summary of the results is presented below.

Advanced MH materials for hydrogen storage and compression

Material studies performed within WP1 have been in the focus of the project activities during the first stage. On the basis of systematic analysis of the literature data on the application potential of MH materials performed with active participation of the project consortium [15,49], main material problems in MH hydrogen storage and compression have been identified as:

- matching operating pressure and temperature ranges;
- increase of reversible H sorption capacities at the operating P – T conditions;
- minimising plateau slope and hysteresis;
- accelerating kinetics of H_2 absorption/desorption;
- increase of cycle stability;
- minimising volume increase upon hydrogenation.

Due to high reversible hydrogen storage capacity, variable operating pressure – temperature range, fast H_2 absorption/desorption kinetics, high cycle stability, as well as lower cost and better availability of the starting materials as compared to AB_5-type alloys on the basis of rare-earth metals and nickel, Laves phase intermetallic alloys of Ti and Zr with transition metals have shown to be promising candidates for hydrogen storage and compression applications [15,31,50–52]. Thus the strategy in the selection of the MH H storage and compression alloys allowing to solve the above-listed problems was focused on the use of Laves type solid solutions between TiM_2 and ZrM_2 where $M = Mn + Cr + Ni + V + Fe$. Numerous data on hydrogen sorption performances of $(Ti,Zr)M_2$ hydrogen storage intermetallics published since late 1970s showed a good correlation between the alloys composition and thermal stability of hydrides formed in their systems with H_2 gas [38,53–56]. To reveal the interrelationship between the composition of the material and thermodynamic performances of the corresponding hydride, we have made a regression analysis of the relevant data on AB_2-type intermetallic alloys of various compositions. The following empirical equation was used for the analysis:

$$Y = Y_0 + \sum_{i=1}^{n} A_i X_i \qquad (1)$$

where X_i is the atomic fraction of the i-th component in the intermetallic compound.

The values of the fitting parameters, A_i, are related to the effect of the i-th component on the decrease ($A_i<0$) or increase ($A_i>0$) of the plateau pressure. The literature data and own experimental results obtained by the members of the consortium (IFE, HYSTORSYS, UWC) on PCT properties of C14-$AB_{2\pm x}$ hydrogen storage alloys (~150 entries in total) were collected in a database and further processed with Eq. (1). Due to the effect of correlation between hydrogenation enthalpy and entropy [49], a satisfactory fit (see Fig. 2) was achieved when assuming $Y = \mathrm{Ln}\ (P_0)$, where P_0 is plateau pressure at different temperatures in the range 300–400 K.

The fitting results (Table 2) allowed us to draw the following conclusions:

- Variation of composition of the C14-(Ti,Zr)$(Mn,Cr,Ni,V,Fe)_{2\pm x}$ intermetallics results in the altering thermal stabilities of the corresponding hydrides thus allowing to adjust H_2 equilibrium pressure in very wide limits;
- Increase of Zr/Ti ratio, as well as increase of V content results in the significant decrease of P_0;
- Increase of Fe and Ni content results in the significant increase of P_0;
- Variations of content of Mn and Cr result in the smaller changes of P_0 as compared to the effect of Zr/Ti, V, Fe and Ni.

Additional experimentally observed effects of the component composition on hydrogen sorption performance of the (Ti,Zr) $(Mn,Cr,Ni,V,Fe)_{2\pm x}$ intermetallics included:

- Improving cyclic stability with the increase of Ti content;
- The increase of Ni nickel content results in the flatter plateaux on the pressure–composition isotherms and stabilizes C15 modification of $(Ti,Zr)M_2$ Laves phases;
- The increase of Mn content results in the increase of H storage capacity;
- Introducing V decreases hysteresis between H absorption and desorption;
- Introducing Fe results in the longer H desorption plateaux and more flat isotherms;
- Additional introducing of La in the alloy composition promotes easy activation of the alloys.

It was also shown a possibility to use the Laves phases $(Ti,Zr)M_2$ as advanced anodes for NiMH batteries characterised by high capacity at high discharge current densities (Fig. 3). The most important feature of the Laves phases for this application was found to be structure modification (cubic C15 exhibits better electrochemical performance than hexagonal C14) which can be controlled by stochiometric ratio $M/(Ti + Zr)$, as well as the content of Zr and Ni in the alloy. The alloys with $M/(Ti + Zr) > 2$, higher Zr/Ti ratio and high Ni content stabilise C15 type [57].

Additional material-related studies within HYDRIDE4-MOMILITY project were focused on the upscale effects in the manufacturing of Ti-based hydrogen storage materials, particularly, on the influence of oxygen in the metallic matrix on the material properties including hydrogen sorption performance [58,59]. Some works [60–63] also analysed "high-temperature" MH's and their integration in the heat management applications which potentially can give an opportunity to increase the efficiency of utilization of heat from industry and other sources including renewables that is necessary for driving MH compressors.

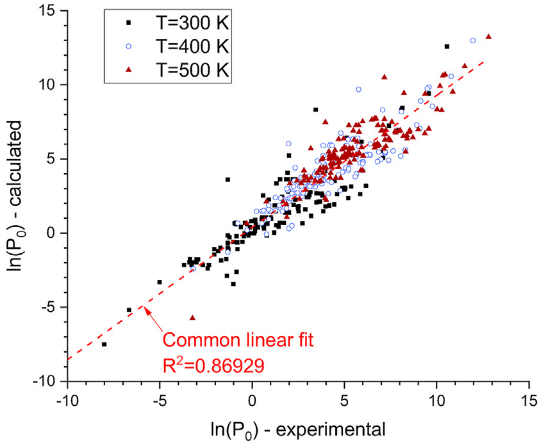


Fig. 2 – Correlations between experimentally observed and calculated (Eq. (1), Table 2) plateau pressures (T = 300–500 K) of intermetallic hydrides on the basis of C14-(Ti,Zr) $(Mn,Cr,Ni,V,Fe)_{2\pm x}$ hydrogen storing intermetallics.

Hydrogen storage systems

Development of hydrogen storage systems for the fuel cell forklifts were in the focus of the project activities within WP2 and WP3. The main system component is a MH container made of 2″ OD stainless steel tube and equipped with internal perforated copper fins (Fig. 4). The basic design initially developed by TFD and UWC was further optimised towards its adaptation for mass production. The container is filled with ~3 kg of the AB_2-type MH material (optimised within WP1) in the form of coarse powder mixed with the powder of expanded natural graphite (ENG) for the improvement of the heat transfer performance. Moreover, the ENG acted as a cushion to absorb the swelling of the metal hydride particles when they increase volume during hydrogenation thus allowing to increase the safe MH loading density.

Further optimising of the hydrogen storage system was focused on the alignment of its characteristics with the requirements of the target application. Compactness and high weight in combination with the necessary hydrogen storage capacity and fast hydrogen charge/discharge were critical problems addressed in the course of the optimisation. As a result, a new engineering solution [43] has been successfully implemented in the MH tank made as an assembly of MH cassettes where the MH containers were staggered together with the heating/cooling tubes encased in molten and further solidified lead. The tank which combines compactness, adjustable high weight, as well as good dynamics of hydrogen charge/discharge has been successfully integrated in fuel cell power module for 3-tonne electric forklift ([64]; see Fig. 5 and Section System integration below).

H_2 compression

The work package 2 also included activities on the development of MH containers for the high pressure (≥500 bar) hydrogen compression. TFD and UWC have developed two prototypes of the MH containers on the basis of stainless steel liner wound by carbon fibres (Fig. 6).

In the first prototype (Fig. 6, top), ~1.8 kg of the powder of AB_2-type hydrogen compression alloy (a series of the materials developed within WP1) was loaded in a cartridge (1) assembled from shaped copper fins attached to the heating/cooling U-tube. The MH cartridge was placed in a liner (2) made of a thin stainless steel tube with attached stainless steel endcaps one of which (3) carried hydrogen input/output pipeline and another (4) – pipelines for the input and output of heating (steam) and cooling (water) fluid. The liner was reinforced by a thick layer of carbon fibre wounding (5).

The pressure tests of the 1st prototype managed by TFD showed that it withstands hydraulic pressure (oil) above 1800 bar and gas pressure (N_2) of 650 bar without rupture and leaks both before and after thermal cycling between 20 and 150 °C. Further tests showed feasibility of the application of the developed MH container for hydrogen compression. Excellent dynamics of H_2 charge ($T = 15–20\ ^\circ C$, $P(H_2) = 100$ bar) and discharge ($T = 150\ ^\circ C$, $P(H_2) = 500$ bar) was observed, when a duration of complete H_2 absorption/desorption was about 5–10 min [15,49].

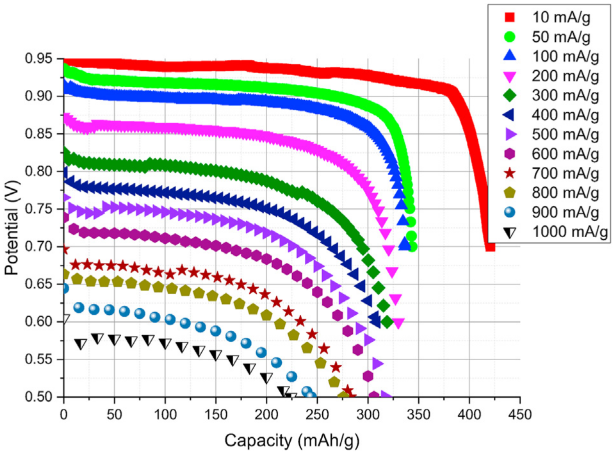


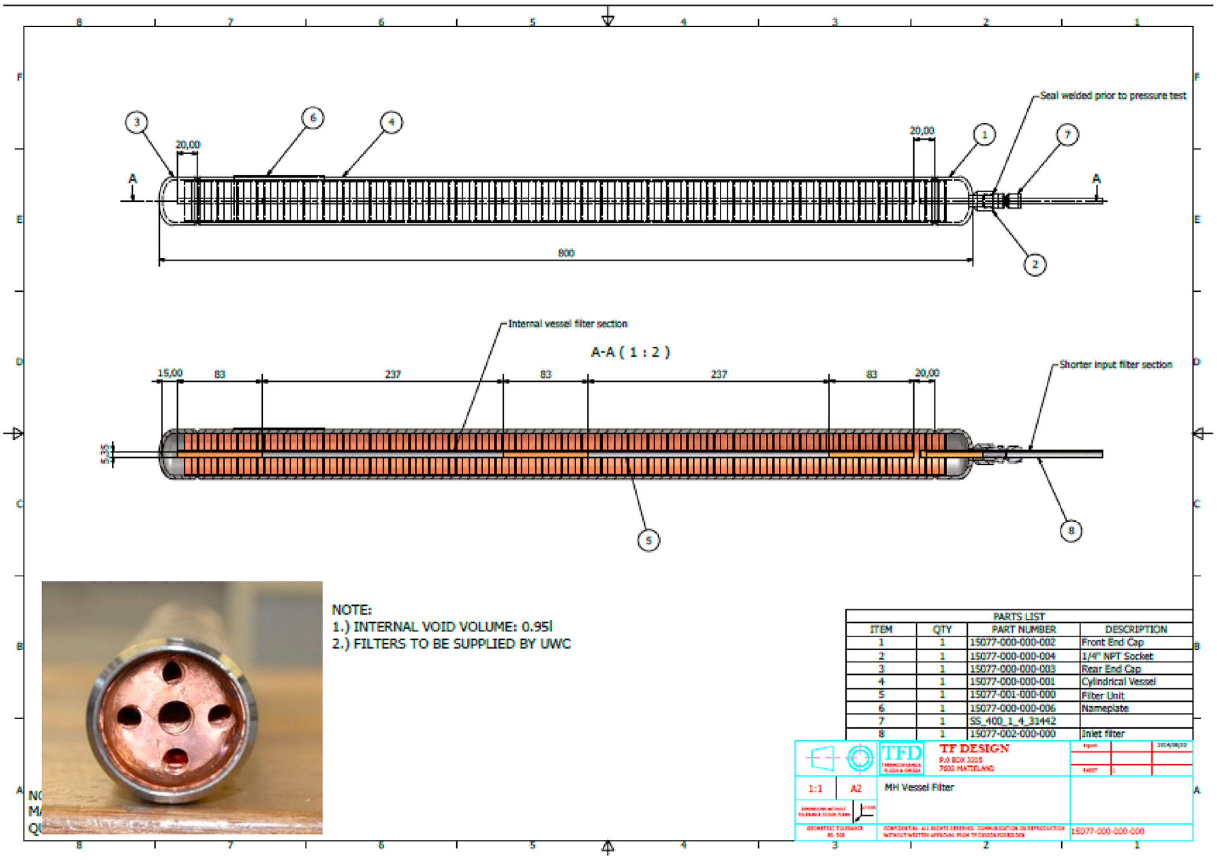
Fig. 3 – Electrochemical capacity of the $AB_{2-x}La_{0.03}$ alloys ($A = Ti_{0.15}Zr_{0.85}$; B=Ni, Mn, V, Fe) at variable discharge current densities and cut-off potentials [57].

However, already after 7 thermal cycles, the fibre wound layer of the MH container exhibited a slight delamination that raised safety concerns. In addition, large void volume of the inner part of the liner and the associated "dead" space resulted in the significant decrease of H_2 compression productivity at the discharge pressures above ~400 bar. Other disadvantage is in the layout of the MH compartment (cartridge inside the liner) that requires interruption of the manufacturing process for loading the MH before the final assembling, thus complicating the manufacturing technology. Finally, the thick carbon filament winding used for the 1st prototype introduces additional cost implications for the manufacturing.

The above-mentioned problems have been recently addressed in the developed 2nd prototype of the composite MH container for H_2 compression (Fig. 6, bottom). In the second prototype, the liner was made of the longer stainless steel tube having two times smaller diameter. This allowed to reduce the thickness of the fibre wound layer thus minimising probability of its delamination after multiple thermal cycling and saving the costs. The MH powder is loaded directly in the liner through a hole made in the thick endcap carrying the H_2 input/output pipeline (3). Despite an insignificant worsening of the dynamics of the heating/cooling of the MH bed, preliminary tests of the 2nd prototype (test pressures up to 2000 bar at the temperatures of 20 and 150 °C) showed its suitability to compress H_2 above 700 bar. The test results will be published in a due course.

System integration

Main activity within WP4 included development, testing and optimisation of fuel cell power module for 3-tonne electric forklift with integrated hydrogen storage system (see Section Hydrogen storage systems). The module (Table 3) build by UWC and its subcontractor uses liquid cooled 9SSL fuel cell stack (Ballard) whose operation is provided by three BoP systems: system for controlled supply of hydrogen fuel and oxidant (air), stack cooling system, and power conditioning



NOTE:
1.) INTERNAL VOID VOLUME: 0.95l
2.) FILTERS TO BE SUPPLIED BY UWC

PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	15077-000-000-002	Front End Cap
2	1	15077-000-000-004	1/4" NPT Socket
3	1	15077-000-000-003	Rear End Cap
4	1	15077-000-000-001	Cylindrical Vessel
5	1	15077-001-000-000	Filter Unit
6	1	15077-000-000-006	Nameplate
7	1	SS_400_1_4_31442	
8	1	15077-002-000-000	Inlet filter

Fig. 4 – Assembly drawing of the metal hydride container used in hydrogen storage systems for the fuel cell forklift. The inset shows inner view of the container with installed copper fins.

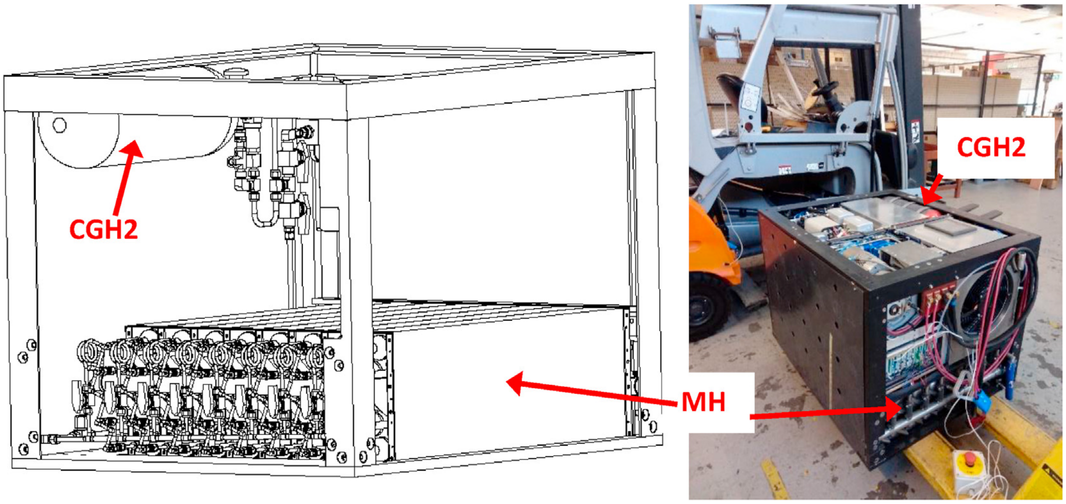


Fig. 5 – Hydrogen storage system comprising MH tank and compressed gas cylinder (CGH2) integrated in the forklift fuel cell power module. Left – 3D drawing, right – installation of the power module in the forklift.

and control system [64]. Direct integration of the MH tank in the power module allowed to decrease minimum H_2 pressure on the high-pressure side of H_2 subsystem from 13.5 to 3–4 bar and to use more stable MH resulting in a lower refuelling pressure (100–150 against 185 bar) at the similar useable H_2 storage capacity and refuelling time as compared to the commercial FC power module with MH extension tank [16].

The power module provided stable operation of the forklift during 60 complete cycles of the on-board test according to VDI2198/VDI60 testing protocol. Further optimisation will be focused on reducing the BoP power consumption and H_2 fuel

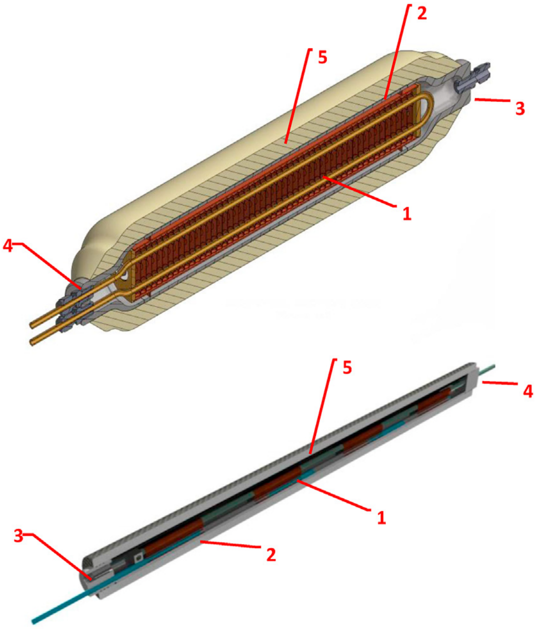


Fig. 6 – Composite MH containers for H_2 compression. Top – 1st prototype, bottom – 2nd prototype. 1 – MH compartment, 2 – SS316 liner, 3 – SS316 endcap with H_2 input/output pipeline (and MH loading hole for the 2nd prototype), 4 – SS316 endcap with pipelines for the supply/removal of the heating/cooling fluid, 5 – carbon fibre wounding.

consumption, as well as on the improvement of operation control algorithm towards increase of the operation stability at high loads.

Analysis of long-term operation of fuel cell forklift with MH H_2 storage extension tank and refuelling station with integrated MH compressor at Impala Platinum refineries

The project activities during 2017–2019 related to WP5 included analysis of long-term operation of the pilot prototypes of fuel cell forklift with metal hydride hydrogen storage extension tank and hydrogen refuelling station with integrated metal hydride compressor earlier developed by UWC and TFD with participation of FESB and commissioned at Implats (Springs, South Africa) in September–October 2015 [16,19]. Fig. 7 shows on-site demonstration of the forklift refuelling during the last inspection by the European HYDRIDE4MOBILITY consortium members seconded to South Africa at the end of 2019.

During four-year long operation of the fuel cell forklift at Implats (October 2015–February 2019), the operating time of the fuel cell stack counted about 1000 h at average electric power between 12 and 15 kW. All major issues in the operation of the fuel cell power module (Plug Power) identified during the course of its service were related to failures of Li-ion battery and, less frequently, other BoP components (stack cooling system, air compressor). No issues in the operation of the metal hydride hydrogen storage extension tank were observed.

Analysis of system malfunctions allowed the project team to further optimise layout of the advanced fuel cell power module with integrated metal hydride hydrogen storage tank developed within this project (see Section System integration above).

Main parameters of the hydrogen refuelling station during its on-site operation since commissioning in end September 2015 [65] are summarised below:

- 4500 operating hours (MH compressor);
- Compressed ~1500 Nm^3 H_2;
- Dispensed ~900 Nm^3 H_2;

Typical issues, mainly resulting in the drop of the MH compressor productivity and resolved during service works, included: (i) contamination of pipelines with fine powder of the MH material; (ii) malfunctions of the control system; (iii) slow decrease of the productivity possibly caused by the accumulation of gas impurities in the system.

The breakdown of capital costs incurred by Implats and UWC for the development, manufacturing and installation of the hydrogen refuelling station was the following:

- MH compressor parts – 25%;
- Assembling – 28%;
- Dispenser – 33%;
- Other costs – 14%.

The annual operation costs of the refuelling station were estimated as ~5.2% of the capital costs. We note that these costs mainly incurred for the service and upgrade of the prototype to eliminate its defects which can be identified only during prolonged operation, will be significantly lower in the future when the defects will be eliminated already at the design stage.

Summary and outlook

In order to achieve successful implementation of the project's technical targets, an interdisciplinary collaboration between the staff of the consortium members was undertaken. By exchanging staff in complementary fields of hydrogen technologies (materials, containers, hydrogen storage and supply systems, BoP of fuel cell power module), the participating members got a better training for taking up future technical

Table 3 – Power module main specifications.

Donor vehicle	STILL RX60-30L
Bus voltage	80 VDC
Output power	~15 kW average, 30 kW peak
Dimensions	840 mm (W) x 1010 mm (D) x 777 mm (H)
Weight	1800 … 1900 kg
Stack	14.5 kW closed cathode PEMFC stack (Ballard)
H_2 storage	Integrated MH storage unit, 20 Nm^3
Battery bank	Deep cycle lead-acid, 8 … 10 kWh

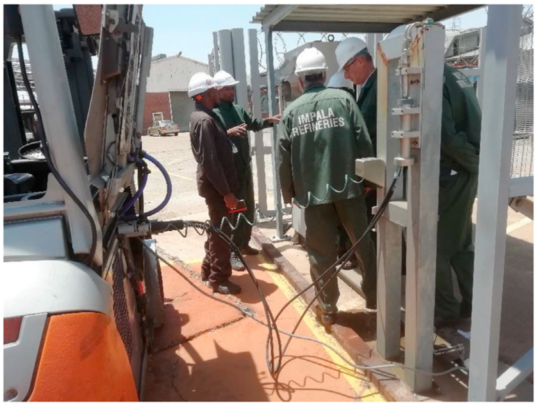


Fig. 7 – Implats representatives demonstrate to seconded HYDRIDE4MOBILITY consortium members (HZG, HYSTORSYS) on-site refuelling of the fuel cell forklift with MH hydrogen storage extension tank. Springs, South Africa, November 2019.

challenges connected to the different market areas in emerging hydrogen technologies. The HYDRIDE4MOBILITY staff exchange was focused on knowledge exchange between various participants exploring the available complementary expertise at different participating institutions. During the first phase of the project, the total duration of the inter-institutional secondments of the project consortium members was about 28 months. Regretfully, the staff exchange activities were interrupted in end March 2020 due to COVID-19 related lockdown.

The materials studies within the project activities showed that Zr/Ti-based Laves type alloys are excellent choice for the H storage and compression systems capable of reaching pressures above 500 bar H_2. Their results, together with the results of engineering-related project activities have shown feasibility of realisation of the general system concept related to the integration of MH in both onboard hydrogen storage systems for the utility vehicles (test case – forklift), and, also for their H_2 refuelling systems.

Various features of materials development and system building and system integration should be addressed in parallel to arrive to the commercially competitive solutions.

The project results will facilitate further market penetration of efficient and environment friendly hydrogen energy technologies by the establishment of a promising market niche in the emerging Hydrogen Economy, both in Europe and in partner countries. The particular niche for the products to be implemented upon finalising the project will include materials handling units and their service facilities characterised by zero emissions of carbon dioxide and able to operate at conditions (e.g., confined space) which don't accept emissions of any harmful exhaust gases and significant heat emissions (including waste heat generated by industries).

Research outputs generated during the first two years of running the progress include three reviews [15,49,60], 8 research articles [57–59,61–65] and numerous presentations at international conferences relevant to energy and hydrogen storage technologies. Additional details are presented on the project website http://hydride4mobility.fesb.unist.hr/.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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