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HyCo

Hydrogen Metal Hydrides Thermal Compressor with Low Operational Cost

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Summary

The project aims at demonstrating the technical and economic performance of a metal hydride hydrogen compression technology ("HyCo") at an industrial scale and under real-working conditions. The system was developed with the aim to reach a capacity of 30 kg_{H2}/h and a pressure range from 10 bar to 200 bar. The technology has the potential to replace the conventional mechanical compression in certain applications, for instance where waste heat is available, combined storage-compression is needed or where other factors such as noise, maintenance and vibration are of relevance. This project includes the development, manufacturing and testing of such a metal hydrides compressor. The development included major work in materials science (development of the right metal hydrides materials), thermal design (optimization of the design), process engineering and mechanical engineering. The testing on site requested substantial effort in the optimization of the process logic, software development, and plant integration. The compressor has been successfully manufactured and installed. The system is now operated under normal industrial conditions. This final report details the work done and the results from the project. The compressor is able to reach the 200 bar target using the thermal energy available on site in the form of steam for heating and river water for cooling. The system has already been operated for days in the filling of hydrogen trailers. The thermal heating consumption averaged 8.8 kWh_{th}/kg_{H2}. The thermal energy must be provided at a temperature of around 120°C, which corresponds to low-pressure steam. The electrical energy consumption was measured to 0.2 kWh_{el}/kg_{H2}. To the knowledge of the authors, the compressor built within this project is one of the largest metal hydrides hydrogen compressors worldwide. The target sales price of the metal hydrides compressor is at the same level as a comparable mechanical compressor, however with potentially lower OPEX if a free or very cheap heat source is available, which could lead to typical levelized costs of compression reduced from around up to CHF 1.5 per kg_{H2} to CHF 0.55 per kg_{H2}. The results obtained show the potential competitiveness of the technology in application cases where waste heat in the form of low-pressure steam is readily available. This typically includes industrial sites such as chemical plants (e.g., Ammonia production, synthetic fuel production, etc.), refineries, steel plants, and other industries with high stream of thermal energy available. Based on these results, the commercial launch of a new product is planned.

Zusammenfassung

Das Projekt zielt darauf ab, die technische und wirtschaftliche Leistungsfähigkeit einer Metallhydrid-Wasserstoffkompressionstechnologie („HyCo“) im industriellen Massstab und unter realen Betriebsbedingungen zu demonstrieren. Das System wurde mit dem Ziel entwickelt, eine Kapazität von 30 kgH_2/h sowie einen Druckbereich von 10 bar bis 200 bar zu erreichen. Die Technologie hat das Potenzial, die konventionelle mechanische Kompression in bestimmten Anwendungen zu ersetzen – beispielsweise dort, wo Abwärme zur Verfügung steht, eine kombinierte Speicherung und Kompression erforderlich ist oder andere Faktoren wie Lärm, Wartungsaufwand und Vibrationen eine Rolle spielen. Dieses Projekt umfasst die Entwicklung, Herstellung und Erprobung eines solchen Metallhydridkompressors. Die Entwicklungsarbeiten umfassten wesentliche Tätigkeiten in der Materialwissenschaft (Entwicklung geeigneter Metallhydridmaterialien), im thermischen Design (Optimierung des Aufbaus), in der Verfahrenstechnik sowie im Maschinenbau. Die Tests vor Ort erforderten einen erheblichen Aufwand bei der Optimierung der Prozesslogik, der Softwareentwicklung und der Integration in den Industriestandort. Der Kompressor wurde erfolgreich gefertigt und installiert. Das System wird nun unter normalen industriellen Bedingungen betrieben. Dieser Abschlussbericht dokumentiert die durchgeführten Arbeiten sowie die Ergebnisse des Projekts. Der Kompressor erreicht den Zielwert von 200 bar mithilfe der am Standort verfügbaren thermischen Energie in Form von Dampf zum Heizen und Flusswasser zum Kühlen. Das System wurde bereits über Tagen beim Befüllen von Wasserstoff-Trailern betrieben. Der thermische Energieverbrauch lag im Durchschnitt bei 8,8 kWh_{th}/kg_{H2}. Die thermische Energie muss bei einer Temperatur von etwa 120 °C bereitgestellt werden, was niedrigem Dampfdruck entspricht. Der elektrische Energieverbrauch wurde mit 0,2 kWh_{el}/kg_{H2} gemessen. Nach Kenntnis der Autoren handelt es sich bei dem im Rahmen dieses Projekts entwickelten Kompressor um einen der grössten Metallhydrid-

Wasserstoffkompressoren weltweit. Der angestrebte Verkaufspreis des Metallhydrid-Kompressors liegt auf dem gleichen Niveau wie der eines vergleichbaren mechanischen Kompressors, jedoch mit potenziell geringeren Betriebskosten falls eine kostenlose oder sehr günstige Wärmequelle verfügbar ist, was zu typischen reduzierten nivellierten Kompressionskosten von etwa bis zu CHF 1.5 pro kg_{H2} auf CHF 0.55 pro kg_{H2} führen könnte. Die erzielten Ergebnisse zeigen die mögliche Wettbewerbsfähigkeit der Technologie in Anwendungsfällen, in denen Abwärme in Form von Niederdruckdampf leicht verfügbar ist. Dies umfasst typischerweise Industrieanlagen wie Chemiewerke (z. B. Ammoniakproduktion, Herstellung synthetischer Kraftstoffe usw.), Raffinerien, Stahlwerke und andere Industrien mit einem hohen Aufkommen an verfügbarer thermischer Energie. Auf Grundlage dieser Ergebnisse ist die Markteinführung eines neuen Produkts geplant.

Résumé

Le projet vise à démontrer la performance technique et économique d'une technologie de compression d'hydrogène par hydrures métalliques (« HyCo ») à l'échelle industrielle et dans des conditions de fonctionnement réelles. Le système a été développé dans le but d’atteindre une capacité de 30 kg_{H_2}/h et une plage de pression allant de 10 bar à 200 bar. Cette technologie a le potentiel de remplacer la compression mécanique conventionnelle dans certaines applications, notamment lorsque de la chaleur résiduelle est disponible, qu’une solution combinant stockage et compression est nécessaire, ou encore lorsque des facteurs tels que le bruit, l’entretien et les vibrations sont importants. Ce projet comprend le développement, la fabrication et les essais d’un tel compresseur à hydrures métalliques. Le développement a nécessité des travaux importants en science des matériaux (développement des matériaux hydrures appropriés), en conception thermique (optimisation du design), en génie des procédés et en ingénierie mécanique. Les essais sur site ont demandé des efforts considérables pour optimiser la logique de processus, développer les logiciels et intégrer le système à l'installation. Le compresseur a été fabriqué et installé avec succès. Le système est désormais en fonctionnement dans des conditions industrielles normales. Ce rapport final détaille les travaux réalisés et les résultats du projet. Le compresseur est capable d’atteindre l’objectif de 200 bar en utilisant l’énergie thermique disponible sur site, sous forme de vapeur pour le chauffage et d’eau de rivière pour le refroidissement. Le système a déjà fonctionné plusieurs heures pour le remplissage de remorques à hydrogène. La consommation d’énergie thermique s’élevait en moyenne à 8,8 kWh_{th}/kg_{H2}. L’énergie thermique doit être fournie à une température d’environ 120°C, ce qui correspond à de la vapeur basse pression. La consommation d’électricité a été mesurée à 0,2 kWh_{el}/kg_{H2}. À la connaissance des auteurs, le compresseur développé dans le cadre de ce projet est l’un des plus grands compresseurs à hydrures métalliques pour l’hydrogène au monde. Le prix de vente cible du compresseur à hydrures métalliques se situe au même niveau que celui d’un compresseur mécanique comparable, mais avec des coûts d’exploitation (OPEX) potentiellement bien inférieurs si une source de chaleur gratuite ou à basse prix est disponible, ce qui pourrait réduire les coûts nivelés de compression typiques d’environ CHF 1.5 par kg_{H2} à CHF 0.55 par kg_{H2}. Les résultats obtenus démontrent la compétitivité potentielle de cette technologie dans des applications où la chaleur fatale, sous forme de vapeur à basse pression, est facilement disponible. Cela inclut généralement des sites industriels tels que les usines chimiques (par exemple, la production d’ammoniac, la production de carburants synthétiques, etc.), les raffineries, les aciéries et d’autres industries disposant d’un important flux d’énergie thermique disponible. Sur la base de ces résultats, le lancement commercial d’un nouveau produit est prévu.

Main findings («Take-Home Messages»)

- The metal hydrides hydrogen compression technology was demonstrated at an industrial scale never done before, successfully filling industrial hydrogen trailers with a compression ratio of 10 bar to 200 bar.
- The system was successfully integrated in an industrial environment and used to refill hydrogen trailers.
- The thermal heating consumption averaged 8.8 kWh_{th}/kg_{H2}. The electrical energy consumption was measured to 0.2 kWh_{el}/kg_{H2}.
- For industrial sites with waste heat available in the form of low-pressure steam, the metal hydride compressor can potentially achieve lower operation costs than the mechanical, leading to reduced costs of hydrogen.
- The technology will be commercialized as a standard product in the upcoming months.

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AGAS	Advanced Gas Sorption Analysis System
COP	Coefficient of Performance
HP	High Pressure
HPS	High Pressure Stage
HyCo	Hydrogen Compressor, name given to the metal hydrides hydrogen compression technology developed by GRZ
LP	Low Pressure
LPS	Low Pressure Stage
MH	Metal hydrides
PCT	Pressure – Composition isothermal curves
PID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
SFOE	Swiss Federal Office of Energy
TRL	Technology Readiness Level

1 Introduction

1.1 Context and motivation

The compression of hydrogen is one of the main challenges to be solved in order to accelerate the widespread use of hydrogen as a fuel and to reduce its costs. The current technology relies on the use of mechanical compressors which compress hydrogen with the use of motors, pistons, membranes or other moving parts. These technologies often have significant drawbacks as follows:

- High electrical energy consumption, which increases the levelized costs of hydrogen
- High noise generation, which requires costly mitigation measures
- Substantial heat generation, which must be evacuated through adequate cooling systems
- Vibration, which can lead to mechanical failures of connected systems if not dealt with properly
- High maintenance needs, leading to high OPEX and frequent down-time

Alternative compression technologies (non-mechanical solutions) such as electrochemical hydrogen compression often cannot reach very high pressures and high capacities and require the use of expensive membranes and other materials. Further, the question of the compression efficiency (electrical consumption per kilogram of hydrogen compressed) is of paramount importance.

Hydrogen compression using metal hydrides has the potential to address some of these problems. Advantages of this technology include:

- The metal hydride compressor may be exploited as a storage unit at the same time, i.e. the system represents a combined storage and compressor unit: in operation, hydrogen can be stored directly from an electrolyzer (without compression, liquefaction, etc.) and then kept until compression is required.
- Use of thermal energy: if available, thermal energy can be used instead of mechanical energy, opening up new options for energy optimization and integration.
- No noise: as there are no major moving parts, the noise level is extremely low.
- Low maintenance: another advantage of the lack of moving parts is the low level of maintenance required.
- Metal hydride materials have already been developed to reach extremely high pressures (>875 bar) and due to the modular nature of the technology, it is easily scalable.

The basis of metal hydride-based hydrogen compression is the use of metal alloys to first absorb the hydrogen at a low temperature and pressure. This process is exothermic, and the heat must be released (and can potentially be used elsewhere). The pressure of the absorbed hydrogen is directly related to the temperature of the metal hydride material, and hence the hydrogen can be compressed by increasing the temperature of the system. At the high pressure, the hydrogen is desorbed from the metal hydride material. This desorption process in endothermic and only requires a heat input. This allows for a purely thermal compression – the system needs to be cooled down while hydrogen is being charged to the metal hydrides and then heated while the hydrogen is being compressed and released.

Two key areas necessitating research and engineering efforts in the development of metal hydride compressors are the material development and the thermal management of metal hydride systems. The heart of the metal hydride compression technology is the development and production of suitable metal alloys for compression. In this regard, the main challenge is maintaining the hydrogen storage capacity across the large number of cycles (absorbing – compressing – desorbing), which is termed as cycle stability. Further, the absorption and desorption characteristics of the materials should be favorable, and the materials used in the alloy should have stable and low market prices.

The second main challenge is the thermal management of the system. Metal hydride compression is thermally driven, and thermal management of the system directly affects efficiency and cost of the whole system. Availability of waste heating and cooling can significantly increase efficiency of the system and minimize operating costs. When using electricity for heating/cooling power, high COP heat pumps must be integrated into the system. Moreover, low thermal conductivity of the alloy powder necessitates the careful design of metal hydride container for proper spreading of heat within the powder.

GRZ Technologies has specialized in both the development and optimization of metal hydrides materials and the thermal management systems, becoming a global leader in the field of metal hydrides hydrogen compression. This fact is underlined by the involvement of Hyundai Motor Company in GRZ Technologies SA and the collaration on the technology.

The need for exclusively thermal heating and cooling means that metal hydride compressors have potential applications in several markets including the chemical industry, renewable energy, emergency power, hydrogen infrastructure etc. Many industrial processes generate a large amount of waste heat and require pressurized hydrogen as feedstock. Metal hydride compressors become an ideal choice for these applications [1].

Several technologies already utilizing metal hydride compression technology exist across the world. The Flexi HyCo systems developed by GRZ with an output pressure of up to 200 bar providing pressurized hydrogen to laboratory needs is available commercially and has been sold internationally. A distribution agreement was reached with the company KEP International in November 2021[1]. Apart from this, the metal hydride compression technology has also received interest from research and development teams from United states and Europe and several projects related to the development, scaling and commercialization of such systems have been funded. Recent projects include:

- ATLAS – H2, EU FP7 project, 2010-2014 [2]
- ATLAS - MHC, follow-up of ATLAS - H2 2014-2019 [3]
- COSMHYC DEMO, EU Horizon 2020 project, 2021-2023 [4]

The COSMHYC project specifically focuses on the application of metal hydride compression in hydrogen mobility.

HYSTORYSYS developed two proof-of-concept compressor systems that compress hydrogen from 10 bar to 200 bar namely HYMEHC-10 (hydrogen throughput of 10 Nm^3_{H2}/h) and HYMEHC-5 (hydrogen throughput of 5 Nm^3_{H2}/h). HyMEHC-10 was operated for about 3500 h and the only maintenance during operation was replacement of a shut off valve after 2000 h of operation. This proof-of-concept system demonstrated the reliability of using metal hydride compression with reduced maintenance costs.

SAIAMC/UWC built a metal hydride compressor for Eskom Holdings Ltd., South Africa for pressuring hydrogen from 3 bar to 200 bar. The compressor was designed to provide the required compression operating between 25°C and 130°C. However, pressures as high as 240 bar were achieved at the same operating temperatures (at reduced throughput).

Over the past years, several researchers published studies that focused on assessing efficiencies of the MH compression. Lototskyy et al. [5] presented the operation data of hydrogen refueling station consisting of MH compressor for a duration of three years. This station provides hydrogen dispensing at a pressure up to 185 bar at a flow rate of 13 Nm^3_{H2}/h. The heating power is provided by steam at 140°C and cooling by water at 20°C. The refueling station has shown the feasibility of metal hydride

[1] https://setaramsolutions.cn/en/flexi-hyco-is-launched

compression. The study also described ways of further optimization of the compression system and demonstrated the feasibility of metal hydride compression for refueling station.

Gkanas et al. [6] presented the design study performed on seven stage metal hydride compressor for application in hydrogen refueling stations. This study is a part of the project ATLAS-MHC. The study has also provided detailed estimates of energy required for each stage. In general, the addition of extra stage of compression has lowered the efficiency of the thermal compressor but has achieved a higher output pressure.

Costamagna et al. [7] performed assessment and comparison of environmental and economic impact between MH compression, mechanical compression, and air booster. The use of waste heat and cooling reduced both the economic and environmental impact of the metal hydride compressor. The authors noted reducing the mass of steel used and increasing cycle stability can further reduce the environmental impact.

Tarasov et al. [8] provided a study that demonstrated the feasibility of metal hydride compressors for industrial applications. The compressed hydrogen capacity dropped with increasing cycles due to degradation of the metal hydride material. Having a longer cycle time has slowed down the drop in compressed hydrogen capacity and throughput rate.

In the current project, GRZ Technologies focuses on the design and scale-up of a continuous metal hydride based compressor system to demonstrate the technology in an industrial environment.

1.2 Project objectives

The purpose of the project is to upscale and validate the potential of the novel compression technology by applying it in an industrial environment and directly comparing it with existing technologies. Eventually, the successful realization of this project will set the basis for the commercialization of a novel hydrogen compression technology that could replace the conventional one with significant additional advantages.

The project should enable improving the technology readiness level (TRL) by several levels to reach a TRL 8 according to the European Union definition (System prototype demonstration in operational environment / System complete and qualified). This makes is ready for commercialization. Continuous testing, improvement of the system and additional design features will enable GRZ to reach a TRL9 and start the commercialization of the technology.

The main objectives of the project were set as follows:

1. Technology demonstration at industrial scale: currently, Messer operates a mechanical membrane compressor (2 stages) on the site of Arxada in order to compress hydrogen and refill trailers. One objective of the current project is to demonstrate the metal hydrides hydrogen compression technology at industrial scale and under real-working conditions.
2. Measurement of performance data under real-working conditions: another critical objective of the project is to obtain actual performance data on the performance, costs (CAPEX and OPEX), reliability and efficiency of the compressor. This will be monitored at the critical locations of the system and values such as the outlet pressure, the flow rate, and the energy consumption of the system will be recorded.
3. Reference project for commercialization: finally, the project should be a milestone for the commercialization of the HyCo technology at industrial scale. Potential customers shall be invited to the site. A comparison of the levelized cost of hydrogen compression will be provided based on actual data to demonstrate the advantages of the metal hydrides hydrogen compression

technology. The levelized cost of compression is calculated by considering the CAPEX of the system, the OPEX of the system over the full lifetime (typically 20 years) of the compressor and under consideration of a discount rate (typically 4%). The OPEX includes the cost of energy (electricity) as well as the maintenance costs. The total costs (CAPEX + OPEX) are discounted and divided by the total quantity of hydrogen compressed, discounted over time. This results in the levelized cost of compression. A detailed calculation is shown in Table 6.

2 Approach, Method, Results and Discussion

The design of the metal hydrides hydrogen compressor to be built is based on the existing, mechanical compressor, which has the following specifications:

- Inlet pressure: 10 bar
- Outlet pressure: 200 bar
- Flow rate: 30 kg_{H2}/h

Operational data from the mechanical compressor are available and compared to the metal hydrides compressor in Table 6. The two systems are then compared based on their levelized costs of compression.

The metal hydrides system is designed to meet the same specifications. In addition, the following specifications have been set:

- Type: Metal Hydrides compressor
- Cooling medium: water (through intercooler with the river water)
- Heating medium: steam (2.5 bar)
- Number of stages: 2

The different aspects of the compressor design are described in the following sections.

2.1 Overall Project Concept

The basic functioning of metal hydride-based compressors involves a cycle where the hydrogen is first charged (absorbed), then compressed and then discharged at the higher pressure (desorbed). Due to this cycle, most metal-hydride based systems operate in a batch mode.

To overcome this, the system is designed to use two modules in parallel such that when one module is getting recharged (i.e., undergoing absorption), the other module is discharging the compressed hydrogen (i.e., undergoing desorption). The hydrogen compression is to be done from 10 bar to 200 bar. This is a relatively high compression ratio (20x) and therefore it is done in two stages. The first stage compresses the hydrogen from 10 bar to 45 bar, and the second stage further increases the pressure to 200 bar. To achieve the continuous compression, we therefore use two modules of each stage, leading to a total of four metal hydrides stacks required.

The basic compression diagram as well as the functioning of the four stacks at different points in the compression cycle are shown in Figure 1 and Figure 2 below. The figure shows how by cycling two modules of the compressor – each containing a low and high pressure compressor –a constant inlet flow can be achieved at 10 bar (the lowest horizontal line) and a constant outlet flow at 200 bar (the highest horizontal line).

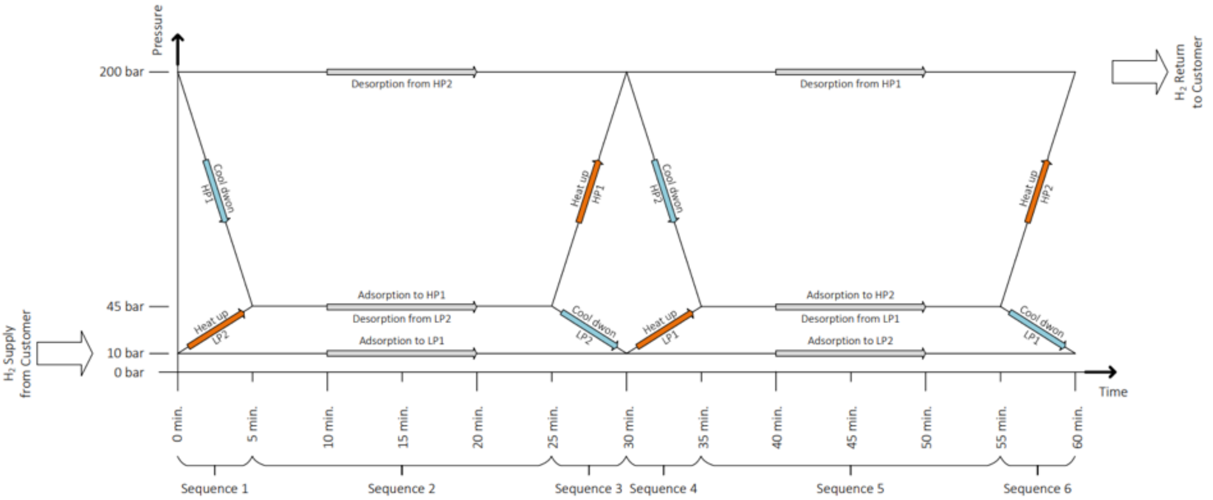


Figure 1: Various compression steps and corresponding pressure of each stage (LPS: Low-pressure stage, HPS: High-pressure stage).

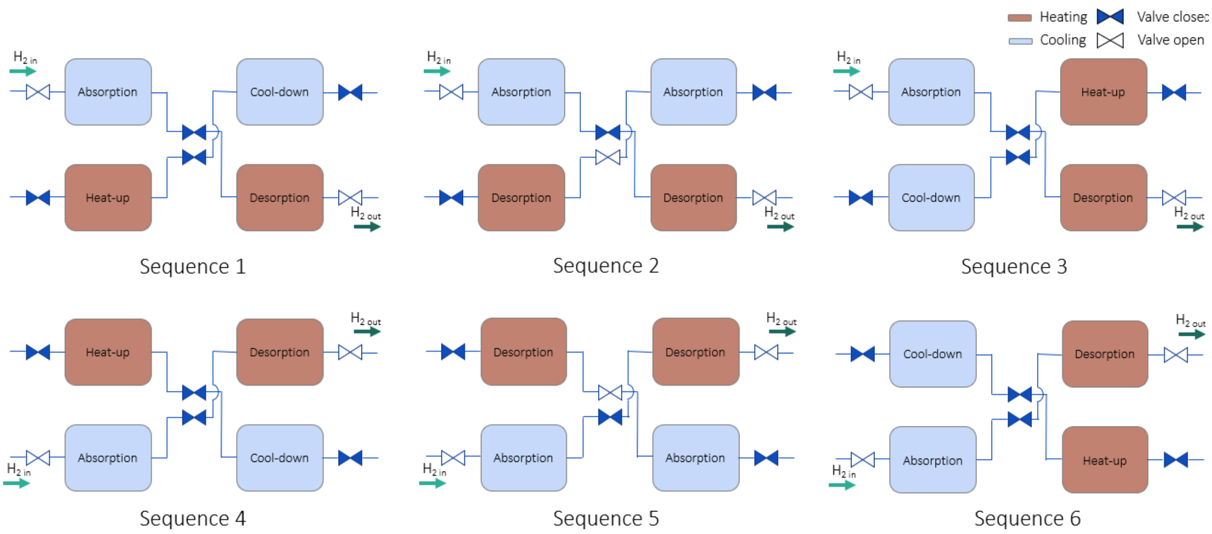


Figure 2: Modes of individual stacks during the compression cycle

During the absorption and cool-down (for preparation of stack for the next absorption cycle) modes, the stacks must be cooled down. Conversely, during the desorption and heat-up (compression) modes, the stacks must be heated up.

The cooling is done via free cooling using the river water available on site, and the heating is done using the steam available from the steam mains. Both the heating and cooling fluids were chosen based on availability at the installation site, and the temperature range of operation was fixed accordingly. The use of water and steam as direct thermal medium was chosen as efficient way to transfer heat. However, this approach also bears the risk of water hammer effect and has some limitations on the design. One of the findings from the project is that a system with a single-phase, closed-loop thermal fluid could potentially be beneficial. This will be further analyzed in future.

The thermal and material design of the system was then conducted based on these limits – further displaying the flexibility of MH based hydrogen compressors to able to be designed for varying operating ranges.

A description of the material development, thermal development and the actual engineering of the system is mentioned in the following chapters.

2.2 Metal Hydride Material development

The metal hydrides material compositions were developed by GRZ Technologies. Several different alloy compositions were created, tested and compared till optimal performance characteristics were obtained. The materials were tested in-house to determine the pressure-composition isotherms (PCT) characteristics, the thermal conductivity, and the bulk density of the materials. The PCT curve shows the equilibrium pressure as a function of the concentration, measured at constant temperature. It is the most important characterization method for metal hydrides materials. The material testing takes place in GRZ's laboratory facilities.

Experimental Setup and Equipment:

Hydrogen supply at the required pressures takes place with the help of an electrolyser and the GRZ FLEXI HyCo systems, which are smaller lab-scale versions of the metal hydride compressor. The electrolyser produces hydrogen from distilled water when needed and charges the FLEXI HyCo with hydrogen at 12 bar (this corresponds to the output pressure of the electrolyser). The FLEXI HyCo can then compress hydrogen from 12 bar to 200 bar. It is used as H_2 source absorption measurements up to 200 bar. Additionally, the FLEXI HyCo is also used to charge the HyCo 700 (an upgraded version of the FLEXI HyCo) which can be used to further compress hydrogen from 100 bar to 700 bar.

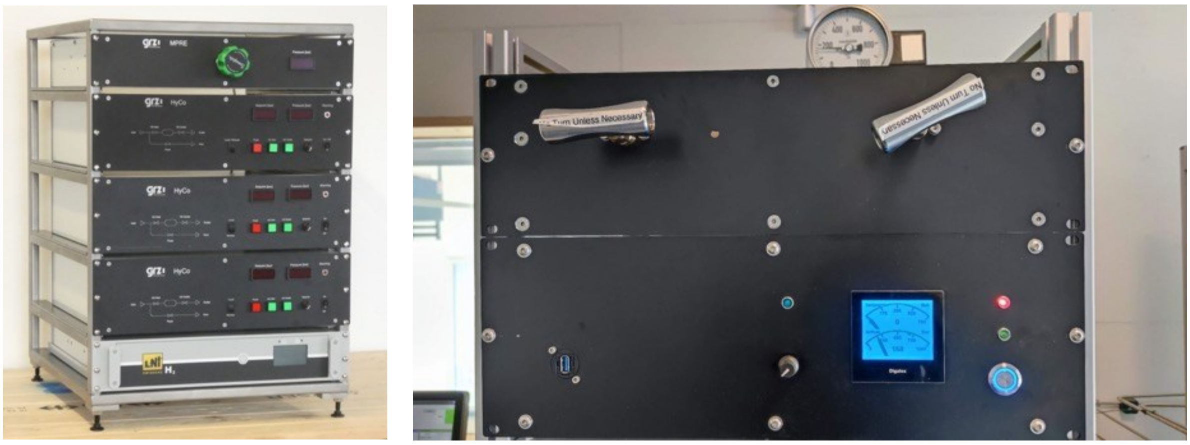


Figure 3. High Pressure Sources for the lab: electrolyzer and standard FLEXI HyCo (left) and HyCo 700 (right).

The material testing is done in custom-made AGAS systems, which are used to test the ab-/desorption PCT curves and the cycling performance of the metal hydrides. Both AGAS devices are automatically controlled by computer, and capable of running a measurement up to 200 bar. The AGAS C is an upgraded version of AGAS B, with a higher accuracy, stability and an optimized software which can perform faster, more accurate measurements.

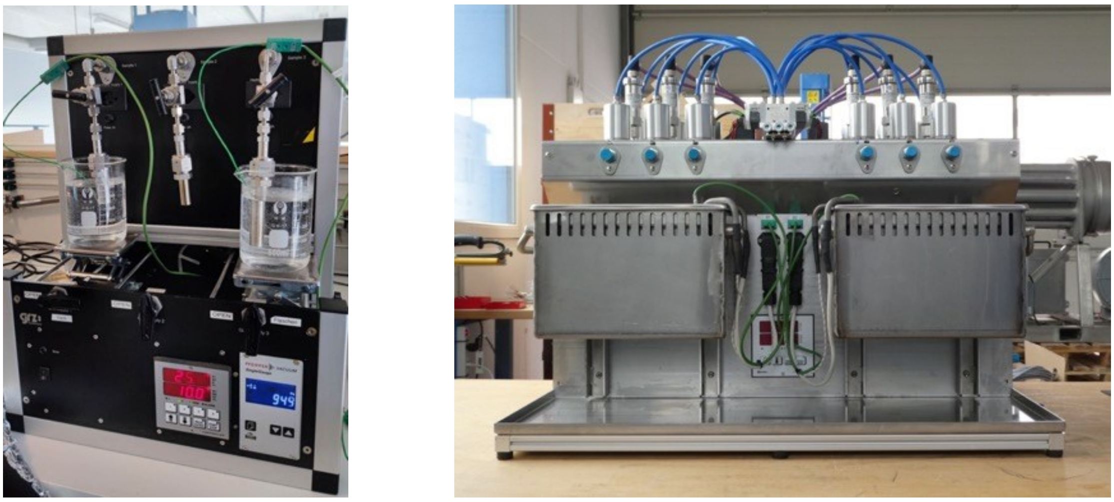


Figure 4: AGAS B (left) and AGAS C (right), both custom-made devices.

For capacity and weight measurements, the Rubosorp-700 is a commercial device using magnetic levitation balance technology. It can be used for the highly accurate weighting of the small amounts of sample under extreme measuring conditions. Measurements up to 700 bar can be carried out. It is a critical tool to design systems working at higher pressures.

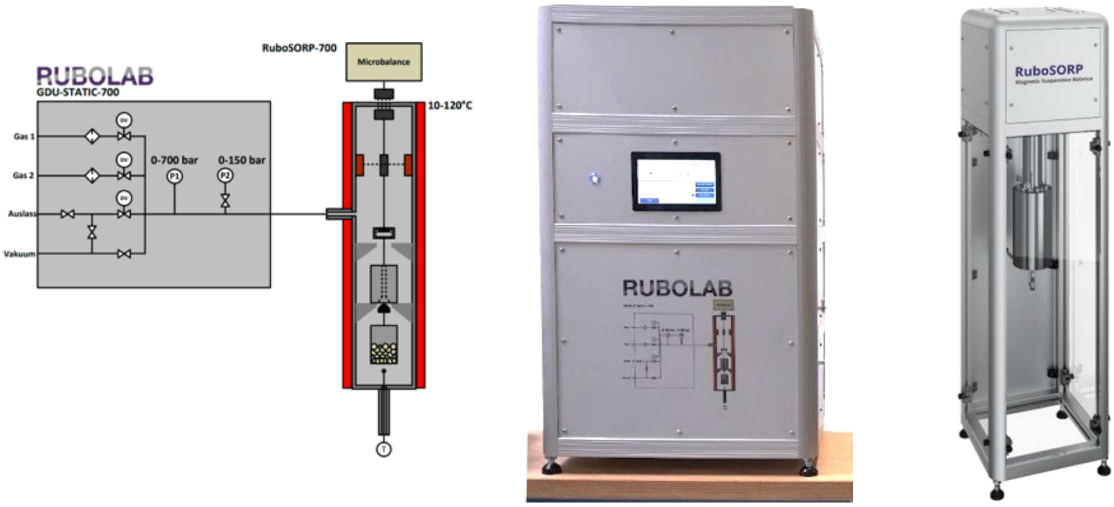


Figure 5. High-pressure sorption analysis system Rubosorp 700 with the basic layout (PFD) on the left, the main control unit containing the valve blocks (middle), and the actual measurement cell (right).

GRZ also has a thermal conductivity measurement analysis setup based on the *Transient Hot Probe (THP)* method, which provides high-resolution (0.01 W/(m·K)) thermal analysis and thermophysical properties measurement. It is used to measure the thermal conductivity of the metal hydride at different charging states (0-100% charged). Combined with the high-pressure measuring cell, we can perform measurements up to 200 bars. The thermal conductivity of the metal will be used to carry out the thermal design of the whole system and the optimization of energy consumption.

Figure 6. Thermal conductivity tester (left) and high-pressure measurement cell (right).

The last important setup for metal hydrides characterization is a custom-made loading density testing device for measurement of the actual volume expansion of the metal hydride during charging. The measurement result can be used to calculate the maximum amount of metal hydride alloy to be loaded into the cell. This helps prevent the deformation of the cell during charging/discharging cycles.

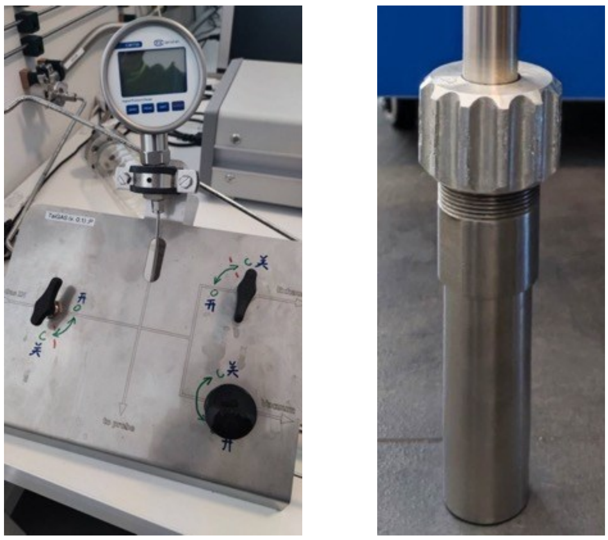


Figure 7. Loading density testing device with the control panel (left) and the measurement cell (right).

Metal Hydride Material Selection Strategy:

Among various hydrogen storage alloys, AB_5-type alloys have been extensively studied due to their advantageous properties such as easy activation, high reversibility, and moderate hydrogen absorption/desorption plateau pressures. One of the key benefits of AB_5-type alloys is their compositional tunability, which allows for a broad adjustment of operating pressures in hydrogen compression modules. Specifically, modifying the AB_5 composition enables suction pressures to vary from below 1 bar up to 20–30 bar at ambient temperature, and discharge pressures to range from 15–20 bar to approximately 200 bar when heated to 100–150 °C.

The pressure characteristics of these alloys can be finely controlled through elemental substitutions. For instance, replacing La in $LaNi_5$ with elements such as Ce, Mm (mischmetal), Ca, or Y results in a significant increase in plateau pressure. Conversely, substituting Ni with Al, Co, Mn, or Sn typically leads to a decrease in pressure. Studies on various $La_{1-x}R_xNi_5$ systems (where R = Ce, Sm, etc.) have shown that A-site substitution, especially with Ce, causes a notable rise in plateau pressure. This is attributed not only to electronic effects but also to a reduction in the unit cell volume, further influencing hydrogen absorption thermodynamics.

However, a major challenge in applying AB_5-type metal hydrides for long-term hydrogen compression is performance degradation over extended H_2 absorption/desorption cycling. This deterioration primarily arises from thermodynamically favoured disproportionation reactions (also known as hydrogenolysis), which break down the alloy structure. Additionally, repeated cycling can induce lattice strains and defect formation in the metallic matrix, contributing to a loss of reversible hydrogen storage capacity, a downward shift in plateau pressure, and a steepening of the pressure plateau slope—all of which compromise performance. To address these issues, many studies have found that partial substitution of Ni with Co can effectively suppress degradation mechanisms, thereby enhancing the cycle stability and extending the operational life of the alloy. Previous studies have also shown that the introduction of iron (Fe) significantly enhances the ductility of the alloy and serves as a buffer against microstrain and plastic deformation during hydrogen absorption/desorption cycles. This buffering effect helps to stabilize the crystal structure, thereby extending the cycling life of the alloy.

In addition to the pressure characteristics (i.e. the “plateau” pressures in the PCT curves at which the material and absorb and desorb hydrogen at specific temperatures) and the cycle stability, the performance of different metal hydride alloy compositions were also assessed by considering the following criteria:

- Useful (Net) capacity: the useful capacity is the amount of hydrogen that can be absorbed and released per kg of metal hydride material under the specific conditions (below absorption pressure and above desorption pressure at the relevant temperatures). This value needs to be maximized.
- Hysteresis: the hysteresis is the difference in pressure between absorption and desorption, at the same temperature. This difference represents a net loss and must therefore be minimized. A candidate alloy that was rejected because of high hysteresis is shown in Figure 8 (left).
- Slope: the plateau slope of a metal hydrides will have a direct influence on the useful capacity. An example of an alloy candidate rejected because of a high plateau slope is shown Figure 8 (right).
- Compression ratio: the compression ratio describes the pressure increase for a given temperature increase. This ratio should be as high as possible. It is dependent on the thermodynamic properties of the alloy (enthalpy and entropy of reaction), as shown schematically in Figure 9.

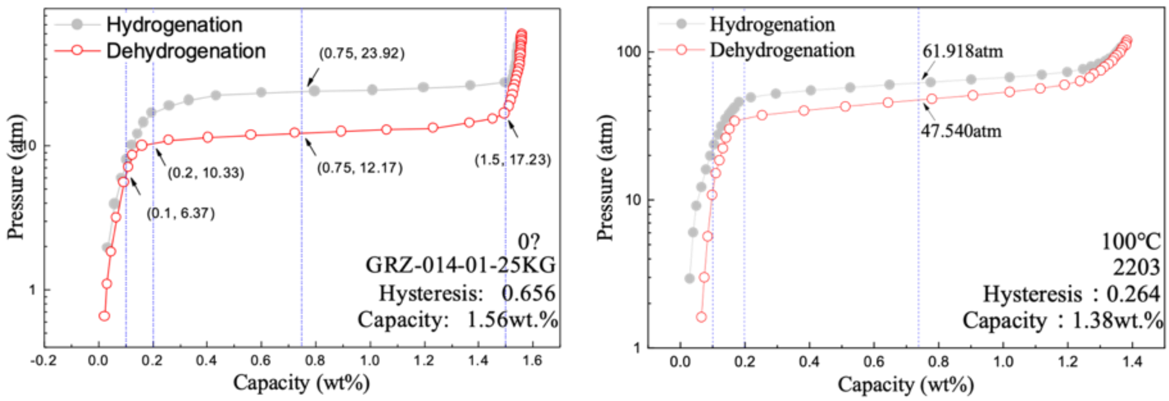


Figure 8: Example of an alloy rejected because of a high hysteresis (left) and an alloy rejected because of a high plateau slope (right).

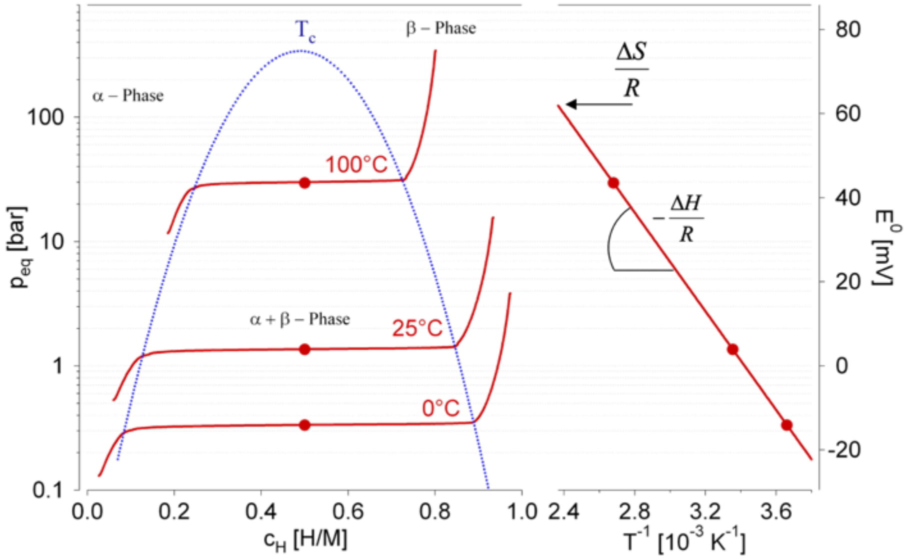


Figure 9: Van't Hoff plot showing the relationship between the equilibrium pressure of an alloy and the temperature. A curve as steep as possible is targeted in order to have a high compression ratio for a low temperature change.

To meet the above listed requirements, the present study builds upon the original $LaNi_5$ alloy framework. Ce was introduced to finely adjust the plateau pressure, while Co was incorporated to enhance the cycling stability of the metal hydride through suppression of structural degradation. For the second-stage compression, which is required to raise the hydrogen pressure from 50 bar to over 200 bar, the alloy composition was further optimized. A reduced La/Ce ratio was employed to effectively increase the plateau pressure. In line with the operational requirements of a two-stage metal hydride hydrogen compressor—which needs to compress hydrogen from 10 bar to 45 bar and ultimately deliver over 200 bar—tailored alloy compositions were developed and their PCT characteristics compared.

Final Choice of Materials:

Several different alloy compositions based on the modifications mentioned above were considered for the current project. The summary is shown in Table 1.

The selection was finally settled on two candidate materials that showed favourable plateau pressures, low plateau slopes, low hysteresis and good cycle stability. These alloys were developed in-house by GRZ and were labelled GRZ-096 for the low-pressure stage and alloy GRZ-134 for the high-pressure stage. Both alloys are of the AB5-family. However, the accurate metal hydrides composition is a confidential information owned by GRZ Technologies SA and cannot be published. The pressure-composition isotherms (PCT) for each of these alloys at low and high temperatures are shown in Figure 10 and Figure 11, respectively.

Pressure Level	Type	Alloy ID	Composition								Absorption @25°C	Desorption @25°C	Capacity	Hysteresis	Slope	Comments on Performance
			La	Ce	Ni	Mn	Fe	Zr	Al	Other						
LP	AB_5	GRZ-150	H	M	H	-	-	-	-	-	1.5	0.9	Low	Middle	High	Both Plateau too low Slope too big
	AB_5	ZZ03	-	-	H	-	-	-	-	-	6	4	High	Low	Middle	Cost too high Patent owned by other company
	AB_5	GRZ-071	M	H	H	-	M	-	-	H	36	23	High	High	High	Plateau too high
	AB_5	GRZ-190	M	M	H	H	-	-	L	L	4	2 - 3	High	Middle	Low	Double plateau on desorption
	AB_5	GRZ-192	M	L	H	M	-	L	L	L	3-5	2-4	High	High	High	Double plateau on both absorption and desorption
	AB_5	GRZ-195	H	L	H	-	-	-	-	H	5	3	High	Low	Low	Desorption Plateau too low
	AB_5	GRZ-191	H	L	H	-	-	-	-	H	4	2.7	High	Low	Low	Desorption Plateau too low
	AB_5	GRZ-179	H	L	H	-	-	-	-	L	4	2	High	High	Low	Desorption Plateau too low
	AB_5	**GRZ-096**	**M**	**M**	H	**-**	**M**	**-**	**-**	**M**	**7**	**6**	High	Low	Low	**Suitable**
HP	AB_5	GRZ-013-05-11kg	M	M	H	-	-	-	-	L	34	22	High	High	Low	Desorption Plateau too low
	AB_5	GRZ-059	M	H	H	L	-	-	-	M	17	15	High	Low	Low	Desorption Plateau too low
	AB_5	GRZ-112	M	M	H	H	-	-	-	L	31	21	High	Middle	Low	Desorption Plateau too low
	AB_5	GRZ-075	M	M	H	-	-	-	-	M	40	26	Middle	High	Low	Desorption Plateau too low
	AB_5	GRZ-014-01	L	H	H	-	-	L	-	L	46	26	High	High	Low	Hysteresis too big
	AB_5	GRZ-189	L	M	H	-	M	-	L	L	39	14	Low	High	High	Hysteresis too big
	AB_5	**GRZ-134**	**L**	**H**	H	**-**	**M**	**-**	**L**	**M**	**44**	**35**	**High**	**Low**	Low	**Suitable**

Table 1: Overview of the alloy candidates and comments on their performance. The indication on the composition is as follows: L = Low, M = Medium, H = High.

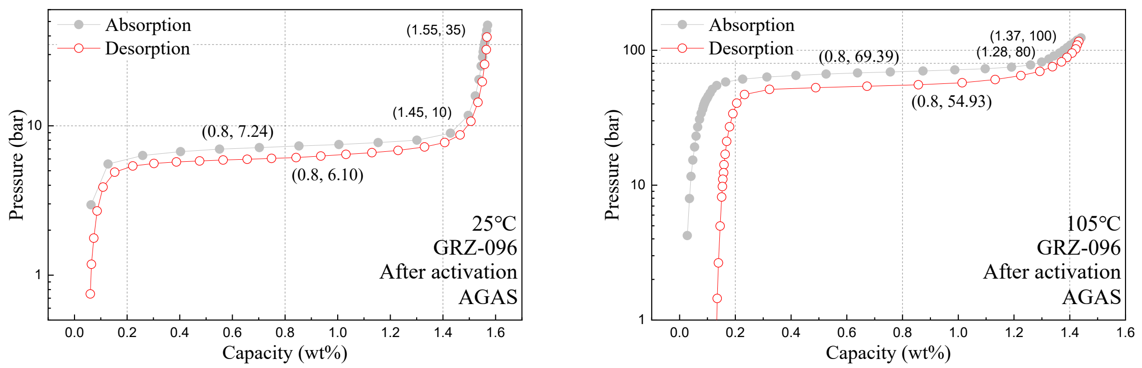


Figure 10: PCT curve of the alloy selected for the first stage.

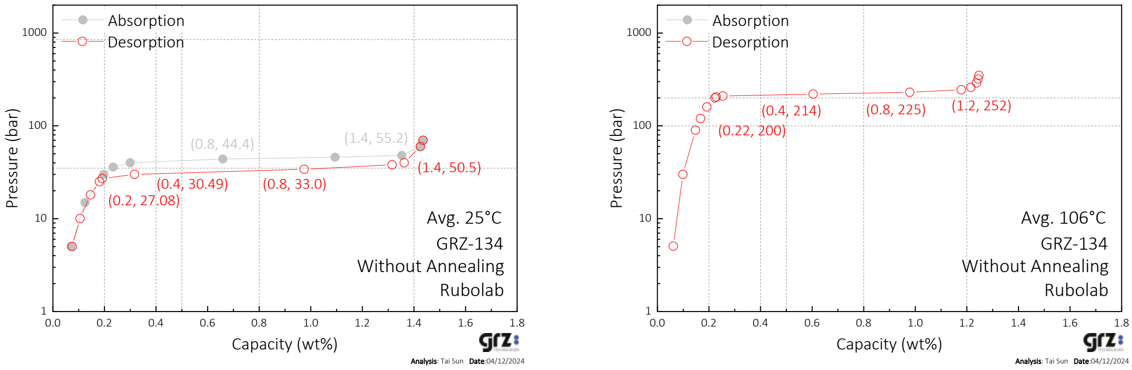


Figure 11: PCT curve of the alloy selected for the second stage.

Superimposing the PCT curves onto the same diagram as done in Figure 12 shows how the system is expected to function to compress the hydrogen from 10 bar to 200 bar in 2 stages.

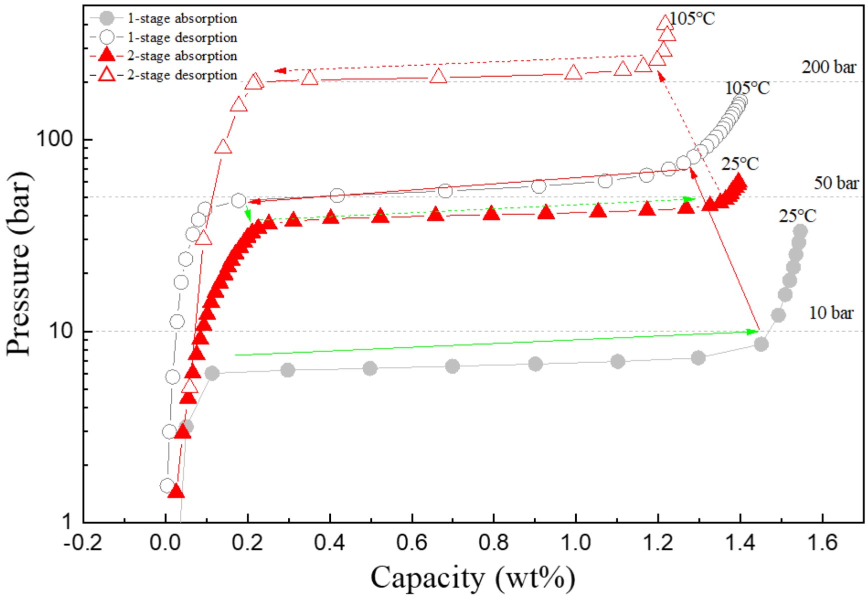


Figure 12: PCT diagram of 2 stage compression

2.3 Thermal Design

Metal hydride compression effectively functions as a thermal process. Reaching the required flow rates for absorption at low pressure and desorption at high pressure is directly dependent on the cooling power during charging the system, and the heating power during discharging the system. The pressure level reached is directly dependent on the temperature. This means that efficient thermal design of the system is tantamount to efficient operation.

To ensure efficient heat transfer to the system, the compressor is designed in the form of a shell and tube heat exchanger, where the metal hydride material (and therefore the hydrogen) is stored in the tube side in metal “cells” and the heating and cooling medium are circulated on the outside of these cells on the shell side of the system.

The thermal design was aimed at reaching the most efficient design of this shell and tube configuration by varying several parameters including the number and diameter of the cells, the thermal fluid flow rates, the arrangement of the cells inside the shell, the number of baffles, etc. Due to the nature of the system, i.e., 2 modules running in alternate cycles, there are additional flexibilities based on the system size and cycle times.

The thermal engineering was performed in a two-step process. In the first step, a semi-analytical, two-dimensional model was developed in the programming language *python*. This was used to assess the suitability of a number of design candidates based on several design variables (cell diameter, flow rate of the thermal fluid, useful capacity of the metal hydride material, temperature at various locations of the system). The constraints on the system are set based on the metal hydride materials (the energy required for absorption/desorption, and the temperatures required to reach the target pressures). The design candidates were compared based on energy and temperature requirements, and the most efficient configuration identified. The parameters used or resulting from the thermal design calculation are summarized in Table 2.

Variable Name	Value [Units]	
Flow rate of hydrogen	30.0 kg_{H2}/h	
Absorption pressure	10.0 bar(a)	
Desorption pressure	200.0 bar(a)	
Steam temperature at inlet	120.0 °C	
Steam pressure at inlet	1.98 bar (a)	
Cooling water temperature at inlet	14.0 °C	
Cooling water pressure at inlet	2.0 bar (a)	
Stage	Low pressure	High pressure
Material selected	GRZ-092*	GRZ-075*
Enthalpy of reaction (absorption)	27'800 J/molH2	22'700 J/molH2
Enthalpy of reaction (desorption)	30'400 J/molH2	24'600 J/molH2
SOC at absorption at 20°C	10 bar, 1.47 wt [%]	44 bar, 1.37 wt [%]
SOC at desorption at 105°C	44 bar, 0.20 wt [%]	200 bar, 0.20 wt [%]
Useful H_2 storage capacity	1.27 wt [%]	1.17 wt [%]
Loading density of MH	4450 kg/m3	4450 kg/m3
Heat capacity of the MH without (with) hydrogen	345 (520) J/kg-K	345 (520) J/kg-K
Steel material for thermal calculation	SS316 (1.4401/1.4404)	SS316 (1.4401/1.4404)
Heat capacity of steel	500 J/kg-K	500 J/kg-K
Thermal conductivity of steel	16.3 W/m-K	16.3 W/m-K
Density of steel	8000 kg/m3	8000 kg/m3
*These are the same alloy compositions as chosen in Section 2.2 and are labelled differently based on the manufacturing batch		

Table 2: Thermal parameters used for the design of the compressor.

An extract of the results obtained from the 2D semi-analytical model is shown in Figure 13 and in Figure 14. Through the model, the pressure drop across the heat exchanger was observed to not be a limiting factor. The limiting condition of design was the required absorption temperature. The curves show the combined effect of the different cell diameter options and the flow rate of the coolant on the pressure drop across the system as well as the "center temperature" which refers to the temperature at the center of the metal hydride materials located inside the cells. The limiting condition for design in the case of both the low- and high-pressure stages was the absorption temperature. A trade-off had to be made between the pressure drop across the compressor (which affects the pumping energy requirements) and the diameter of the cells. Additional factors such as the ease of manufacture (the cells cannot be too small such that uniform filling of the material is not possible) as well as the availability of standard sizes in the market were also considered. The red dot indicates the chosen thermal configuration.

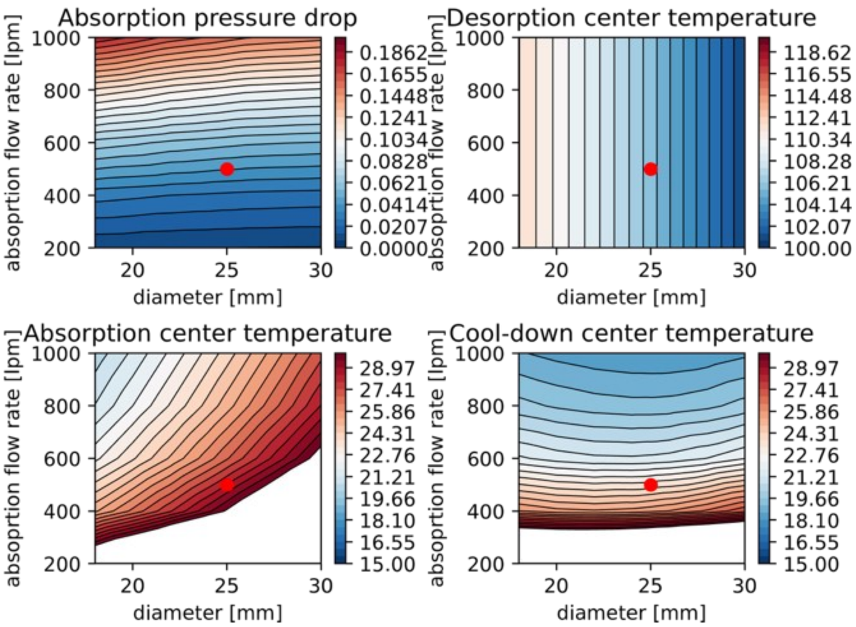


Figure 13: Evaluation of the thermal performance for different pipe size candidates (plots shown for LP stage). The red dot indicates the chosen thermal configuration.

Similar to the cell diameter, the effect of the overall cycle time (i.e. time for absorption – heatup – desorption – cooldown) was also checked. The cycle time did not appear to have a significant influence on the center temperatures and increasing the cycle time only marginally improved performance. In this case, the lowest cycle time was chosen. The red dot indicates the chosen thermal configuration.

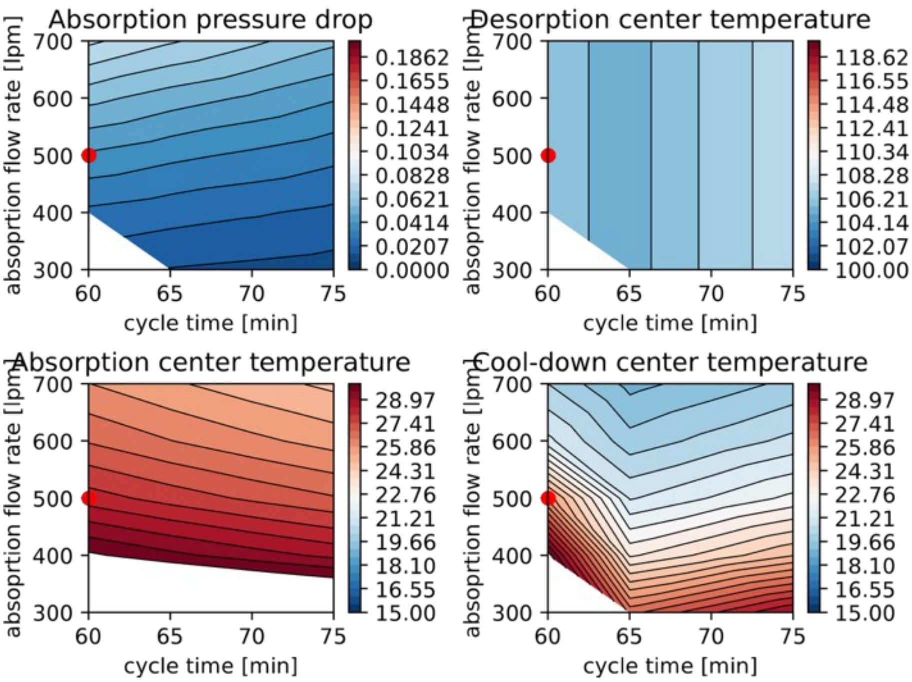
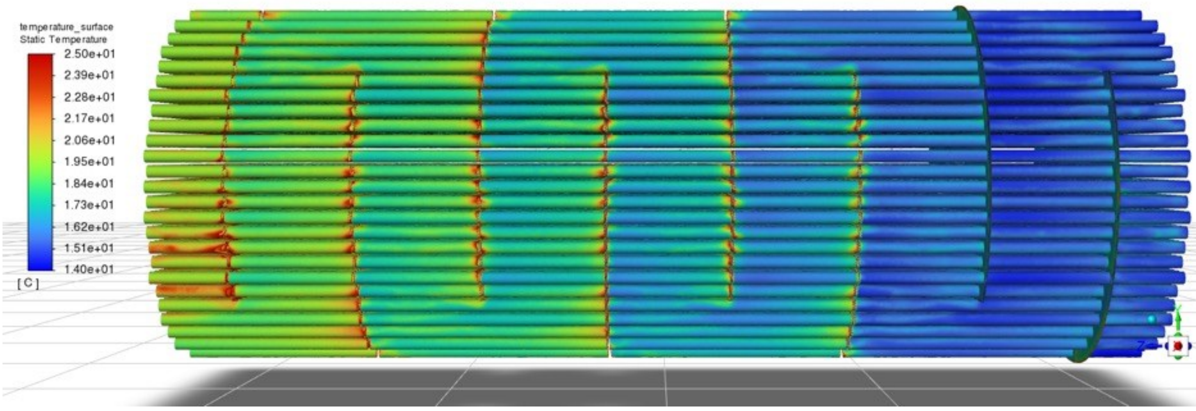


Figure 14: Evaluation of the thermal performance for different cycle times (plots shown for LP stage).

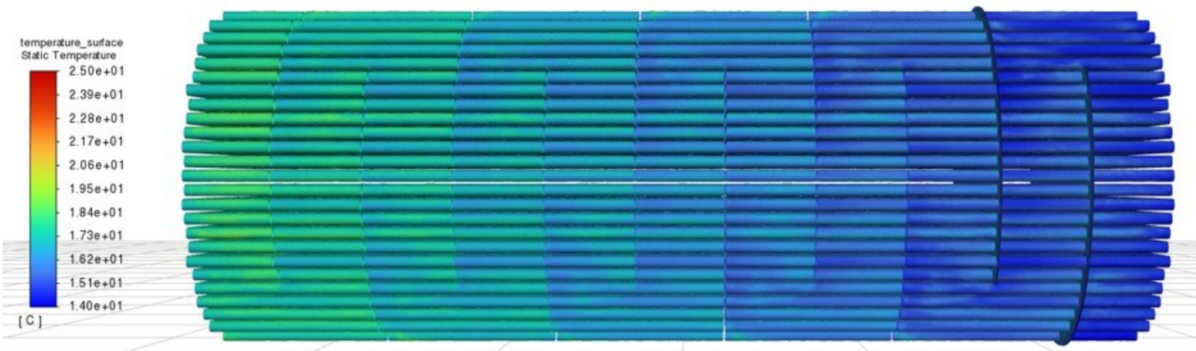
Based on the 2D model and mechanical design considerations, the design selection for the metal hydride tubes was made. Tubes with an outer diameter of 25 mm and a wall thickness of 1mm (low-pressure stage) and 2 mm (high-pressure stage) were selected.

Following the choice of the tube sizing, a 3D model was set up in ANSYS to validate the results of the semi-analytical model and optimize the flow profile of the heating/cooling fluids in the shell of the compressor. The 3D simulations helped to finalize the shell sizing, number of baffles and baffle sizing. For example, Figure 15 shows the comparison between the flow profiles for the low-pressure shell with 8 baffles vs 10 baffles. The option with 10 baffles showed a superior flow profile with less “hot-spots” and in general a lower average metal-hydride temperature. Similar analysis was done for the high-pressure stage, and a final heat exchanger design was chosen for the system. The choice of baffles was a trade-off between a better thermal flow profile (mostly cross-flow, achieve through an increasing number of baffles) and a lower pressure drop (achieved through a lower number of baffles).

The geometric parameters resulting from the thermal and mechanical engineering calculations are summarized in Table 3.



(a)



(b)

Figure 15: 3D Thermal simulation of the low-pressure stage of the metal hydrides hydrogen compressor with (a) 8 baffles and (b) 10 baffles.

Stage	Low pressure	High pressure
Enclosure inner diameter	750 mm	850 mm
Enclosure inner length	2020 mm	1995 mm
Enclosure thickness	3.0 mm	3.0 mm
Number of cells	385	511
Number of baffles	10	10
Baffle height	600 mm	680 mm
Steam/Water inlet & outlet diameter	160 mm	160 mm
Single cell inner length	2010 mm	1985 mm

Single cell outer diameter	25.0 mm	25.0 mm
Single cell wall thickness	1.0 mm	2.0 mm
Safety factor for mass of alloy	1.10	1.10
Safety factor for cell volume	1.10	1.10
Total H2 stored in the MH per stage	16.5 kg	16.5 kg
Total amount of MH per stage	1299 kg	1410 kg
Amount of MH per cell	3.37 kg	2.76 kg
Total volume of alloy	321.1 lt	348.6 lt
Total cells inner volume	321.5 lt	351.3 lt
Required thermal conductivity	2.5 W/m-K	2.5 W/m-K

Table 3: Geometric parameters of the HyCo compressor designed.

2.4 System Engineering and Manufacture

Following the choice of metal hydrides and the thermal design, the tasks related to process, electrical and mechanical engineering were performed using standard engineering tools, norms, and codes.

Process Engineering:

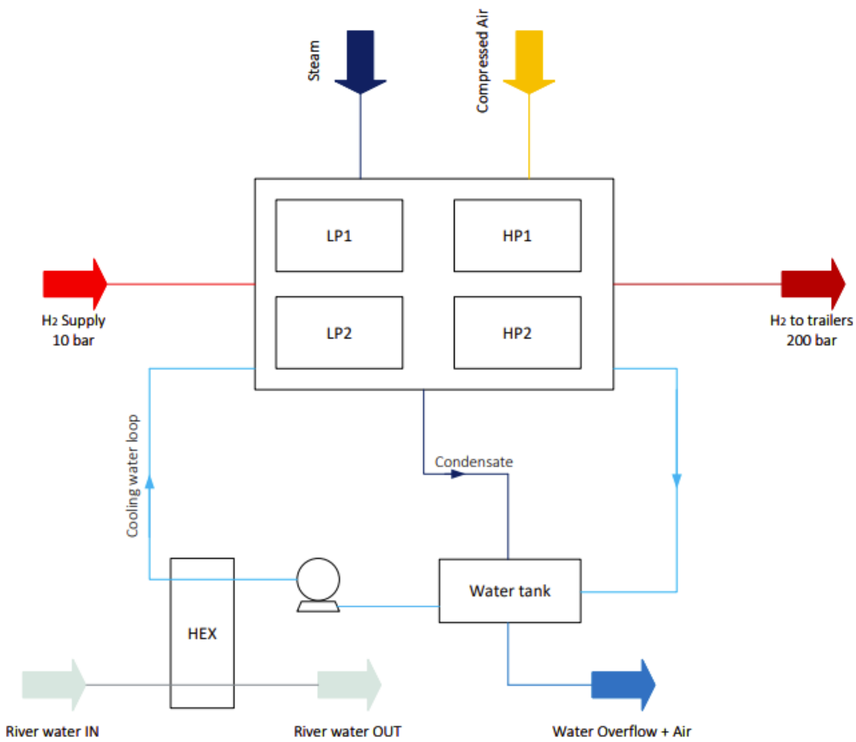


Figure 16: Process Block Diagram

As described in Section 2.1, the process concept uses two compressor modules in parallel and alternates between each with the aim to achieve continuous compression. In practice, between the sequence steps there is a short drainage/depressurization step to separate the water and steam streams from coming in contact with each other to minimize the effects of steam hammer. This drainage is done with the help of compressed air that is available on site.

The system is cooled via a cooling water loop that releases the energy to the river water available on site through a heat exchanger. The steam is provided separately on site and completely condensed in the system mainly in the compressor shells and then with the help of a separate condenser for the residual steam. This condensate is then sent to the common water tank, from which the excess water is removed from the system.

During each phase of the cycle, different compressor modules are in different phases – normally two and heated and two are cooled. The steam and cooling water are directed to the required compressors with the help several pneumatically controlled ON-OFF valves.

As a part of the process engineering, relevant documentation such as the P&ID, valve, safety valve and equipment lists, and the process operating logic were created.

A detailed HAZOP study was conducted on the system and the recommendations from the HAZOP implemented (eg: safety valve positioning, draining of the stacks before sequence change to minimize water/steam hammer, required safety sensors including H_2 detectors for leaks, fire alarms, etc.). A detailed system safety concept was developed based on the results of the HAZOP study

Mechanical Design and Engineering:

Following the generation of the P&ID, the mechanical design of the compressor system was completed. The design was made in SOLIDWORKS. The cross section of a low-pressure metal hydrides compression unit is shown in Figure 17. The metal hydride material is stored in the “cells” visible inside the assembly shown, and the cooling water / steam flows in the outer shell – effectively forming a shell and tube heat exchanger type setup. There are additional inlets located at the top of the shell which are used to provide compressed air during drainage of the shell, and outlets are provided at the bottom for the same. The baffle sizing and spacing was done according to the thermal design.

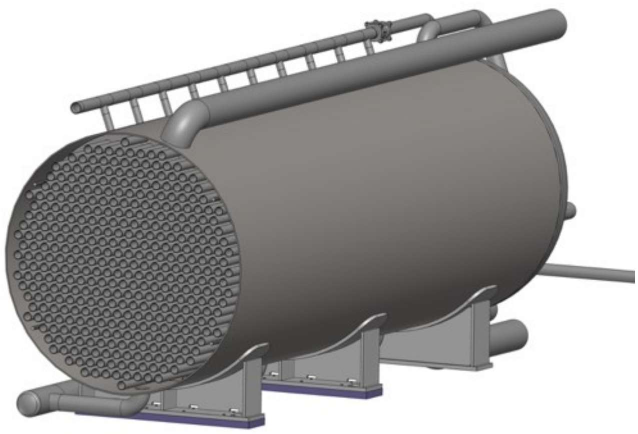


Figure 17: Cross-section of a low-pressure compression module.

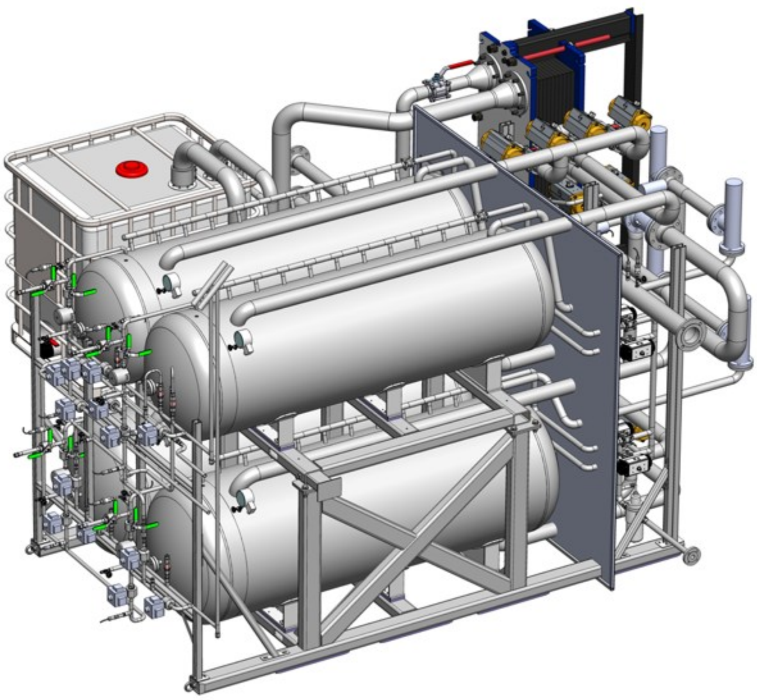


Figure 18: Mechanical design of the compressor system including all four stacks and the thermal system.

The overall layout of the system is shown in Figure 18. The four large cylindrical units are the metal hydrides hydrogen compression units; the two high-pressure units are installed at the lower part, and the two low-pressure units are mounted at the top. The separation heat exchanger for the cooling loop is shown at the back, on the right (blue press plates). The whole system is housed in two 20’ ISO containers. One of the complexities of the mechanical and process design was to develop a system that can control the cooling and heating fluids (steam and water) as well as enabling the changeover from one thermal fluid (e.g., water) to another (e.g., steam) of each process sequence step without any damage to the system (water-hammer effect, etc.). The full system with the container is shown in Figure 19.

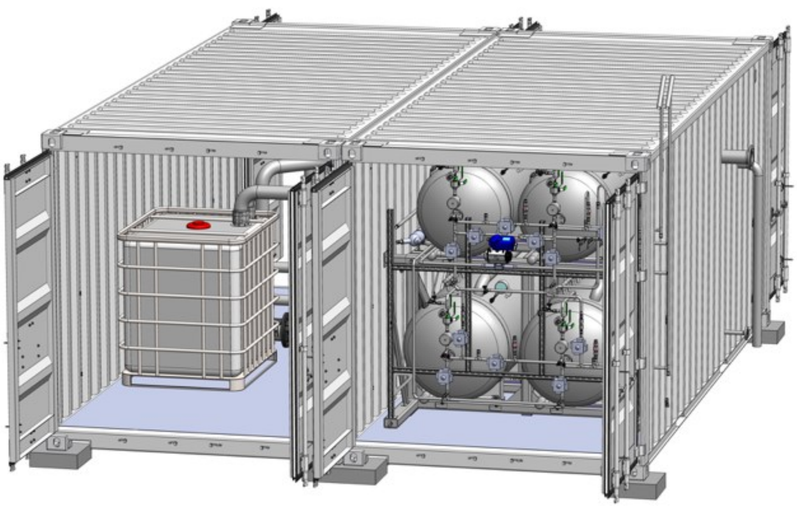


Figure 19: Final design of the container included in two 20' standard ISO containers. The water separation loop is specific to the installation in Visp and included in the container depicted on the left. The compressor itself is included in the container on the right.

Electrical Engineering and Instrumentation:

As described in the measurement concept in Section 2.5, numerous sensors are used to record all relevant data in real time. In total, around 50 signals are recorded. Additionally, several safety devices including multiple emergency stop buttons, hydrogen detectors as well as smoke alarms are installed in the system. The system software is set to be integrated into the existing software of the Messer system that operates the mechanical compressor already on site, allowing for easy operation of both compressors.

Manufacturing and installation:

The manufacturing of the compressor was completed at GRZ's facilities. To that purpose, several steps had to be undertaken. For instance, a workstation for the filling and welding of cylinders was designed and set up. A new welding system was acquired to ensure a fast production process.

Figure 20: Manufacture of system inside container on GRZ site

The compressor has been installed on the site of Messer/Arxada in Visp. The GRZ compressor was installed right next to the mechanical compressor already located on site as shown in Figure 21 with the piping and electrical systems integrated. Both compressors are connected in parallel, with the hydrogen inlet piping splitting into two inlet lines – one to each compressor. The outlet lines from each compressor then merge into a single line going to the trailer filling stations. The flow of hydrogen to both compressors is controlled with the help of ON-OFF valves. In this way, each compressor can be used optionally as required.

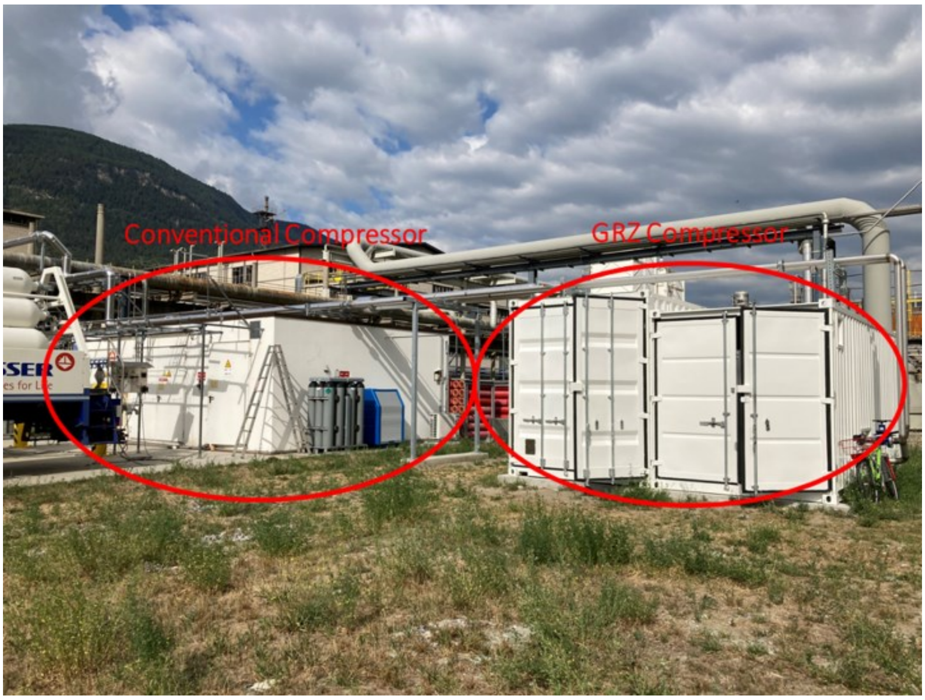


Figure 21: Installation site of the metal hydrides hydrogen compressor in Visp.

The existing site enables the operation of the compressor under real-working conditions. In addition, all relevant values (flow rates, pressure, temperatures, etc.) are recorder directly within the metal hydrides hydrogen compressor. The existing mechanical compressor was manufactured by Hofer and has the technical specification corresponding to the pressure levels and flow rates as shown above. The compressors are used to fill hydrogen trailers which then transport hydrogen to the final customers. A typical trailer is filled with 150 kg_{H2} to 300 kg_{H2} with a pressure up to 200 bar.

Within this project, the HyCo metal hydrides hydrogen compressor will be used in parallel to the mechanical compressor. The application remains the refueling of hydrogen trailers. By operating the two compressor technologies in parallel, the project will allow comparing the advantages and challenges of both compressors under real-working environment.

2.5 Measurement Concept

To test the performance of the compressor system developed, there are a number of parameters measured during system operation. The real-time physical parameters are measured with the help on in-line sensors. The list of performance critical physical properties measured are mentioned in Table 4. Performance criteria such as the energy consumption are calculated based on these measured physical values. The measurement campaign will be carried out by Messer, supported by the other partners. As part of a broader industrial system, the metal hydrides compressor will be operated following the actual needs of the plant, i.e., when empty trailers are connected to the refueling station, the compressor will be operated. While the detailed operating plan is yet to be defined, the basic idea is as follows:

- Both the mechanical and thermal compressors will be used each for around 50% of the time;
- A typical operating profile is based on an empty trailer docking at the station and requiring to be refilled as soon as possible. Thereby, we consider an operating profile changing from 0% to 100% capacity as soon as possible, and then operating at 100% capacity for around 6 to 10 hours;
- The key focus of attention during the comparison of both technologies lies on the following metrics:

- Energy consumption (thermal/electrical)
- Availability (down-time, maintenance, etc.)
- Levelized costs of hydrogen compression

Originally, the flow rate fluctuation was defined as a key point of attention for the project. However, in the course of the project, the partners came to the conclusion that this specific parameter is less relevant than other parameters – in particular in the present application. The following is highlighted:

- The application of trailer refuelling is not sensitive on flow rates fluctuations at the compressor's outlet; the relevant parameter is the time required to refuel a trailer. Therefore, only the average flow rate is relevant for this application. Fluctuation in the flow are barely noticed/recorded;
- In discussion with industry experts, it appears that conventional compressors also have fluctuations due to rotation/moving equipment.
- In cases in which a particular process requires absolutely constant flow rates, this is achieved with additional measures down-stream of a compressor. Such measures can include a buffer tank, high-precision flow controllers, or similar hardware implementations.

Based on this, the analysis of the system's performance was focused on the average flow rate achieved, and on the pressure levels at the outlet of the compressor. The corresponding data is shown in Figure 22 and Figure 23, and discussed thereafter.

Parameters Measured	**Sensor Location**
Hydrogen Inlet Flow Rate	Flowmeter on line to GRZ Compressor
Hydrogen Outlet Flow Rate	Flowmeter on line from GRZ Compressor
Hydrogen Pressure LP1 Stack	Pressure sensor on inlet/outlet line to LP1 Stack
Hydrogen Pressure LP2 Stack	Pressure sensor on inlet/outlet line to LP2 Stack
Hydrogen Pressure HP1 Stack	Pressure sensor on inlet/outlet line to HP1 Stack
Hydrogen Pressure HP2 Stack	Pressure sensor on inlet/outlet line to HP2 Stack
Steam Inlet Pressure	Pressure sensor on steam inlet line
Steam Inlet Temperature	Temperature sensor on steam inlet line
Steam Inlet Flow Rate	Flowmeter on steam inlet line
Condensate Outlet Temperature LP1 Stack	Temperature sensor on condensate outlet line from LP1 stack
Condensate Outlet Temperature LP2 Stack	Temperature sensor on condensate outlet line from LP2 stack
Condensate Outlet Temperature HP1 Stack	Temperature sensor on condensate outlet line from HP1 stack
Condensate Outlet Temperature HP2 Stack	Temperature sensor on condensate outlet line from HP2 stack
Water Inlet Temperature	Temperature sensor on pipeline at outlet of cooling HEX
Water Inlet Flow Rate	Flowmeter on pipeline at outlet of cooling HEX
Water Outlet Temperature LP1 Stack	Temperature sensor on water outlet line from LP1 stack
Water Outlet Temperature LP2 Stack	Temperature sensor on water outlet line from LP2 stack

Water Outlet Temperature HP1 Stack	Temperature sensor on water outlet line from HP1 stack
Water Outlet Temperature HP2 Stack	Temperature sensor on water outlet line from HP2 stack

Table 4: Measurement of performance critical parameters

2.6 System Certification

The certification of the system was done according to the Pressure Equipment Directive (PED 2014/68/EU). This required the validation of the design by a notified third-party inspection body. The design examination was filed to the Swiss Safety Center (STS, https://www.safetycenter.ch/). Various elements were subject to such an examination (low-pressure cells, high-pressure cells, steam shells, etc.).

2.7 System Testing and Operation

Extensive testing has been conducted on the installed GRZ compressor during the commissioning process to optimize system operation, as well as measure the performance of the GRZ compressor.

The preliminary testing results were obtained initially by manually operating the system through the software, and finally by letting the system cycle automatically in operation mode. The complete integration of the GRZ system software with the Messer software is being finalised. As it currently stands, the GRZ compressor can be operated automatically by selecting it through the Messer software to run and is currently completely operational on demand.

The results from the testing of the system are shown in the following sections.

Hydrogen compression and trailer filling:

The GRZ compressor was used to compress hydrogen and fill up a trailer provided by Messer on several occasions. The trailer was connected to the filling panels located on the Messer filling site, and compressed hydrogen was supplied to the trailers from the GRZ compressor.

Over multiple days of testing in both manual and automatic mode, the system has been in operation for around 250 hours, successfully compressing hydrogen from a 10 bar source to up to 200 bar in trailers.

Exemplary testing data of the compressor operation in automatic mode conducted on 27th November 2024 is shown in the figures below.

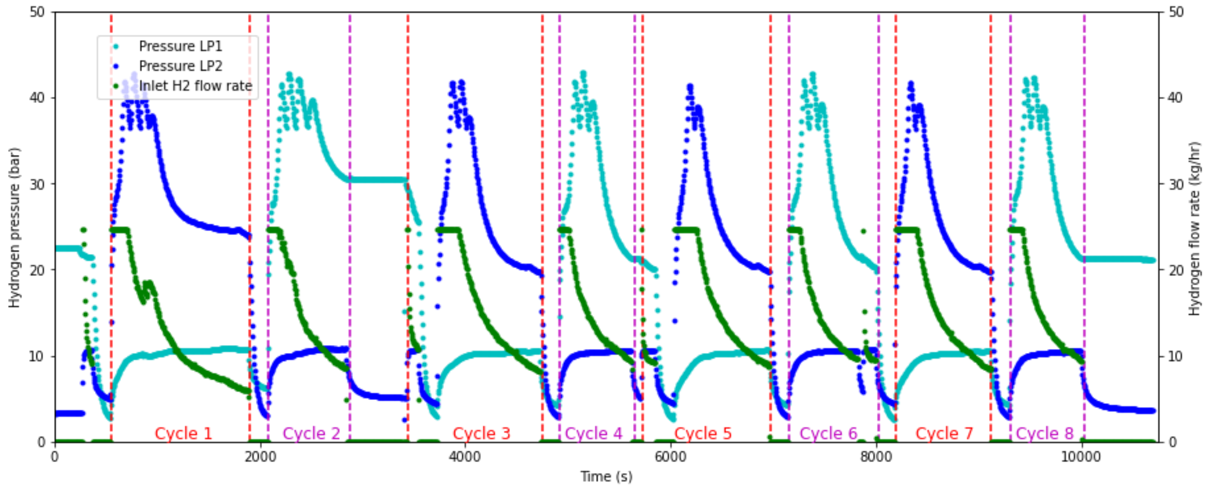


Figure 22: Hydrogen inflow to LP stacks (testing on 27.11.2024)

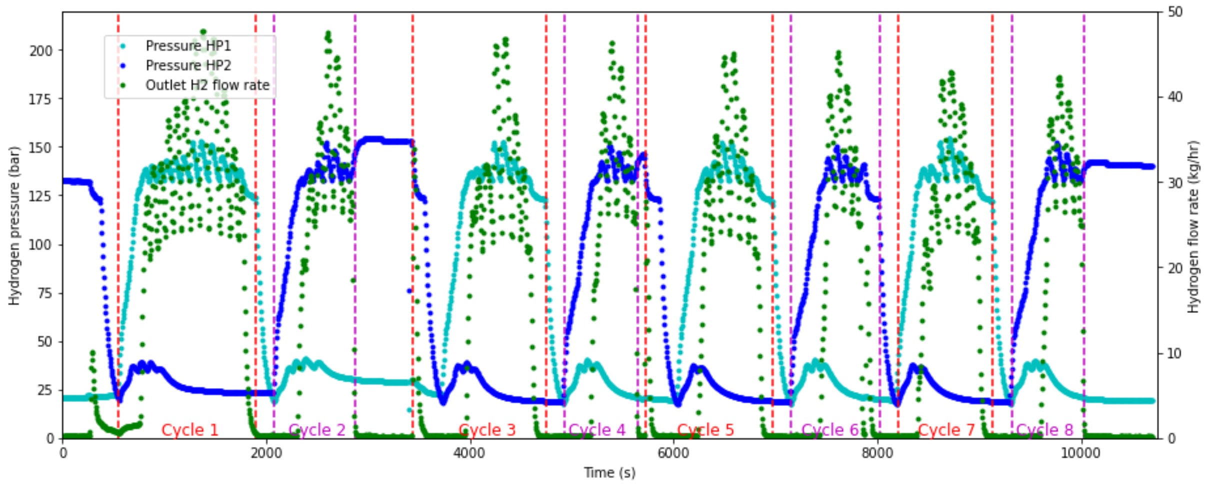


Figure 23: Hydrogen outflow from HP stacks (testing on 27.11.2024)

Multiple “cycles” of compression were conducted over several hours with the system operating autonomously and filling up a trailer connected at the Messer Filling station.

During discharge of hydrogen, the pressure of hydrogen rises quite fast due to the high temperature steam and so heating is provided in bursts to the system to control the overall pressure rise. The reason for this is that the steam is supplied at a higher temperature than was accounted for in the thermal design of the system leading to a much faster heatup than required by the cycle time. Sending the steam to the system in bursts causes the flow rate out of the compressor to fluctuate but stronger heating than designed ensures the desorption process is not a limiting factor in process operation.

Operating Flow Rates:

The design operating flow rate is 30kg/hr. During the desorption phase, the instantaneous flow rate spikes reach almost 50 kg/hr when the pressure difference between the compressor and the trailer is large. During absorption, the current installed flowmeter caps the maximum flow rate reading to 300 Nm3/hr (~25 kg/hr) but it is expected that the actual initial flow rate is at a higher value. However, it was noticed that the absorption flow rate subsequently drops to lower values. In general, this means that less hydrogen is absorbed and consequently less hydrogen is desorbed in each cycle.

The average rate of compression for the testing conducted in Figure 23 is equal to approximately 17.9 kg/hr. This is limited by the absorption process, which is slower than the desorption process. As was described in Section 2.3, the absorption temperature was the limiting factor in the thermal design. The lower capacity of the system can have a few possible explanations:

- The thermal design was conducted for a system which directly uses river water. However, an additional separation heat exchanger had to be implemented in the course of the project due to the abrasive nature of the cooling water. This was not foreseen in the original design and led to a loss of efficiency in the process. This is the major for the lower hydrogen flow rate during the absorption.
- Since there are no moving parts, the hydrogen flow is dictated exclusively by the pressure difference in the system. Preliminary analysis showed that some pressure drop might be caused by some upstream components (e.g., across the flowmeter, long pipeline, etc.).

The lower absorption flow rate – which basically acts as the limiting criteria for achieving the full design capacity of the system will be studied in the upcoming months and various ways to increase the absorption flow rate by adjusting the operating parameters will be investigated. Nevertheless, the demonstration of the working principles was successfully achieved.

In the test site of the present project, the fluctuation of the flow rate was registered, but no effort was invested towards the fine regulation of the flow given the fact that the target application is the filling of a trailer. Based on feedback from the users and experts, the effort should be directed at increasing the average flow rate, while fluctuations in the range observed by the operation of the metal hydrides compressor do not pose a problem for the operation.

Operating Pressures:

The system is able to achieve the design compression target of 200 bar without any issue. In the testing shown in Figure 23, the system software limited the upper pressure of desorption because the trailers being filled were at lower pressure. However, as the hydrogen pressure in the trailer increases, the final pressure provided by the GRZ compressor also increases till it reaches around 200 bar. This was observed in a prior round of testing conducted on the system in March 2024, as seen in Figure 24. By increasing the outlet pressure with the actual pressure of hydrogen in the trailers, the outflow rate of hydrogen to the trailers remains in control and the whole system need not operate continuously and at unnecessarily high pressures. This is a further advantage of the metal hydrides hydrogen compression technology compared to mechanical compressors: the outlet pressure can be regulated based on the actual needs, leading to increased efficiency.

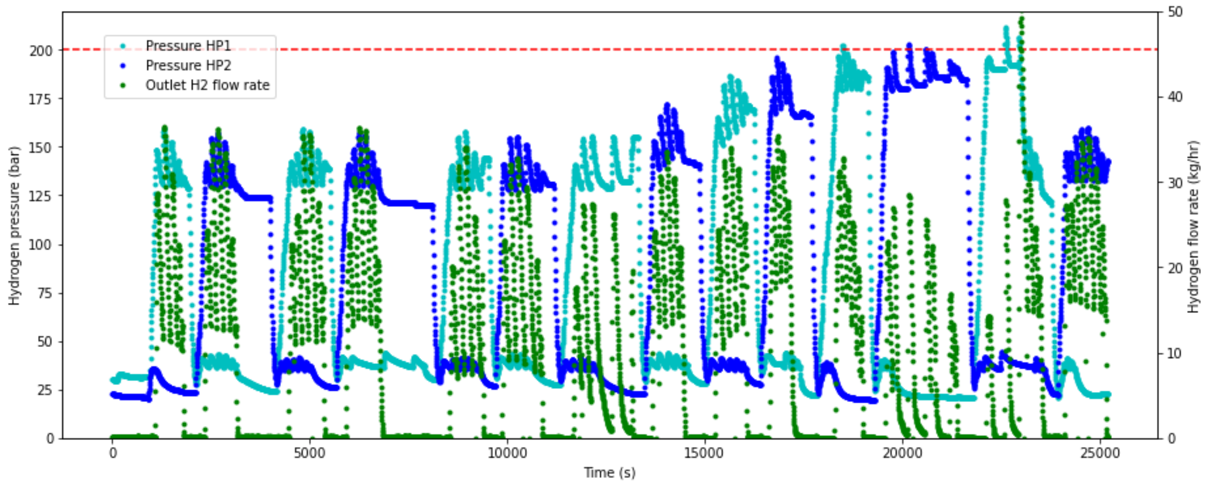


Figure 24: Target desorption pressures reached (testing on 06.03.2024)

Energy Consumption:

The system operates on mainly thermal energy inputs from the available steam and cooling water utilities on the site.

The overall heating energy consumption is calculated based on the inlet steam flow rate and the inlet temperature (assuming saturated conditions). The steam flow rate variation (during the steam injections while the system cycles) as well as the measured inlet temperature are shown in Figure 25 below. The value obtained for the overall energy consumed over all cycles is divided by the average amount of hydrogen absorbed and desorbed over all cycles.

The total cooling side energy consumption includes the thermal energy removed from the system by the cooling water, as well as the electrical power required for the water circulation. The water flow rate and the pump electrical power drawn are shown in Figure 26.

Based on the testing conducted on 27.11.2024, the calculated energy consumption values are shown in Table 5.

Energy consumption [kWh/kg_{H2}]	Unit	Value
Heating energy provided by steam	kWh_{th}/kg_{H2}	8.8
Electric energy provided by pump	kWh_{el}/kg_{H2}	0.2

Table 5: Energy consumption per kg of H_2

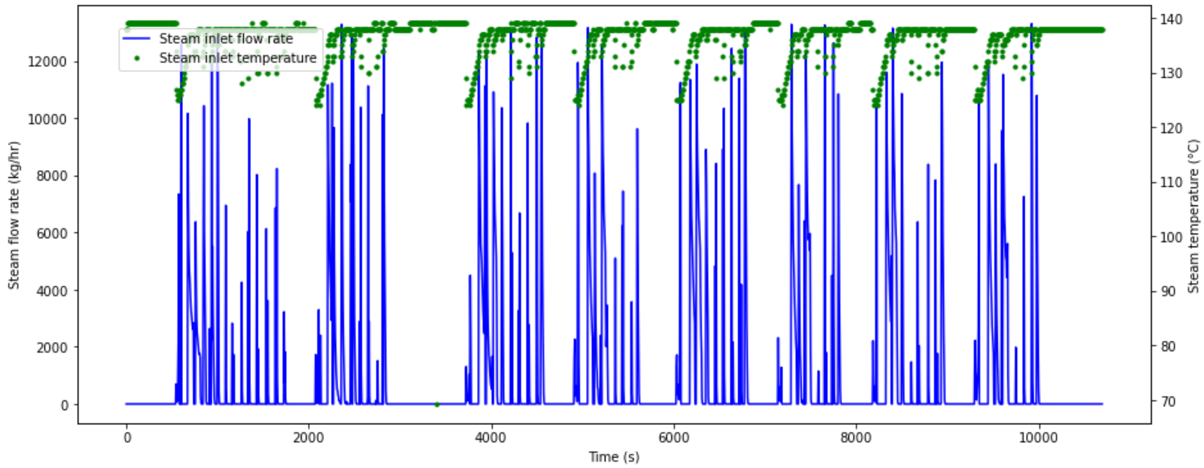


Figure 25: Steam inlet flow rate and temperature (testing on 27.11.2024)

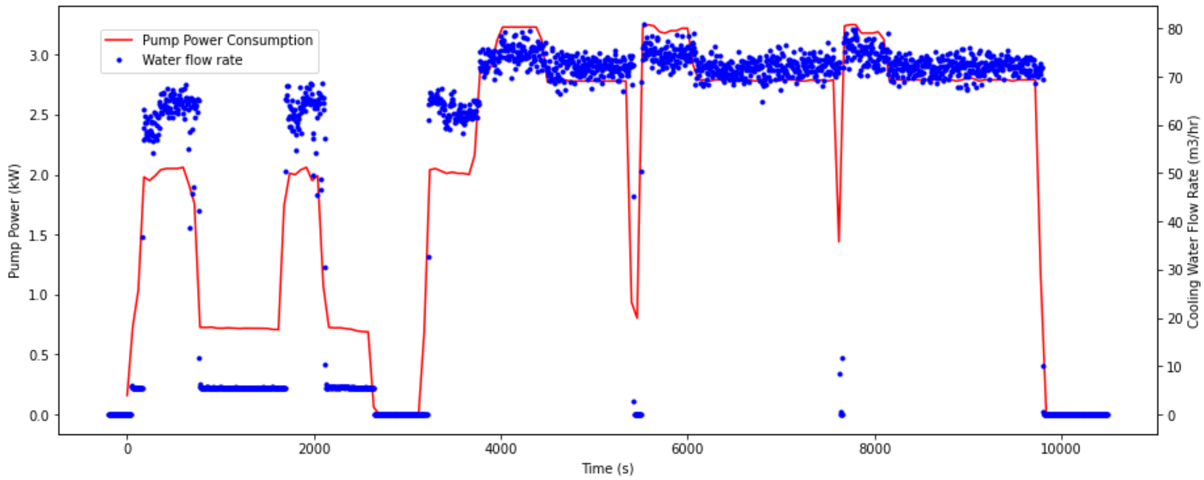


Figure 26: Pump Power consumption and Cooling Water Flow rate (Testing on 27.11.2024)

System Operation Robustness:

The functioning of the system is highly dependent on the amount of heating and cooling provided to the MH stacks. The heating is done via steam which is supplied by the steam mains available on the plant site and hence has minimal variation. The cooling is performed by releasing the heat generated to the river water, which is then dependent on the ambient temperature conditions.

The system has been designed to function at 100% capacity at the ambient temperature limits (ambient temperatures of 38°C). Figure 23 and Figure 24 show minimal variability in overall compressor performance when the testing was done in November vs in March. Further data on system operation during hot summer days is expected to be generated in the coming months, but this has already been taken into account in the design of the system.

System Comparison with Mechanical Compressor:

The operating information of the existing mechanical compressor (Hersteller: Hofer, Typ: MKZ 560-10/380-25) was obtained from Messer Schweiz after operation of the mechanical compressor over the last 2 years and is shown in Table 6. A link to the specification of the Hofer compressor is found here.

Year	2023	2024
Amount of H_2 compressed (kg)	70'746	70'713
Electricity consumption (kWh, *approximate*)	148 MWh	148 MWh
Electricity Costs (CHF)	31'000	32'500
Maintenance hours (h)	57	102
Total OPEX incl. electricity, cooling water, maintenance, etc. (CHF)	65'000	85'000
OPEX per kg H_2 compressed (CHF/kg_{H2})	0.92	1.20

Table 6: Operating costs and figures for the on-site mechanical compressor

The amount of hydrogen compressed is almost constant between the two years. The electricity costs are also very similar from one year to the next. However, the number of hours for maintenance in 2024 are substantially higher in 2024 than in 2023. This can be explained by the fact that maintenance work is not always very precisely foreseeable, and that some servicing activities can take longer in one year than in another one. The total OPEX include not only the electricity costs, but also the cooling water and the maintenance. The maintenance costs include the man-hours and also the material required. The specific electricity consumption of the mechanical compressor amounts to just above 2 kWh per kilogram hydrogen. The value can depend on various parameters such as the outlet pressure, the inlet pressure, and the ambient conditions.

Based on the above values, the electricity and maintenance downtime costs seem to be significant contributors to the overall operation costs of the mechanical compressor. In contrast, the metal hydride based compressor installed by GRZ operates mainly with the help of free cooling provided by the river, and using the steam available on site. The electric energy consumption in the system is limited to the pump system used for water circulation.

We can estimate the costs of operation of the metal hydride based compressor based on the electrical energy consumption value mentioned in Table 5 and cost of steam consumption. For the testing done on 27.11.2024, we have previously estimated the electrical energy consumption as 0.2 kW_{el}/kg_{H2} based on the steam flow rates measured as shown in Figure 25, we can estimate the total steam consumption per kg of H2, which leads to a value of ~10.7 kg_{steam}/kg_{H2} used (since the steam is completely condensed in the MH compressor).

Using these values we can compare the expected costs of running the MH compressor with the mechanical compressor at different costs of electricity and steam (as shown in

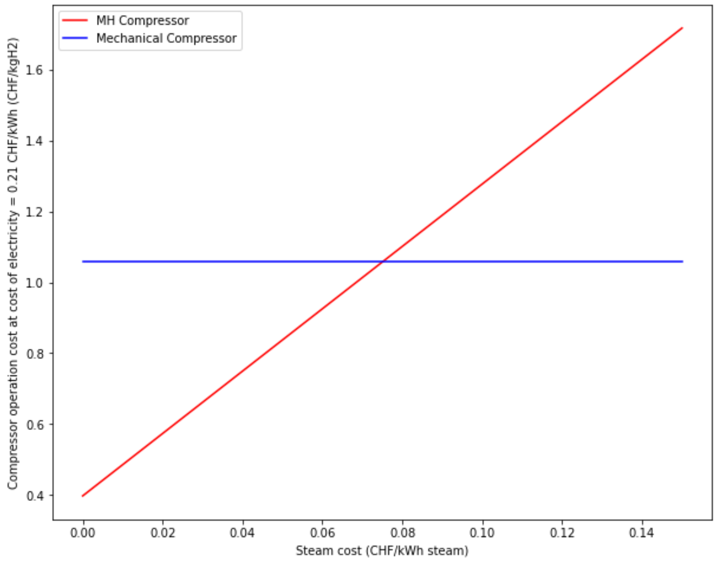


Figure 27 below), and observe the boundary where the cost matches the operation cost of the mechanical compressor.

As seen, when the price of steam reaches 0.1 CHF/kg_{steam}, the operating costs of the two compressors match. In relative terms, the cost of electricity on the operation of the metal hydride compressor is negligible, making the metal hydride compressor favored in regions of high electricity cost and where excess heating and cooling energy is freely and cheaply available.

Further thermal optimization on the system can reduce the amount of steam used. Over the coming months, GRZ will work on optimizing the software operating parameters to improve the steam condensation inside the compressor shells and reduce overall steam consumption. For future projects, improved thermal design and uptake of steam/heating fluids is expected to further reduce the operating costs.

The aspect of maintenance and availability is also an important point to compare both technologies. As seen in Table 6, the mechanical compressor had a total of 57 and 102 hours of maintenance per year in 2023 and 2024, respectively. This resulted in interruption of the operations during several days, in which the whole plant was not operated.

The metal hydrides compressor, on the other hand, required substantial work for the commissioning and optimization of the operating mode. However, during normal operation, the metal hydrides compressor did not require any planned maintenance so far. This is due to the inherent design of the metal hydrides compressor, which works mostly without moving parts. The only exception is linked to water pumps, which require comparatively little maintenance and do not cause a major interruption of the operations. Other maintenance activities required include the regular calibration of various sensors (hydrogen, flame, etc.), which is a routine operation. Based on the experience obtained operating the metal hydrides hydrogen compressor in the project so far coupled with the inherent design features of the system, it is expected that the downtime of the metal hydrides compressor for planned maintenance can be limited to one day per year.

Due to the limited duration of the operation of the metal hydrides compressor, a quantitative assessment of the availability and cost of maintenance of both technologies cannot yet be made. This aspect will be further investigated and confirmed during the next years of operation.

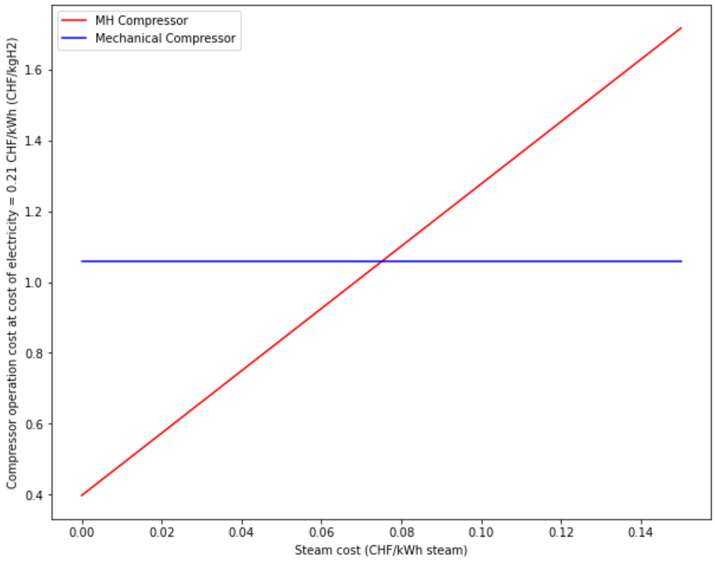


Figure 27: Levelized costs of hydrogen compression at different values of electricity and steam cost. The calculation is made considering the existing parameters on the testing site, i.e., the parameters shown in Table 6.

At the condition that the hydrogen supplied to the compressor is of high purity, the lifetime of the metal hydrides compressor is expected to reach 20 years or beyond, as most components are passive. Single components such as pumps, sensors or valve can be replaced if needed at moderate costs. A cost comparison showing the potential economic advantage of the metal hydrides thermal compression over the lifetime of the system is shown in Table 7. Thereby, the following conditions have been taken:

- The parameters for the mechanical compressor (electrical consumption, maintenance costs) are taken as per the actual data shown in Table 6;
- The HyCo has a substantial advantage in terms of maintenance. Only minor auxiliary systems such as pumps, filters, or similar low-cost components need regular replacement. The estimated cost of maintenance is based on a yearly maintenance intervention, but without major part replacement;
- The CAPEX of the mechanical compressor is based on the prices offered currently by European suppliers for similar systems;
- The CAPEX of the HyCo is based on the target sales price upon commercialization of the system. A detail of the current CAPEX (prototype – CHF 847'000.-) and the target CAPEX (product – CHF 650'000.-) is shown in Figure 28 and Figure 29.

The expected cost reduction between the prototype and the product is expected to be achieved through the following actions:

- Metal hydrides material: the reduction will be achieved through a reduction in the quantity needed on the one hand, and on the reduction of the specific costs on the other hand. The first aspect will be achieved by reducing the cycling time of the compressor, which will lead to a direct reduction of the quantity of metal hydrides needed. This potential is estimated to 20%. In addition, the upscaling of the systema and bulk orders will enable substantial reduction in specific costs, achieved through reduced cost of shipping and packing as well as economies of scale. This potential is estimated to 20% as well. The total cost reduction expected on the metal hydrides material is therefore estimated to 40%.
- Metal hydrides stacks: the cost for the metal hydrides stacks has a very large potential for cost reduction. This can be achieved through the automatized production of the system. Since 2023,

this is already becoming a reality through the partnership between GRZ and the German-based company fischer, who is a supplier for the automotive industry. The company fischer is specialized in the manufacturing of large series of parts in stainless steel. The collaboration has already led to substantial cost reduction for GRZ’s DASH product line in the order of the 55% value targeted for this product. Similar results are expected for the HyCo products. Corresponding efforts are ongoing.

- Looking at the overall costs, the thermal system consisting of pumps, valves, sensors, piping, and heat exchangers is a very important cost factor. The reduction of this cost category will be instrumental in the achievement of the overall cost objective. This will be achieved by combined economies of scale, but also a complete redesign of the system in collaboration with key suppliers to achieve a cost-effective solution.
- The cost reduction in the electrical & Pneumatic, Sensors and Skid & Container categories will be achieved through expected economies of scale and negotiation with suppliers, combined with minor optimization of the design.

Based on this, the target sales price of CHF 650’000.- is expected to be reached for a small series of around 10 units already. Current efforts by the consortium partners are directed at (i) progressing towards the cost reduction targeted, and (ii) obtaining concrete leads and projects to launch the commercialization.

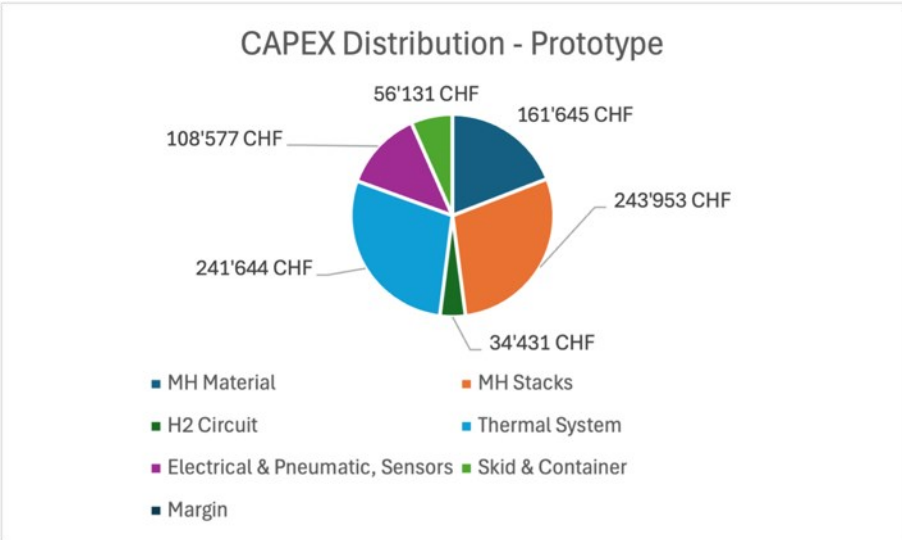


Figure 28: Distribution of the CAPEX for the prototype built.

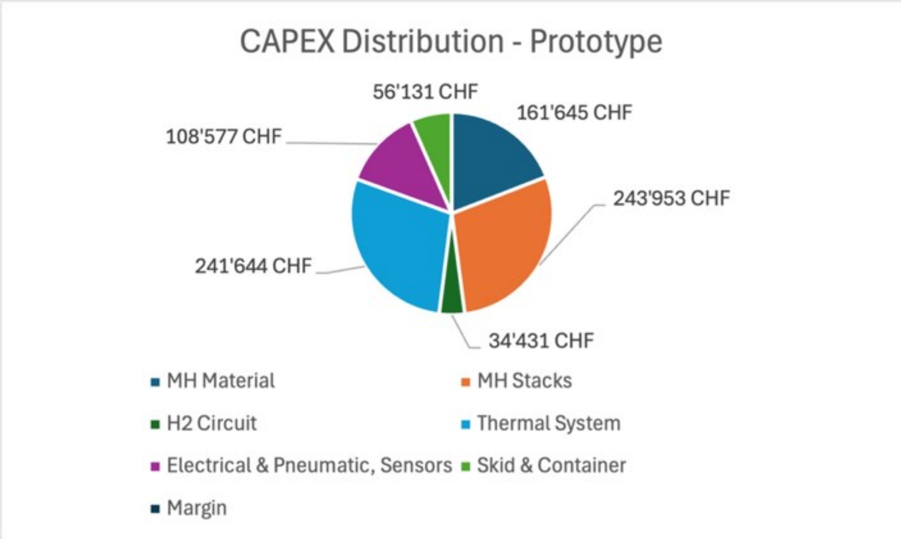


Figure 29: Estimation of the CAPEX distribution for the commercial product.

Parameter	Unit	Value
CAPEX Mech. Compressor	CHF	CHF 650'000
CAPEX HyCo	CHF	CHF 650'000
Capacity	kgH2/h	30
Inlet pressure	bar	10
Outlet pressure	bar	200
Cost of electricity	CHF/kWh	0.25 CHF
Cost of thermal energy	CHF/kWh	- CHF
Specific electrical consumption mech. Comp.	kWh/kgH2	2.1
Specific electrical consumption HyCo	kWh/kgH2	0.2
Specific thermal energy consumption HyCo	kWh/kgH2	8.8
Specific cost of maintenance mech. Comp.	CHF/kgH2	CHF 0.61
Specific cost of maintenance HyCo (estimate)	CHF/kgH2	CHF 0.10
Hours of operation per year	h/y	4000
Interest rate	%/y	4.00%

Year	Mech. Comp.		HyCo		Amount H2 Processed
0	CHF	650'000	CHF	650'000	-
1	CHF	130'962	CHF	17'308	115'385
2	CHF	125'925	CHF	16'642	110'947
3	CHF	121'081	CHF	16'002	106'680
4	CHF	116'424	CHF	15'386	102'577
5	CHF	111'946	CHF	14'795	98'631
6	CHF	107'641	CHF	14'226	94'838
7	CHF	103'501	CHF	13'679	91'190
8	CHF	99'520	CHF	13'152	87'683
9	CHF	95'692	CHF	12'647	84'310
10	CHF	92'012	CHF	12'160	81'068
11	CHF	88'473	CHF	11'692	77'950
12	CHF	85'070	CHF	11'243	74'952
13	CHF	81'798	CHF	10'810	72'069
14	CHF	78'652	CHF	10'395	69'297
15	CHF	75'627	CHF	9'995	66'632
16	CHF	72'718	CHF	9'610	64'069
17	CHF	69'921	CHF	9'241	61'605
18	CHF	67'232	CHF	8'885	59'235
19	CHF	64'646	CHF	8'544	56'957
20	CHF	62'160	CHF	8'215	54'766
TOTAL	CHF	2'501'002	CHF	894'626	1'630'839
Cost per kgH2	CHF	1.53	CHF	0.55	
Cost reduction HyCo				64%	

Table 7: Comparison of the levelized cost of compression between a conventional mechanical compressor and the HyCo.

Overall, the following conclusion can be drawn:

- The competitivity of the metal hydrides compressor is dependent on the availability of affordable or even free heat;
- Under ideal conditions, and if the expected reduction in CAPEX mentioned above and the lower maintenance costs are confirmed, the levelized costs of compression could potentially be reduced by up to 64%, as illustrated in Table 7;

- The reduction in the levelized cost of compression is driven by free (or very cheap) heat. Potentially lower costs of maintenance further support this trend. The expected break-even point takes place at a steam cost of around CHF 0.08.-/kWh (depending on other parameters such as electricity price, etc.), as shown in Figure 27;
- High electricity prices favor the use of the HyCo technology.

2.8 Commercialization

In parallel with the testing and commissioning of this metal hydride compressor, several activities are ongoing to prepare the commercialization of the technology. The key activities are summarized below:

- GRZ filed an additional patent on new aspects of the HyCo technology. This should strengthen GRZ's intellectual property and create a barrier of entry to potential competitors. The patent was filed under the number EP21192688.
- Messer and GRZ signed an agreement for the further commercialization of the technology. Messer will be responsible for all work on site, such as site preparation, installation and commissioning of a hydrogen refueling station. GRZ will focus on the further development and on the production of the compressor.
- Several formal quotes have been submitted for large-scale projects which includes the HyCo technology. The completion of the pilot project in Visp will be a strong support for the credibility of the technology and will be used as a reference object in support of the quotes submitted.
- Simultaneously to the development of the continuous compression technology, engineering and development is ongoing for metal hydride compressors for direct refueling of vehicle tanks. The basis of the technology remains the same, but there are additional constraints regarding meeting refueling protocols, safety requirements during fast refueling etc. GRZ in collaboration with several partners including Messer Schweiz and Hyundai Motor Company is working on developing a first full scale metal hydride based hydrogen refueling station (HyCo HRS) for 350 bar refueling.
- The material- and manufacturing cost of the current prototype were comparatively high. In order to commercialize a product that is competitive in terms CAPEX, the manufacturing costs must be reduced by around 35%. From a past experience with similar products, this is well within range from transitioning from a prototype build to a small series of a standard product.

Further commercial activities will be carried out in the upcoming months.

3 Conclusions and outlook

This report outlines the work conducted in the design, manufacture and demonstration of the operation of the hydrogen metal hydride thermal compressor. The purpose of the compressor was to demonstrate the use of metal hydride technology for continuous compression of hydrogen at an industrial scale. With the chosen specifications and to the best of our knowledge, the current system is the largest continuous metal hydride-based hydrogen compressor in the world.

The chosen application for the demonstration of the technology was the compression of the available hydrogen on the customer site from 10 bar to 200 bar to fill up trailers.

As described in this report, the metal hydride compressor has been successfully installed on the customer site and initial operation testing has been successfully conducted. Compression has been observed from 10 bar to 200 bar and automatic operation of the system with start and stop signals from the control software has been established. The system logic has been adapted to the available thermal energy on site and operates in cycles that ensure an almost continuous supply of hydrogen. The sensors installed on the system allow for performance measurement of relevant parameters and the calculation of the thermal and electrical energy consumption in the system. The overall capacity of the system was observed to be limited on the absorption side, and potential solutions are being explored.

The successful demonstration of the required compression as well as automatic, continuous operation proves the acceptability of the overall process logic and the robustness of the technology. Nevertheless, there were several learning opportunities encountered in the development of the system and consequently there are several design features that can be improved upon and optimized in the future. Examples include the potential usage of a single phase fluid for both heating and cooling (to avoid the problems with steam hammer, as well as smooth out system operation), the optimization of the overall thermal design of the system for a more efficient thermal performance (including testing different system configurations), the optimization of steam usage where possible (instead of condensing all leftover steam, we could redirect the spent steam to steam lines or a boiler), etc. Improvements on hydrogen line design to reduce line pressure drops can further streamline operation between upstream systems, the metal hydride compressor and downstream systems. Stricter control of heating and cooling input can reduce wastage of thermal energy during operation and cut operating costs.

In parallel with this project, there have already been multiple advances in the metal hydride development in terms of pressures as well as capacities. The development of materials as well as prototype systems that can compress hydrogen to as high as 875 bar – which combined with the continuous compression system design, can allow for metal hydride compressors that are able to achieve higher pressures. Higher metal hydride material capacities imply lower thermal energy requirements in the process (as there is less amount of metal hydride to heat/cool for a larger amount of hydrogen). There is also a shift from the use of AB_5 type materials to AB_2 type materials which show excellent cyclability performance and lower production costs.

The results obtained from this project, and the successful demonstration of the technology at the current scale in an industrial environment (TRL 8) also set the basis for standardization of this product as well as a commercial launch.

In the upcoming months, the operation of the compressor will be continued, focusing on further improving the operational parameter and gathering additional performance data. The compressor will then be fully integrated in the operations of Messer as a standard compression unit. It will also serve as reference to potential customers interested in the technology. As has been observed from past data, the economics of mechanical compressors are strongly controlled by high electrical energy requirement as well as significant down time for maintenance. It is in these two aspects that the metal hydride compressors have potential advantages over conventional mechanical compressors – they require mainly thermal energy and they have no moving parts and so are expected to require less down time for maintenance. Additionally, further optimization of the design and engineering around the MH compressor system will reduce thermal energy requirements and improve the utilization of available resources.

The metal hydride based compression technology has the ability to target a niche but sizable market, especially including sites which have plenty of low-cost, excess thermal energy to provide for hydrogen storage and compression. This in particular could include chemical industries, green ammonia production sites, or even areas with high availability of solar energy which could be used as a source of free heat. The compactness of metal hydride-based technology, and the added safety of such systems also make them a suitable option for commercial hydrogen refueling stations with designs for such system already well underway.

The learnings from this project, and the progressing hydrogen landscape means that metal hydride technology can lead to a cost-efficient and scalable solution for storage, compression and transport of hydrogen on a large scale, to facilitate the integration of hydrogen as a clean energy carrier in various sectors and contribute to accelerating the energy transition.

4 National and international cooperation

The following collaborations are active:

- Auto AG: GRZ and Messer have realized a hydrogen refueling station for trucks (350 bar refueling) on the premises of the Swiss company Auto AG (https://www.autoag.ch/de/home.html). The objective of the project is to produce hydrogen on-site thanks to a photovoltaic plant, to store the hydrogen in the metal hydrides hydrogen storage and then compress it on demand to refuel hydrogen trucks. Eventually, the aim is to offer this kind of product alongside the sales of hydrogen trucks to offer a full solution (vehicle + own infrastructure) to potential customers.
- GRZ has a strong collaboration with Hyundai Motor Company (South Korea). A demonstration project is ongoing to increase the outlet pressure of the HyCo system beyond 700 bar, in order to offer a refueling solutions for vehicles up to 700 bar. A first prototype for compression up to 875 bar has been created.
- An upcoming project involves a collaboration between GRZ, Hyundai and Messer, along with a number of other local and international partners such as the Korean Advanced Institute of Science and Technology (KAIST) and Doowon, to produce a hydrogen compression system for direct refueling of vehicles at 350 bar. The project is expected to be realized on the same site as the current system in Visp.

5 Publications and other communications

A scientific publication entitled “*Performance investigation and model based process optimization of an industrial scale continuous metal hydride compressor*” is in preparation.

GRZ was nominated as a finalist to the “Building Award” (https://www.building-award.ch/cont/nominationen_2025.html).

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