# NHA CONFERENCE 2007: STEPS TOWARDS A BREAKTHROUGH OF HYDROGEN VEHICLES WITH HYDROGEN COMBUSTION ENGINE AND LIQUID HYDROGEN STORAGE

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## 1. Introduction

Sustainability is an essential part of BMW Group's corporate strategy. For 25 years BMW has been taking environmental responsibility by promoting hydrogen technology through their BMW CleanEnergy initiative. After several generations of research prototypes, a first set of research vehicles was sent on the CleanEnergy World Tour in 2001/02 to emphasize BMW's vision of sustainable mobility. Recently, the *BMW Hydrogen 7* - the first premium hydrogen sedan and the first hydrogen powered BMW that was developed and produced in a common series process - was presented to the public. *BMW Hydrogen 7* is designed to fascinate pioneers in politics, business, science, culture and sports encouraging them to support the idea of a hydrogen driven economy. It reflects the current state of the art in hydrogen internal combustion engines (ICE) and liquid hydrogen ($LH_2$) storage. It proves feasibility of hydrogen within BMW's proven development and production structures and is a first step towards industrialization of automotive $H_2$ technologies. However, there are still several issues that need to be addressed in the transition phase to a hydrogen future.

## 2. Challenges

From today's viewpoint, the transition period to a hydrogen economy in the sense of a market penetration of hydrogen powered vehicles is rather unpredictable in time and slope. Responsible for this are necessary technological steps as well as the limited fuel infrastructure. Thus, $H_2$ vehicles will be in a long term competition with conventional and other alternative vehicles. BMW CleanEnergy is therefore faced with the challenge to create a premium customer value product that is fully competitive. This implies that hydrogen vehicles are on one hand required to emphasize very convincing $H_2$ specific benefits such as practically freedom of emissions and the prospect of a $CO_2$ free driving machine. On the other hand, they may however not have any significant disadvantages concerning conventional vehicles` characteristics such as range, comfort, usability, dynamics, robustness and affordability. Besides, vehicle architectures flexible enough to adapt to heterogeneous fuel types as well as cost effective technologies and feasible industrialization are absolutely essential for any OEM and crucial while bridging over the pre-transition period lacking any positive business cases. In order to meet these requirements, breakthrough steps in hydrogen powertrain and storage technology are necessary enabling cost effective vehicle concepts that meet customer demands.

## 3. Future steps in $H_2$ vehicle concepts

Since hydrogen is a fuel with very low energy density (~$^1/_4$ to gasoline) it causes a lot more target conflicts than conventional vehicles are handling today. A good but very expensive approach to bear these challenges are $H_2$ purpose design vehicle concepts.

[1] BMW Group

These however, do not appear to be adequate before a market penetration phase. For the transition time frame, a cost effective conversion design featuring high commonality to existing vehicle platforms but also fulfilling all functional requirements needs to be found.
BMW addresses this challenge with the following vehicle concept approach: Applying a hydrogen combustion engine allows a power density converging to conventional engines (see chapter 5). Additionally, a combustion engine ensures a maximum of commonality and takeover parts in the engine itself as well as in the surrounding structure - e.g. the vehicle's front end. Implementing a hydrogen storage in a vehicle asks for the highest possible gravimetric and volumetric energy density which is best accomplished by an $LH_2$ storage (see chapter 4). Besides, a $LH_2$ system holds the possibility of moderate freeforming and lightweight construction. Above all, it enables vehicle body integration which puts an end to spiraling additional space and weight demands as well as resulting vehicle modifications.

When determining the biggest possible contiguous construction space in a vehicle potentially suited for hydrogen storage one inevitably comes across the center tunnel:

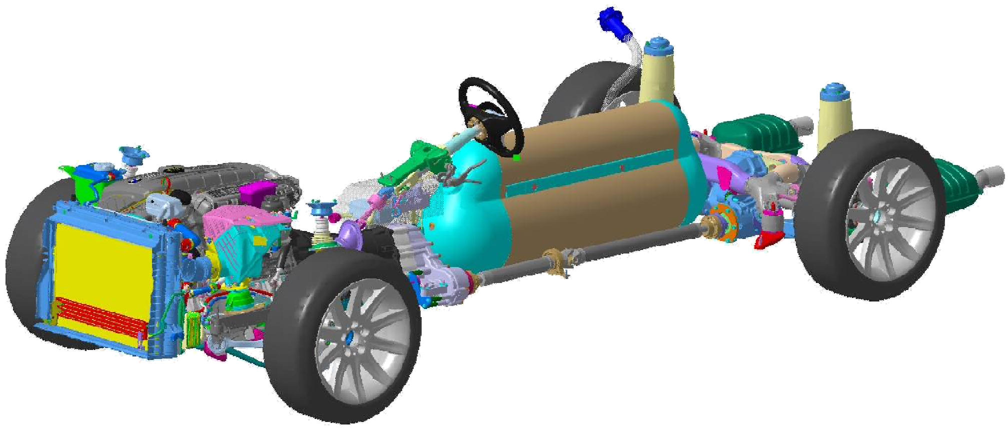

*Figure 1: $H_2$ vehicle concept*

The center tunnel of a vehicle is the safest place for integrating a large system and reduces disadvantages from the additional weight: Since a hydrogen storage system is much heavier than any conventional fuel tank, the vehicle concept features a very low center of gravity, optimized axle load distributions and minimized inertia. Therefore, the approach supports core demands of typical BMW customers who focus on excellent driving and handling characteristics. Furthermore, it provides another striking opportunity: When integrating the light weight $LH_2$ storage the outer vessel can be applied as a part of the vehicle body structure. Thus, the vehicle can benefit from a stronger backbone and resulting weight synergies instead of adding structural measures.

This approach is the key to the weight neutral integration of $H_2$ in suitable vehicle platforms. At BMW, limiting weight is understood as one of the most crucial goals for hydrogen vehicles due to its relevance for consumption, dynamism and riding comfort. Vehicle weight management decides whether or not it will be possible to stay within the weight range of the conventional platform's heaviest vehicle variant. Moreover it determines whether or not the basic vehicle's positive characteristics can be kept and costs can be limited by maximizing commonality. Therefore limiting weight is the key success factor for $H_2$ conversion design concepts:

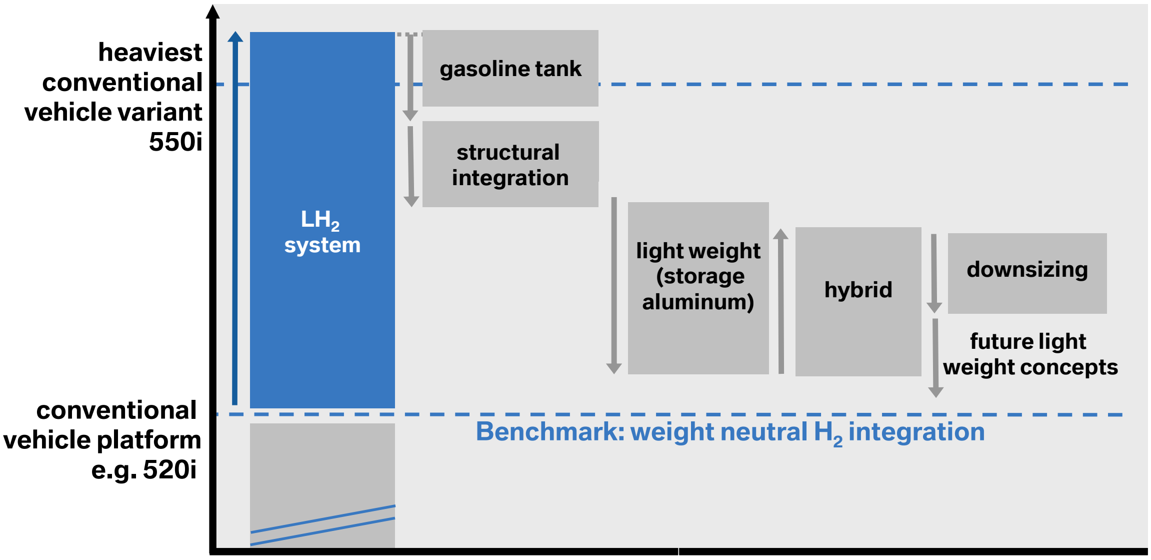


*Figure 2: vehicle weight management*

## 4. Future steps in cryogenic hydrogen storage

BMW CleanEnergy's conversion design approach asks for the highest possible gravimetric and volumetric energy density. The next generation $LH_2$ storage is unrivalled in both compared to any other available storage technology:

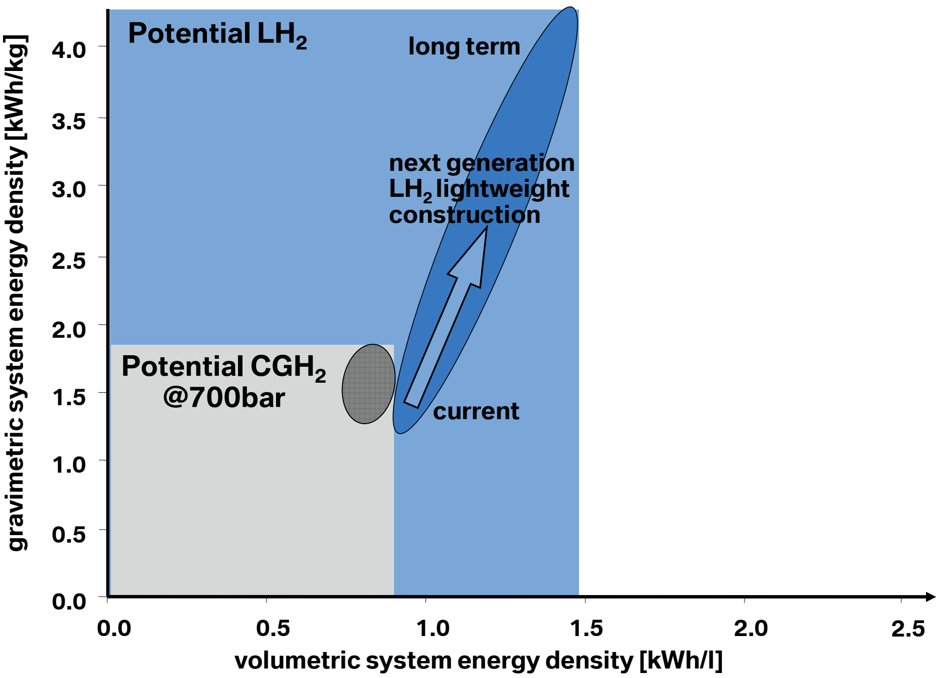


*Figure 3: hydrogen energy density*

Thus, the approach allows storing a hydrogen mass of 7-10 kg in compact / midsize vehicles, which is twice the amount $CGH_2$@700bar could provide under typical vehicle package restrictions. Moreover, it holds the possibility of structural vehicle body integration and offers great light weight capability: BMW's research together with Air Liquide have already developed a full functional light weight aluminum $LH_2$ storage that proves the tremendous weight potential still existing in $LH_2$ technology. Based on

this research next generations of light weight aluminum $LH_2$ tanks are feasible with half the weight of the current *Hydrogen 7* system. For future generation further light weight potential e.g. with carbon fibre composite (CFC) is thinkable.
The next generation of BMW's hydrogen storage systems will also comprise different measures for significant cost reductions. Current $LH_2$ technology is a very first step of industrialization and costs are very high compared to $CGH_2$ systems that could already benefit from several evolutionary steps in gas cylinder development. However, by means of consistent design to cost and design to manufacturing BMW could already proof in a detailed cost analysis, that cost reductions of 75% are feasible in the next generation and a cost level comparable to $CGH_2$ systems is in sight - even for smaller production figures:

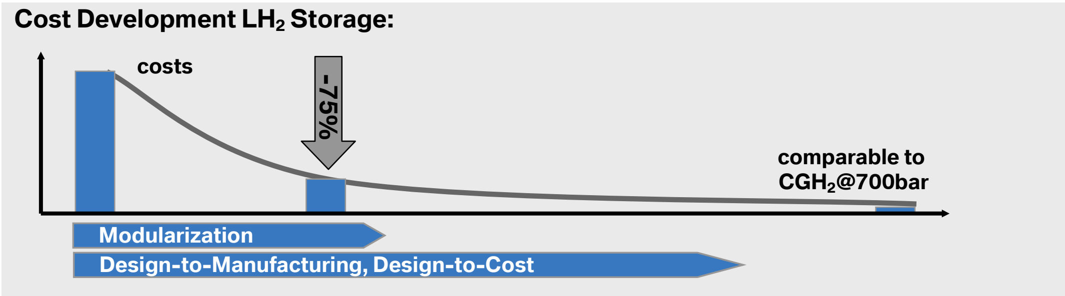


*Figure 4: $LH_2$ storage system cost development*

Key elements of BMW's cost down approach are modularization (potentials for standardization, market competition, optimized manufacturing and testing), mechanized insulation and integration of complex welded systems to aluminum casting elements. Thus, concepts for high volume industrialization lead to a perspective of system cost of 10 $/kWh:

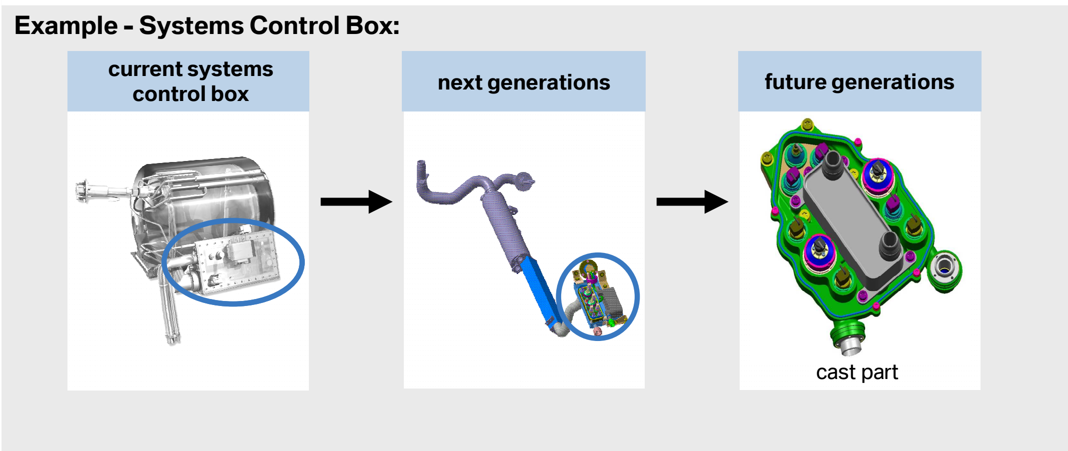


*Figure 5: $LH_2$ storage system industrialization*

However, the biggest remaining challenge for cryogenic hydrogen is minimizing potential energy losses (boil-off losses) when long term parking. New concepts in thermal layout, optimized insulation systems and advanced concepts for fuel extraction [2] allow a significant step in thermal performance. Hence, the next generation hydrogen storage system's dormancy time period can be more than tripled and enlarged to approx. 3 days. Thus, a completely energy loss free usage is possible in typical BMW customer user profiles e.g. commuter driving cycles ($\geq$ 8 km / weekdays). This makes $LH_2$ the ideal solution for frequently driving customers getting benefits of the stored

hydrogen's higher energy density in terms of driving range and more valuable vehicle characteristics resulting from BMW's vehicle integration concept [3] that is uniquely possible with $LH_2$.
Further optimization of energy availability is possible in consequent steps, but physics do not allow a complete elimination of the $LH_2$ specific boil off gasses. Thus, an LH2 storage concept cannot be recommended for drivers or vehicle types with very infrequent driving patterns. A very promising future option addressing these target groups could be cryocompressed hydrogen $CCH_2$ (supercritical hydrogen) solving the energy loss problem for infrequent drivers while keeping volumetric energy density comparable to $LH_2$ if fueled cryogenically[3].

## 5. Future steps in $H_2$ powertrains with $H_2$ internal combustion engines

The engine of *BMW Hydrogen 7* is a naturally aspired multi port injection V12 6,0l engine with 191 kW. Currently, it is in real-life customer usage proving that all well known advantages of combustion engines such as power density, robustness, reliability and endurance over vehicle lifetime apply to hydrogen combustion engines as well. Furthermore, the approach allows to keep cost effective core components as well as highly industrialized production and inhouse value creation.
However, significant advances in power and torque density are necessary to support requirements of future drivetrains and vehicle concepts. Current engines in BMW CleanEnergy's advanced development prove the potential of doubled power and torque density in the range of best current gasoline engines by means of turbo charging or direct injection. Moreover, turbo charged direct injection engines in research have proven potentials of up to 100 kW/l.

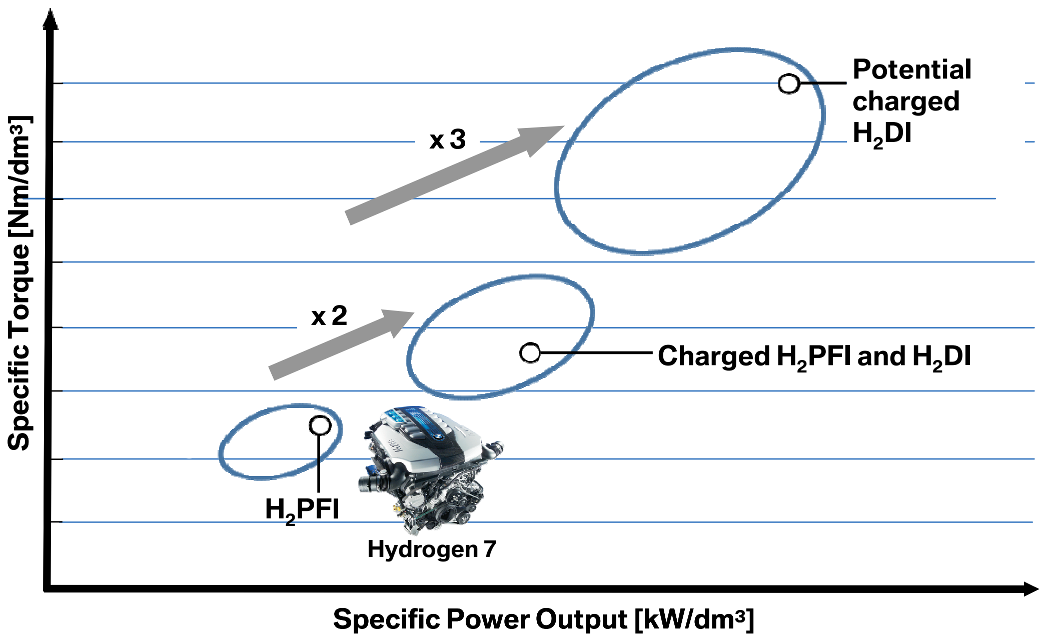


*Figure 6: $H_2$ combustion engine power density potential*

Whereas fuel cell electric vehicles (FCEVs) are considered to be zero emission vehicles per definition, hydrogen combustion engines are predefined as "advanced technology partial-ZEVs" and need to undergo strict emission testing procedures. Nevertheless, BMW proved that all non NOx emissions occurring during lubricant combustion are well below detection limits. The only challenge remaining is NOx whereof

*BMW Hydrogen 7* currently reaches up to 10 % monofuel / 30 % bifuel of SULEV II NOx limits during FTP 75. BMW CleanEnergy's approach to this is an intelligent operating strategy that applies well known exhaust treatment methods while running in stoichiometricial mode, skips the high NOx combustion area and operates during partial load in the inherent clean, lean combustion mode where only extremely low NOx occur:

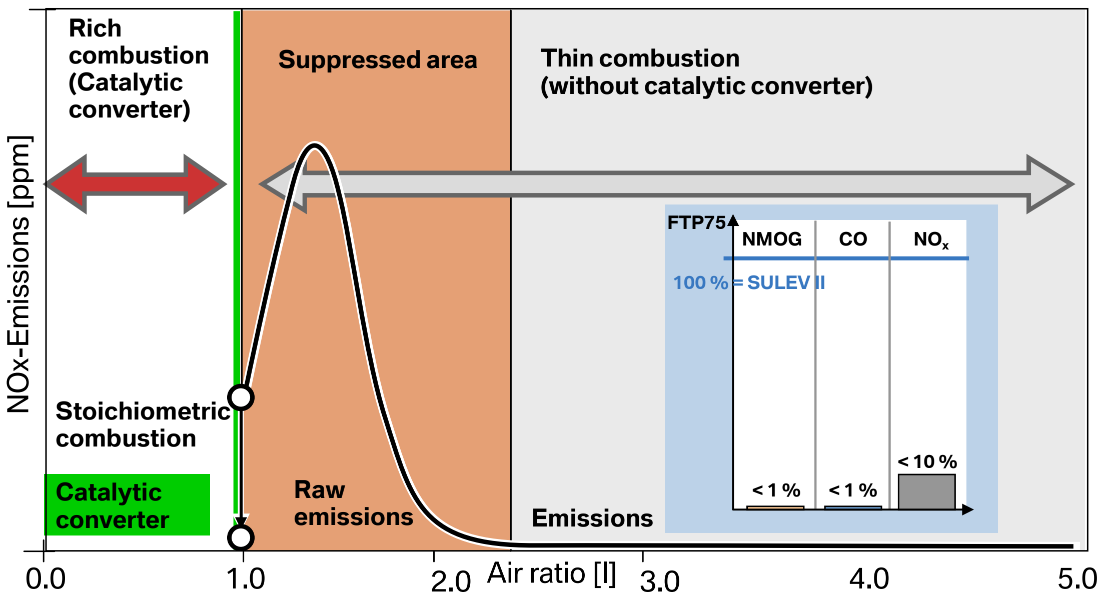


*Figure 7: emission treatment*

Therefore, hydrogen combustion engines prove their potential as robust, practically emission free advanced technology [1].
Besides, further optimization of efficiency is addressed in consequent steps featuring an advanced hybrid powertrain with a downsized hydrogen ICE [4]. Even though FCEVs claim to reach a higher degree of efficiency than combustion engines, advanced powertrains' consumption levels have the potential to converge to those of FCEVs:

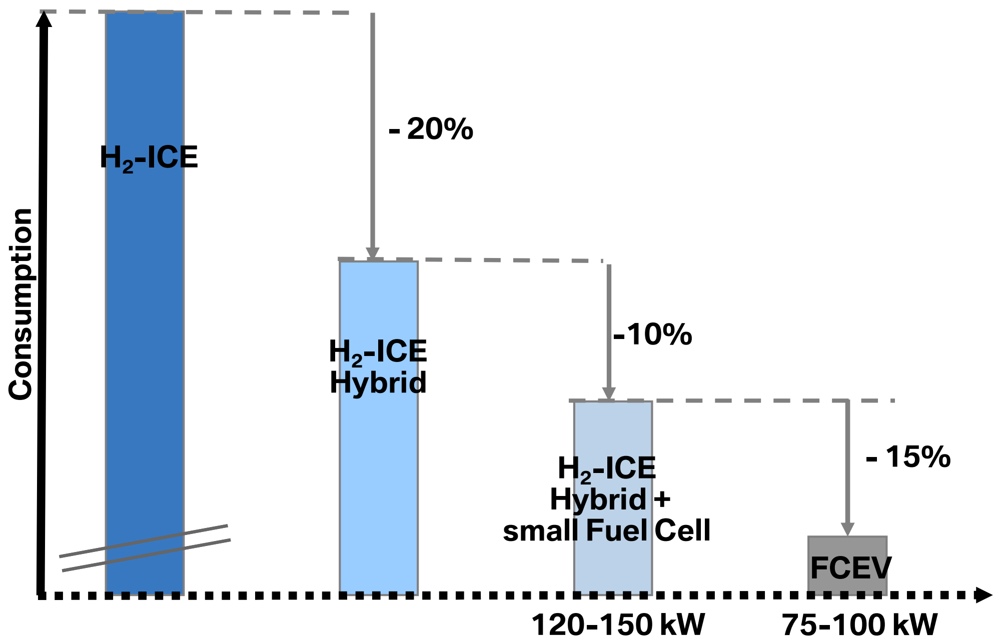


*Figure 8: $H_2$ advanced powertrain efficiency potential*

## 6 Perspectives for future vehicle applications

BMW CleanEnergy's approach of combining an advanced hydrogen ICE powertrain with a conformable lightweight $LH_2$ storage to a coherent conversion design vehicle emphasizes all core customer value vehicle characteristics: Integrating the $LH_2$ storage in the vehicle's center tunnel allows the customer to fully utilize their trunk and load their vehicle as they can with any other conventional car. Furthermore, it provides an optimized weight balance allowing for dynamism and driving characteristics unlike any other BMW. Optimized consumption promises double the *BMW Hydrogen 7* driving range in NEDC driving cycle. Moreover, technological advances in $LH_2$ storage system make it possible to experience no evaporation losses in commuter driving profiles ($\geq$ 8 km / weekdays). Thus, BMW CleanEnergy has presented a concept for next generation hydrogen vehicles that emphasizes convincing $H_2$ specific benefits such as practically no emissions and features high customer value characteristics that are nothing short of other conventional or alternative vehicles.

## 7 Conclusion

BMW Group is a successful and responsible company in whose corporate strategy sustainability plays an essential role. With their EfficientDynamics and CleanEnergy initiative, BMW is pursuing the vision of sustainable mobility. *BMW Hydrogen 7* is a first step in the transition to a hydrogen economy fascinating pioneer customers and giving an impulse for a hydrogen infrastructure. At the same time, several challenges are identified that need to be solved when enabling a market penetration of $H_2$ powered vehicles. Nevertheless, BMW CleanEnergy has framed all the determining technological steps to embrace these:

The next $LH_2$ storage generation features high energy density with dramatically minimized energy losses. The concept of a vehicle integrated conformable storage system enables light weight benefits and puts an end to spiraling additional weight and modification measures. At the same time, modularization approaches permit cost potential and advanced manufacturing.

Technological advancement in $H_2$ powertrains promise doubled power and torque density in the next generation. Furthermore, intelligent downsizing and hybridization measures can significantly reduce consumption. Equipped with a modern emission treatment, BMW's advanced hydrogen powertrain combines all well known advantages of combustion engines such as robustness, reliability and endurance over vehicle lifetime with an inherent clean operating strategy.

BMW CleanEnergy`s approach features all state-of-the-art technologies to create an ultimate premium hydrogen vehicle in the next generation and enable coherent subsystem optimization. At the same time, all potentials for managing costs and industrialization are addressed to master the transition period to a hydrogen economy.

Nevertheless, enabling a new technology to meet automotive standards needs a lot of time, endurance and continuous financing. Before hydrogen vehicles can be fully approved for any customer's use or misuse a long way of technological steps has to be mastered. A time when OEMs will actually make money with their hydrogen commitment is far from being in sight. No company can lift such a technological progress by themselves, serious cooperations with other OEMs, suppliers and politics are needed.

## 8 References


1. Edgar Berger, Christian Bock, Hubert, Fischer, Manfred Gruber, Gerrit Kiesgen, Herrmann Rottengruber, *The New BMW 12-Cylinder Hydrogen Engine as Clean, Efficient and Powerful Vehicle Powertrain*, FISTA World Automotive Congress, Yokohama (Japan), October 2006.

2. Tobias Brunner, Dr. Oliver Kircher, Josef Lutz, *On the way to a New Generation of Production Passenger Car Integrated Liquid Hydrogen Storage Systems*, Proceedings, World Hydrogen Energy Conference, Lyon (France), June 2006.

3. Tobias Brunner, *Liquid Hydrogen Vehicle Storage – Progress and Challenges*, Proceedings, NHA Annual Hydrogen Conference, San Antonio TX (USA), March 2007.

4. Manfred Klüting, Theodor Melcher, *Efficient Dynamics – an Integral Approach to Future BMW Powertrains*, 14th Aachen Colloquium Automobile and Engine Technology, Aachen (Germany), October 2005.