

## **Optimization of Fuel Cell Powertrain within the Triangle of Technology, Cost and Customer Requirements**

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### **Executive Summary**

Daimler AG is a technology leader in the field of automotive fuel cells. Over two decades, competence, know-how and extensive experience have been built up from component up to vehicle level, in hydrogen infrastructure, as well as by the long-term operation of two generations of vehicle fleets, also in customer requirements. When it comes to optimization of fuel cell drive, the parameters of customer requirements, technology, cost and also hydrogen infrastructure have to be taken into account. Depending on the weighting of the parameters, the vehicle category and the point in time of the analysis, one is led to different configurations of a hybrid fuel cell drive. The resulting generic types of powertrain architectures are described. In the practical implementation, also the availability of standard components plays an important role for the piece cost. A current solution as well as the resulting well-to-wheel energy and greenhouse gas balance is discussed in detail taking Daimler's next generation fuel cell drive as an example.

*Keywords: bus, fuel cell, hydrogen, ZEV (zero emission vehicle), passenger car*

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### **1 Introduction**

In order to reduce the fleet emissions, Daimler AG is relying essentially on three pillars in powertrain technology: The internal combustion engines are consistently developed further and still improved in their efficiency by different measures. Next to it, a comprehensive portfolio of full- and plug-in-hybrid electric vehicles is created. For example, with the C 350 e, the GLC 350 e, the E 350 e and the S 500 e, high-volume vehicles in the middle, upper and luxury class are offered with plug-in-hybrid drives now. However, completely emission-free mobility is only offered by the cars with pure electric drives, which have either a battery-electric or a fuel cell drive. Current products are the B-Class Electric Drive and the smart electric drive as battery powered electric vehicles, as well as the B-Class F-CELL as a fuel cell vehicle.

Fuel cell technology is still an integral part of Daimler's powertrain strategy. The benefits are obvious: high range with short refueling times and at the same time a wide field of possible applications from passenger cars up to city buses.

## 2 Current Generation of Fuel Cell Vehicles: B-Class F-CELL

The B-Class F-CELL, which had been produced under series production conditions, has been in customer's everyday use in the European and the American market already since 2010. One of the vehicles from the Daimler fuel cell fleet has even achieved a record of continuous operation under normal daily conditions with a mileage of more than 300.000 km.

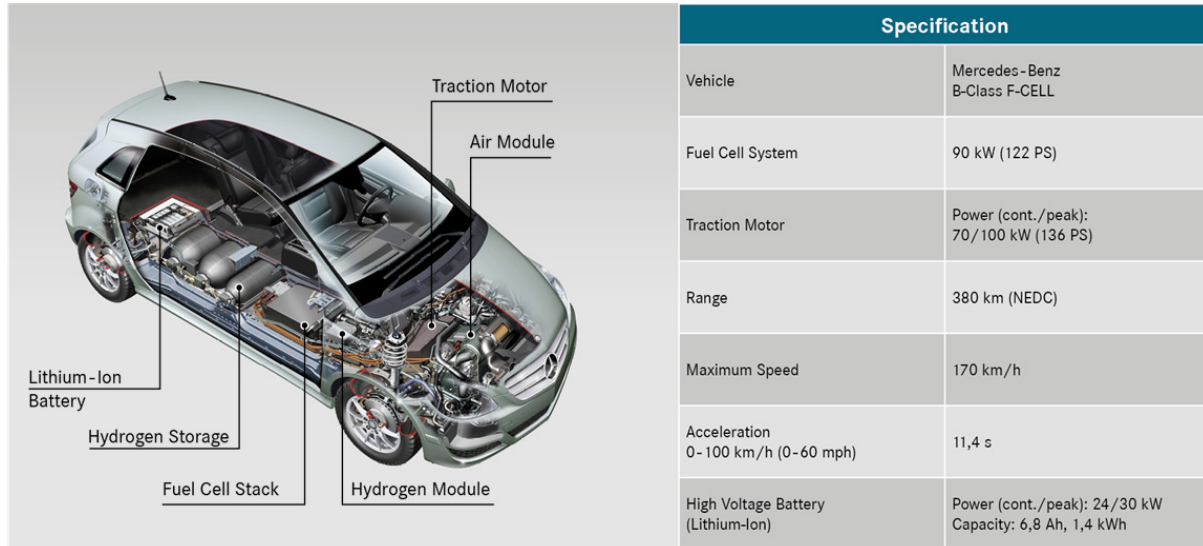


Figure 1: Technical data of the B-Class F-CELL

The B-Class F-CELL has a fuel cell system net power of 90 kW, whereat the fuel cell stack is located below the driver and the passenger seat in the sandwich floor of the vehicle. The air supply of the fuel cell stack, as well as the 100 kW traction motor for the front axle, are housed in the engine compartment of the B-Class. Further back and below the rear bench seat, there is the hydrogen tank system of the vehicle. It consists of three containers and stores a sufficient amount of hydrogen to enable an NEDC range of 380 km. Finally, there is a lithium-ion battery installed beneath the floor of the luggage compartment, which is used for hybridization of the fuel cell system. Furthermore, using the battery, brake energy can be recovered as well as vehicle acceleration is supported. The battery has a capacity of 1.4 kWh and can provide a maximum discharge power of 30 kW.

## 3 The Citaro FuelCELL-Hybrid as the Current Generation of Fuel Cell Busses

Besides the B-Class F-CELL passenger cars, an important step towards achieving the vision of emission-free commercial vehicles succeeded with the Citaro FuelCELL-Hybrid. The drivetrain concept of the Citaro FuelCELL-Hybrid consists of a fuel cell as a power supply linked with a serial hybrid drive. Therefore, an internal combustion engine is unnecessary. A powerful, water cooled lithium-ion battery with a capacity of 26.9 kWh serves as intermediate storage for the electrical energy generated in the fuel cell. The battery supplies the two liquid-cooled, electric wheel hub motors on the drive shaft with a total power of 160 kW as well as the ancillary components of the vehicle through a 650V DC high voltage link. Thus, it is possible to regain energy (recuperation) during braking and deceleration of the vehicle and store it in the battery. Because only harmless water vapor is created as the only "exhaust gas" in the fuel cell, the Citaro FuelCELL-Hybrid is also suitable for particularly environmentally sensitive routes, such as pedestrian zones and environmental zones in polluted cities. Since the fuel cell system as energy supply reaches a higher efficiency than an internal combustion engine and since braking energy is recovered by recuperation in addition, the energy balance in the operation of the city bus is very positive.

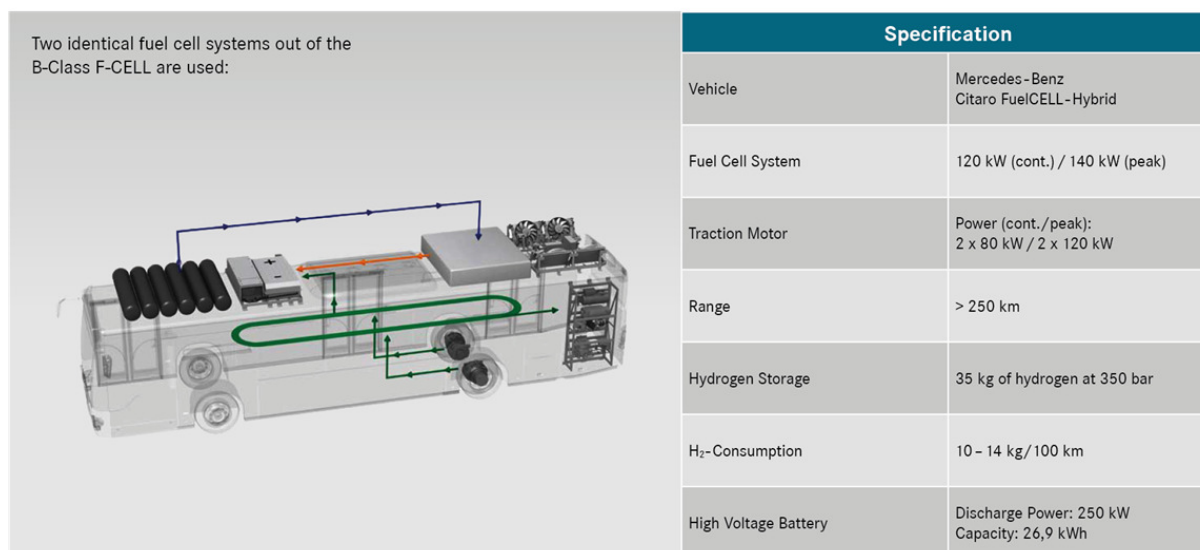


Figure 2: Technical data of the Citaro FuelCELL-Hybrid

## 4 Experiences and Feedback from the Fleet Operation of Fuel Cell Cars and Busses

With more than eight millions of kilometers travelled in the B-Class F-CELL fuel cell fleet, Daimler AG has the biggest experience with fuel cell vehicles in customer hands. A single B-Class F-CELL was even able to achieve a record of continuous operation under normal daily conditions with a mileage of more than 300.000 km. For this record, the Daimler AG was awarded the "f-cell award 2014". In addition, also the short refueling time - one of the advantages of the fuel cell - could be verified within the fleet operation impressively: the evaluations showed a refueling time of less than three minutes during real operation on the basis of 36.000 refueling processes. Also the customer feedback drops out to be positive.

In addition to the fuel cell passenger cars, currently 23 Mercedes-Benz Citaro FuelCELL-Hybrid buses are on duty in six cities in Europe. Thereby, the five busses of Postauto Schweiz AG in the canton of Aargau in the Alps gathered the most kilometers so far. Second ranked the four busses operated by the Hamburger Hochbahn are following. In third rank there are the five busses operated by the Società Servizi d'Area (SASA) in Bolzano. Three more busses are in use in Milan, four busses in Stuttgart at the Stuttgarter Straßenbahnen AG (SSB) and two busses at the Karlsruhe Institute of Technology (KIT). The European Union reaffirmed their support for the further development and the introduction of fuel cell buses in the CHIC (Clean Hydrogen in European Cities) project, which includes among other things the demonstration fleets in Hamburg (DE), Aargau (CH), Milan (IT) and Bolzano (IT). Overall, the busses have covered a distance of more than four millions of kilometers in emission-free driving. The passengers appreciate the low noise level and the comfortable, smooth ride. If busses as means of transport itself apply as eco-friendly and emit the lowest emissions related to the passenger-kilometers – then the fuel cell buses are completely emission-free. The operators appreciate the high availability of the busses in the different usage scenarios and especially the short refueling times of a few minutes.

## 5 Important Parameters for Optimization of Fuel Cell Drivetrains

In the foreground of fuel cell drivetrain optimization there are four parameters to be brought in line: technology, costs, hydrogen infrastructure and customer wishes. A detailed description of these parameters is shown in figure 3.

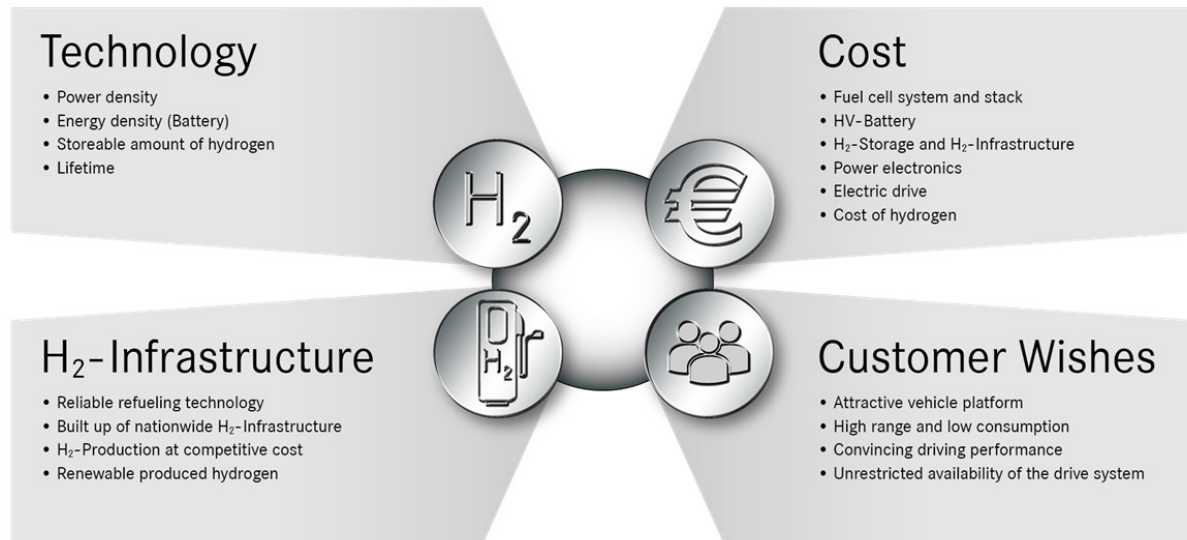


Figure 3: Parameters for Optimization of Fuel Cell Drivetrains

Additionally, the boundary conditions of the respective vehicle platform, such as available packaging spaces, weight, and driving resistances, have to be taken into account for the fuel cell drive.

Finally, it also plays a weighty role for the product cost, which proportion of components in the fuel cell drive has to be developed specifically for this purpose. Because fuel cells are at this stage far away from the production quantities of other drivetrain options, such as the pure combustion engine or the plug-in-hybrid, it is beneficial if standard components produced in high volumes can be used in many places. Here, the increasing electrification of conventional drivetrains provided very good support in recent years. So, this development offers a growing modular system of high-voltage batteries, power electronics and electric traction motors, which also can be applied to fuel cell drivetrains.

## 6 Fuel Cell Drivetrain Architectures for Passenger Cars

Depending on the weighting of the parameters cost, hydrogen infrastructure, technology and customer wishes - as well as the availability of standard components and the boundary conditions of the target vehicle - different hybrid drive configurations are resulting. Three such variants are shown in figure 4.

A common variant of the fuel cell drive is the fuel cell hybrid, see figure 4, left column. For example, the Mercedes-Benz B-Class F-CELL falls under this category. The fuel cell hybrid is equipped with a high-voltage battery with a relatively low energy content, which is primarily used for the recuperation of braking energy or for the support of acceleration processes. Almost the entire energy on board of the vehicle is stored in the form of hydrogen at this concept. This allows a very quick "recharge" of the full vehicle range within a very short time, but requires a nationwide hydrogen infrastructure to provide the customer with a maximum availability. Moreover, the fuel cell represents the primary source of propulsion and accordingly has to cover all load cases and operational scenarios.

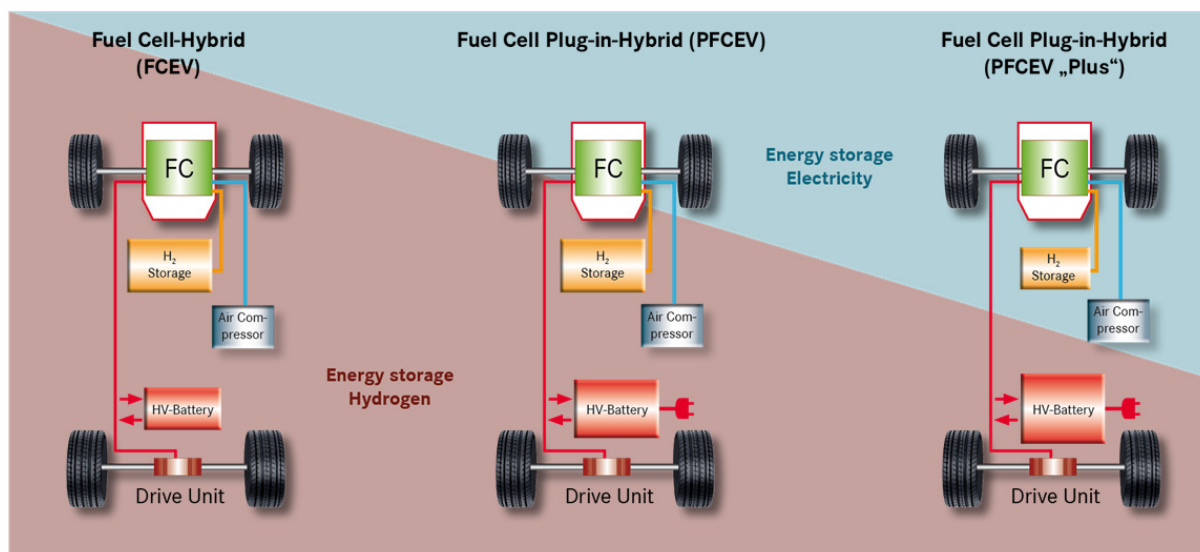


Figure 4: Possible configurations for a fuel cell drive

The concept of the fuel cell plug-in-hybrid combines a high-voltage battery with higher energy content and a high discharge power with a fuel cell system. In addition, this approach uses an on-board charger, so that the battery can also be charged by an ordinary house connection, a wall box or a supercharger. A smaller proportion of the available amount of energy in the vehicle is stored in the battery, however, most of the energy in the form of hydrogen. So, a high vehicle range can be refueled very quickly in the form of hydrogen, whereas a smaller proportion of range can be charged electrically into the battery. During piecemeal expansion of the hydrogen infrastructure, the availability of the vehicle can be ensured always by the on-board charger. In addition, batteries and charging systems are available as standard components due to the progressive electrification of conventional drives and therefore can be applied to the fuel cell drive at low cost.

Is the percentage of battery energy in the drive system further increased, the concept of the fuel cell plug-in-hybrid "Plus" arises. In this case, a high-energy and high-performance battery is applied. Now, the total energy content in the drive system is stored in approximately equal parts in the form of hydrogen and in the form of electrical energy in the battery. Accordingly, half of the vehicle range may be refueled very quickly in the form of hydrogen gas, the other half however - depending on the existing charging infrastructure - takes significantly more time. Due to the high battery-electric vehicle range, the availability of the drivetrain in the case of an incomplete hydrogen infrastructure can be ensured by charging even better with this approach. Furthermore, here the battery is the primary source of propulsion due to its high power output. The fuel cell complements the power output of the battery only when needed and is used for the range extension. Due to the high demand for building space of such a battery, the amount of hydrogen storage in the vehicle, as well as the volume of the fuel cell system, are restricted.

For Daimler's next generation fuel cell vehicle after the Mercedes-Benz B-Class F-CELL, the drivetrain concept of a fuel cell plug-in-hybrid was decided after considering the parameters described in chapter 5, the target vehicle and the available standard components.

## 7 Daimler's Next Generation Fuel Cell Vehicle

Significant enhancements compared to the B-Class F-CELL could be achieved in its successor. One of the major advances is the accommodation of the complete fuel cell unit in the engine compartment. This enables the application of fuel cell drive on various types of vehicles, since a sandwich floor as in the B-Class F-CELL is no longer mandatory in future. In order to achieve this, the space required by the fuel cell unit was reduced by an increase in power density of 30%. Also the amount of platinum in the fuel cell stack could be reduced by 90%.

The next generation hydrogen tank system consists of only two instead of three containers as in the B-Class F-CELL. However, the amount of usable hydrogen and thus the NEDC range could be increased from 380

km to 500 km total distance. Improvements were also made in the field of drive power and hence in the customer tangible performance. The overall drive power, which results from the interaction of fuel cell unit and battery, could be increased by 40% compared to the previous fuel cell vehicle. Another main difference in comparison to the B-Class F-CELL is the use of a plug-in-battery which enables charging by an ordinary house connection, a wall box or a quick charger. Thus, the gradual expansion of hydrogen infrastructure is taken into account in an ideal way. An important contribution to cost reduction is represented by the proportion of adopted standard components in the drive train, which could be expanded significantly compared to the B-Class F-CELL.

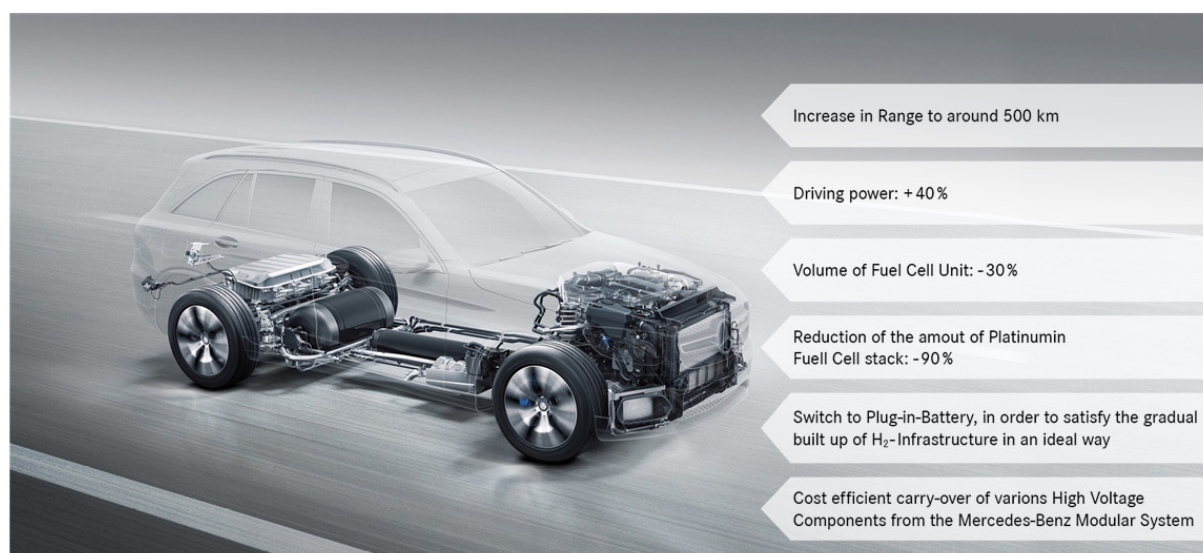


Figure 5: Development progress of next generation fuel cell vehicle

## 8 Well-to-Wheel Energy- and Greenhouse-Gas-Balance of a Fuel Cell Plug-In-Hybrid Vehicle

For the assessment of different propulsion and fuel options, the well-to-wheel (WTW) comparison of energy consumption and greenhouse gas emissions is gaining more and more importance, because finally not only the fuel consumption and emissions of the vehicle itself, but also that one of the entire energy chain are climate and environmentally effective. Both, battery-powered as well as fuel cell vehicles, do not produce any emissions during operation and are characterized by a significantly lower tank-to-wheel energy consumption compared to internal combustion engine powered vehicles.

Using electricity and hydrogen as fuel, all emissions and a significant portion of the energy losses in the entire chain are caused by production, transport, and - in the case of hydrogen- in the fuel conditioning. Overall, considering the majority of processes for the production of electricity and hydrogen, both types of drivetrains will lead to a significant reduction of well-to-wheel energy consumption and greenhouse gas emissions. Using renewable energies (and only in this case), however, the WTW energy consumption of a battery vehicle is lower than that of a fuel cell vehicle by a factor of two to three. Because renewable energy may not be available at any time and in any quantity, there is a need of storage which generates additional energy losses, which can be substantially depending on the method of storage.

The combination of a fuel cell and a larger battery in a fuel cell plug-in-hybrid, which can also be charged from the grid with renewable generated electrical energy, in turn leads, depending on the customer behavior, to significant reductions in WTW energy consumption compared to a pure fuel cell vehicle. Thus, the two concepts of battery electric vehicle and fuel cell plug-in-hybrid vehicle are approaching each other and are located in the same order of magnitude regarding well-to-wheel energy consumption, see figure 6.

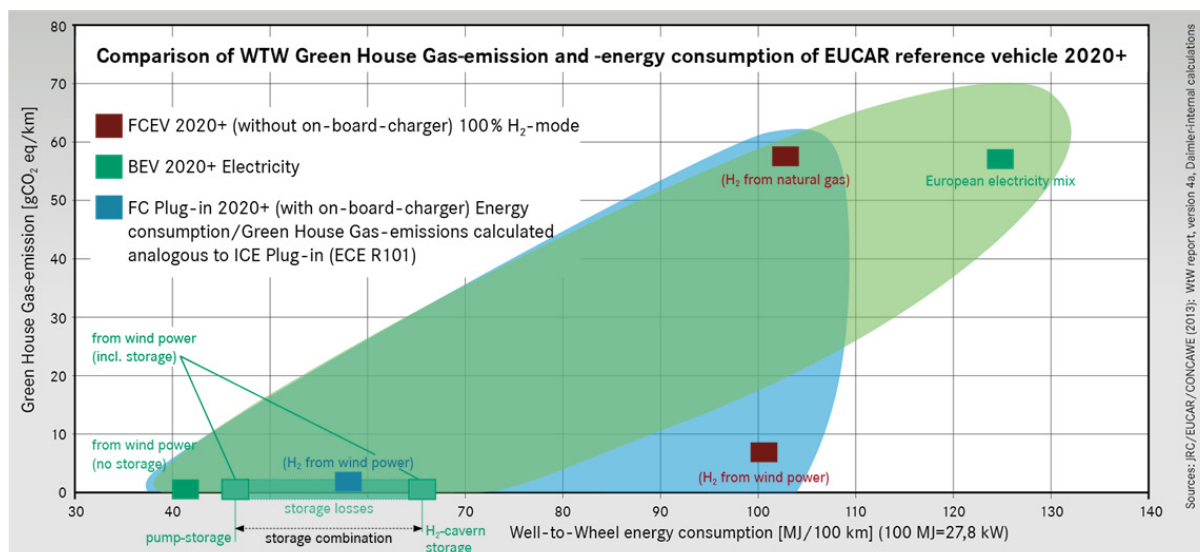


Figure 6: Well-to-wheel consideration of energy consumption and greenhouse gas emissions

## 9 Hydrogen Council

In the first global initiative of its kind, the ‘Hydrogen Council’ is determined to position hydrogen among the key solutions of the energy transition. Hydrogen is a versatile energy carrier with favorable characteristics since it does not release any CO<sub>2</sub> at the point of use as a clean fuel or energy source, and can play an important role in the transition to a clean, low-carbon, energy system. Hydrogen technologies and products have significantly progressed over past years and are now being introduced to the market. The Council will work with, and provide recommendations to, a number of key stakeholders such as policy makers, business and hydrogen players, international agencies and civil society to achieve these goals.

During the launch, members of the ‘Hydrogen Council’ confirmed their ambition to accelerate their significant investment in the development and commercialization of the hydrogen and fuel cell sectors. These investments currently amount to an estimated total value of € 1.4 Bn/year. This acceleration will be possible if the key stakeholders increase their backing of hydrogen as part of the future energy mix with appropriate policies and supporting schemes.

Meeting in Davos on Tuesday January 17<sup>th</sup> for the first time, the ‘Hydrogen Council’ is currently made up of 13 CEOs and chairpersons from various industries and energy companies committed to help achieve the ambitious goal of reaching the 2 degrees Celsius target as agreed in the 2015 Paris Agreement. The international companies currently involved are: Air Liquide, Alstom, Anglo American, BMW GROUP, Daimler, ENGIE, Honda, Hyundai Motor, Kawasaki, Royal Dutch Shell, The Linde Group, Total and Toyota. The Council is led by two Co-Chairs from different geographies and sectors, currently represented by Air Liquide and Toyota.

## 10 Summary

Within the last years, Daimler has made significant progress with fuel cell technology. Advanced fuel cell vehicles like the Mercedes-Benz B-Class F-CELL have proven reliability and customer acceptance. Daimler’s next generation fuel cell vehicle again shows significant technical progress compared to its predecessor. The global initiative of the ‘Hydrogen Council’ is a good opportunity for Daimler and other OEMs to succeed together with various actors from different industries in positioning hydrogen as one key solution of the energy transition.

## Authors



Dr. Steffen Dehn entered the Daimler AG Group Research and Mercedes-Benz Cars Development Division in 2011 after graduating in electrical engineering at the University of Ulm and subsequently obtaining a doctorate in the field of passenger car fuel cell drives from the University of Duisburg-Essen. Between 2011 and 2016, he held various positions at Daimler AG in the field of fuel cell development and development of alternative drive systems. Since 2016, Dr. Dehn is a Manager System Engineering Fuel Cell Powertrain at NuCellSys GmbH, a 100% subsidiary of Daimler AG. In addition to the development of fuel cell drivetrain architectures, these activities also include the assessment with respect to performance, consumption and cold-start time by means of simulation, the development of freeze start strategies as well as the conception and design of the high-voltage system.



Dr. Jörg Wind has studied physics at the Technical University of Munich (TUM). After doing his Ph.D. in the field of semiconductor physics and sensor technology at the TUM in 1992, he started working in the field of fuel cells and hydrogen. As a project manager, he was responsible for material development for high temperature fuel cells and exhaust treatment at DASA and DaimlerChrysler from 1992 until 1998. From 1998 until 2002, he was responsible for PEM stack development at DaimlerChrysler. Since 2002, he is responsible for strategic energy projects and EC funded projects, comprising projects in the field of fuel cell vehicles and battery electric vehicles (including energy systems analyses and well-to-wheel-analyses). He has been involved in the setup of the FCH JU from the beginning on and is currently co-chair of the Hydrogen Europe transportation committee.



Prof. Dr. Christian Mohrdieck has been a Director Fuel Cell at the Daimler AG Group Research and Mercedes-Benz Cars Development Division since 2012 and at the same time CEO of NuCellSys GmbH since 2015. After studies of physics in Germany and France, Prof. Mohrdieck joined Daimler-Benz Research in 1989. In 1995 he became head of the Executive Office of the Member of the Board responsible for Research and Technology in Stuttgart. From 1999 on Prof. Mohrdieck has been a Senior Manager Fuel Cell Systems with DaimlerChrysler Corporation in the USA. Back in Germany, he became a Director of Structural Materials at DaimlerChrysler AG and afterwards in 2003 Director of Alternative Energy- and Drive Systems. In 2005 Prof. Mohrdieck assumed the responsibility for Fuel Cell Drive System Development. In 2006 he got the additional responsibility for Li-Ion battery development at Daimler AG. Two years later Prof. Christian Mohrdieck became a Director of Fuel Cell & Battery Drive Development. In 2013 the University Ulm appointed Dr. Mohrdieck Honorary Professor.