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Safety Concept of a H_2-Fuel Cell Integrated System with High Pressure Storage

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Abstract

Magna Steyr’s prototype concept Mobile Hydrogen Power Supply (MH_2PS) enables zero emission mobile charging of electric vehicles. Based on a commercial car trailer, the system contains a compressed hydrogen storage system, a fuel cell module, a high voltage battery and high voltage power electronics. Naturally, the application of high voltage and compressed hydrogen provides potential hazards, which has to be considered in the development of the system’s safety concept.

The overall objective of this thesis is to provide data for the safe development of the MH_2PS according to ISO 26262 as well as for the upcoming failure mode and effects analysis (FMEA) process. For this purpose, the system, the components and the operational strategy were analysed. In a next step the collected data of the overall system’s analysis can be used for an FMEA and development steps according to the ISO 26262 standard.

As part of the functional development according to ISO 26262, the scope, items and functions were defined. In order to provide input data for the forthcoming FMEA, the thesis offers a design proposal of the compressed hydrogen path of the MH_2PS and a structure analysis. To derive functions, failures and safety requirements, manuals of the components used in the MH_2PS are examined. In a final step, functional sequences are derived out of the analysed operational strategy as it plays an indispensable safety-relevant role for the system.

This thesis contributes to the development of a safety concept for the MH_2PS. In this way, the results serve as input for an upcoming FMEA and for the development process according to ISO 26262.

Kurzfassung

Magna Steyr's Prototyp „Mobile Hydrogen Power Supply (MH_2PS)“ ermöglicht das lokal emissionsfreie und mobile Laden von Elektrofahrzeugen. Das Konzept basiert auf einem Fahrzeuganhänger und enthält ein Druckwasserstoffspeichersystem, ein Brennstoffzellenmodul, eine Hochvoltbatterie und Hochvolt-Leistungselektronik. Da sowohl Hochspannung als auch Druckwasserstoff eine erhebliche Gefahr für den Bediener und Dritte darstellen, muss bei der Entwicklung besondere Rücksicht auf das Sicherheitskonzept des Systems gelegt werden.

Vor diesem Hintergrund beschäftigt sich die Masterarbeit mit der Bereitstellung von erforderlichen Daten für die Entwicklung des MH_2PS nach dem automotiven Standard für funktionale Sicherheit ISO 26262 sowie für den im weiteren Verlauf der Entwicklung anstehenden FMEA-Prozess. Zunächst wurden das System, die Komponenten und die Betriebsstrategie analysiert. In einem nächsten Schritt wurden die gesammelten Daten aus der Gesamtsystemanalyse als eine Basis für ISO 26262 und die FMEA verwendet. Im Rahmen der funktionalen Entwicklung nach ISO 26262 wurden Items und Funktionen definiert. In Bezug auf die bevorstehende FMEA wurde in der vorliegenden Arbeit eine Strukturanalyse des Druckwasserstoffpfades des MH_2PS durchgeführt, welche notwendige Eingangsdaten bereitstellt. Betriebsanleitungen der im MH_2PS verwendeten Komponenten wurden herangezogen um Funktionen, mögliche Fehler und Sicherheitsanforderungen abzuleiten. In einem letzten Schritt wurden aus der analysierten Betriebsstrategie relevante Funktionen abgeleitet. Die Betriebsstrategie spielt eine unverzichtbare, sicherheitsrelevante Rolle für das System.

Die Masterarbeit trägt zur Entwicklung eines Sicherheitskonzeptes für den MH_2PS bei. Die Ergebnisse liefern einen Input für die bevorstehende FMEA und für die Durchführung des Entwicklungsprozesses nach ISO 26262.

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Abbreviations

AFC	Alkaline Fuel Cell
AGM	Absorbent Glass Mat
Al	Aluminium
ASIL	Automotive Safety Integrity Level
ATR	Autothermal Reforming
CH_3OH	Methanol
CH_4	Methane
CO_2	Carbon Dioxide
CP	Critical Point
DMFC	Direct-Methanol Fuel Cell
DOD	Depth of Discharge
ETA	Event Tree Analysis
EV	Electric Vehicle
FCM	Fuel Cell Module
FCREEV	Fuel Cell Range-Extended Electric Vehicle
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
GDL	Gas Diffusion Layer
H_2	Hydrogen
H_2O	Water
HARA	Hazard and Risk Assessment
HAZOP	Hazard and Operability Study
HSS	Hydrogen Storage System
HT	High-Temperature
HT-PEMFC	High-Temperature Polymer Electrolyte Membrane Fuel Cell
HV	High Voltage
K_2CO_3	Potassium Carbonate
KOH	Potassium Hydroxide
$LaNi_5$	Lathanum-Nickel
Li_2CO_3	Lithium Carbonate
$LiAlH_4$	Lithium Aluminium Hydride
LSM	Lanthanum Strontium Manganite
LT	Low-Temperature
LT-PEMFC	Low-Temperature Polymer Electrolyte Membrane Fuel Cell
MCFC	Molten-Carbonate Fuel Cell
MEA	Membrane Electrode Assembly
MH_2PS	Mobile Hydrogen Power Supply
MPa	Megapascal
N_2	Nitrogen
$NaBH_4$	Sodium Borohydride
$NaBO_2$	Sodium Metaborate
NCA	Lithium Nickel Cobalt Aluminium
$Ni(OH)_2$	Nickel(II) Hydroxide
NiCd	Nickel Cadmium
$NiCl_2$	Nickel(II) Chloride
NiMH	Nickel-Metal Hydride
NMC	Lithium-Manganese-Cobalt Technology
O_2	Oxygen

OEM	Original Equipment Manufacturer
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cell
POX	Partial Oxidation
QM	Quality Management
SB	Supply Battery
SiC	Silicon Carbide
SiH_4	Silane
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
TPL	Triple Point for Liquid State
TPS	Triple Point for Solid State
TPV	Triple Point for Vapour State
VDA	Verband der Automobilindustrie
VRLA	Valve Regulated Lead Acid
YSZ	Yttria-Stabilized Zirconia

1 Introduction

As introduction to this master thesis, the initial situation and motivation is outlined after a short company overview of Magna Steyr. Moreover, the structure and content of this thesis are explained in section 1.3.

1.1 Company Overview of Magna Steyr

Magna Steyr is a brand-independent engineering and manufacturing partner of automobile manufacturers. Magna Steyr's expertise covers development services up to overall vehicle development as well as flexible solutions in complete vehicle manufacturing [1]. In addition, there is a product and service portfolio for alternative drive and energy storage systems. With the FCREEV, Magna Steyr managed to combine both, hydrogen and electric drive, to achieve long range, emission free driving [2]. The know-how gained in this project represents an important basis for continued development in fuel cell hybrid systems.

1.2 Initial Situation and Objective

The Austrian government identified electric mobility as a key measure for the decarbonisation of traffic. Reducing the environmental pollution caused by traffic and a reduction in dependence upon fossil fuels are challenges, which have to be consistently pursued over the coming years and decades. Electric mobility in combination with renewable energies is an essential element for an effective implementation of the Paris Climate Agreement. Additionally, it is a key to fulfil national and EU regulations on air quality and emission limitation. The Austrian government wants to achieve an almost climate-neutral transport sector by the year 2050. This in particular includes the electrification of road transport. [3]

A big advantage of battery electric vehicles is driving locally emission free, but at the current stage of development they come with a number of disadvantages. Electric vehicles (EV) have small operating ranges and often poor or inexistent charging infrastructure. Another obvious drawback of EVs is that in case of an empty battery, the EV usually needs to be towed off to the next charging station. According to the ÖAMTC, almost one third of all breakdown assistance operations in Austria in the year 2017 were caused by empty or weak batteries [4]. However, recharging the empty battery of an electric vehicle with a spare canister is not possible as it is for cars with internal combustion engines using gasoline or diesel as fuel. Therefore, the project Mobile Hydrogen Power Supply (MH$_2$PS) was established to enable zero emission mobile charging for electric vehicles. Based on a commercial car trailer, the system contains a compressed hydrogen storage system, a fuel cell module, a high voltage battery, high voltage power electronics and a high voltage delivery system. The project and the system are described in more detail in chapter 2.

The MH$_2$PS's zero emission mobile charging concept is promising from an environmental point of view. However, on-board storage of compressed hydrogen, delivery of hydrogen to the fuel cell module, electrical energy generation by the fuel cell and storage in a high voltage battery provide different types of potential hazards, which have to be considered by the engineers throughout the development project.

As preparation for the development of a safety concept for the MH_2PS, the objective of this master thesis include the provision of data for the functional safe development of the system according to ISO 26262 and for an upcoming FMEA process.

1.3 Structure and Content of the Thesis

Overall, this master thesis is divided into 6 chapters. The first chapter gives a brief overview of the company Magna Steyr, the initial situation and the objective of the present study.

Chapter 2 aims to explain the MH_2PS project, the overall system of the MH_2PS, and the operating strategy. Moreover, it provides a detailed technology review of the components used in the system.

Chapter 3 outlines the process of creating a safety concept for a prototype in the predevelopment department at the company. Safety-associated terms are defined and the legal background is explained. Furthermore, the methodological approach of this master thesis is outlined.

In chapter 4, the standard ISO 26262 is pointed out. As a preliminary stage for a functional development process according to ISO 26262, the item definition is given.

Chapter 5 explains the theoretical process of the FMEA methodology. For an upcoming FMEA process, the design of the compressed hydrogen path of the MH_2PS and its structure analysis are presented. Moreover, functions, failures and safety requirements are derived from component manuals. By analysing the operational strategy, the functional sequences of operating modes are determined.

A discussion of the results and an outlook is given in the final chapter 6.

Detailed information of components used in the MH_2PS is provided in the appendix. It includes the technical data sheets of the fuel cell module Ballard FCveloCity-MD30, the DC/DC converter Brusa BSC624-12V, the DC/DC converter Brusa BDC546 and the HV distribution unit Brusa PDU254.

2 H_2-Fuel Cell Integrated System with High Pressure Storage

Magna Steyr's FCREEV combines both, hydrogen and electric drive, to achieve long range, emission free driving [2]. Based on the knowledge gained in this project, further fuel cell hybrid systems are in the planning stage.

In order to implement a safety concept, it is important to deal with, and to understand the system layout to which the safety concept is applied. Therefore, the following chapter addresses topics including a description of the MH_2PS project, an overview of the system, the components and their technology used in the system and the operating modes of the MH_2PS.

2.1 Description of the MH_2PS Project

Battery electric vehicles have a lot of advantages including local emission free driving. On the other hand, they also come with a number of disadvantages like small operating ranges and a poor or inexistent charging infrastructure. In Austria almost one-third of all ÖAMTC breakdown assistance operations in the year 2017 were caused by empty or weak batteries, but recharging a battery with a spare canister is not possible [4]. This brought up the idea to set up a zero emission mobile charging station with the purpose of charging zero emission electric vehicles in the field. This project was given the name Mobile Hydrogen Power Supply (MH_2PS).

Based on a commercial car trailer (aggregate carrier) the system contains following main components:

- Hydrogen storage system (HSS)
- Fuel cell module (FCM)
- High voltage (HV) battery
- HV power electronics
- HV delivery system

The hydrogen storage system can be fueled on a hydrogen fueling station. Subsequently, the fuel cell provides electric energy and charges the battery.

Figure 1 illustrates the preliminary design of the MH_2PS.

Figure 1: Preliminary design of the MH_2PS [5]

2.1.1 List of Preliminary Requirements

The MH_2PS is still in the pre-development phase. System requirements are constantly updated. The following preliminary requirements of the MH_2PS serve as input data of the present master thesis:

- Mobile charging system, mounted on a light trailer (750 kg maximum permissible total weight)
- System consists of components available on the market.
- Target is charging of electric vehicles with a defined amount of electric energy. Energy output is provided in so called "shots" with a quantity of 5 kWh.
- Charging of electric vehicles is performed via connector standard CCS-Typ2 or CHAdeMO.
- Charging is performed under consideration of 4 operation modes:
    - Charging of electric vehicles via provision of electric energy from fuel cell system. Power output at a level of 20 kW.
    - Boost function: Provision of electric energy from both, fuel cell system and supply battery.
    - Charging of electric vehicles via discharging the supply battery.
    - Charging the supply battery via electric energy provision from fuel cell system.

2.2 System Description of the MH_2PS

Figure 2 illustrates the preliminary system layout of the MH_2PS. Electrical energy is provided to the consumer by converting the chemical energy of hydrogen into electricity with the help of a proton exchange membrane fuel cell. The oxidant used for hydrogen conversion in the fuel cell is atmospheric air. Hydrogen is stored in gaseous state at 70 MPa in the hydrogen storage system. Hydrogen can be supplied by a hydrogen filling station. Electrical energy can be stored in a high voltage battery in order to provide an additional output of electrical energy to the consumer. The battery can only be charged by the fuel cell.

In the following subchapters, an overview of the components used in the system is given, their technologies and alternative technologies are described and the task of the components in the MH_2PS is explained in more detail.

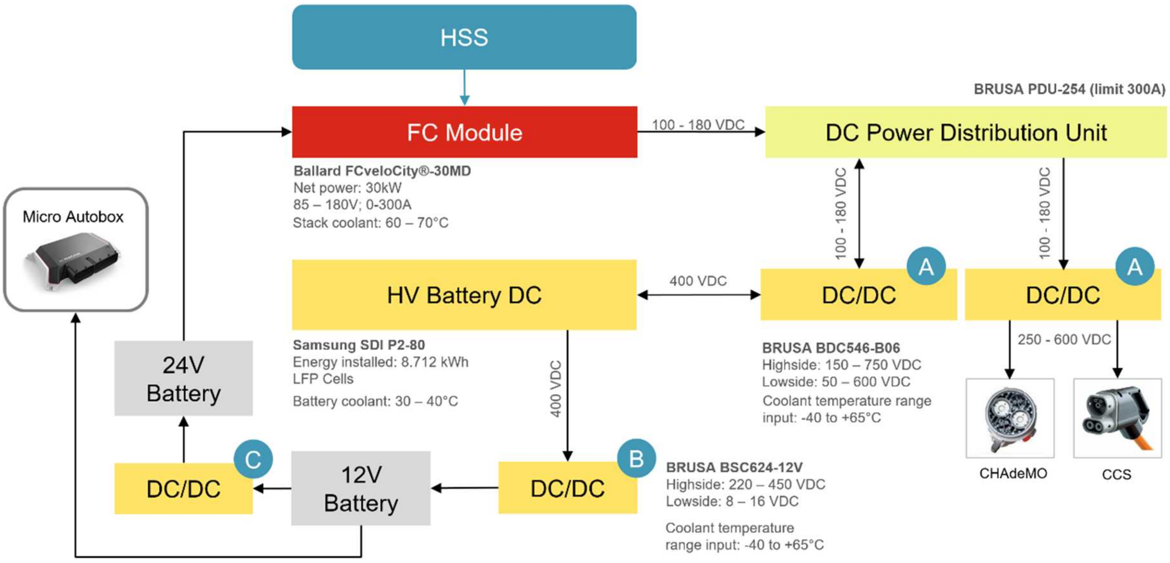

Figure 2: Preliminary system layout of the MH_2PS

Figure 3 illustrates the abstracted layout of the MH_2PS with its subsystems and functions.

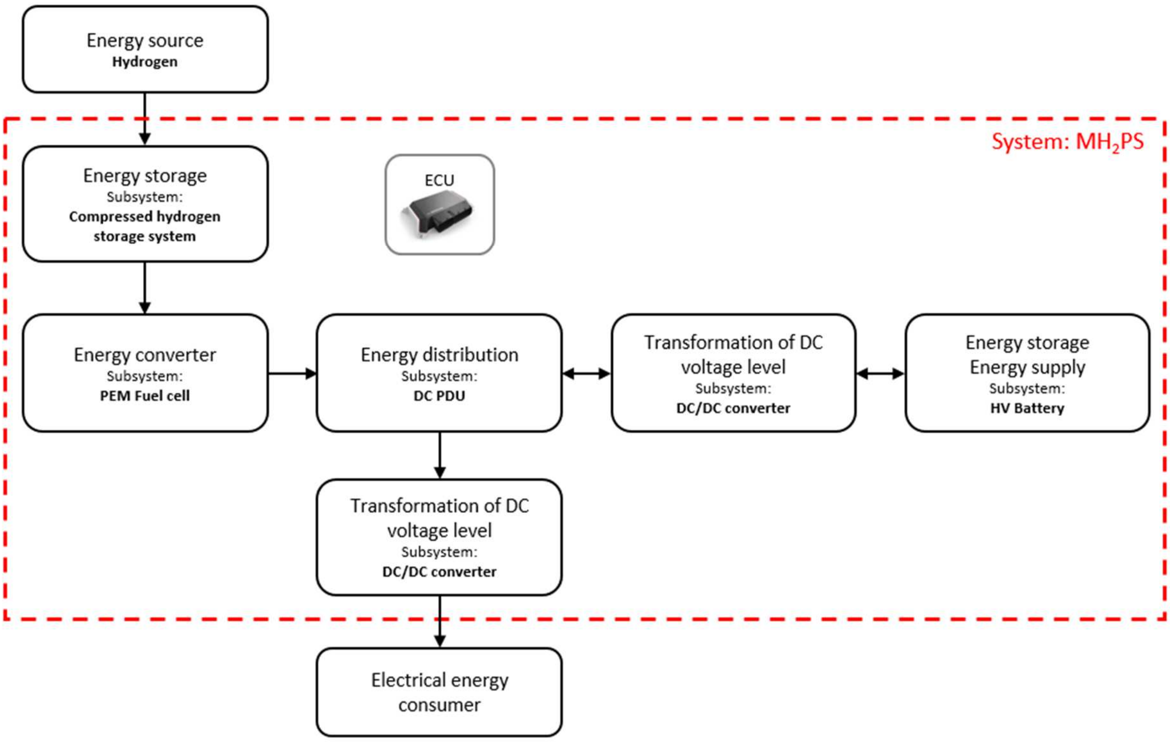

Figure 3: Abstracted system layout

2.3 Hydrogen Storage

The chemical and physical properties of hydrogen are challenging factors when it comes to storing. For automotive applications, different approaches have been pursued. The most common forms of hydrogen storage for mobile applications are compressed gaseous hydrogen in pressure vessels and liquid hydrogen in cryogenic tanks. Other possibilities, which are still in the laboratory stage, are hybrid storage methods or hydrogen in physical or chemical bonds. [6–8]

2.3.1 Basics and Properties of Hydrogen

Hydrogen is a secondary energy carrier. An energy carrier is a substance that contains energy. Unlike primary energy (energy found in nature that has not been subjected to any conversion process), secondary energy is energy transformed from primary energy sources through an energy conversion process. The energy carrier can be stored in the storage unit of an energy storage system. Energy storage systems can be classified by the physical form of the energy stored. A distinction between following forms of energy can be made: [7, 9]

- Electrical energy
- Chemical energy
- Mechanical energy
- Thermal energy

Out of this distinction, different storage technologies can be classified. They are described in Table 1. [9]

Table 1: Storage system technologies acc. to [9]

Storage system	Description
Electric storage systems (electromagnetic storage, electrostatic storage)	Electric storage systems use electric or magnetic fields to store energy. Examples are double layer capacitors or superconducting coils.
Electrochemical storage systems	Electrochemical storage systems like batteries store energy in chemical bonds of electrodes. They are both, energy storage systems and energy converters. They are further differentiated in primary batteries, which can be discharged only once, or secondary batteries. Secondary batteries can be charged and discharged repeatedly.

Chemical storage systems	A chemical storage system is an energy storage system for converted, compressed primary or secondary energy. It can be a primary and secondary energy storage system. Primary storage systems are storage systems, which can be charged and discharged only once. Secondary energy storage systems can be charged and discharged multiple times. Energy storage in gaseous media (e.g. hydrogen), in liquid media (e.g. gasoline), or in solid media (e.g. coal) is possible. They are stored for instance in tanks (e.g. hydrogen pressure vessels) or caverns.
Mechanical storage systems	Mechanical storage systems involve changes in potential energy, changes in the motion of mass (kinetic energy) or energy stored in form of compressed air. Examples are pump storages, flywheels or compressed air reservoirs.
Thermal storage systems	Thermal energy storage systems are secondary energy storage systems. They store heat according to thermodynamic principles.

At normal pressure (0.1 MPa) and temperature (298 K), hydrogen is a colourless and odourless gas. As the element with the lowest density, it is about fourteen times lighter than air. [7, 10] The phase diagram of hydrogen is shown in Figure 4. [6, 7]

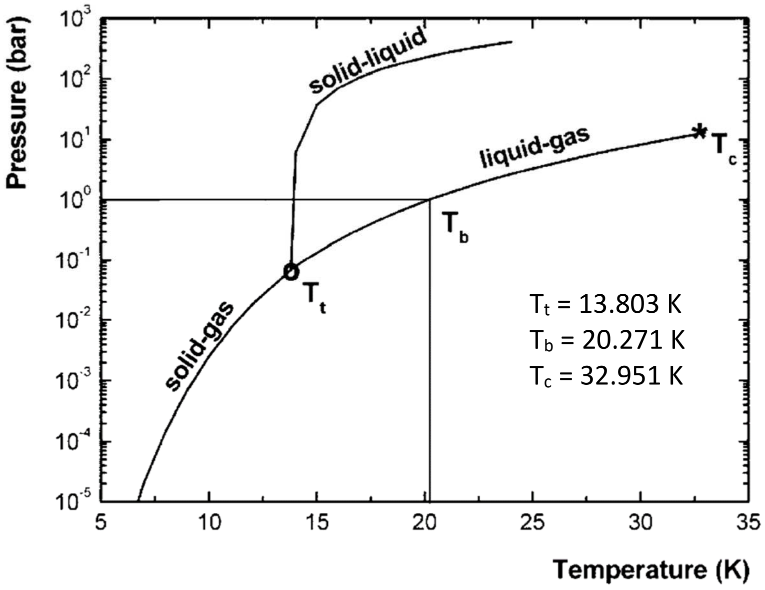

Figure 4: Phase diagram of hydrogen acc. to [10]

The triple point of hydrogen (T_t), where all three phases coexist, is at a temperature of 13.803 K (-259.3740 °C) and 0.0070411 MPa. Hydrogen is in solid state at temperatures below the triple point. In solid state, hydrogen forms a dense crystalline hexagonal sphere packing. The phase transition from liquid to gas (T_b) occurs at 1.01325 MPa and 20.271 K (-252.879 °C). Hydrogen has a low evaporation rate of 446.08 kJ/kg. In liquid form it weighs 70.828 g/l. The critical point (T_c) is at 32.951 K (-240.199 °C) and 1.2869 MPa. [6, 7, 10]

Hydrogen has high specific heat capacities. It has the highest heat conductivity of all gases and the highest physical and chemical diffusibility and therefore diffuses through most metals. These properties and especially its ignition behaviour when mixed with air at low ignition energy are safety-relevant and have to be considered when dealing with hydrogen. [6, 7]

Table 2 gives an overview of important properties of hydrogen. [7]

Table 2: Properties of Hydrogen acc. to [7]

Properties	**Value and unit**
Molar mass M	2.0159 kg/kmol
Special gas constant R	4124.4 J/kgK
At triple point:	
Temperature T_{Tr}	-259.347 °C (13.803 K)
Pressure p_{Tr}	0.0070411 MPa
Density gaseous ρ_{Tr}	0.12555 kg/m^3
Density liquid ρ_{Tr}	76.977 kg/m^3
Density solid ρ_{Tr}	86.507 kg/m^3
Enthalpy of fusion $\Delta_{\mathrm{fus}}h$	58.039 kJ/kg = 16.122 kWh/kg
Enthalpy of vaporization $\Delta_{\mathrm{vap}}h$	450.05 kJ/kg = 125.01 kWh/kg
Enthalpy of sublimation $\Delta_{\mathrm{sub}}h$	508.09 kJ/kg = 141.14 kWh/kg
At boiling point at normal pressure 0.101325 MPa:	
Boiling temperature T_{S}	-252.879 °C (20.271 K)
Evaporation heat $\Delta_{\mathrm{v}}h$	446.08 kJ/kg = 123.91 kWh/kg
(Gravimetric) Heat value $\mathrm{H}_{\mathrm{u,\,gr}}$	118.58 MJ/kg = 32.939 kWh/kg
Calorific value B	183.64 MJ/kg = 51.011 kWh/kg
Liquid phase at T_{s} and p_{N}:	
Density ρ	70.828 kg/m^3
(Volumetric) Heat value $\mathrm{H}_{\mathrm{u,\,vol}}$	8.3988 MJ/dm^3 = 2.333 kWh/dm^3
Thermal conductivity λ	0.099 W/mK
(Dynamic) Viscosity η	11.9 × 10^{-6} Ns/m^2
Sound velocity a	1111.1 m/s
Vapour phase at T_{s} and p_{N}:	
Density ρ	1.3385 kg/m^3
(Volumetric) Heat value $\mathrm{H}_{\mathrm{u,\,vol}}$	0.15872 MJ/dm^3 = 0.044089 kWh/dm^3
Thermal conductivity λ	0.017 W/mK
(Dynamic) Viscosity η	1.11 × 10^{-6} Ns/m^2
Sound velocity a	355.04 m/s
At critical point:	
Temperature T_{cr}	-240.199 °C (32.951 K)
Pressure p_{cr}	0.12869 MPa
Density gaseous ρ_{cr}	31.449 kg/m^3
At normal conditions 0°C and 0.101325 MPa:	
(Gravimetric) Heat value $\mathrm{H}_{\mathrm{u,\,gr}}$	119.83 MJ/kg = 33.286 kWh/kg

Calorific value B	142.19 MJ/kg = 39.497 kWh/kg
Density ρ	0.089882 kg/m^3
(Volumetric) Heat value $H_{\mathrm{u,\,vol}}$	0.010771 MJ/dm^3 = 2.9918 Wh/dm^3
Compressibility factor Z	1.0006
Specific heat capacity c_{p}	14.198 kJ/kgK
Specific heat capacity c_{v}	10.071 kJ/kgK
Isentropic exponent κ	1.4098
Thermal conductivity λ	0.184 W/mK
Diffusion coefficient D	0.61 cm^2/s
(Dynamic) Viscosity η	8.91×10^{-6} Ns/m^2
Sound velocity a	1261.1 m/s
Mixtures with air:	
Lower explosion limit (Ignition limit)	4 Vol% H_2 ($\lambda = 10.1$)
Lower detonation limit	18 Vol% H_2 ($\lambda = 1.9$)
Stoichiometric mixture	29.6 Vol% H_2 ($\lambda = 1$)
Upper detonation limit	58.9 Vol% H_2 ($\lambda = 0.29$)
Upper explosion limit (Ignition limit)	75.6 Vol% H_2 ($\lambda = 0.13$)
Ignition temperature	585 °C (858 K)
Minimum ignition energy	0.017 mJ
Maximum laminar flame speed	ca. 3m/s
Maximum adiabatic flame temperature	ca. 2200 °C

2.3.2 Hydrogen Production

About 600 billion Nm^3 (50 billion t) hydrogen are produced and consumed worldwide per year. This corresponds to the energy content of approximately 6 exajoules (1.7 PWh), which is about 1% of the global energy consumption. About 40% of the hydrogen required is a by-product of industrial processes such as the chlorine-alkali electrolysis for manufacturing chlorine or oil refining processes. When producing methanol or ethane, hydrogen is also generated as a by-product. About 60% of the required hydrogen is produced deliberately. The industrial-scale manufacturing of hydrogen is mainly carried out of hydrocarbons (about 95%). Approximately 5% is produced by electrolysis today. [7]

Reformation of fossil hydrocarbons is the most used manufacturing process. The three primary reformation techniques are steam reforming, partial oxidation (POX), and autothermal reforming (ATR). The majority of hydrogen is produced by steam reforming short-chained hydrocarbons, for instance fossil fuels like natural gas, which has a high methane content. For the endothermic process an external heat source is required. Oxygen is not needed. Efficiency levels up to 80% can be achieved. Partial oxidation exothermically converts long hydrocarbons and residual oils by partially oxidizing them with the help of oxygen at high temperatures. A catalyst is not required. Efficiencies of about 70% are reached. A combination of both processes is autothermal reforming by using partial oxidation for heat provision and steam reforming for a higher output of hydrogen. The thermal neutral process has efficiency levels over 70%. [7, 11]

Gasification is another commercially used process for hydrogen production. Commonly, coal or biomass are gasified. In addition to hydrogen, the gas produced contains other components and therefore requires complex purification. The process emits carbon dioxide but gassing biomass is considered as CO_2-neutral. Energy levels of 55% are reached depending on the source material. [7, 11]

Research is also being conducted in bio hydrogen. It is the hydrogen production by biological and photochemical processes like photolytic hydrogen production from water with the help of green algae or cyanobacteria and fermentative hydrogen production processes. [7, 11]

Other possibilities of hydrogen production are thermally splitting (cracking) of fossil hydrocarbons at high temperatures and chemical splitting of water with metals or metal oxides, however those processes are complex and expensive. [7]

As climate change is happening and a reduction of greenhouse gases is essential, production methods of hydrogen without releasing carbon dioxide are necessary. The electrolysis of water represents splitting of water into hydrogen and oxygen by using an electrical current, which is passing through two electrodes. Besides the production out of biomass, it is considered as the only emission free hydrogen production process, provided that the necessary electricity is won from renewable energies. Energy levels up to 80% and high degrees of purity can be achieved. [7, 11, 12]

2.3.3 Storage of Compressed Hydrogen

The system described in this thesis is storing the energy carrier hydrogen in a pressure vessel. The storage of compressed gaseous hydrogen in pressure vessels is the most common form of hydrogen storage for automotive applications today [8]. If diffusion is prevented, provided that proper materials are selected, hydrogen can be stored without any loss over a longer period of time, which leads to the fact that soring hydrogen in pressure vessels is a closed system. For gaseous hydrogen, storage pressure vessels with storage pressures of 20, 35 and 70 MPa are in use. Such high pressures require correct selections of materials, vessel design and safety considerations. Those factors result in hydrogen pressure tank systems being a complex and heavy matter. The storage weight is approximately 20 to 40 kg per kg hydrogen stored, which leads to about 5 to 2.5% gravimetric storage density. [6, 7]

Figure 5: Compressed hydrogen storage system using cylindrical vessel shape [13]

For automobile use, a cylindrical vessel shape is used because of its favourable stress distribution. An exemplary compressed hydrogen storage system with cylindrical vessels is illustrated in Figure 5. Due to being small in size and mass on atomic level, hydrogen has the highest diffusion capacity of all elements. Normally, metals with high hydrogen solubility have high hydrogen diffusion rates. Additional to high diffusion rates, the gas tends to absorb and dissociate at material surfaces, which makes a proper use of materials necessary. Austenitic stainless steel as well as aluminium alloys are primarily used when dealing with hydrogen. [6, 7, 14]

Table 3 shows a selected number of hydrogen diffusion coefficients in different gases and liquids. [14]

Table 3: Hydrogen diffusion coefficients in various substances (p=0.1013 MPa) acc. to [14]

Diffusion in	**D [cm²/s]**	**T [°C]**
N_2	0.674	0
O_2	0.701	0
H_2 (self-diffusion)	1.285	0
H_2O, vapour	0.759	0
H_2O, liquid	4.8×10^{-5}	25
Iron, smelting	5.64×10^{-3}	1600
Al, smelting	1.28×10^{-5}	960
Palladium	5.0×10^{-7}	25
Vanadium	5.0×10^{-5}	25

A distinction between four vessel types is made as illustrated in Figure 6. Type I vessels are made out of metal (steel/aluminium). While offering safety and strength, the downside is their high weight. Energy densities of about 400 Wh/kg can be realised. Type II and type III vessels use a thin inner line made of metal (steel/aluminium). While type II vessels are partially reinforced by composite materials like carbon fibers, the stability of type III vessels is given by a complete mesh of carbon fibers. The liner of type IV vessels consists of synthetic material. The stability is provided by a complete mesh of carbon fiber. For automobile applications, type III and type IV vessels are used because of their weight advantage and their ability to store hydrogen with pressures up to 70 MPa (type IV). [6–8]

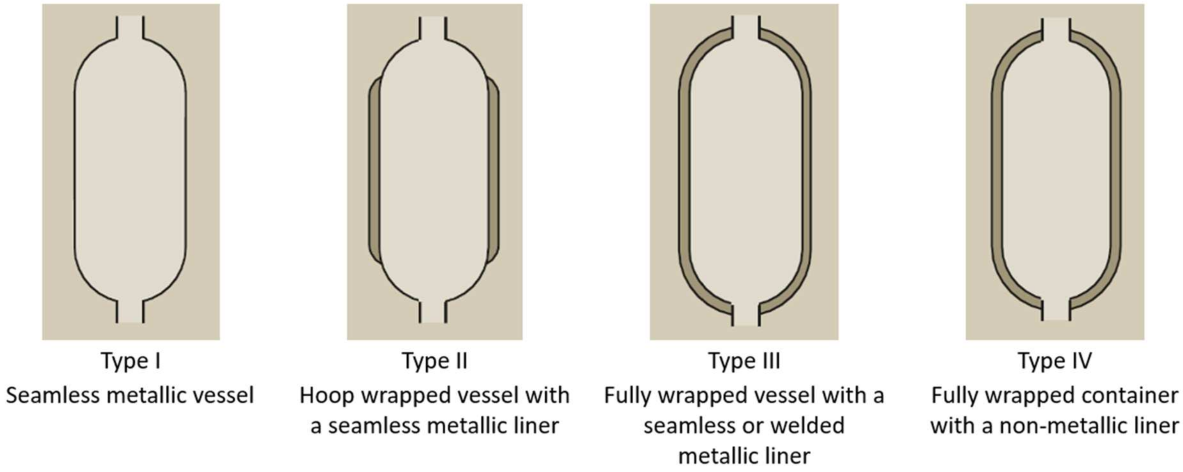

Figure 6: Vessel types acc. to [8, 15]

Figure 6 provides an overview of the characteristics of commercially available vessels for automotive applications. With 70 MPa pressure vessels, storage of high gravimetric and volumetric energy densities can be achieved. [8]

In a hydrogen pressure tank system, additional parts like pressure reducing valves and a number of sensors to control tightness, temperature or pressure, are required as well as a container for safety reasons. To ensure safe operations, there are, especially for automobile applications, a number of regulations, standards and test specifications. [6, 7]

Table 4: Overview of technical characteristics of commercially available type III and type IV pressure vessels for automotive applications [6]

Net volume [dm^3]	**34**	**100**	**50**	**100**	**36**	**65**	**30**	**120**
Type	III	III	III	III	IV	IV	IV	IV
Nominal pressure [MPa]	35	35	70	70	35	35	70	70
Test pressure [MPa]	52.5	52.5	10.5	10.5	52.5	52.5	10.5	10.5
Tank system weight [kg]	18	48	55	95	18	33	26	84
Tank system volume [dm^3]	50	150	80	150	60	100	60	200
H_2 density [kg/m^3] at 25°C	23.3	23.3	39.3	39.3	23.3	23.3	39.3	39.3
H_2 content [Nm^3]	8.83	26	21.84	43.69	9.35	16.96	13.5	51.7
H_2 content [kg]	0.79	2.33	1.96	3.83	0.84	1.52	1.21	4.65
Grav. H_2 content [kgH_2/kg]	0.044	0.049	0.036	0.041	0.047	0.047	0.047	0.055
Vol. H_2 content [kgH_2/dm^3]	0.016	0.016	0.025	0.026	0.014	0.015	0.021	0.023
Grav. energy density [kWh/kg]	1.467	1.633	1.2	1.367	1.567	1.567	1.567	1.833
Vol. energy density [kWh/dm^3]	0.533	0.533	0.833	0.867	0.467	0.5	0.7	0.767

High complexity and expensive materials of pressure tank systems result in high costs. 35 MPa/type III tank systems cost up to 40 €/kWh, 70 MPa/type IV tank systems up to 150 €/kWh per kWh of stored hydrogen energy. [6, 7]

The filling of hydrogen in the vessel is realized by a pressure gradient. Therefore, and to avoid long filling times, the reservoir pressure needs to be significantly higher than the hydrogen vessel’s nominal pressure. Safety measures prevent overfilling and overheating of tank systems. Hydrogen dispensers are similar to natural gas dispensers. To check for leak tightness, a pressure pulse is emitted. If leak tightness is given, the valves open and fuelling can be started. Hydrogen expansion from the high pressure reservoir to the vessel, as well as the compression of the gas into the vessel to be filled itself, result in a temperature increase. If these effects are not countered, the nominal pressure would be higher than the vessel pressure and therefore result in a loss of contained mass. This can be prevented by cooled and by slow filling. When filling slowly, more time is needed because heat has to dissipate into the external environment. The established, faster method is by filling hydrogen that is cooled by a heat exchanger with liquid nitrogen. After filling it might be the case that the vessel temperature is below the ambient temperature. Because hydrogen expands when being warmed, thus building up pressure, it has to be ensured that the maximum allowed pressure is not exceeded. Refuelling times of hydrogen are nearly as short as the ones of gasoline or diesel. The contained energy of 5 kg hydrogen is about 600 MJ. It can be expected that a hydrogen tank system can be filled within 300 s and thus resulting in a power of 2 MW (600 MJ/300 s). [6, 7]

To generate the high pressure needed to achieve a pressure gradient for a 70 MPa container, multi-stage piston compressors are usually used. The technical demands for those compressors are high. The materials must be suitable for the use of hydrogen. To ensure the purity of hydrogen, self-lubricating pistons are required. Another possibility to compress hydrogen is by the usage of ionic liquid piston compressors. This type of compressor uses an ionic liquid as piston. [6, 7] Ionic liquids are substances, which only consist of cations and anions, but have completely different properties than typical salts. Typical salts normally have high melting points and high boiling temperatures, which result from strong binding forces in ionic crystals. If an ionic bond consists of large, low charged ions, the ionic bonding components can become so small, that melting points achieve temperatures lower than 100 °C. [16] The characteristic of ionic liquids can be specifically tailored for certain applications. For compressing hydrogen, hydrogen insoluble ionic liquids are used. By cooling the ionic liquid, nearly isothermal compressions can be achieved. [6, 7]

2.3.4 Storage of Liquid Hydrogen

Another possibility of storing hydrogen is in liquid state. While liquid hydrogen has a significantly higher density than gaseous hydrogen, liquefaction, storage and handling are complex and energy-intensive. To reduce heat transfer into the tank, the specially insulated storage system consists of an inner and an outer container. Between them lies a vacuum layer to minimize heat transport through convection and conduction. The tank material needs to withstand low temperatures. Diffusion and embrittlement have to be avoided. Materials that fulfil the requirements in the best way are aluminium alloys and stainless steels. For automotive applications, austenitic stainless steels are mainly used due to their good plastical properties at low temperatures. The vacuum layer normally contains a multilayer insulation. The multilayer insulation is build up by combining aluminium foil and glass fiber matting to further reduce heat radiation. Perfect thermal insulation, enabling an adiabatic system, is not possible. Heat transfer by conduction occurs at spacers between the containers, at feedthroughs as well as at pipework for filling and emptying. Because of the intrinsic heat leaks, temperature inside the container rises and the liquid hydrogen starts to evaporate, resulting in a pressure increase. For safety reasons, a pressure relief system and a safety valve must be included in a liquid hydrogen container to keep a constant pressure. In Figure 7, the pressure build-up phase due to heat input is illustrated in a T-s diagram. At point 1, pressure builds up along an isochoric line until the maximum operating pressure is reached at point 2. To keep a constant pressure level, hydrogen is released with the aid of a valve. The process of releasing the gaseous hydrogen is called boil-off (point 2 to point 3), which also changes the vapour fraction x. The hydrogen released is catalytically burnt or vented into the atmosphere. [6, 7, 10]

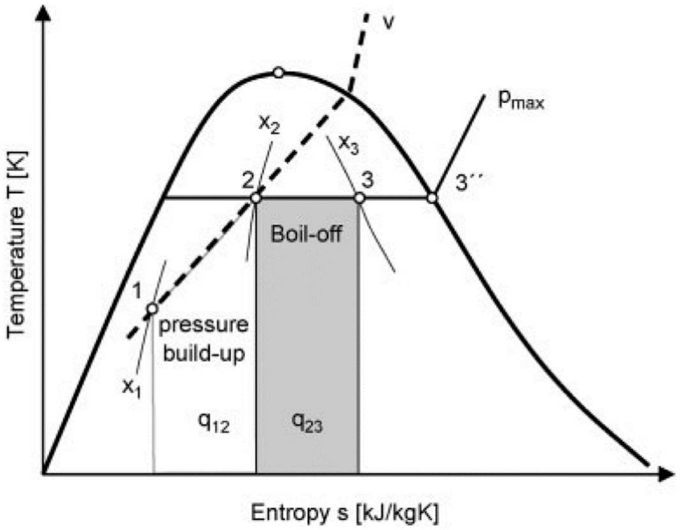

Figure 7: T-s diagram of hydrogen for pressure build-up phase due to heat input [6]

In practical application of liquid hydrogen storage systems, the evaporation rate is about 0.3 to 3% per day and is proportional to the surface/volume ratio. Therefore, larger container systems are advantageous. Spherical shapes have the best surface to volume ratio, though not state of the art in manufacturing. Furthermore, the free surface of the liquid in the spherical tank would be greater in a partially empty tank than in a standing cylinder. For these reasons usually cylindrical tank systems are used, but also flat shapes are found in automotive applications because of their volume-saving properties. [6, 7, 10]

If hydrogen is required by an energy converter, liquid hydrogen is heated and thus evaporated by a heat exchanger. Pressure in the tank rises, a pressure difference between tank and energy converter is built up and the hydrogen is extracted. [6, 7, 10, 17]

Gravimetric and volumetric energy densities of 0.06 kg H_2/kg or 2000 Wh/kg and 0.04 kg H_2/dm^3 or 1200 Wh/dm^3 can be achieved respectively. [6, 7]

2.3.5 Hybrid Storage

The storage possibilities of hydrogen result from its phase diagram. The density changes with pressure and temperature. Whilst gases have higher pressure dependencies, the influence of temperature increases when the critical point is approached. The density of hydrogen versus pressure with temperature as parameter is illustrated in Figure 8. Figure 9 shows the density of hydrogen versus temperature with pressure as parameter. CP indicates the triple point, TPS, TPL, and TPV indicate the triple points for solid, liquid, and vapour state. Lines of phase transition are also illustrated. It can be seen that hydrogen stored at high densities and pressures and at low temperatures has great potential as fuel. [6, 7]

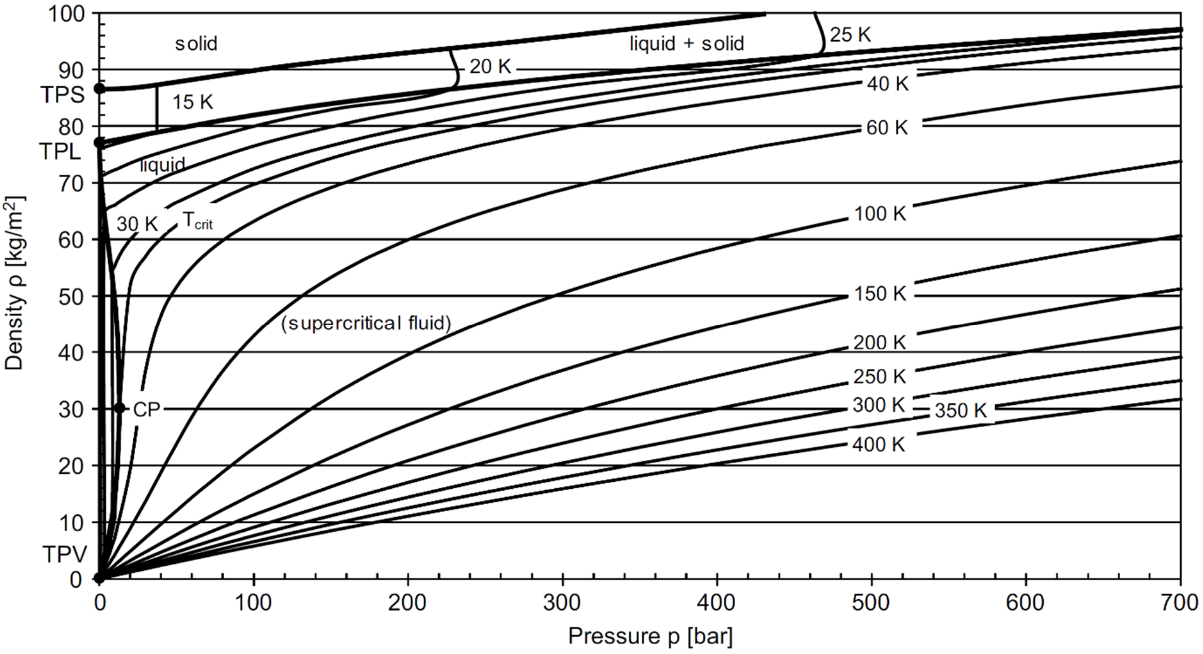

Figure 8: Density of hydrogen as a function of pressure and temperature [6]

A hybrid storage system combines different storage technologies. In this thesis, two different hybrid storage systems are going to be explained briefly, supercritical storage and hydrogen slush. A supercritical fluid is a medium in a state at pressures and temperatures above the critical point, between gaseous and liquid state. When temperatures and pressures exceed 33.2 K and 3,11 MPa hydrogen is a supercritical fluid. If elements of cryogenic liquid and compressed storage are combined, it is referred to as cryo-compressed storage, enabling that high energy densities can be achieved. Cryo-compressed storage has reduced evaporation losses because there is no phase transition. A boil-off is still inevitable because of the pressure rise as a result of the unavoidable heat input. The demands on the storage system are high due the combination of high pressures and low temperatures. [6, 7]

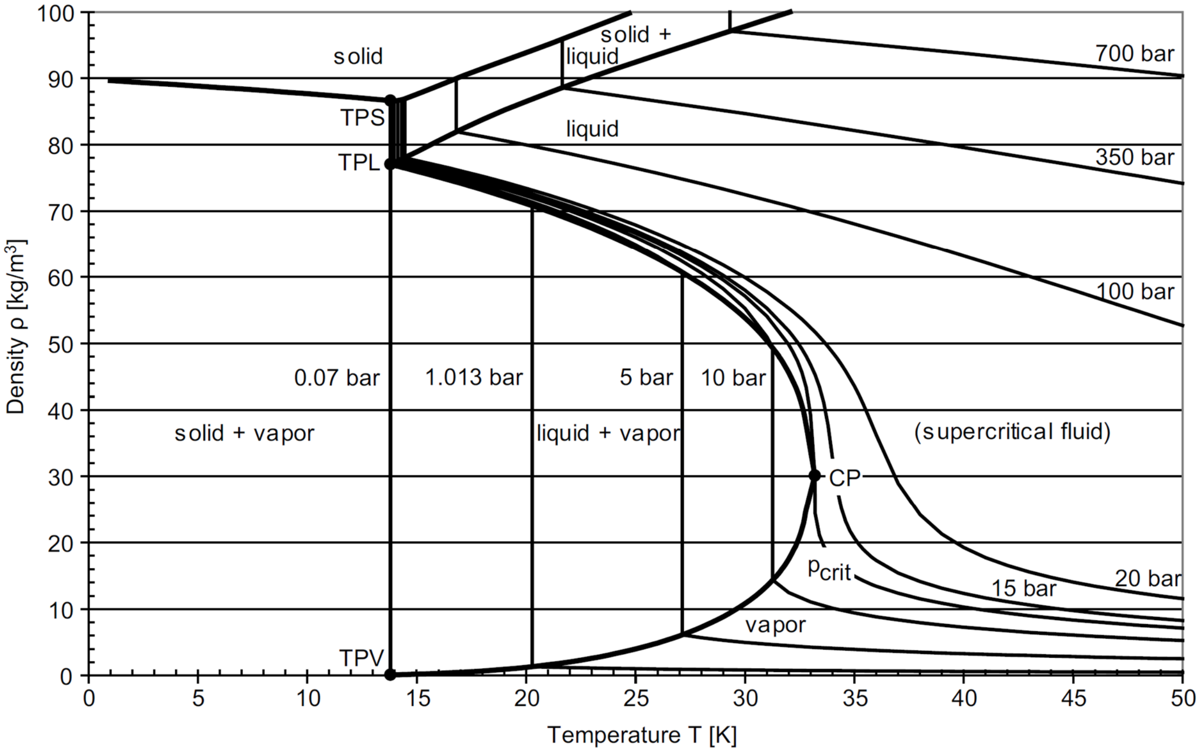

Figure 9: Density of hydrogen as a function of temperature and pressure [6]

At the triple point at 13.8 K and 0.007 MPa, hydrogen is a liquid-solid two-phase mixture called hydrogen slush. It consists of solid hydrogen particles and liquid hydrogen. Normally, hydrogen slush has 50% mass fraction of solid hydrogen and a density of 82 kg/m^3, which exceeds the density of hydrogen at the boiling point at 0.1 MPa by 16%. The energy for sublimation is higher than the evaporation enthalpy. As a result, hydrogen slush storage systems have longer pressure build-up times than liquid hydrogen storage systems. The benefits deriving from these properties make hydrogen slush an interesting fuel for aerospace applications. On the other hand, manufacturing of hydrogen slush is complicated and still in laboratory phase. [6, 7, 18]

2.3.6 Physical Absorption

Based on temperature and pressure, hydrogen is absorbed by solid surfaces. Hydrogen absorbs either by Van der Waals-type physisorption of molecular hydrogen or chemisorption of atomic hydrogen. The bond energy of physical absorption is weak. Large material surfaces are necessary to maximise the storage area. Extensive research was conducted in the field of physical absorption of hydrogen on carbon to design fullerenes. Fullerenes are grids of five or six-membered rings of carbon molecules structured in the form of a sphere or ellipsoid. They can be transformed into nanotubes, which are tubes made of carbon, as illustrated in Figure 10. At temperatures of 50 to 80 K, hydrogen is stored on the surface of nanotubes by physical absorption. Only low storage densities of 3 to 5 percent by weight of hydrogen are achieved and the rapid release of hydrogen bound up in the nanotubes causes problems. Therefore, they are not available on the market yet. Certain polymers like polyaniline or polypyrrole have the potential to store up to 8 percent by weight of hydrogen and research is ongoing in the combination of physical and chemical processes. [7, 16, 19]

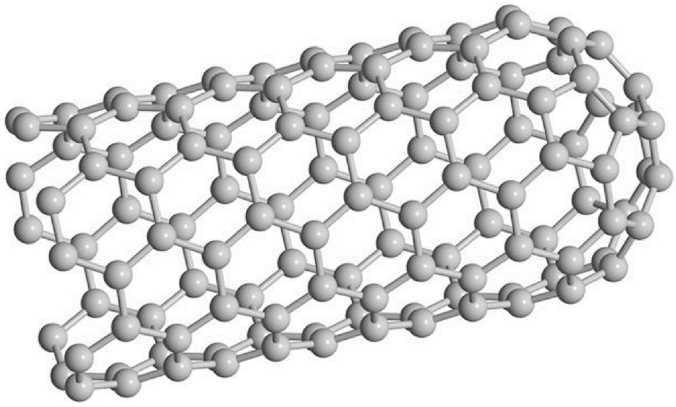

Figure 10: Structure of a carbon nanotube [16]

2.3.7 Chemical Absorption

The most important representatives of metalloid and non-metal hydrogen compounds in group 3 to 7 of the periodic table are liquids and gases like water and hydrocarbons (e.g. gasoline, methane). Dependent on the polarity of the bond, a distinction can be made between binding partners with formal positively charged hydrogen (e.g. H_2O), binding partners with formal negatively charged hydrogen (e.g. SiH_4) and bonds that have weak polar hydrogen bonds and are described as nonpolar or covalent (e.g. CH_4). There are also metals, which can form covalent hydrides like aluminium. Some liquid hydrogen compounds can be reformed to hydrogen. The reformation can be done on board of the vehicle. Hydrides have high energy densities. On the other hand, complex reformation at high temperatures is necessary. A further disadvantage is the toxicity of some compounds and the CO_2 release when hydrocarbons are used. Experiments have been conducted with compounds like methane, ammonia or methanol. [7]

Saline hydrides are ionic compounds, which crystallise in an ion lattice. They are composed of the hydride ion H- and have electropositive alkali metals and alkaline earth metals except beryllium (e.g. alanates like $LiAlH_4$). Hydride ions H_z are found in complex compounds consisting of transition metals and an electropositive metal G_x. They are called complex metal hydrides and come in the form $G_xM_yH_z$. A lot of compounds like these exist consisting of alkali metals and alkaline earth metals for example sodium borohydride ($NaBH_4$): $NaBH_4 + 2\ H_2O \rightarrow NaBO_2 + 4\ H_2$. [7]

The most important hydrides for hydrogen storage are metal hydrides. They are formed by heating the metal under high pressure. Hydrogen atoms are chemically integrated in the metal lattice as seen in Figure 11. At high temperatures, hydrogen is released as H_2. This process is energy-intensive. [7, 16]

Hydride storage systems have safety advantages in case of an accident or leakage. Due to an absence of heat and pressure, the hydrogen release is deactivated. Metal hydrides can be used to power fuel cells. Impurities are absorbed by the metal surface and high purity hydrogen is released. Disadvantages are next to high costs and weight, the complex storing and releasing, and low storage densities of 2 to 8 percent by weight. A complex filling station infrastructure is required. Repeated storing and releasing of hydrogen leads to decomposition of the metal. Hydride storage systems are occasionally used in mobile applications or submarines. [7]

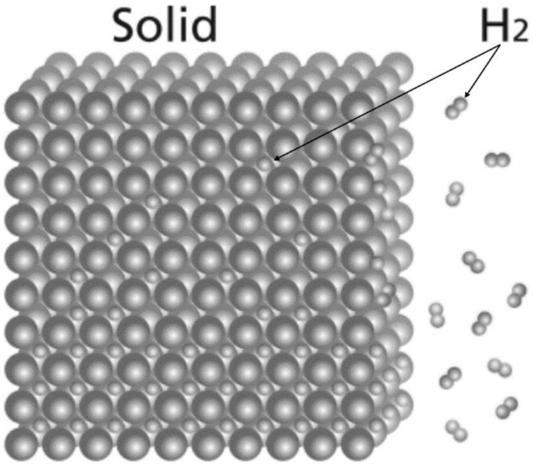

Figure 11: Hydrogen atoms chemically integrated in metal lattice acc. to [20]

2.3.8 Energy Densities in Comparison

Figure 12 provides an overview of density and volumetric energy density of hydrogen at different pressure levels and in different states. The common operating pressure of liquid hydrogen lies between 0.2 to 0.4 MPa. The density at 0.2 MPa is 67.67 kg/m^3. For gaseous hydrogen the highest in automotive applications used nominal working pressure is 70 MPa. The density at 70 MPa and 25 °C is 39.3 kg/m^3 and therefore nearly 40 kg/m^3 lower as the density of liquid hydrogen. Without consideration of the storage system, volumetric energy densities up to 2300 Wh/dm^3 can be reached in fluid state at 0.2 MPa. When hydrogen is in gaseous state under ambient temperature and 70 MPa, about 1300 Wh/dm^3 are achievable. [6]

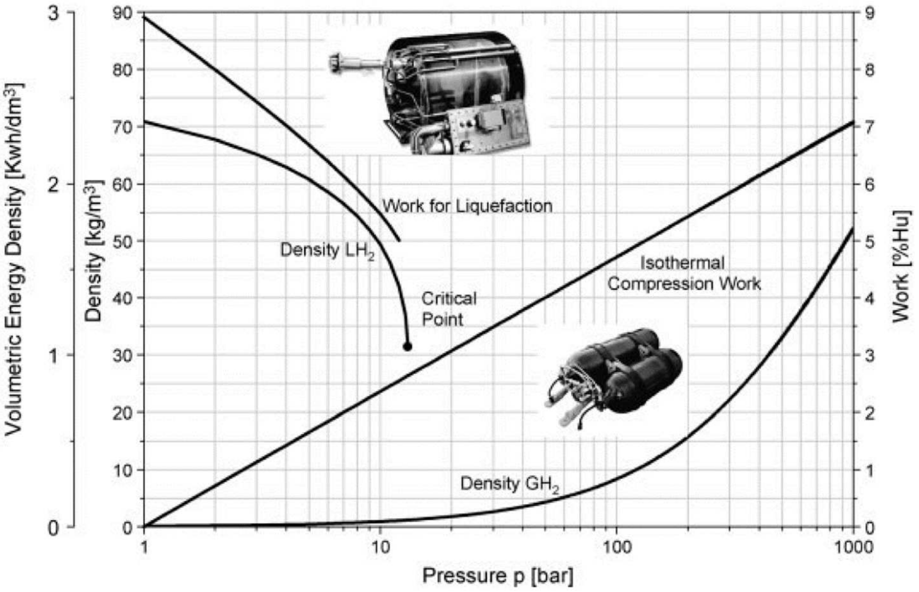

Figure 12: Storage density and work required for different hydrogen storage technologies [6]

Figure 12 also illustrates the required minimum work for compression and liquefaction in percentage of the calorific value Hu of 120 MJ/kg. For compression an isothermal state of change, for liquefaction an ideal cyclic process with isobaric cooling are assumed. Efficiency levels of 0.3 to 0.5 are not taken into consideration. It can be seen that compression and liquefaction require a high expenditure of energy. Because of the low boiling point of liquid hydrogen at -253 °C, 20 to 30% of the energy content is required for its generation whereas for the compression of hydrogen just up to 15% of the fuel energy content is required. Figure 13 compares the volumetric energy densities of different storage systems for pure substances in dark grey and for the whole storage systems in light grey. [6, 7]

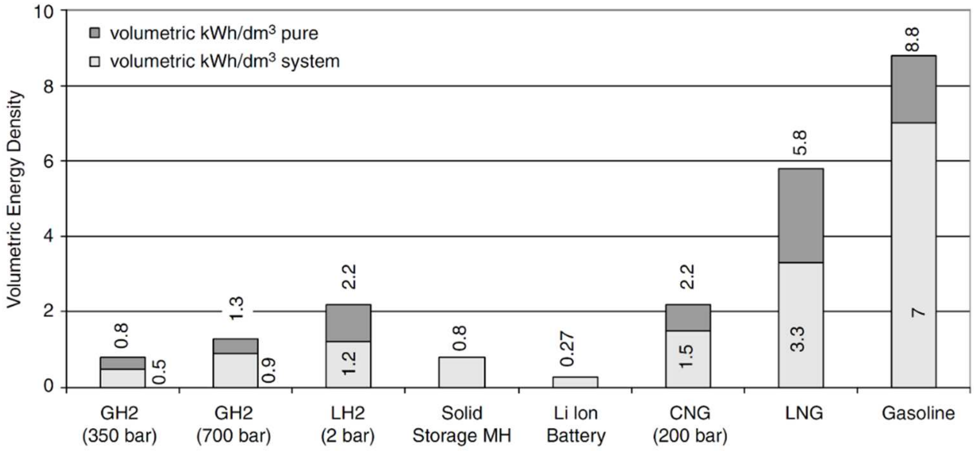

Figure 13: Volumetric energy densities of storage systems in comparison [6]

Whereas the storage density of lithium-ion batteries is at least one order of magnitude less than the one of liquid hydrogen, the energy densities of liquid natural gas and liquid hydrocarbons like gasoline are much higher. Furthermore, the tank system of liquid hydrocarbons is lightweight and uncomplicated. In Figure 14 different storage systems are compared regarding their gravimetric energy densities. [6, 7]

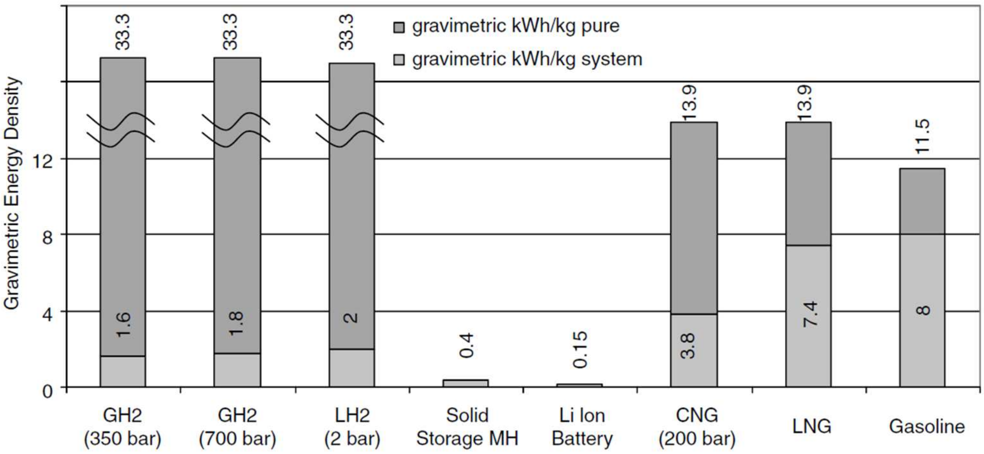

Figure 14: Gravimetric energy densities of storage systems in comparison [6]

Of all pure fuels, hydrogen has the highest calorific value at 3330 Wh/kg. Current hydrogen tank systems have a relatively high dead weight. Thus the gravimetric energy density of hydrogen is still considerably lower than the gravimetric energy density of gasoline but significantly higher than energy densities of batteries or solid hydrogen storage systems. [6]

In Figure 15, a comparison of volumetric versus gravimetric storage density of hydrogen storage technologies is summarised. In contrast to the listed hybrid storage systems, weight and volume of compressed and liquid hydrogen storage systems are taken into consideration. Pressurised gas in composite materials has an advantage over steel regarding the gravimetric density, but the volumetric energy density of both pressure tank types is low compared to the other storage systems. Higher volumetric energy densities are achievable with cryogenic storage. Liquid hydrocarbons (chemisorbed on carbon) have the highest gravimetric storage densities. Hybrids are promising opportunities; however the highest gravimetric energy densities are only achievable by irreversible hybrids. [7] Furthermore, most of the solid storage systems are still in laboratory stage. [6]

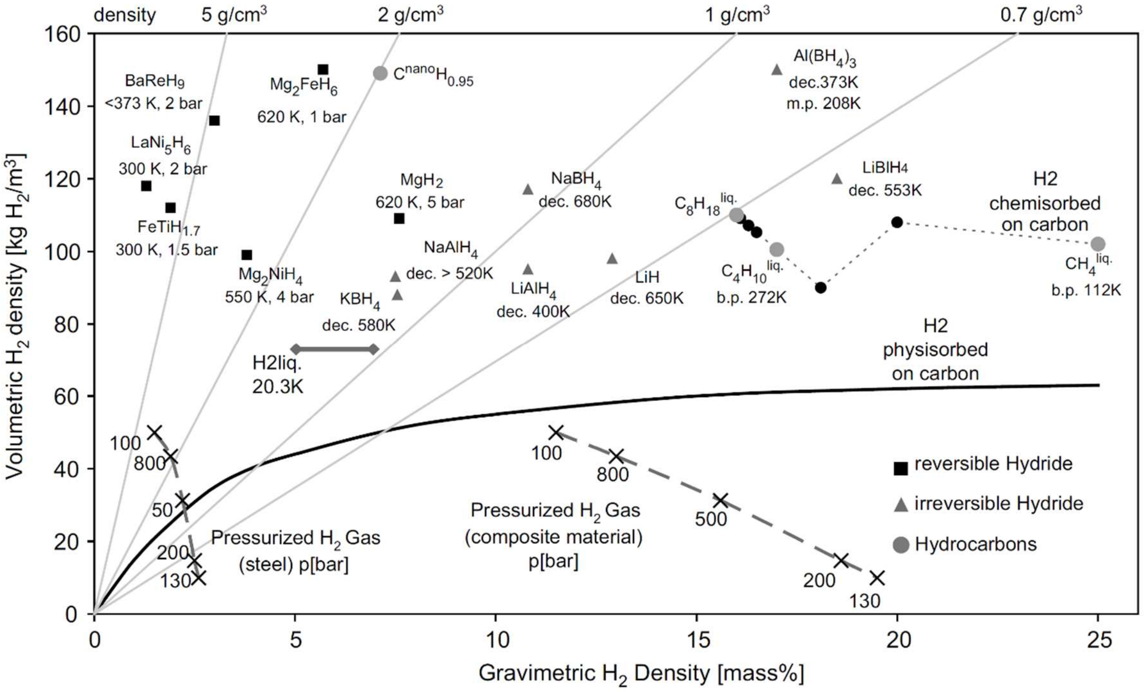

Figure 15: Volumetric and gravimetric density of different hydrogen storage technologies [6]

2.3.9 Hydrogen Storage in the MH_2PS

For gaseous hydrogen storage a type 4 vessel from Hexagon Lincoln [21] is installed in the MH_2PS. Hydrogen is stored at 70 MPa and delivered to the PEM fuel cell module as illustrated in Table 5.

Product specifications of the applied vessel are listed in Table 5.

Table 5: Product specifications of the type 4 vessel from Hexagon Lincoln [21]

Description	**Value**
Nominal Working Pressure	70 MPa
Maximum Allowable Working Pressure	87.5 MPa
Proof Pressure	105 MPa
Operating Temperature	- 40 to + 85°C
Internal Water Volume @ 70 MPa 15°C	77 l

2.4 Fuel Cell

Fuel cells are energy converter. The energy stored in the fuel is converted into electric energy by a reaction with oxygen. Reaction components are supplied continuously and the reaction product, water, is dissipated. Energy carriers like hydrogen or natural gas are usually stored in pressure vessels or conventional fuel tanks. Depending on the type of fuel applied, the energy conversion is clean, quiet and high efficiency levels can be achieved. [22]

In this subchapter, the fuel cell basics and types are described in order to give an overview of the technology underlying the fuel cell module, which is used in the MH_2PS.

2.4.1 Principle and Basics of Fuel Cells

The fuel cell principle can be realised with different fuels and electrolytes. In Figure 16, the working principle of fuel cells is illustrated by the example of a hydrogen-oxygen fuel cell. In this case, a single cell of a polymer electrolyte membrane fuel cell (PEMFC) is described. [7]

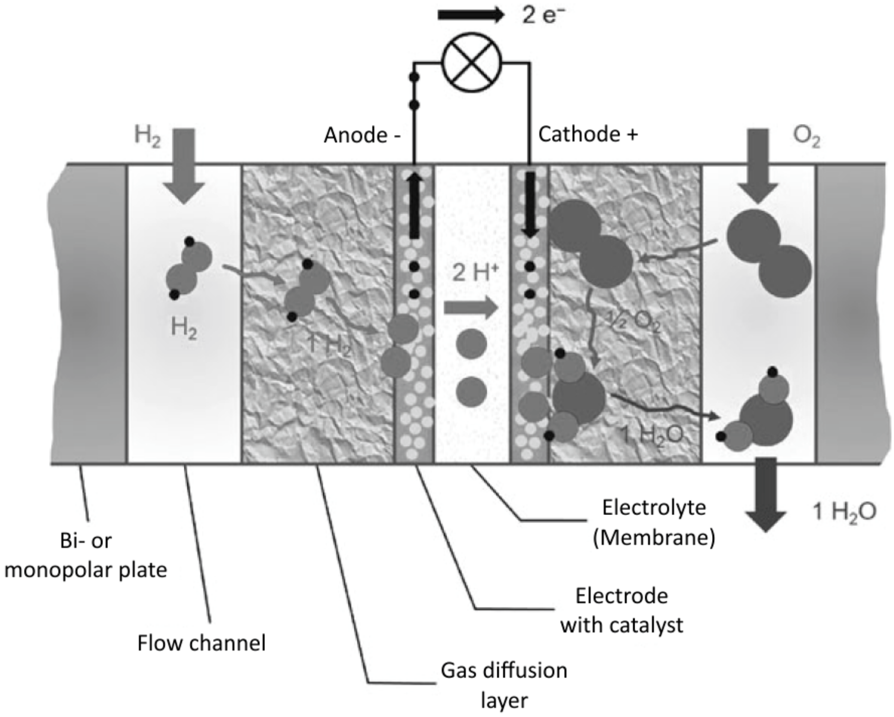

Figure 16: Principle of the fuel cell (PEMFC) acc. to [7]

Fuel, in this case hydrogen, is supplied by the flow channel. The hydrogen diffuses through the gas diffusion layer to the anode (fuel or hydrogen electrode). Hydrogen is oxidised at the electrode with the aid of a catalytic converter to 2 H^+ ions (protons). In the hydrogen oxidation reaction process two electrons are released. They are absorbed by the anode. [7]

Oxidation at the anode:

$$H_2 \rightarrow 2\,H^+ + 2\,e^-, \qquad E^0_{\text{Anode}} = 0\text{ V}.$$

The electrolyte is a strongly acid proton conducting polymer membrane. Electrons cannot pass through the membrane as it is an electrical insulator. It also separates the two gas compartments. The protons flow to the cathode through the membrane. The proton conductivity is determined by temperature and water saturation. Due to the potential difference, the electrons flow to the cathode through an external circuit and are able to drive an electrical load. Without electrical consumer an off-load voltage is set, which is the highest voltage a single cell is able to reach. Oxygen as the oxidising agent flows through the gas diffusion layer to the cathode and is reduced by receiving the electrons with the help of the catalyst. The oxygen then binds with two protons and reacts to a water molecule (product water). [7, 23]

Reduction at the cathode:

$$\tfrac{1}{2}\,O_2 + 2\,H^+ + 2\,e^- \rightarrow H_2O\,(l), \qquad E^0_{\text{Cathode}} = 1.229\text{ V}.$$

The oxygen reduction reaction can take place directly in the four-electron process (four electrons are exchanged by two hydrogen molecules). Another possibility is the indirect conversion in a two-electron process with several intermediate steps and hydrogen peroxide as an intermediate product. Product water diffuses through the gas diffusion layer and flows into the channels out of the cell. The overall reaction is a redox-reaction in which a stream of two electrons (2 e^-) per hydrogen molecule (H_2) flows. [7, 24]

Redox reaction:

$$H_2 + \tfrac{1}{2}\,O_2 \rightarrow H_2O\,(l), \qquad \Delta E^0 = E^0_{\text{Cathode}} - E^0_{\text{Anode}} = 1.229\text{ V}.$$

The standard electrode potential E^0 is the tendency of elements to form ions in aqueous solutions at standard conditions of 25 °C and 0.1013 MPa. The difference of the potentials of electrodes is referred to as reversible cell voltage. [7, 24]

The electrodes usually used are made of carbon-supported platinum nanoparticles and a proton conducting ionomer. The electrodes are porous in order to increase the surface of the triple phase boundary. The triple phase boundary, illustrated in Figure 17, is a region of contact between electrode, electrolyte and gaseous fuel, where the electrochemical reaction takes place. A reaction will only be possible if ion conduction phase, catalyst and reactants are in contact. Noble metals such as platinum or palladium are used as catalyst. [7]

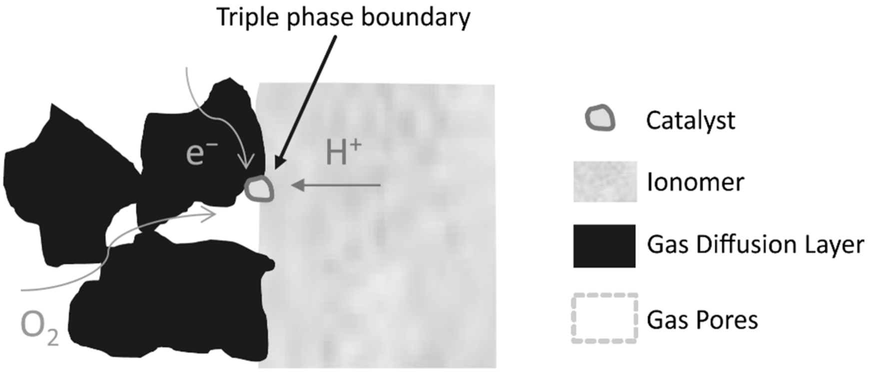

Figure 17: Triple phase boundary acc. to [7]

Fuel cells can be operated with a variety of fuels and therefore have different voltage and energy level outputs dependent on the fuel used. Table 6 provides an overview of possible fuels used in fuel cells. It lists the number of electrons involved in the reaction η_{el}, the standard reaction enthalpy in relation to 1 mol of fuel $\Delta_R H_m$, the free standard reaction enthalpy $\Delta_R G_m$, the standard potential E^0 and the thermodynamic efficiency η_{th}. [7]

Table 6: Parameters of fuel cells using different fuels [7]

Fuel	**Overall reaction**	η_{el}	$\Delta_R H_m$ **[kJ/mol]**	$\Delta_R G_m$ **[kJ/mol]**	E^0 **[V]**	η_{th} **[%]**
Hydrogen (l)	$H_2 + ½ O_2 \rightarrow H_2O$	2	-285.83	-237.13	1.229	83
Hydrogen (g)	$H_2 + ½ O_2 \rightarrow H_2O$	2	-241.82	-228.57	1.184	94.5
Methane	$CH_4 + 2 O_2 \rightarrow CO_2 + 2 H_2O$	8	-890.8	-818.4	1.06	91.9
Methanol	$CH_3OH + 3/2 O_2 \rightarrow$ $2 H_2O + CO_2$	6	-726.6	-702.5	1.21	96.7

Fuel cells directly convert the chemical energy contained in the fuel into electrical energy. Respecting the first law of thermodynamics, the fuel cell is a non-adiabatic system. The missing energy is taken up by the environment and therefore cooling it. This is an advantage when comparing it to an internal combustion engine that needs additional conversion processes. The efficiency of internal combustion engines is limited by the Carnot cycle, described in following formula. [7]

$$\eta_C = 1 - \frac{T_C}{T_H}$$

η_{th} is the efficiency of the Carnot cycle. T_H is the upper mean temperature. It is limited by the thermo-mechanical stability of the materials used. The lower mean temperature T_C is limited by the ambient temperature. So in theory the fuel cell is an ideal energy conversion system, easily outscoring heat engines. However, the high theoretical efficiencies cannot be achieved as there is a number of losses, which reduce the cell voltage. As a difference, efficiencies of about 75% can be reached for a single cell. Fuel cell stacks achieve efficiencies of around 70% and the overall system can achieve efficiencies of 60%. [7]

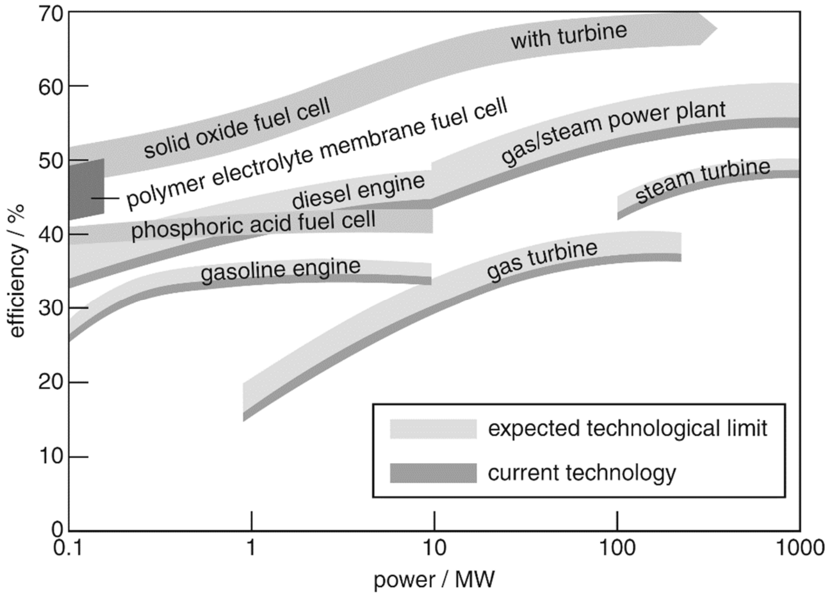

Figure 18: Comparison of fuel cell types and other energy conversion technologies regarding energy and power [25]

Figure 18 compares fuel cell types with other energy conversion technologies regarding efficiency and power. Small fuel cells are capable of reaching high efficiencies whereas high efficiencies of heat engines are only reached by large units like steam turbines. Fuel cells are therefore a good option at ranges up to 10 MW. [25]

Degradation of Cells

The performance of cells degrades over time with an increasing number of cycles. Figure 19 illustrates the fuel cell performance after different numbers of cycles. The voltage drop due to aging consists of a reversible and an irreversible part. The main reasons of degradation are structural changes in the electrodes. The degradation of electrodes of polymer electrolyte fuel cells is mainly caused by carbon corrosion and platinum dissolution. [7, 26]

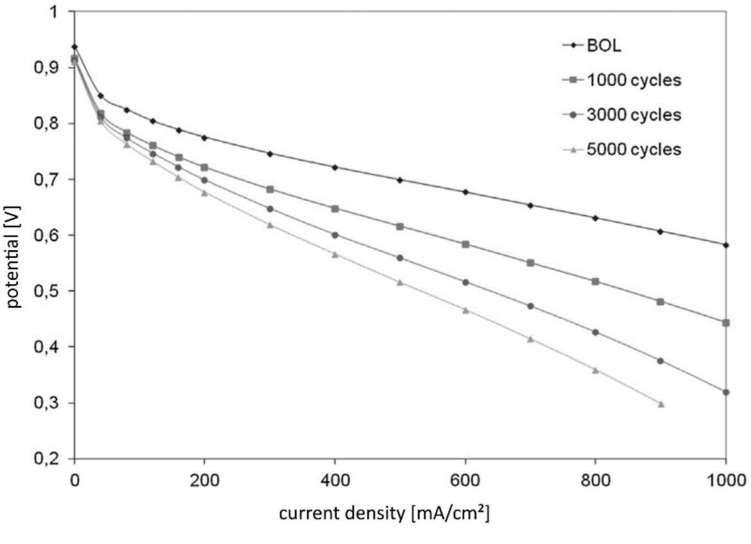

Figure 19: Effects of degradation on fuel cell performance [26]

2.4.2 Types of Fuel Cells

Fuel cells are either classified by their operating temperature or by the electrolyte used. Table 7 provides an overview of the different types of fuel cells. [7]

Table 7: Types of fuel cells [7]

Type	Operating temp.	Electrolyte	Ionic conduction	Fuel	Temp. range
AFC	approx. 60 to 80 °C	aqueous potash lye	OH^-	H_2	LT
DMFC (PEMFC)	approx. 80 °C	proton conducting membrane	H^+	COH_3OH	LT
NT-PEMFC	approx. 60 to 120 °C	proton conducting membrane	H^+	H_2	LT
HT-PEMFC	approx. 120 to 200°C	proton conducting membrane	H^+	H_2	LT
PAFC	approx. 160 to 200 °C	concentrated phosphoric acid	H^+	He	LT
MCFC	approx. 650 °C	molten carbonate	CO_3^{--}	He, CO	HT
SOFC	approx. 1000 °C	doped zirconium dioxide	O^{--}	H_2, CO	HT

In terms of temperature, there is a differentiation between low-temperature fuel cells (LT) and high-temperature fuel cells (HT) at temperatures above 600°C. When classified by their electrolyte, there are alkaline fuel cells (AFC), proton-exchange membrane fuel cells (also called polymer electrolyte membrane fuel cells) (PEMFC), phosphoric acid fuel cells (PAFC), molten-carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC). The proton-exchange membrane fuel cells can be further divided in direct-methanol fuel cells (DMFC), low-temperature polymer electrolyte membrane fuel cells (LT-PEMFC) and high-temperature polymer electrolyte membrane fuel cells (HT-PEMFC). Fuel cells are used in a wide range of portable and stationary applications. They have, depended on their type, different efficiencies and power output as summarised in Table 8. [7]

Table 8: Fuel cell properties [7]

Type	Power [kW]	El. efficiency (cell) [%]	El. efficiency (system) [%]	Application
AFC	10-100	60-70	60	aerospace, vehicles
PEMFC	0.1-500	50-75	45-60	aerospace, vehicles
DMFC	0.01-1	20-30	20-30	small devices
PAFC	up to 10000	55	40	small power plants
MCFC	up to 100000	55	50	power plants
SOFC	up to 100000	60-65	55-60	power plants

Alkaline Fuel Cell (AFC)

Alkaline fuel cells are low-temperature fuel cells. In Figure 20, the function principle of the AFC is illustrated. An aqueous potassium hydroxide solution (KOH solution) is used as an electrolyte and is conductive for OH^--ions. Produced at the cathode, they pass through the electrolyte to the anode. By reacting with hydrogen, water is composed and electrons are formed. It is used for an output range from 10 to 100 kW and achieves good efficiencies. A disadvantage is the use of potash as electrolyte.

It is a safety risk and leads to corrosion of the electrodes, which results in a short lifetime of the fuel cell. [7]

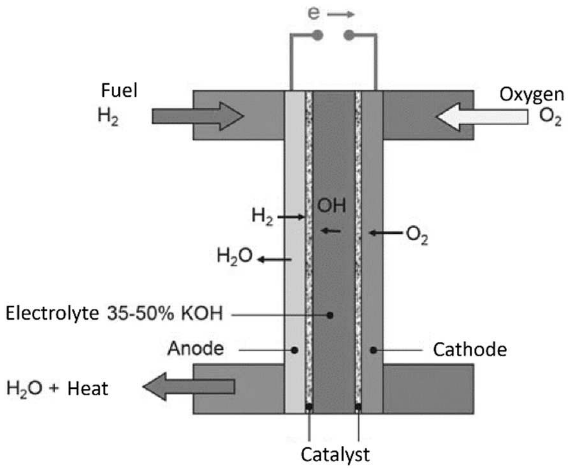

Figure 20: Function principle of the alkaline fuel cell acc. to [7]

Oxidation at the anode:

$$H_2 + OH^- \rightarrow 2\ H_2O + 2\ e^-$$

Reduction at the cathode:

$$H_2O + ½\ O_2 + 2\ e^- \rightarrow 2\ OH^-$$

Redox reaction:

$$H_2 + ½\ O_2 + 2\ H^+ + 2\ e^- \rightarrow H_2O$$

Proton-Exchange Membrane Fuel Cells (PEMFC)

The Proton-exchange membrane fuel cell is a low-temperature fuel cell. It can be further divided in DMFC, LT-PEMFC and HT-PEMFC. A not corrosive polymer is used and dependent on the PEMFC type the operating temperature range is between 60 and 200°C. [7]

Direct-Methanol Fuel Cell (DMFC)

Figure 21 illustrates the principle of the DMFC. Methanol as fuel is supplied to the anode in liquid or gaseous state and CO_2 is produced as exhaust gas. The cathode is supplied by atmospheric oxygen. A proton-conductive polymer membrane is used as electrolyte. The membrane needs water to stay conductive. Therefore, a methanol-water mixture is introduced on the anode side. H^+ ions take over the charge transport. The fuel cell is mostly used for small systems in portable applications with a power output of maximal 5 kW. The so called methanol-crossover is a disadvantage. Methanol diffuses to the cathode side and mixes with oxygen on the cathode surface reducing the efficiency. [7]

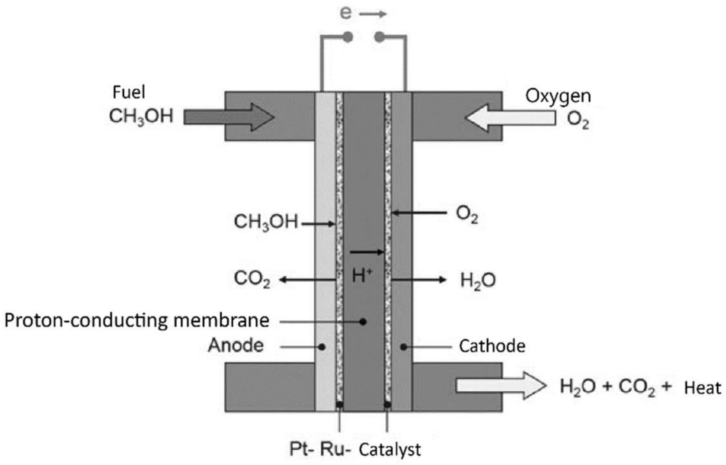

Figure 21: Function principle of the direct-methanol fuel cell acc. to [7]

Oxidation at the anode:

$$CH_3OH + H_2O \rightarrow CO_2 + 6\ H^+ + 6\ e^-$$

Reduction at the cathode:

$$3/2\ O_2 + 6\ H^+ + 6\ e^- \rightarrow 3\ H_2O$$

Redox reaction:

$$CH_3OH + 3/2\ O_2 + 2\ H_2O + CO_2$$

Low-Temperature Polymer Electrolyte Membrane Fuel Cell (LT-PEMFC)

LT-PEMFCs use hydrogen as a reducing agent and atmospheric oxygen as oxidising agent. Its function principle is illustrated in Figure 22. H_2 is absorbed on the surface of the catalytic converter. It dissociates to H and oxidises in the next step to hydrogen protons H^+ in order to form H_3O^+ ions. Hydrogen protons can migrate from water molecule to water molecule to the cathode. H_3O^+ ions can diffuse to the cathode. Oxygen is reduced on the catalyst surface of the cathode side. It receives two electrons and forms water with two H^+ ions. Water migrates as the ions are transported. A possibility to prevent drying is the humidification of hydrogen and atmospheric oxygen. LT-PEMFCs are used for power outputs up to 500 kW and are able to reach high current densities. This fuel cell type operates in a temperature range of about 60 to 120 °C. In LT-PEMFCs about 40% of the energy is produced as heat, which causes degradation of the materials if not removed immediately. Conventional cooling technologies used in passenger cars are usually insufficient because of the low temperature gradient between the fuel cell and the surrounding environment. Specialised thermal management technologies are therefore required. [7, 27]

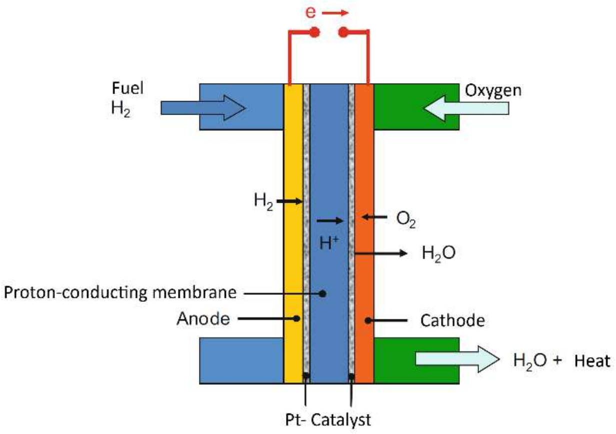

Figure 22: Function principle of the low-temperature polymer electrolyte membrane fuel cell acc. to [7]

Oxidation at the anode:

$$H_2 \rightarrow 2\,H^+ + 2\,e^-$$

Reduction at the cathode:

$$\tfrac{1}{2}\,O_2 + 2\,H^+ + 2\,e^- \rightarrow H_2O$$

Redox reaction:

$$H_2 + \tfrac{1}{2}\,O_2 \rightarrow H_2O$$

High-Temperature Polymer Electrolyte Membrane Fuel Cell (HT-PEMFC)

The function principle of the HT-PEMFC and the LT-PEMFC is the same and illustrated above in Figure **22**. The main difference between these fuel cell types is the membrane used. The HT-PEMFC uses a polybenzimidazole-doped polymeric membrane with phosphoric acid. The fuel cell runs in a temperature range between 120 and 200 °C and is able to operate without humidity. The higher temperature gradient between the fuel cell and the surrounding environment compared to the LT-PEMFC makes it possible to use conventional passenger car cooling systems. Weight advantages, cost advantages and packaging benefits are the result. On the other hand, high quality materials resistant to heat and acid have to be used, which increase the costs. Condensation of the produced water has to be avoided in order to prevent leaching of the acid from the membrane. [7, 27]

Oxidation at the anode:

$$H_2 \rightarrow 2\,H^+ + 2\,e^-$$

Reduction at the cathode:

$$\tfrac{1}{2}\,O_2 + 2\,H^+ + 2\,e^- \rightarrow H_2O$$

Redox reaction:

$$H_2 + \tfrac{1}{2}\,O_2 \rightarrow H_2O$$

Phosphoric Acid Fuel Cell (PAFC)

The phosphoric acid fuel cell is a low-temperature fuel cell and uses concentrated phosphoric acid saturated in a silicon carbide matrix (SiC) as electrolyte. Figure 23 illustrates the principle of the PAFC. H^+ ions move from anode to cathode. Hydrogen is used as a fuel and atmospheric oxygen is used as oxidising agent. The electrodes are made of porous graphite and are coated in platinum. It is used for an output range from 50 kW to 11 MW but has high material requirements and a short lifetime because of the phosphoric acid used as electrolyte. [7]

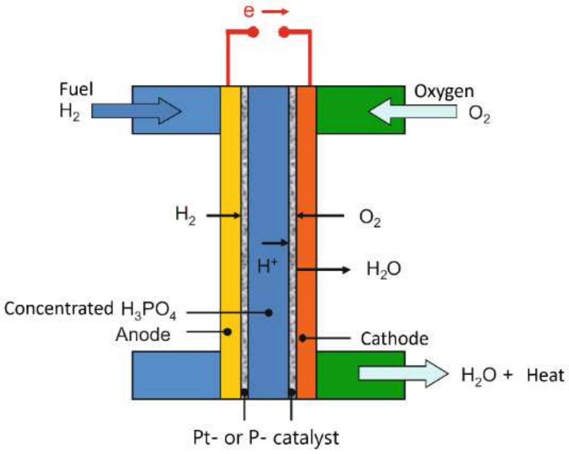

Figure 23: Function principle of the phosphoric acid fuel cell acc. to [7]

Oxidation at the anode:

$$H_2 \rightarrow 2\,H^+ + 2\,e^-$$

Reduction at the cathode:

$$\tfrac{1}{2}\,O_2 + 2\,H^+ + 2\,e^- \rightarrow H_2O$$

Redox reaction:

$$H_2 + \tfrac{1}{2}\,O_2 \rightarrow H_2O$$

Molten Carbonate Fuel Cell (MCFC)

The function principle of the molten carbonate fuel cell is illustrated in Figure 24. It is a high-temperature fuel cell with an operating temperature of around 650 °C. As electrolyte, an alkaline carbonate melt made out of lithium carbonate (Li_2CO_3) and potassium carbonate (K_2CO_3) is used. It is saturated in a lithium aluminate matrix. Carbonates migrate from the cathode to the anode through the electrolyte. As fuel, a gaseous mixture of hydrogen and carbon monoxide can be used, which is manufactured by internal reforming of gases that contain methane. A gaseous mixture of oxygen and carbon dioxide is supplied to the cathode side. There is a formation of carbonate. On the anode side, there is a formation of water and carbon dioxide. Because of the high temperatures occurring in this fuel cell type, there is no need for precious metal catalysts. Instead nickel can be used. High temperature-resistant materials are required to withstand the heat. The MCFC is used in power plants for outputs of up to 100 MW, but intensive fluctuations in temperature through heating and cooling processes lead to high wear. An overall efficiency of 90% can be achieved with a simultaneous utilization of the heat. [7]

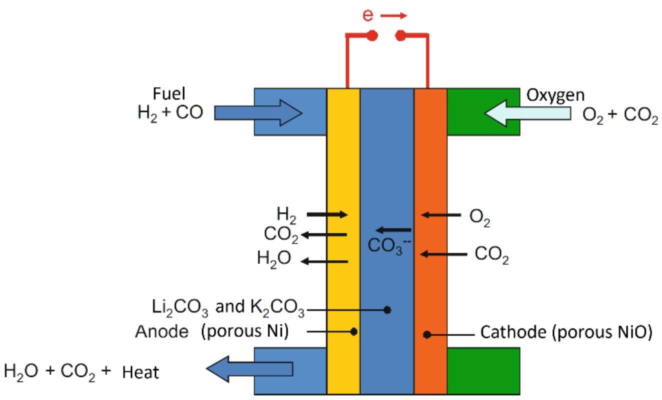

Figure 24: Function principle of the molten carbonate fuel cell acc. to [7]

Oxidation at the anode:

$$H_2 \rightarrow CO_3^{--} + 2\ H_2O + CO_2 + 2\ e^-$$
$$(CO + CO_3 \rightarrow 2\ CO_2 + 2\ e^-)$$

Reduction at the cathode:

$$\tfrac{1}{2}\ O_2 + 2\ CO_2 + 2\ e^- \rightarrow CO_3^{--}$$

Redox reaction:

$$H_2 + \tfrac{1}{2}\ O_2 + CO_2 \rightarrow H_2O + CO_2$$

Solid Oxide Fuel Cell (SOFC)

The solid oxide fuel cell is a high temperature fuel cell, which is currently at the research stage. It has an operating temperature between 750 and 1000 °C. Figure 25 illustrates the function principle of the SOFC. A solid ceramic material, like yttria-stabilised zirconia (YSZ), is used as electrolyte. The electrolyte is conductive to oxygen ions but non-conductive to electrons. For the cathode, a material conductive to electrons and ions like lanthanum strontium manganite (LSM) is used. The anode is made of a ceramic-metallic cermet material. For the catalyst, ruthenium and cerium is used. Fuel is reformed to carbon monoxide and hydrogen. This can be done directly by the system because of the high operating temperature. An external heating system is necessary to start the fuel cell. O_2 ions are responsible for the transport of charge. CO_2 is emitted if hydrocarbons are used, but the fuel cell is CO_2 emission-free when hydrogen is used as a fuel. The solid oxide fuel cell is robust and water management is not necessary. The future area of application of the SOFC is energy supply, as outputs of up to 100 MW are achievable. By simultaneous utilization of the heat, high overall efficiencies are possible. [7]

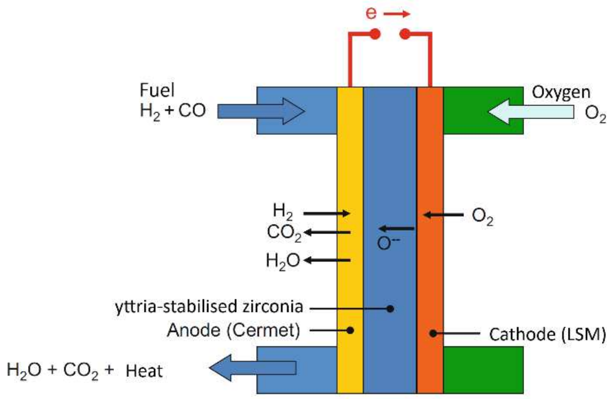

Figure 25: Function principle of the solid oxide fuel cell acc. to [7]

Oxidation at the anode:

$$H_2 + O^{--} \rightarrow H_2O + 2\ e^-$$
$$(CO + O^{--} \rightarrow CO_2 + 2\ e^-)$$

Reduction at the cathode:

$$½\ O_2 + 2\ e^- \rightarrow O^{--}$$

Redox reaction:

$$H_2 + ½\ O_2 \rightarrow H_2O + CO_2$$
$$(CO + ½\ O_2 \rightarrow H_2O)$$

2.4.3 Structure of the Fuel Cell

The objective of this sub-chapter is to give an overview of fuel cell systems structures by describing the single cell, the stack and the fuel cell system with the anode and cathode subsystem.

Single Cell

The single cell of a fuel cell, as illustrated in Figure 26, consists of an electrolyte enclosed by two porous electrodes that have a catalyst embedded in them to accelerate the reaction. The assembly of electrolyte and electrodes is called membrane electrode assembly (MEA). The reaction takes place in the triple phase boundary, the region of contact between electrode, electrolyte and reactants. To achieve high current densities, this area should be as large as possible. The MEA is sandwiched by the gas diffusion layer (GDL). The assembly is held together by the bipolar plates. If arranged in a stack, the reactants are supplied to the membrane electrode assembly through the flow structures of the bipolar plates. In addition, the bipolar plate conducts electricity to the connected single cells of a fuel cell stack. [7]

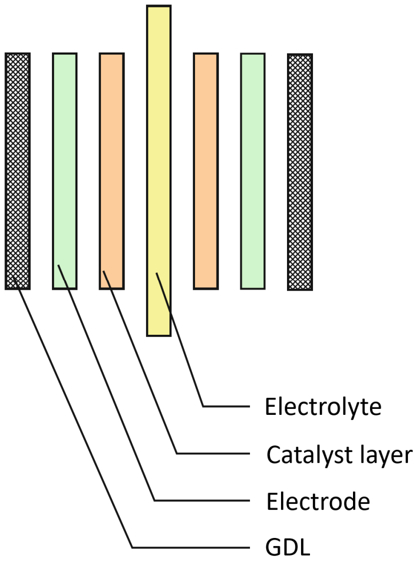

Figure 26: Schematic structure of the membrane electrode assembly including GDL acc. to [7]

Stack

Figure 27 illustrates the structure of a bipolar fuel cell stack with solid state electrolyte as it is used in polymer electrolyte membrane fuel cells. The stack is assembled out of MEA, bipolar plates, seals and end plates. [7]

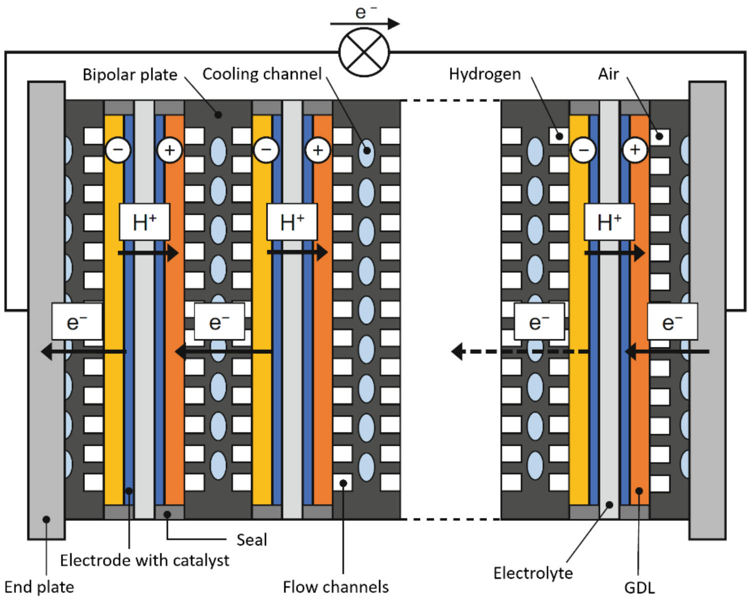

Figure 27: Structure of a bipolar fuel cell stack acc. to [7]

The bipolar plate connects the single cells. On one end of the bipolar plate there is the negative pole and on the other end the positive pole. Electrons flow from the anode side of one cell to the cathode side of the cell next to it. The assemblies of bipolar plate and MEA are sandwiched by the end plates, which hold the stack together. The voltages of the singe cells mount up and as the cells are arranged in-line, the current flow is the same through all cells. It is a disadvantage of this arrangement that the weakest cell limits the power of the whole stack, which can be responsible for its total failure. [7]

Fuel Cell System

To operate a fuel cell stack, auxiliary units and a control system are necessary. Stack and auxiliary units form the fuel cell system. The system can be divided into following subsystems: fuel cell stack, anode subsystem, cathode subsystem, cooling system (thermal management) and electronic control unit. The subsystems can differ in terms of design and components depending on the manufacturer of the fuel cell. The layout of a PEM fuel cell system is illustrated in Figure 28. [7]

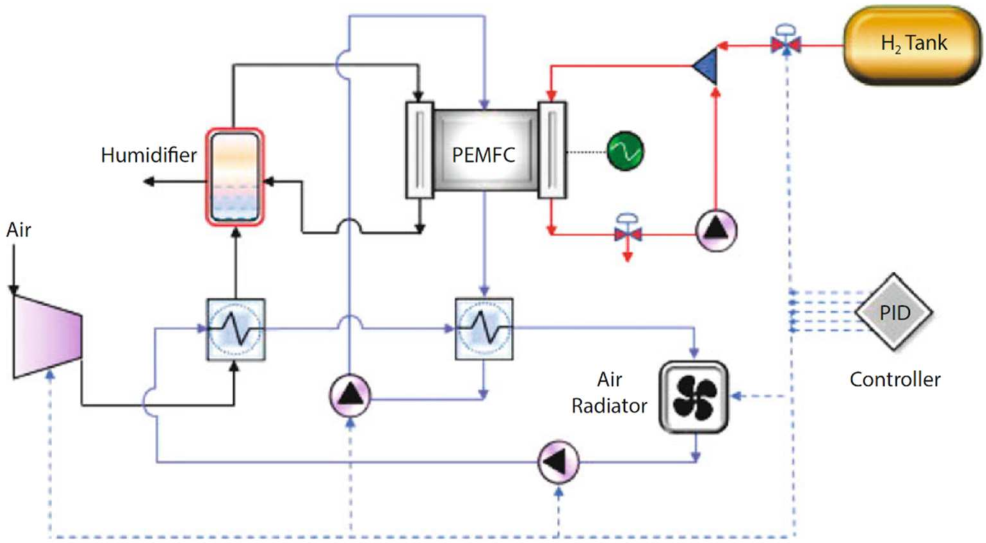

Figure 28: Schematic layout of a PEMFC system [7]

Anode Subsystem

The anode subsystem as illustrated in Figure 29 is described by means of the PEMFC. The anode subsystem has to deliver the requested amount of fuel. The fuel, in this case hydrogen, has to be provided in the right concentration, temperature and pressure. Hydrogen is transported from the hydrogen storage system in the middle pressure line at 0.5 to 1 MPa to the low-pressure valve, where the pressure is regulated to the operating pressure of the anode side. As a pressure difference between anode and cathode side could harm the membrane, the anode and cathode pressure should be kept on the same level. The heat exchanger adjusts the temperature according to the stack temperature although not every fuel cell system has a built-in heat exchanger for the fuel stream. In the anode the hydrogen is consumed. In order to avoid a shortage of hydrogen on the anode side, more hydrogen is supplied than consumed. The excess hydrogen from this process is recycled. Due to diffusion impurities, nitrogen or product water get to the anode side, which dampens the reaction. A high water content on the anode side can block the gas diffusion layer and the flow channels and lead to a performance loss of the fuel cell. Therefore, a water drain valve drains the excess water. If the content of impurities on the anode side is too high, they are pushed out with the help of the purge valve. [7]

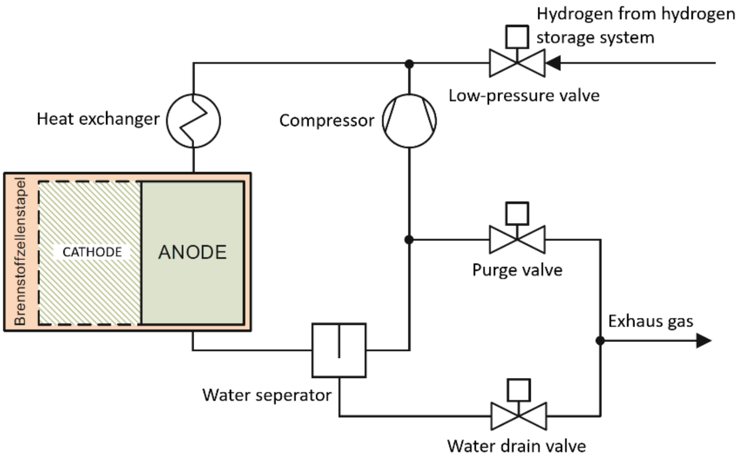

Figure 29: Anode subsystem acc. to [7]

Cathode Subsystem

The cathode subsystem is described by the example of a PEMFC. It is illustrated in Figure 30. In this subsystem, the cathode side is supplied with oxygen from the ambient air with the required humidity, temperature and pressure. The air filter purifies the ambient air, which is supplied by a compressor in the desired mass flow. The compressor, the largest energy consumer of the fuel cell system, also increases the pressure. The cathode pressure is a result of the interaction between compressor and pressure-sustaining valve. The air is heated as a result of the compression and has to be cooled down by a heat exchanger in order to not exceed the inlet temperature. Water management is an important part of the fuel cell control strategy. A dry out of the membrane has to be prevented but the water content must not be too high to avoid a flooding of the electrode. Therefore, the humidity of the air has to be adapted by the humidifier. [7]

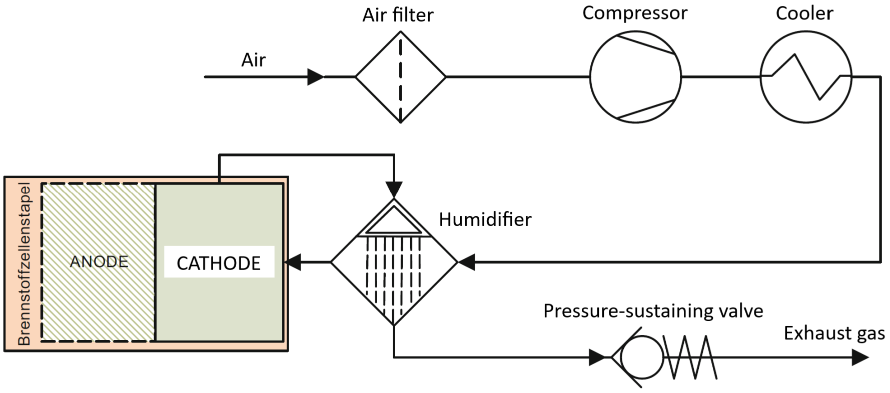

Figure 30: Cathode subsystem acc. to [7]

2.4.4 Fuel Cell Module in the MH_2PS

Ballard's proton exchange membrane fuel cell module FCveloCity-MD30 (illustrated in Figure 31) is used in the MH_2PS as power output.

Figure 31: Ballard FCveloCity-MD30 [28]

Depending on the selected operating mode, the fuel cell generates electrical energy, which is then delivered to the electric vehicle to be charged, the HV battery or both as illustrated in Figure 32. The module itself requires a 24V power supply to operate; therefore a 24V battery is installed in the system.

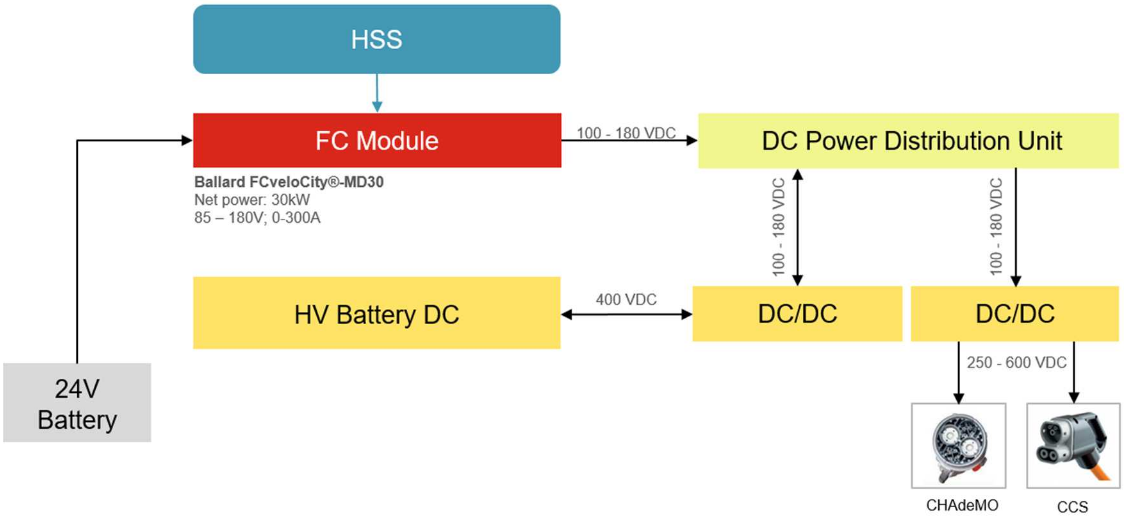

Figure 32: Fuel cell module in the MH_2PS

The fuel cell has a rated net power of 30 kW, an operating DC voltage range of 85 to 180 V and a current output range of 0 to 300 A. The FCveloCity-MD30 uses gaseous hydrogen from the hydrogen storage system as fuel and ambient air as oxidant. Table 9 summarises the preliminary product specifications of the Ballard FCveloCity®-MD30. [28]

Table 9: Product specifications of the Ballard FCveloCity-MD30 [28]

Technology	Fuel cell	Proton exchange membrane
Performance	Rated net power	30 kW
	Operating DC voltage range	85 - 180 V
	Current	0 - 300 A
Physical	Dimensions (l x w x h)	900 x 480 x 375 mm
	Weight	125 kg (fuel cell module)
Fuel	Type	Gaseous hydrogen
	Composition	As per SAE specification J2719
Operation	Oxidant	Air
	Stack coolant	50/50 pure ethylene glycol and deionized water WEG 60°C to 70°C
	Fuel supply pressure	0.8 MPa nominal
	Fuel flow rate	0.7 g/s maximum
Safety Compliance	Design Standards	ISO 6469-2:2009, ISO 6469-3:2009 and ISO 23273:2013
	Enclosure	IP55
Monitoring	Control interface	CANbus
Emissions	Exhaust	Zero-emissions
	Sound level	Less than 75 dBA

Detailed information of the fuel cell used in the MH_2PS is given in the appendix of this thesis. It provides the product data sheet of the Ballard FCveloCity-MD30.

2.5 Battery

Storage and supply of electrical energy on demand are one of the key technologies for the electrification of the drive train. Battery systems are commonly used today for this purpose. In Magna's MH_2PS, a high voltage battery is used to store and to provide an additional output of electrical energy. In the following paragraphs, the basics of battery technology are described, followed by an overview of different battery types and a more detailed look into the lithium-ion battery, which is used in the MH_2PS.

2.5.1 Principle Structure of Electrochemical Storages

Basically, the principle of all electrochemical batteries is the same. It is illustrated in Figure 33. Electrochemical batteries consist of two electrodes made from different materials surrounded by an electrolyte and separated by a separator. The electrode materials are called active masses and have an electrochemical potential with respect to the electrolyte. The potential of the cell is the difference of the potentials of the two electrodes. [29]

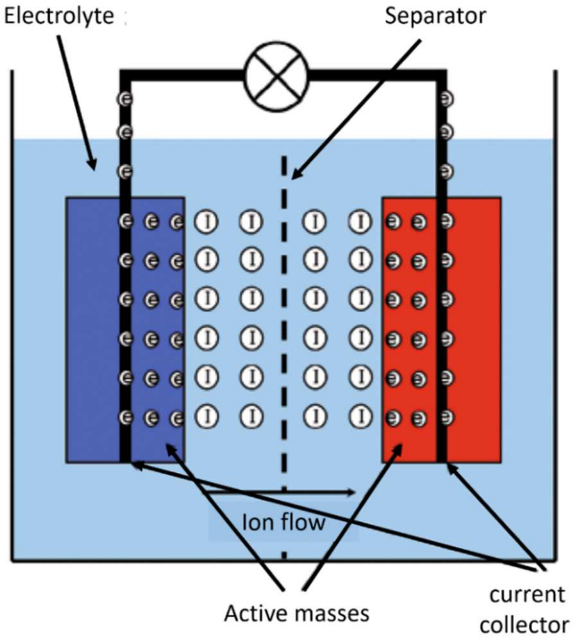

Figure 33: Principle structure of a battery cell acc. to [29]

Electrons are released and received by the current collector in the active masses of the electrodes. During the electrochemical reaction the charge carrier is transferred to an ion. The ion diffuses through the electrolyte to the other electrode where the charge carrier is taken from the ion and released as electron. The electrolyte acts as an electrical insulator. To insulate the active masses from electric energy, a separator is used to separate the electrodes. The electrolyte can either be liquid or solid. In nearly all batteries, the specific resistance for the ionic current of the electrolyte is much higher than the resistance for the electric current in the active masses. That is why the performance of batteries decreases with decreasing temperature and the associated decrease of ionic conductivity. [29]

Normally, a single battery cell has too less capacity and voltage to meet the requirements of a consumer regarding electrical energy. The open circuit voltage of a lithium-ion battery's single cell lies between 2.2 and 3.7 V. Lead-acid batteries have a nominal voltage of 2 V, nickel-cadmium and nickel-metal hydride batteries have a nominal voltage of 1.2 V. The capacity of a battery is the amount of electric charge, which can be delivered at the rated voltage. It is stated in ampere hours (Ah) and should not be confused with the capacity of a capacitor, which is stated in farad (F, F=As/V). Dependent on the battery type, capacities of over 1000 Ah are available. To achieve higher capacities and voltages, single cells are connected in series and/or parallel. If they are connected in series, the capacity stays the same, but the total voltage results from multiplying the single voltage with the number of cells. When connected in parallel, the capacity is increased. Power and amount of energy always scale linearly with the number of cells. Often, a combination of series and parallel connection is used. Bundles of cells connected in series are connected in parallel. In the automotive sector the voltage varies between 12/14 V for the conventional electrical system or micro hybrids, 42 to 150 V in mild hybrids and 150 to 400 V in full hybrids, plug-in hybrids and pure electric vehicles. Full electric buses even use battery voltages up to 700 V. [29]

2.5.2 Battery Terminal Voltage

Figure 34 illustrates schematically the voltage curve of a battery during discharge with constant voltage.

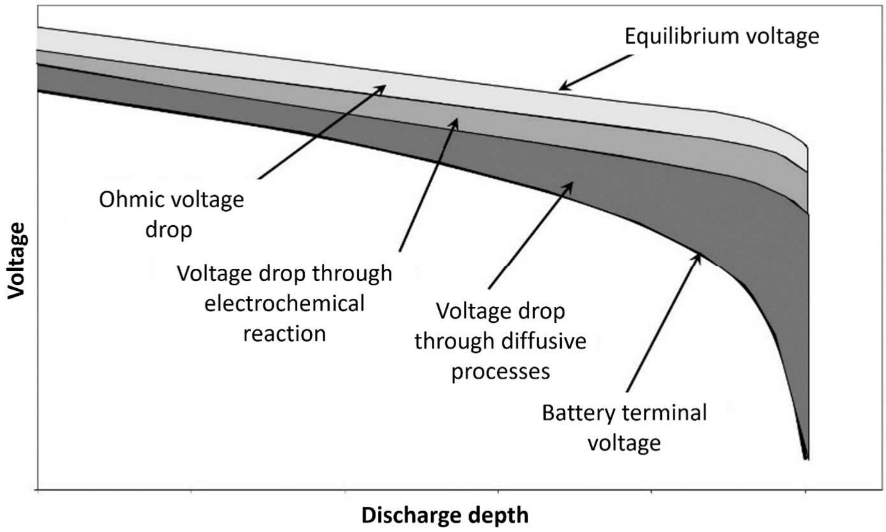

Figure 34: Schematic illustration of the battery's voltage curve acc. to [29]

The terminal voltage of a battery is determined by various factors shown in the formula below.

$$U_{termial\ voltage} = U_{equilibrium} - U_{BVE} - U_{resistance} - U_{diffusion}$$

The open-circuit voltage or equilibrium voltage of an electrode is created because a boundary layer is formed between the metallic electrode material and the electrolyte, similar to a capacitor. At this boundary layer, a continuous transfer of charge carriers from the electrode material in the electrolyte takes place and vice versa from the electrolyte's ions to the electrode material. The difference of the electrode material's energy content in charged and discharged state is the potential of an electrode in a specific electrolyte. [29]

The maximal storable energy of a certain material can be calculated out of the thermodynamic basic equations. No energy density of a given material combination can exceed this theoretical limit. In practice, this limit can only be approached by an appropriate design of the cells. In reality, the achievable energy density is about 30 to 50% of the theoretically achievable energy density. Passive materials, like the electrolyte, the separator, the current collectors or the casing, contribute to the weight of the cell next to the active battery materials. [29]

The reaction over-potential U_{BVE} results out of the electrochemical reaction described by the Butler-Volmer equation shown below. [29]

$$I = A * i_0 * [\exp\left(k_1 (U - U_0)\right) - \exp\left(-k_2 (U - U_0)\right)]$$

Charge and discharge reactions are based on an exponential relation with the over potential. The over potential is a deviation of the open-circuit voltage U_0, which adjusts itself without current flow. The Butler-Volmer equation describes the reaction at one electrode. For every electrode a specific equation exists. The exponential functions describe the oxidation reaction and the reduction reaction of an electrode. I_0 is a material parameter, A is the active surface where the electrochemical reaction occurs. This surface can change during both, charge and discharge cycles and the life cycle. The smaller the active surface gets, the larger the over potential needs to be for a given battery current. This manifests in the fact that at same current the voltage of aging batteries is strongly increased or reduced compared to a new battery. The deviation between terminal voltage and open-circuit voltage multiplied with the current results in the loss of energy during charging and discharging. This leads to the battery cell heating up. Decreasing efficiency results in an increasing heat output and rising temperatures. [29]

The battery's terminal voltage is not only determined by the reaction over-potential U_{BVE}. The voltage drop resulting from the ohmic voltage losses $U_{resistance}$ is also of importance, as well as the voltage drop through diffusive processes $U_{diffusion}$, which is the result of concentration gradients of charge carriers in the electrodes and in the electrolyte. Reaction over potential and ohmic voltage drop are of no importance after switching off the current. However, balancing processes in the battery can last for hours and lead to the fact that the battery voltage changes even long time after the active operation of the battery. For diagnosing the condition of batteries, an accurate knowledge of the voltage components is of major importance. However, only the terminal voltage can be measured, therefore a high effort has to be made to determine the voltage components by analysis of the dynamic behaviour and with the help of appropriate algorithms. [29]

A battery is considered as empty if the battery voltage drops below a previously defined threshold value. Removing a specific amount of charge is not the determining factor. Chemically, a battery is not empty if it is considered as empty in an application. This is evident if a fully charged battery is cooled to low temperatures and discharged. The battery capacity that is available is much lower than the capacity available at high temperatures. The final discharge voltage is reached sooner at low temperatures than at high temperatures. When reaching the final discharge voltage, the usability of the battery cell ends. If the battery cell is reheated it can be further discharged. The electrochemical conversion of the active materials is exactly proportional to the number of charge carriers flowed and therefore the amount of electricity. The battery is chemically empty if at least one of the active masses is completely in a discharged state. The influence of temperature on the battery's capacity is of general validity, which means the higher the temperature, the higher the capacity. This is mainly due to the fact that chemical reactions proceed faster at high temperatures. On the other hand, the aging process of the battery is accelerated at higher temperatures. Therefore, the temperature should not be increased too much. [29]

Voltage limits and final discharge voltage are defined to protect the battery from low and therefore damaging voltages and deep-discharging. In addition, it should guarantee the safe operation of the subsequently arranged electronics units. Both, temperature and voltage are monitored constantly by a battery management system. It interacts, if the permissible values are exceeded. The SOC (State of Charge) is calculated by the integral over the effective charging and discharging current of the battery and shown below. [29]

$$SOC(t) = SOC(t=0) + \frac{1}{C_{nominal}} \int_{t=0}^{t} (I_{battery} - I_{loss})\, dt$$

This is not automatically identical to the battery's terminal current ($I_{battery}$), because the internal losses in side reactions or aging processes consume electricity (I_{loss}). This leakage current can be calculated with the help of adequate models, but only to a certain degree. Furthermore, the terminal current cannot be measured error-free either. Measurement errors and errors in determining the leakage current add up over the operating life and can lead to errors in the percent range. Therefore, algorithms have to be developed to recalibrate the state of charge independently from erroneous measurements. This can be performed for instance by independent identification of SOC and DOD (Depth of Discharge). [29]

- Battery fully charged: SOC = 100% DOD = 0%
- Battery fully discharged: SOC = 0% DOD = 100%

The coulomb efficiency is the ratio of removed charge (measured in Ah) and the amount charged in the battery. The value cannot be higher than 1. The charge, which cannot be discharged, is lost in irreversible side reactions ($\int I_{loss} dt$). This can happen due to uncontrolled gassing in batteries with an aqueous electrolyte (lead-based batteries or nickel based batteries) or due to aging effects like corrosion. The efficiency's deviation from the value 1 therefore represents a measurement of unwanted side reactions. Unlike lead batteries, lithium-ion batteries do not have unwanted side reactions besides the aging process. The energy efficiency is the ratio of the time-related integration of removed charge and the time-related integration of added charge. It combines both, the coulomb efficiency and the overvoltages, which are occurring. The efficiency is important for the temperature of the battery cell because efficiency losses in the battery are mainly converted to heat. [29]

2.5.3 Battery Technologies and Typical Fields of Application in the Automotive Industry

In the automotive sector, various battery technologies are in use, each with its own specific characteristics. The following section should give a short overview of different battery technologies. The technologies sometimes differ considerably regarding energy and power density as illustrated in Figure 35. They also differ regarding costs, efficiency, safety, availability of materials and number of suppliers. Especially energy and power density are of importance in the automotive industry as the energy density plays a major role for battery electric vehicle's driving range and the power density defines the maximum velocity (or acceleration) that can be reached. [29]

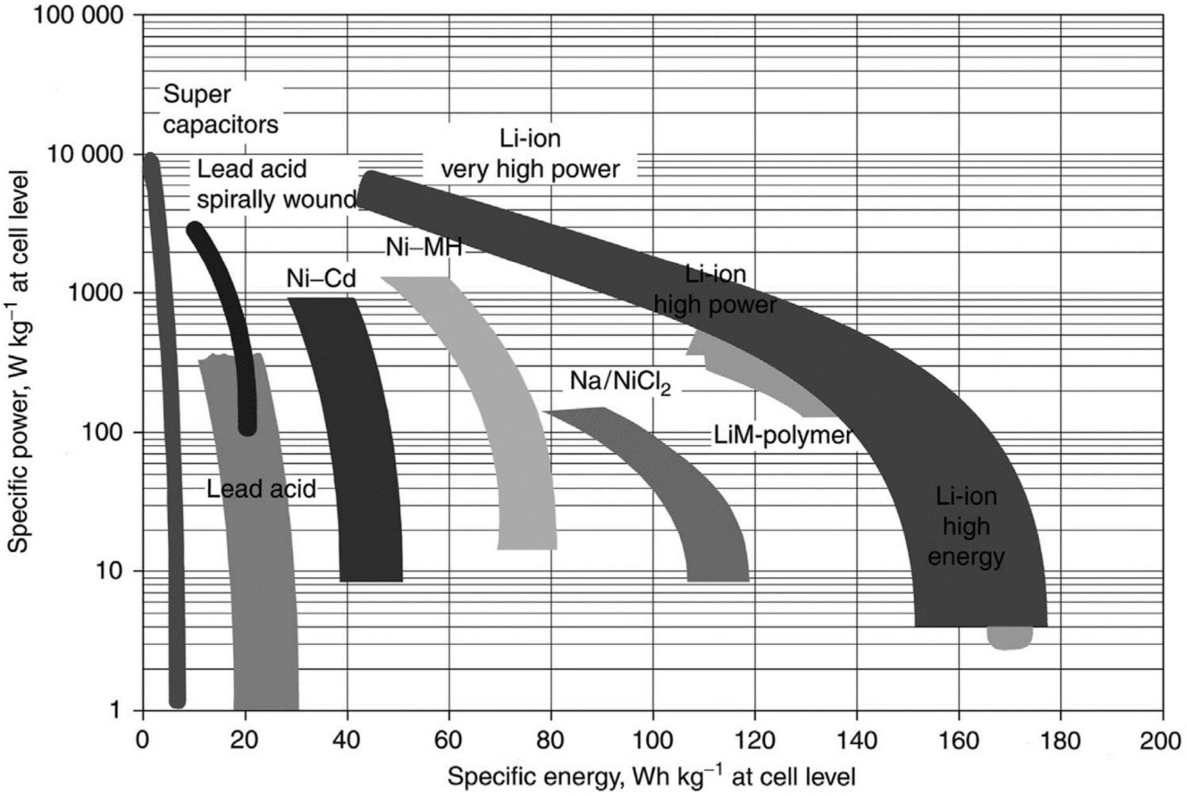

Figure 35: Energy and power density of different battery technologies [30]

Lead–Acid Battery

The lead-acid battery is the oldest type of rechargeable battery and in use for more than 100 years. The schematic layout of the lead-acid battery is illustrated in Figure 36. The positive electrode consists of lead oxide, the negative electrode is made out of porous lead. Both electrodes have a current collector made out of lead. The electrolyte is diluted sulphuric acid. In contrast to the other technologies, the electrolyte of the lead-acid battery is an active part in the reaction. When discharging, the sulphuric acid's sulphate ions of both electrodes react with lead ions and form lead sulphate crystals on the electrodes surface. This reduces the concentration of sulphuric acid. As side reaction, hydrogen is formed at the negative electrode and oxygen at the positive electrode, which escapes as gas. Therefore, the battery loses water, which has to be refilled. Today's starter batteries normally have enough electrolyte so there is no need for a refill. To further reduce gassing, two new types of lead-acid batteries have been introduced. One of them is called VRLA (Valve Regulated Lead-Acid). In a VRLA, excess gas can escape with the help of a valve if over pressure is build-up in order not to harm the battery. In one case the electrolyte is absorbed by a fleece. This type is called AGM (Absorbent Glass Mat). The other type reacts to gel by the addition of silicon dioxide. Both types transfer the generated oxygen to the negative electrode, where it reacts with hydrogen ions and forms water. [29]

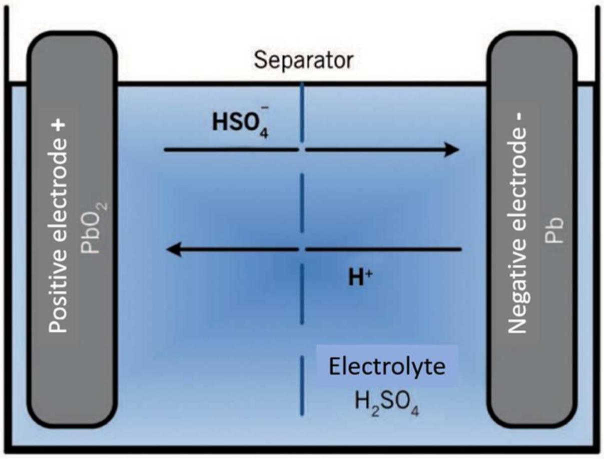

Figure 36: Schematic layout of the lead-acid battery acc. to [29]

Lead-acid batteries are used in vehicles as starter batteries in order to provide energy to start the internal combustion engine and to supply all the vehicle's electrical consumers. They are cheap and offer high intrinsic safety. Another advantage is their nearly full recyclability. Disadvantages are low energy and power densities and the short lifetime. The charge acceptance (ability to receive charge) is low and dependent on many factors, like temperature or state of charge. Efficiency and capacity are strongly dependent on temperature. The capacity is reduced by more than half at -20°C. Therefore, it is not suitable for the use as traction battery in electric vehicles. [29]

Nickel-Metal Hydride Batteries

Nickel-metal hydride batteries (NiMH) were developed to replace the poisonous cadmium in nickel-cadmium batteries (NiCd). The positive electrode is made of $Ni(OH)_2$ and the negative electrode consists out of $LaNi_5$. The electrolyte is a dilute caustic potash solution KOH. During the discharge process, protons from water molecules are removed from the negative electrode and transferred to the positive electrode. The nominal voltage is only 1.2 V. To achieve higher operating voltages, many cells have to be connected in series. They are as temperature-sensitive as lithium-ion cells. Above a temperature of 50 °C they are hardly chargeable and below -10 °C the capacity of the battery is reduced drastically. [29]

NiMH battery technology is considered as safe and reliable. A large share of the hybrid vehicles produced in the last ten years uses NiMH batteries. For new plug-in hybrid cars and battery electric cars, vehicle manufacturers do not rely on this technology. On the one hand the energy density is lower than in lithium-ion batteries, on the other hand the cost reduction potential caused by higher raw material costs is much lower as it is the case with lithium-ion batteries. Additionally, there are only three suppliers for nickel-metal hydride batteries and thus an insufficient level of competition on the market. It is expected that the technology disappears from automotive sector in the next few years. [29]

High-Temperature Sodium Nickel Chloride Batteries

The previously described battery technologies can be operated effectively in a temperature range of about -20 °C to 80 °C. High-temperature sodium nickel chloride batteries have an operating temperature of about 300 °C and are therefore not dependent on the ambient temperature. The negative electrode is molten sodium. The positive electrode is made of solid $NiCl_2$. During discharging the sodium ions pass through the solid-state electrolyte and vice versa if the battery is charged. [29]

Such batteries have good energy densities and long lifetimes in the range of several thousand cycles. Apart from nickel, the materials used are cost-effective. The main disadvantage is the high operating temperature. It leads to high thermal losses. They have to be compensated continuously as a cooling of the battery results in a significant reduction of the lifetime. A battery pack of about 16 kWh has thermal losses of about 100 W. If the battery is not used for a day, 2.4 kWh have to be supplied to compensate the losses. If the battery is fully used once a day, the resulting heat loss is enough to maintain the required temperature. Therefore, the technology is suitable for city buses, which are used on a regular basis. With a decreasing price of lithium-ion batteries, high-temperature sodium nickel chloride batteries face difficulties in establishing their market. [29]

Redox-Flow Batteries

The redox-flow battery's structure is different from the batteries described before. The schematic layout is illustrated in Figure 37. The battery consists of two tanks filled with electrolyte liquids and dissolved ions of different oxidation states and a central stack, where charge and discharge reactions take place. The stack itself does not undergo any changes. The principle is similar to a reversible fuel cell using hydrogen and oxygen gas as reactants. Compared to the fuel cell, the redox-flow battery's efficiency is considerably higher at values of 70 to 80%. The battery's advantage is that energy capacity and power can be scaled independently from each other. It is discussed to use redox-flow batteries in vehicles. The vehicle could be charged by filling the electrolyte but energy densities are similar to the ones of lead-batteries. Therefore, this technology is no alternative to lithium-ion batteries. Ion pairs have to be found, which can achieve higher energy densities and lower costs. Today mostly vanadium redox batteries are offered. Those batteries need to be operated in a temperature range of about 15 to 40 °C. If not, one of the ions is not able to operate. [29]

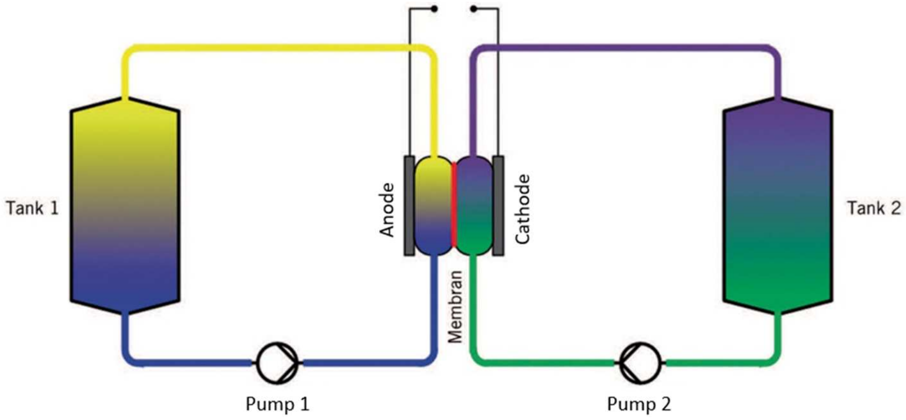

Figure 37: Schematic layout of the redox-flow battery acc. to [29]

Lithium-Ion Batteries

The term lithium-ion battery summarises many different technologies based on the same functional principle. Figure 38 illustrates the schematic structure of a lithium-ion battery. Like every battery, it consists of two electrodes, a separator and the electrolyte. Lithium-ion batteries are intercalation batteries. During the charging or discharging process, one electrode releases lithium ions. The ions pass through the electrolyte to the other electrode and are stored in the electrode material's crystal lattice. It is a reversible process; the crystal structures stay the same, which results in high cycling expectancies. Additionally, lithium does not occur in its highly reactive metallic form like it is the case in lithium metal batteries. Therefore, safety and lifetime are increased as lithium is only stored in defined lattice sites. [31]

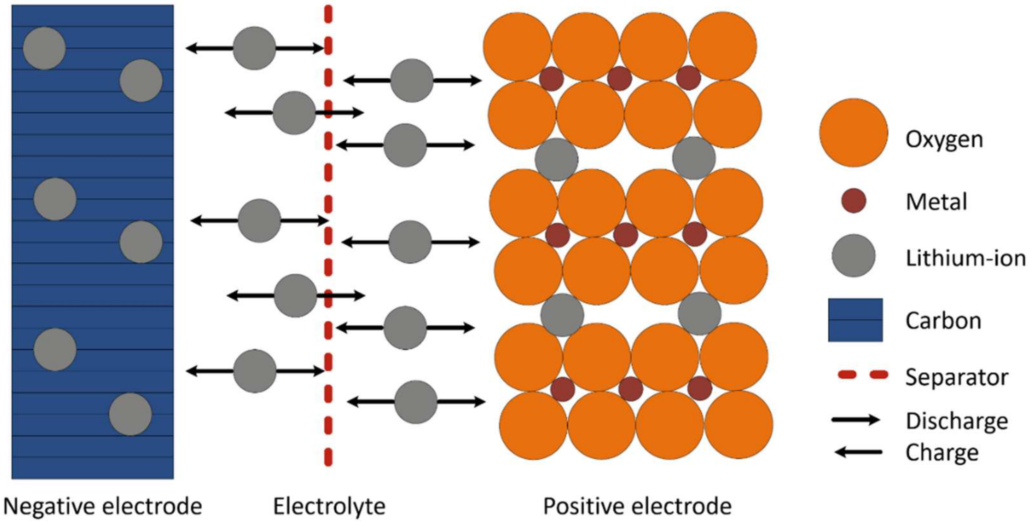

Figure 38: Schematic structure of a lithium-ion battery acc. to [31]

The positive electrode (cathode) is made out of a metal oxide. The negative electrode (anode) consists of a carbon modification like graphite. Both electrodes have highly porous structures. They are composed of single particles of the active masses as well as of binding and conductor materials. They have a large surface to achieve high response rates. As binding materials, variations of polyvinylidene fluoride are used. As conductor material, often carbons are used. The electrode materials are applied to a thin metal foil, that also serves as current collector. For the cathode, aluminium is used, the anode's metal foil is made of copper. The electrolyte is a lithium salt dissolved in an organic solvate. The separator is made of a porous polymer structure. Separator and electrodes are moisturised by the electrolyte. [31]

Lithium-ion cells are offered in various designs. A distinction is made between pouch cells, prismatic and cylindrical cells. All these cell designs consist of multiple layers of electrode-separator-electrode-stacks, whereby the electrodes are coated on both sides. In poach cells, the layers are put on top of another, in cylindrical cells they are wound up. In prismatic cells both variants can be found. Figure **39** illustrates the design types. On the left is the pouch cell, in the middle the prismatic cell and on the right side the cylindrical cell. There are lithium-ion batteries with high energy densities and moderate currents used in electric vehicles as well as batteries with high power densities used in hybrid vehicles. The internal structure differs mainly in the electrode's coating thickness. The thinner the active materials, the higher the power density with simultaneously decreasing energy density. [31]

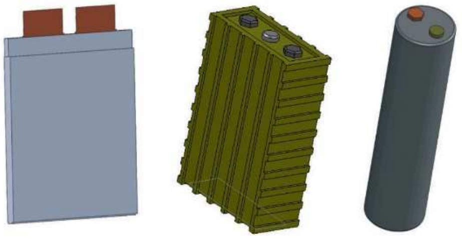

Figure 39: Design types of lithium-ion cells [31]

The biggest difference between the various lithium-ion battery technologies lies in the electrode's material composition. On the cathode side, materials with widely differing properties are used. Of the several material types, only few have been proved to be viable like the lithium-manganese-cobalt technology (NMC) and electrodes made of lithium-nickel-cobalt-aluminium (NCA). [31]

Every lithium-ion cell, independent from the material combination used, has to be operated with an electronic protection circuit in order to avoid voltages that could harm the material. For instance, if the cell is overcharged, the electrolyte will be decomposed. The cell then starts to produce gas, which leads to a breakdown of the cell. In the worst case, fire can occur. If lithium-metal-oxide cathodes are used, overcharging or temperatures over 200 °C can lead to a thermodynamically instable state, where the material is decomposed exothermically while releasing oxygen (thermal runaway). If deep discharged, irreversible capacity losses can occur. Very low state of charges can further lead to dissolution of the current collectors. This can lead to a short circuit. [31]

Because of high safety and lifetime requirements, batteries used in vehicles achieve energy densities of 160 to 180 Wh/kg. In the future, energy densities up to 300 Wh/kg will be possible. Gravimetric power densities are in the range of 500 W/kg for electric vehicle batteries and 3000 W/kg for hybrid vehicle batteries. The energy densities refer to single cells. When integrating the cells to a battery pack, those values drop significantly because of necessary cooling and battery management systems and cell connectors. Lithium-ion batteries tolerate high charging currents and are fast-chargeable but not at low temperatures. Under 0 °C, lithium plating can occur, which leads to accelerated aging and risk of short circuit. As different batteries react differently to lithium plating, permitted charging rates depended on temperature need to be determined individually for every product. [31]

2.5.4 Batteries in the MH_2PS

There are 3 different batteries in the MH_2PS, the HV battery, a 12V battery and a 24V battery. They are described below.

HV Battery

The HV battery used in the MH_2PS is a Samsung SDI P2-80. Depending on the operation mode, it is used as power output in addition to the fuel cell and also supplies the 12V battery via a DC/DC converter. The HV battery itself can be charged by the fuel cell. The HV battery scheme is illustrated in Figure 40.

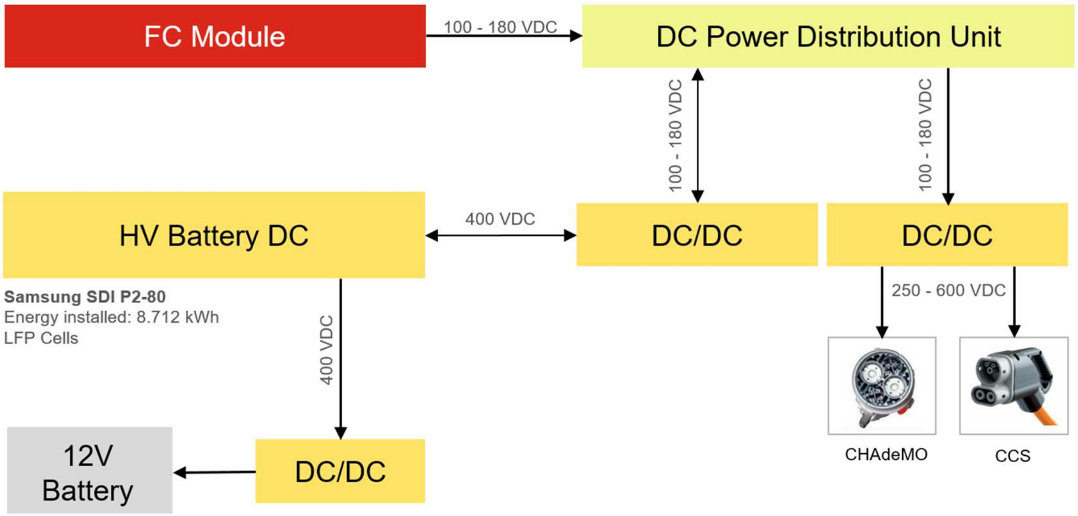

Figure 40: HV Battery scheme of the MH$_2$PS

The high voltage battery is a lithium-ion system using lithium iron phosphate (LFP) as cathode, graphite as anode and lithium hexafluorophosphate solution as an electrolyte. The capacity of a single cell is 22 Ah, the total cell number is 120. The installed system energy is 8.712 kW, the usable system energy of the battery is 6.1 kW. The nominal system voltage is about 400 V. Table 10 lists the product specification of the Samsung SDI P2-80.

Table 10: Product specifications of the Samsung SDI P2-80 [32]

Cell Data	Type	LEV 21F VDA
	Cathode	LFP
	Anode	Graphite
	Electrolyte	LiPF6 in EC/DEC/DMC
	Capacity	22 Ah
	Voltage max.	3.6 V
	Voltage nom.	3.3 V
	Voltage min.	2 V
System Basic Data	Total Cell Number	120
	Usable system energy	6.1 kW
	Installed system energy	8.712 kW
	Usable SOC range	10-99 %
	Cell temperature range	- 20 to + 45°C
	Dimension	905 x 525 x 200 mm
	Weight without brackets	112 kg
Basic Electric Data	System Voltage max.	432 V
	System Voltage nom.	396 V
	System Voltage min.	240 V
	max. cont. Discharge	150 A
	max. cont. Charge	67 A
	Typical cont. Discharge	50 A
	Typical cont. Charge	15 A

12V Battery

The 12V battery in the MH_2PS is used to supply following devices with 12 V direct current:

- DC PDU BRUSA PDU254
- DC/DC converter BRUSA BDC546
- DC/DC converter BRUSA BDC546
- DC/DC converter BRUSA BSC624-12V
- Micro Autobox
- 24V battery via DC/DC converter

The 12V battery itself is supplied by the HV battery via a DC/DC converter as illustrated in Figure 41.

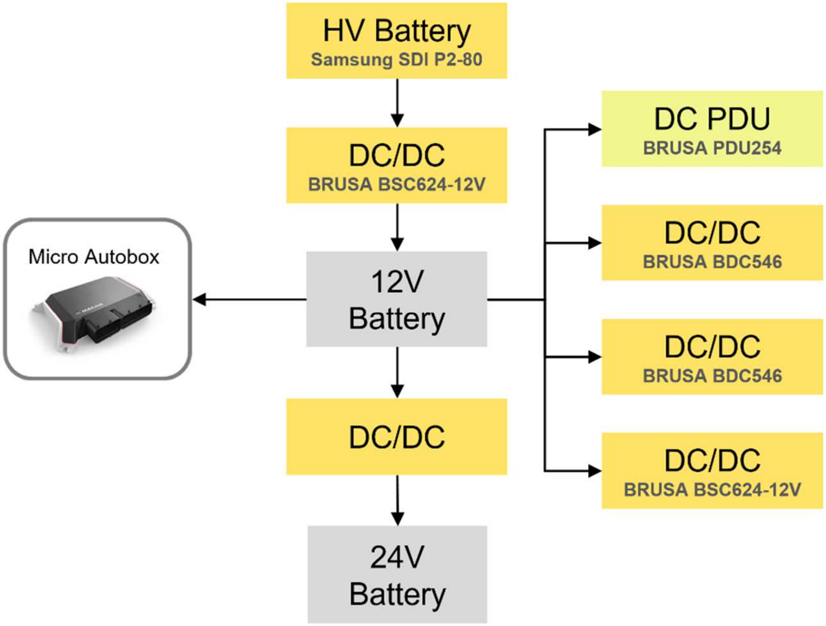

Figure 41: 12V battery in the MH_2PS

The specifications of the 12V battery are not known yet, but it is assumed that a standard automotive lead-acid battery comes to use.

24V Battery

For the 24 V power supply requirement of the fuel cell module, an additional 24V battery is used as illustrated in Figure 42. The current draw of the fuel cell module at 24 V is 20 A. The 24V battery is supplied by the 12V battery via a DC/DC converter.

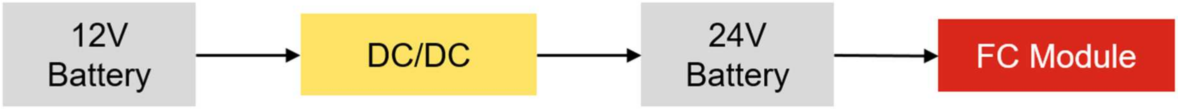

Figure 42: 24V battery in the MH_2PS

The specifications of the 24V battery are not known yet, but it is assumed that a standard automotive battery system comes to use.

2.6 HV Power Electronics

The MH_2PS uses HV power electronics to distribute and convert electrical energy. This subchapter gives an overview of the power electronic components used in the system.

2.6.1 DC/DC Converter

High power DC/DC converters are used in the MH_2PS to control the power flow between fuel cell, batteries and consumer (e.g. electric vehicle) and are therefore important for the design of the system.

By using power electronic components, DC/DC converters change the level of the DC voltage. Different concepts for controlling voltage and current and many different circuit concepts are in use. Potential separation may be required for safety or technical reasons. Depending on whether the input voltage is to be converted to a lower or higher voltage level, it is referred to as buck converter or boost converter. [33]

The main application for instance in the hybrid vehicle is the connection between the conventional 12 V on-board electrical system and the HV traction system. For plug-in hybrid vehicles, it may also be necessary to adjust the external voltage level to the battery voltage for charging. In both applications, potentially separated converter concepts are used almost without exception, i.e. special transformers are used instead of storage chokes. [33]

In hybrid vehicles, a second task is to raise the voltage of the traction battery to a significantly higher level in order to exploit efficiency advantages for the electric drive. Figure 43 illustrates a circuit concept of a DC/DC converter used in hybrid vehicles. C1 and C2 are capacitors, L is inductivity, V1 and V2 MOSFET, U_L low voltage and U_H is the high voltage. Voltages of up to 650 V can be generated. This voltage also represents an upper limit for the typical windings in the electric drives used. [33]

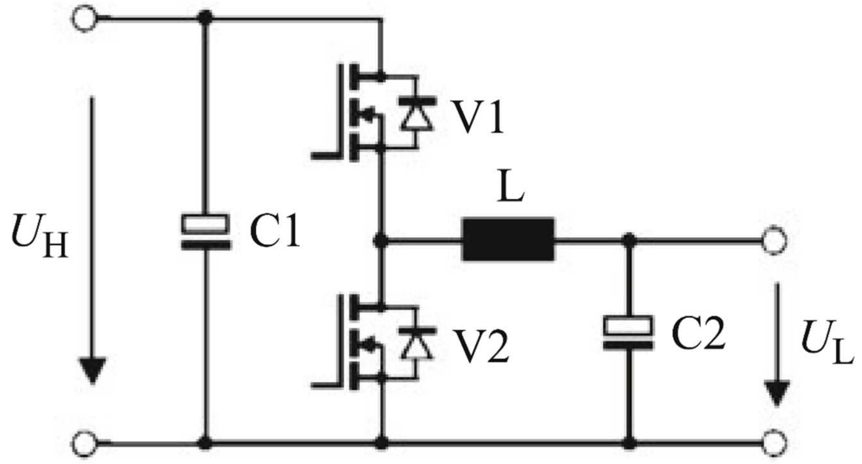

Figure 43: Circuit concept of a DC/DC converter (buck-boost converter) [33]

2.6.2 DC/DC Converters in the MH_2PS

Three different kinds of DC/DC converters are used in the MH_2PS. Their task in the system and product specifications are described here.

DC/DC converter Brusa BSC624-12V

The 12 V battery is supplied by the HV Battery. High voltage direct current delivered by the HV battery is transformed by the DC/DC converter Brusa BSC624-12V into low voltage direct current as illustrated in Figure 44. It is a bi-directional DC-DC converter, which means that it can transfer power in both directions. It also serves as a galvanic isolation between the high voltage and low voltage circuit.

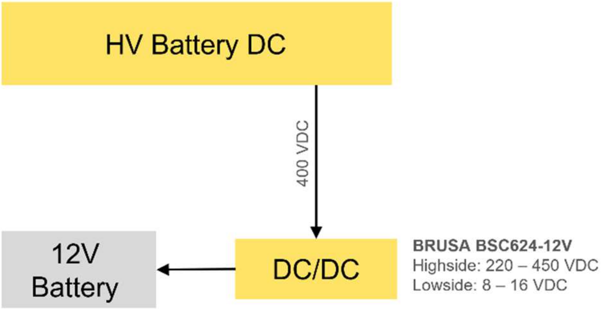

Figure 44: DC/DC converter Brusa BSC624-12V in the MH_2PS

Its high voltage range is 220 to 450 V, the low voltage range is 8 to 16 V. The DC/DC converter is illustrated in Figure 45.

Figure 45: Brusa BSC624-12V [34]

In Table 11, the product specifications of the Brusa BSC624-12V are listed. [34]

Table 11: Product specifications of the DC/DC converter Brusa BSC624-12V [34]

High voltage side	High voltage range	220 - 450 V
Low voltage side	Nominal low voltage	14 V
	Low voltage range	8 - 16 V
Performance	Continuous low voltage current (@ $T_{coolant}$ = 65°C)	200 A
	Max. low voltage current	250 A
	Continuous power (@ nominal low voltage)	2.8 kW
	Max. power (@ nominal low voltage)	3.5 kW
	Efficiency typical (@ nominal voltage)	94.4%
	Switching frequency buck / boost stage	40 - 150 kHz
	Switching frequency transformer stage	197 kHz
Mechanical data	Weight	4.8 kg
	IP - protection	IP65
	Ambient temperature range (operation)	- 40 to + 85°C

Detailed information on the DC/DC converter Brusa BSC624-12V is given in the appendix to this thesis. It provides the product data sheet.

DC/DC Converter Brusa BDC546

The bi-directional DC/DC converter Brusa BDC546 (illustrated in Figure 46) is used twice in the MH_2PS.

Figure 46: Brusa BDC546 [35]

The preliminary location of the DC/DC converters in the MH_2PS is illustrated in Figure 47. The task of the left DC/DC converter depends on the selected operating mode. When an electric car is charged simultaneously by fuel cell and HV battery, the DC/DC converter brings the voltage level of the HV battery to the output voltage of the fuel cell. If the HV battery is charged by the fuel cell, the DC/DC converter converts the output voltage of the fuel cell to a higher voltage level required by the battery.

A high voltage level is required to charge the electric-vehicle battery. The right DC/DC converter converts the output voltage of the fuel cell and/or HV battery to the required input voltage of the electric vehicle.

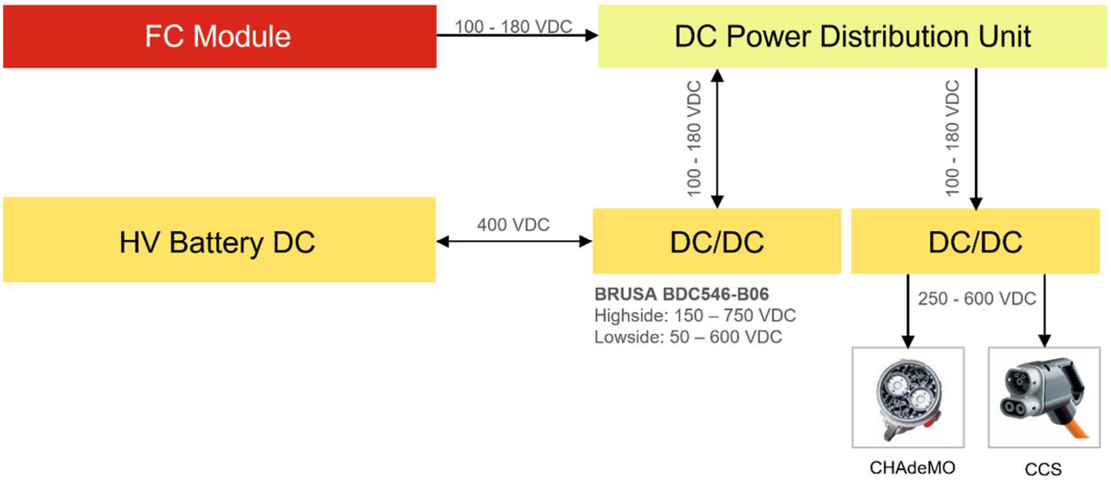

Figure 47: DC/DC converter Brusa BDC456 in the MH$_2$PS

Table 12 lists the product specifications of the DC/DC converter Brusa BDC546.

Table 12: Product specifications of the DC/DC converter Brusa BDC546 [35]

High voltage side	Voltage range	150 - 750 V
	Overvoltage (shut down of power stage)	800 V
	Max. voltage (no operation)	900 V
Low voltage side	Min. voltage (start up)	0 V
	Voltage range (full performance)	50 - 600 V
	Overvoltage (shut down of power stage)	650 V
	Max. voltage (no operation)	900 V
Performance	Continuous lowside current (@ Tcoolant = 60°C)	300 A
	Max. lowside current	400 A
	Continuous output power (@ ULS = 600 V)	180 kW
	Efficiency typical	98.9%
	Switching frequency	41 kHz
Mechanical data	Weight	25.2 kg
	IP - protection	IP6K6, IP6K7
	Ambient temperature range (operation)	-40 to +85°C

Detailed information on the DC/DC converter is given in the appendix of this master thesis. It provides the product data sheet of the Brusa BDC546.

DC/DC Converter (12V Battery to 24V Battery)

The 24V battery is supplied by the 12V battery. A DC/DC converter is used to increase the voltage level. The operating scheme is illustrated in Figure 48.

Figure 48: DC/DC converter in the MH_2PS

The specifications of this DC/DC converter are not known yet.

2.6.3 High Voltage Distribution in the MH_2PS

The high voltage distribution unit Brusa PDU254 (illustrated in Figure 49) assures power distribution between the high voltage components within the MH_2PS.

Figure 49: Brusa PDU254 [36]

Its preliminary location in the MH_2PS is illustrated in Figure 50 as DC Power Distribution Unit.

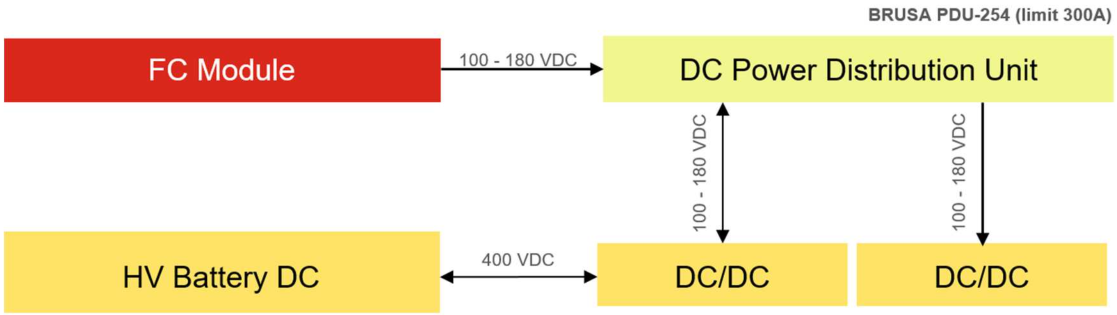

Figure 50: Brusa PDU254 in the MH_2PS

Table 13 lists product specifications of the power distribution unit Brusa PDU254.

In the appendix, detailed information on the PDU is given. It provides the product data sheet of the Brusa PDU254.

Table 13: Product specifications of the Brusa PDU254 [36]

Electrical data	Operating voltage	200 - 500 V
	Allowed voltage drop over interlock loop max.	30 V
Performance data at + 25°C	Allowed peak current for max. duration 10 s	400 A
	Continuous current: BATT - connection 1 + 2 to DMC - connection 1 + 2	300 A
	Continuous current: BATT - connection 1 + 2 to RXT - connection	100 A
	Continuous current: BATT - connection 1 + 2 to NLG - / BSC - / AUX - connection	20 A
Mechanical data	System weight (incl. fuses)	3.9 kg
	IP - protection	IP68
Thermal	Ambient temperature min.	- 40 °C
	Ambient temperature max.	+ 85°C

2.7 Preliminary Operating Strategy of the MH$_2$PS

Since the operating strategy serves as input for a subsequent FMEA, this subchapter describes the four preliminary defined operating modes of the MH$_2$PS. In the course of the preparatory work for a FMEA, functional sequences of the operating modes will be discussed in more detail in chapter 5.

The purpose of the MH$_2$PS is to charge the battery of an electric vehicle to the point where it is able to reach the next charging station. The electrical energy output of the MH$_2$PS should be performed in "shots" with a respective electrical energy quantity of 5 kWh. Electrical energy can be delivered to the EV via fuel cell, battery or both. In the present concept, the supply battery (SB - HV battery) can only be charged by the fuel cell.

Four preliminary operating modes and their preconditions have been defined. They are listed in Table 14.

Table 14: Preliminary operating modes of the MH$_2$PS

Operating Mode	Precondition
Charge EV (Shot)	EV linked, successful Handshake FCM function = ok
Charge EV (Shot-boost)	EV linked, successful Handshake FCM function = ok
Charge SB	Low SOC (SB) No EV linked
Discharge SB	EV linked

Charge EV (Shot)

In “Charge EV (Shot)” mode, the electric vehicle is charged by the fuel cell only. As preconditions for selecting this operating mode, the EV has to be linked and a successful handshake (communication between MH_2PS and EV) with the vehicle must have taken place.

The SOC of the HV battery (Supply Battery) should be kept at a constant level. If the SOC of the supply battery is below its threshold value, the battery is charged simultaneously if enough power can be drawn from the fuel cell.

Figure 51 illustrates an example of a load point when an electric vehicle is charged by the fuel cell module. The SOC of the supply battery is below its threshold value. The electrical power, which can be drawn from the fuel cell module (22 kW) is higher than the power required by the electric vehicle (20 kW). The remaining 2 kW are used to charge the HV battery.

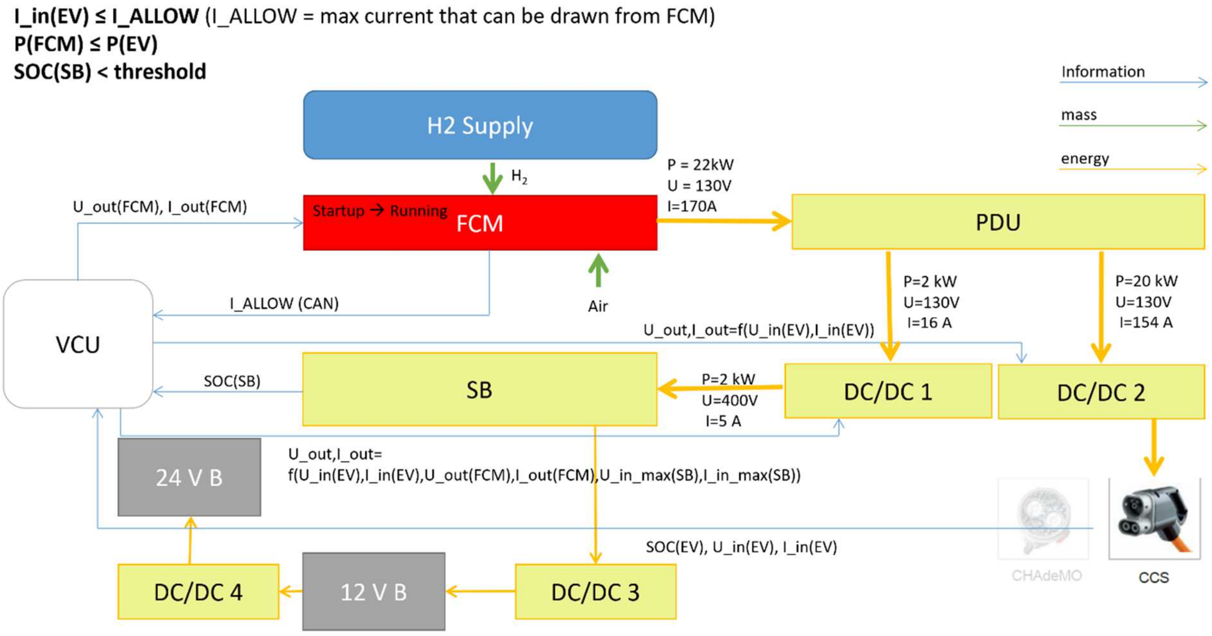

Figure 51: Example of a load point in “Charge EV (Shot)” mode

Table 15 explains the electrical energy flow of the load point example illustrated in Figure 51.

Table 15: Example of electrical energy flow in a load point of “Charge EV (Shot)” mode

Component	Electrical Energy Input	Process	Electrical Energy Output
FCM	-	Energy conversion	P=22kW [U=130V/I=170A] to PDU
PDU	P=22kW [U=130V/I=170A] from FCM	Electrical energy distribution to DC/DC 1 and DC/DC 2	P=2kW [U=130V/I=16A] to DC/DC 1 P=20kW [U=130V/I=154A] to DC/DC 2
DC/DC 1	P=2kW [U=130V/I=16A] from PDU	Voltage level conversion [U=130V to U=400V]	P=2kW [U=400V/I=5A] to SB
DC/DC 2	P=20kW [U=130V/I=154A] from PDU	Voltage level conversion [U=130V to U_in(EV)]	P=20kW [U_in(EV)/I_in(EV)] to CCS/EV
SB	P=2kW [U=400V/I=5A] from DC/DC 1	Electrical energy storage	-

Charge EV (Shot-boost)

If an electric vehicle needs to be charged faster, additional power can be drawn from the supply battery. In “Charge EV (Shot-boost)” mode, the EV is charged by fuel cell and supply battery if the SOC of the battery is above its threshold value. As preconditions for selecting this operating mode, the EV has to be linked and a successful handshake with the vehicle must have taken place.

Figure 52 illustrates an example of a load point if the electric vehicle is charged by the fuel cell and the supply battery simultaneously. The power required by the EV is higher than the power that can be drawn from the fuel cell and the SOC of the supply battery is above its threshold value. Therefore, the battery can supply additional power to the electric vehicle.

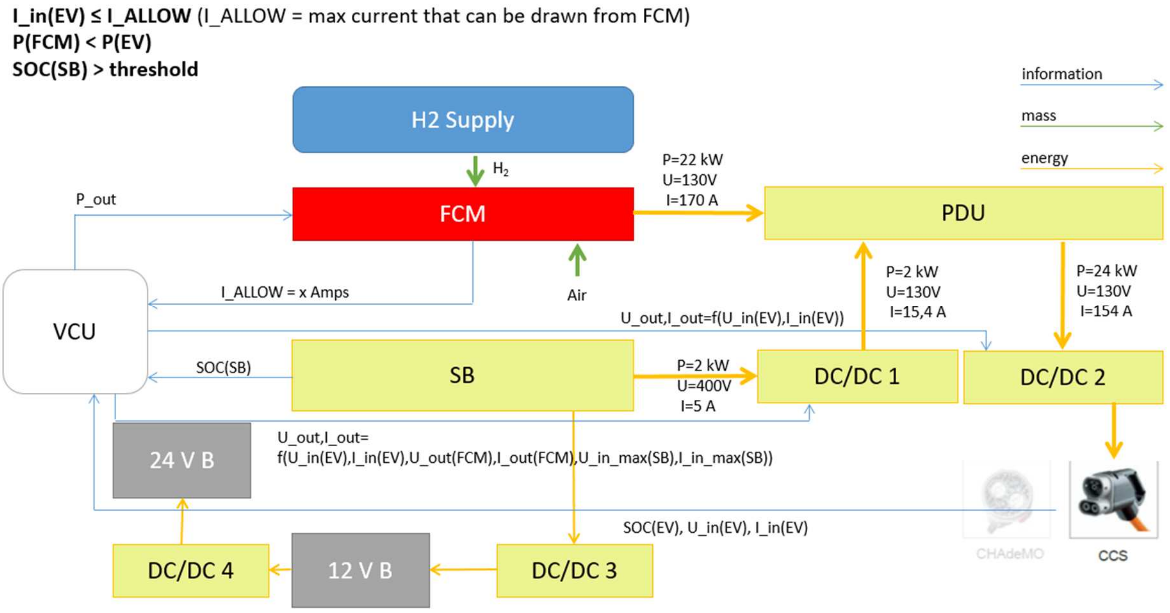

Figure 52: Example of a load point in “Charge EV (Shot-boost)” mode

Table 16 explains the electrical energy flow of the load point example illustrated in Figure 52.

Table 16: Example of electrical energy flow in a load point of “Charge EV (Shot-boost)” mode

Component	Electrical Energy Input	Process	Electrical Energy Output
FCM	-	Energy conversion	P=22kW [U=130V/I=170A] to PDU
PDU	P=22kW [U=130V/I=170A] from FCM P=2kW [U=130V/I=15.4A] from DC/DC 1	Electrical energy distribution to DC/DC 2	P=24kW [U=130V/I=154A] to DC/DC 2
DC/DC 1	P=2kW [U=400V/I=5A] from SB	Voltage level conversion [U=400V to U=130V]	P=2kW [U=130V/I=15.4A] to PDU
DC/DC 2	P=24kW [U=130V/I=154A] from PDU	Voltage level conversion [U=130V to U_in(EV)]	P=24kW [U_in(EV)/I_in(EV)] to CCS/EV
SB	-	Electrical energy output	P=2kW [U=400V/I=5A] to DC/DC 1

Charge SB

If for any reason the SOC of the battery is too low, it can be charged by the fuel cell. The precondition for this operation mode is that no EV is linked to the MH_2PS.

Figure 53 illustrates an example of a load point if the supply battery is charged by the fuel cell. No EV is linked to the MH_2PS and the SOC of the supply battery is below its threshold value.

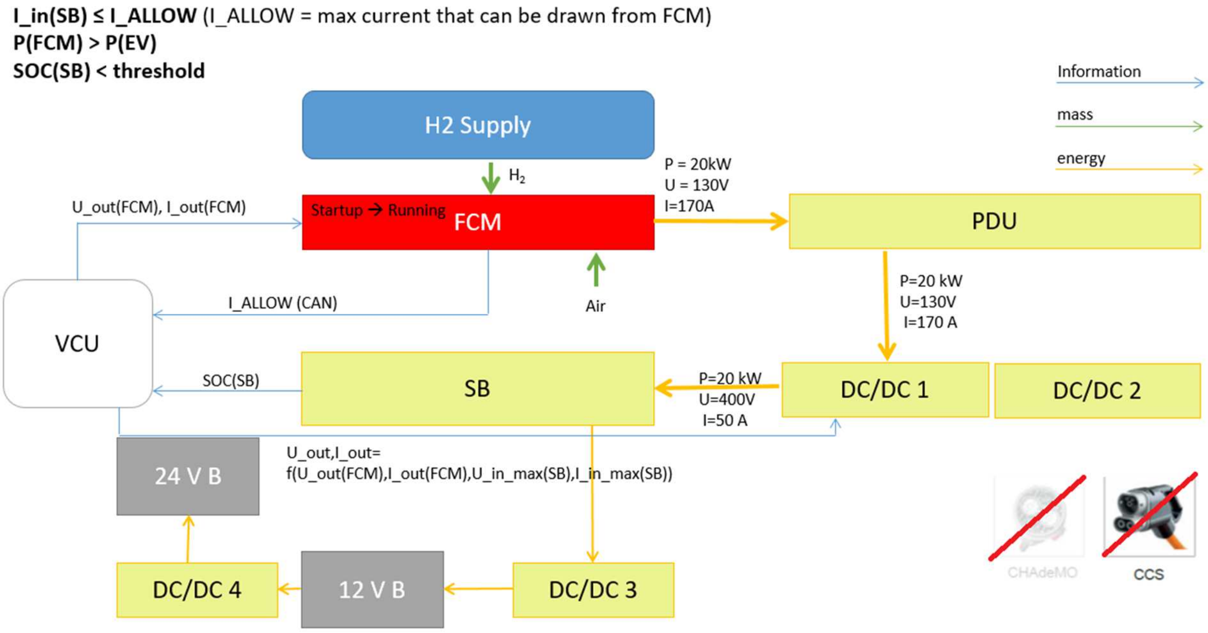

Figure 53: Example of a load point in “Charge SB” mode

Table 17 explains the electrical energy flow of the load point example illustrated in Figure 53.

Table 17: Example of electrical energy flow in a load point of “Charge SB mode”

Component	Electrical Energy Input	Process	Electrical Energy Output
FCM	-	Energy conversion	P=20kW [U=130V/I=170A] to PDU
PDU	P=20kW [U=130V/I=170A] from FCM	Electrical energy distribution to DC/DC 1	P=20kW [U=130V/I=170A] to DC/DC 1
DC/DC 1	P=2kW [U=130V/I=170A] from PDU	Voltage level conversion [U=130V to U=400V]	P=20kW [U=400V/I=50A] to SB
DC/DC 2	-	-	-
SB	P=20kW [U=400V/I=50A] from DC/DC 1	Electrical energy storage	-

Discharge SB

If no power can be drawn from the fuel cell (e.g. hydrogen storage system is empty), the electric vehicle can also be charged by supply battery alone.

In case of service reasons it can be necessary to discharge the supply battery. If an electric vehicle is connected to the MH_2PS, the supply battery can be discharged.

3 Definition of a Safety Concept for the MH_2PS

Design and construction of technical products do not take place in an unregulated form. European and national law oblige manufacturers to produce safe products (system/part). The manufacturer has to determine and evaluate potential hazards of a product and the risks associated with these hazards. A product has to be designed considering the results of a risk analysis and risk assessment. Products have to be built without harming the user, third parties or the environment. This requires the engineer to implement a safety concept early on in the design phase. As a result, the product has to be a functioning complete system. The user of the product shall be able to execute the intended function in a safe way. [37]

The following chapter should give an overview why it is important to implement a safety concept, define safety and the terms related to it.

3.1 Definition of Safety and the Terms related to it

Safety is a diverse term. Before implementing a safety concept for any system, the fundamental terminology has to be defined:

Safety

In [37] safety is defined as the protection of humans when dealing with technical systems. ISO 26262 defines safety as absence of unreasonable risk. [38] In [39] safety is described as a situation, where the risk is smaller than the biggest still justifiable risk of a certain technical procedure or state as seen in Figure 54. It is to be noted that a justifiable or unreasonable risk is not quantifiable in most of the cases. Therefore, safety can only be seen as sufficient with the help of standardized parameters. An enhancement of safety can be achieved by reducing the risk. This can be done either by reducing the probability of occurrence of a damage causing incident or by reducing the extent of damage. [39]

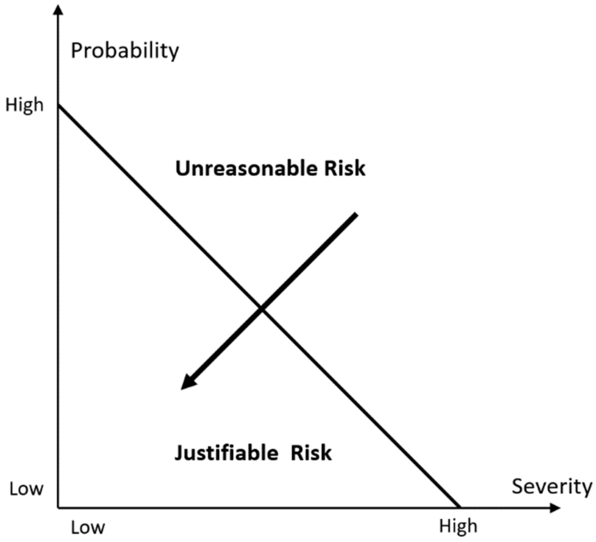

Figure 54: Transition of unreasonable and justifiable risk

In this context, the term “safety” has to be distinguished from the term “security”. Security means the protection against malicious attacks from third parties. The difference of safety and security is illustrated in Figure 55.

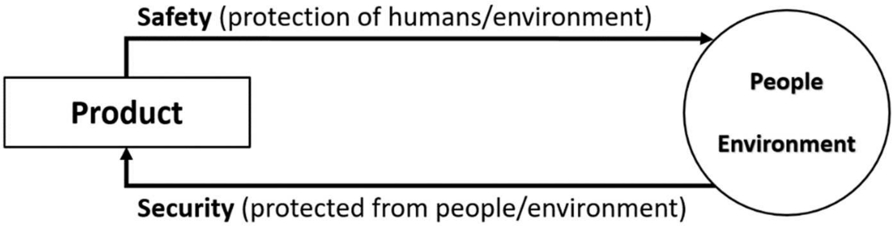

Figure 55: Definition of safety and security

Risk

Risk can be described as a situation in the future, which is uncertain. It can be defined as an event with a possible negative consequence. [39] ISO 26262, which will be explained further in chapter 4.1, describes risk as combination of the probability of occurrence of harm and the severity of that harm. [38]

Hazard

According to ISO 26262, hazard is the potential source of harm. It is caused by a malfunctioning behaviour of a technical system. [38]

Harm

The term harm is defined in the ISO 26262 as physical injury or damage to the health of persons. [38]

3.2 Legal Background

The legislator must ensure with the help of generally binding laws that the demand of safety is adequately taken into account for every user of a technical product. Laws have to ensure legal certainty as it is an essential prerequisite for the development and application of new innovative technologies. The legislator mostly abstains from defining detailed safety requirements. Instead binding objectives of protection are laid down. These objectives of protection have to be achieved or exceeded. Due to continuously shifting systems of value, the legal system introduced a general clause, which contains legal concepts that are not precisely defined, to meet the protection clauses. These general clauses refer to the state of the art or generally recognised codes of practice.

The state of the art is a point of reference in the sense of an objective standard for safety that a manufacturer of a product has to ensure. It is a point of reference if the question arises if a manufacturer has acted with the required diligence. [40]

Two levels are distinguished:

- Generally recognised codes of practice

  Generally recognised codes of practice are generally available technical expertises of applications, which have been tested in trials and proven their worth in actual service. They can normally be found in technical standards or industry standards, e.g. ISO, DIN, VDA or VDE. [40]

- (Latest) state of the art in science and technology

  It refers to the latest discoveries and developments in a specific area, which have been published. They are often not proven in actual service as they are completely new. It requires a systematic analysis of the published findings and is mostly used for completely new technologies with unknown risks. [40]

The extent of necessary safety measurements is therefore determined by the relevant regulation or technical standard. The required safety precautions to achieve a regulation or technical standard have to be determined. Standards contain detailed information. They are worked out by experts and adapted to the technical progress. Although they are not legally binding, they are taken into consideration to solve technical safety issues for instance to prove that a product is state of the art. In Figure 56 the systematic of the product safety law is summarised. [37]

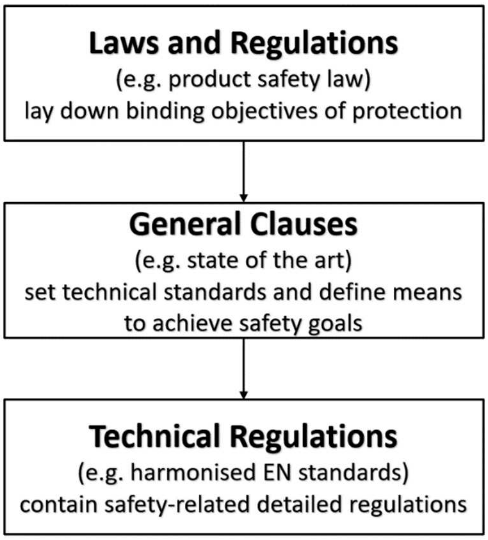

Figure 56: Systematic of the product safety law acc. to [37]

In general, the state of the art in science and technology is the upper limit of possibilities to fulfil safety requirements whereas generally recognised regulations of technology are the lower limit. From an engineering point of view, it is an advantage that there are no detailed regulations in the legislation. Products can be adapted to the technical progress flexibly. A disadvantage is that there is a degree of uncertainty. Regulatory authorities for instance may not immediately see what is required for a safe product. Therefore, safety measures have to be evaluated regarding appropriateness, reliability and effectiveness. [37]

To ensure that a product is safe includes conducting an appropriate risk prevention for instance by suitable tools like FMEA or FTA. Especially the FMEA provides a valuable support in this matter. Based on the intended functions and the expected usage of the product, all relevant risks can be analysed and state of the art possibilities for hazard prevention can be determined with the help of this tool. Necessary measures to counter relevant risks and persons responsible for the execution are defined and documented. [40]

ISO 26262 redefines and increases the standards and parameters of functional safety of mechatronic systems and the documentation of the overall safety life cycle. Design specifications and requirements are exacerbated dependent on the hazard potential defined by the Automotive Safety Integrity Levels (ASILs). In series production of cars, the ISO 26262 has to be applied to provide evidence of compliance with the state of the art. [40]

3.3 Safety Concept for a given Prototype

Implementing a safety concept for a prototype is different from implementing it for a series product. In contrast to series development projects with clear stated requirements at the concept phase, in prototype and pre-development projects, requirements are updated during the entire development process. In addition, a prototype has other, slimmed down, requirements. This starts by the fact that the operation of a prototype at Magna Steyr is restricted to trained personal only, familiar with the risks of the prototype, and conducted under restrictive conditions, often in an isolated test environment. However, if the prototype is operated on public roads it has to be safe in order not to harm the operator or third parties. Additionally, requirements and specifications of the vehicle registration office have to be complied with. To meet the requirements, the prototype has to be compliant with given legal standards, if these exist yet for the respective application. This includes proof that the overall system, subsystems and components meet the required regulations and technical standards, the execution of a state of the art risk prevention and proof that qualified personnel developed the prototype. As a summary, Figure 57 includes the mentioned influence factors, which need to be considered during the development of a safety concept for the presented prototype.

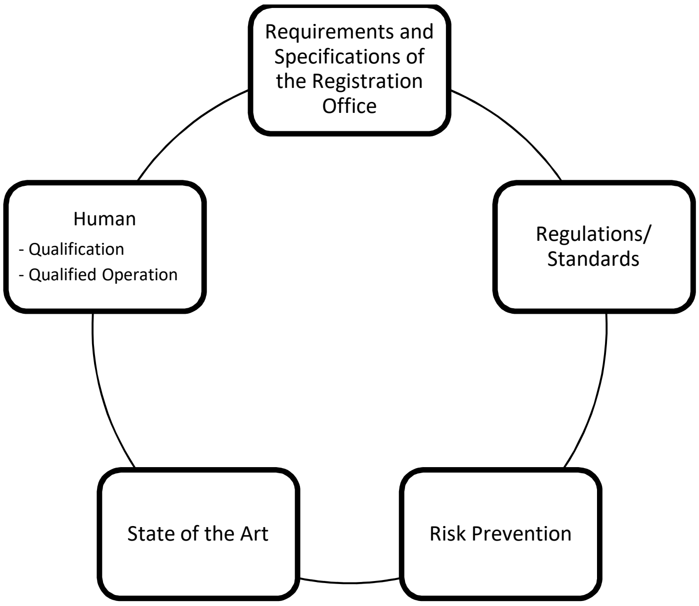

Figure 57: Process and requirements of prototype homologation

This thesis focuses on risk prevention of the overall system of the MH_2PS project. This includes an appropriate hazard analysis, e.g. based on a FMEA, to derive risk reduction requirements.

The development process of series production cars demands applying, among others, ISO 26262 to provide compliance with the state of the art. This standard is applied to the MH_2PS as an additional safety measure, although it is not required for a car trailer, in order to do useful preparatory work in case the project leaves the predevelopment phase and enters the serial development phase.

Conducting a hazard analysis and identifying actions to avoid hazards is especially necessary, if there are no regulations or technical standards in existence for the overall system. This is often the case in the predevelopment at Magna Steyr when developing a prototype. For instance when connecting two subsystems (illustrated in Figure 58), both complying with technical regulations and standards, it is important to analyse the risks that may occur at the interface and the overall system.

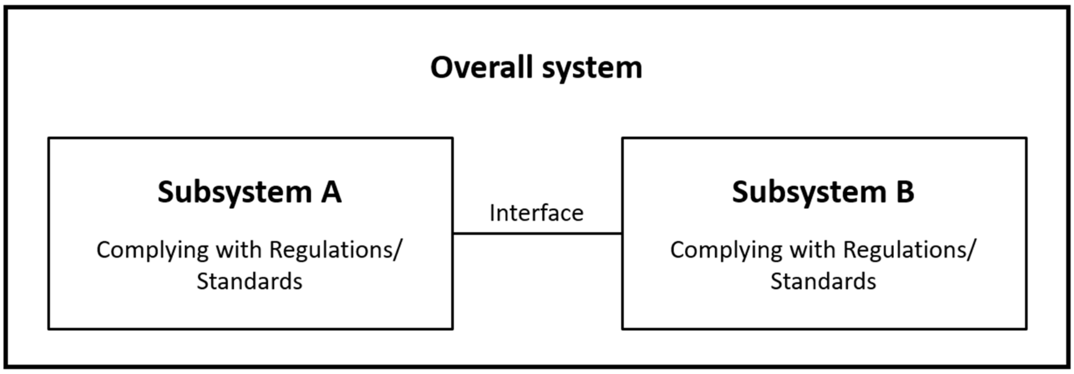

Figure 58: Connecting two subsystems

For the execution of the methodologies, both ISO 26262 and FMEA, need input information. The input data is derived from analysing the system and its functions, the components and the operating strategy of the MH_2PS as illustrated in Figure 59.

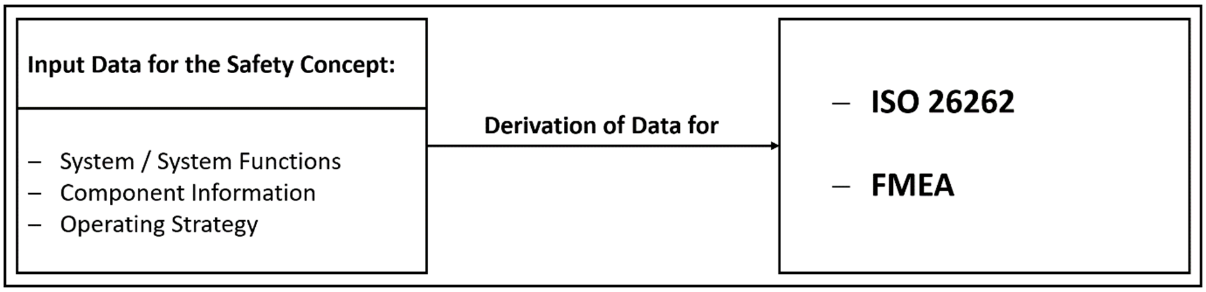

Figure 59: Methodological approach in this master thesis

4 Data Provision for the Functional Development according to ISO 26262

As preparation for a development process according to ISO 26262, the following chapter gives an overview of the standard, especially focusing on the concept phase. As part of the functional development according to this standard, items and functions are defined.

4.1 Application of ISO 26262 Road Vehicles – Functional safety

The growing complexity of the electronic components in vehicles increases the possibility of malfunctions. If a safety relevant component is affected by a malfunction it may cause harm to people. This leads to increasing requirements on manufacturers and their suppliers. The reduction of potential safety risks is crucial, starting from the concept phase to development and decommissioning. To obtain safety it is necessary to develop with the state of the art. It is thus necessary to ensure functional safety of the relevant products and systems. To minimise the risk of harm causing malfunctions of safety relevant electronic systems, they should be developed considering the ISO 26262. Moreover, automotive manufacturers demand to apply this standard to prove a state of the art development and therefore reduce the risks regarding product liability. [38]

4.1.1 ISO 26262 at Magna Steyr

Magna Steyr is active in complete vehicle engineering and complete vehicle manufacturing on a contractual basis. In this way, Magna Steyr is a system integrator as the company does not build systems or components for itself and is therefore dependent on its suppliers. With the help of ISO 26262, functional safety requirements of components or systems are evaluated if demanded by an OEM. ASILs are determined and based on them a list of specifications is prepared. In a next step, suppliers have to be found that can comply with the safety requirements demanded by Magna Steyr.

As ISO 26262 is applied for series production cars, it is usually not taken into consideration for safety concepts of projects in the predevelopment department “Alternative Propulsion and Active Chassis Systems” of Magna Steyr. The idea of this thesis is to perform preliminary work for the functional development of the system according to ISO 26262 in the predevelopment phase of the MH_2PS in order to prove state of the art development and do useful preparatory work in case the project leaves the predevelopment phase and enters the serial development phase (milestone TA) as illustrated in Figure 60.

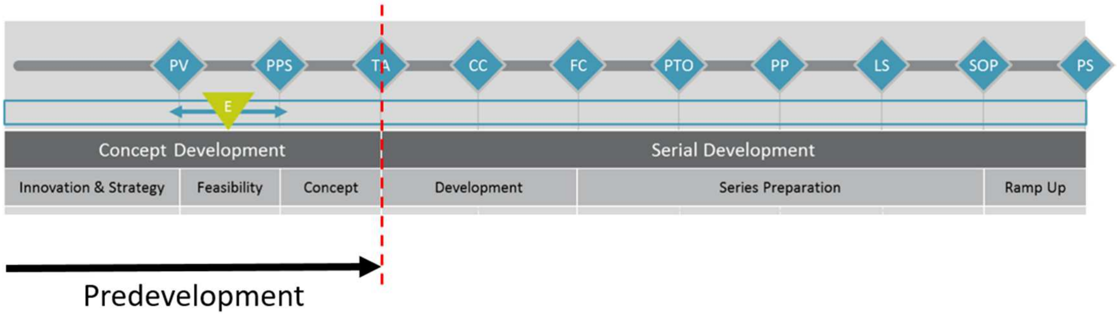

Figure 60: Transition from predevelopment to serial development

4.1.2 Overview and Explanation of ISO 26262

The ISO 26262 – Functional Safety for Road Vehicles is an international standard for functional safety of series production cars with a maximum gross vehicle mass up to 3.5 tonnes. It describes a safety lifecycle and complies to the specific needs of the development and production of series production cars. ISO 26262 defines safety as absence of unreasonable risk. Functional safety is described as a part of the overall system safety that is dependent on the correct functioning of a safety related mechatronic system. The safety life cycle of ISO 26262 refers to management, development, production, operation, service and decommissioning. [38]

An implementation of ISO 26262 should be done as early as possible in the development process. Early changes are much easier to perform than changes in a later stage of development.

ISO 26262 consists of ten parts. Part 3 to 7 refer to the phases of the safety life cycle, the other parts are independent from it. The procedure described in ISO 26262 is based on the V-model of product development. Already at the beginning of the product life cycle, in the concept phase of the respective system, potential hazards that can arise from a function must be determined and the resulting risks have to be quantified. Depending on this risk determination, the safety targets have to be defined and thus the requirements on development methods, quality assurance and monitoring over the entire product life cycle are defined. Figure 61 illustrates the simplified process of ISO 26262. [38, 41]

ISO 26262 consists of the following parts shown in Table 18.

Table 18: Parts of ISO 26262 [38]

Part	Name
Part 1	Vocabulary
Part 2	Management of functional safety
Part 3	Concept phase
Part 4	Product development at the system level
Part 5	Product development at the hardware level
Part 6	Product development at the software level
Part 7	Production and operation
Part 8	Supporting processes
Part 9	Automotive Safety Integrity Level (ASIL)-oriented and safety-oriented analyses
Part 10	Guideline on ISO 26262

As a part of this thesis is to perform a preparation for a functional safety concept of the MH_2PS, the concept phase of ISO 26262 is described in more detail.

4.1.3 ISO 26262 Part 3: Concept Phase

Part 3 of the ISO 26262 deals with possible hazards and the assessment of risks related to functional safety of automotive systems. Functional safety requirements of a system are derived from safety goals, which are defined after a classification of potential hazards in Automotive Safety Integrity Levels (ASIL). [42]

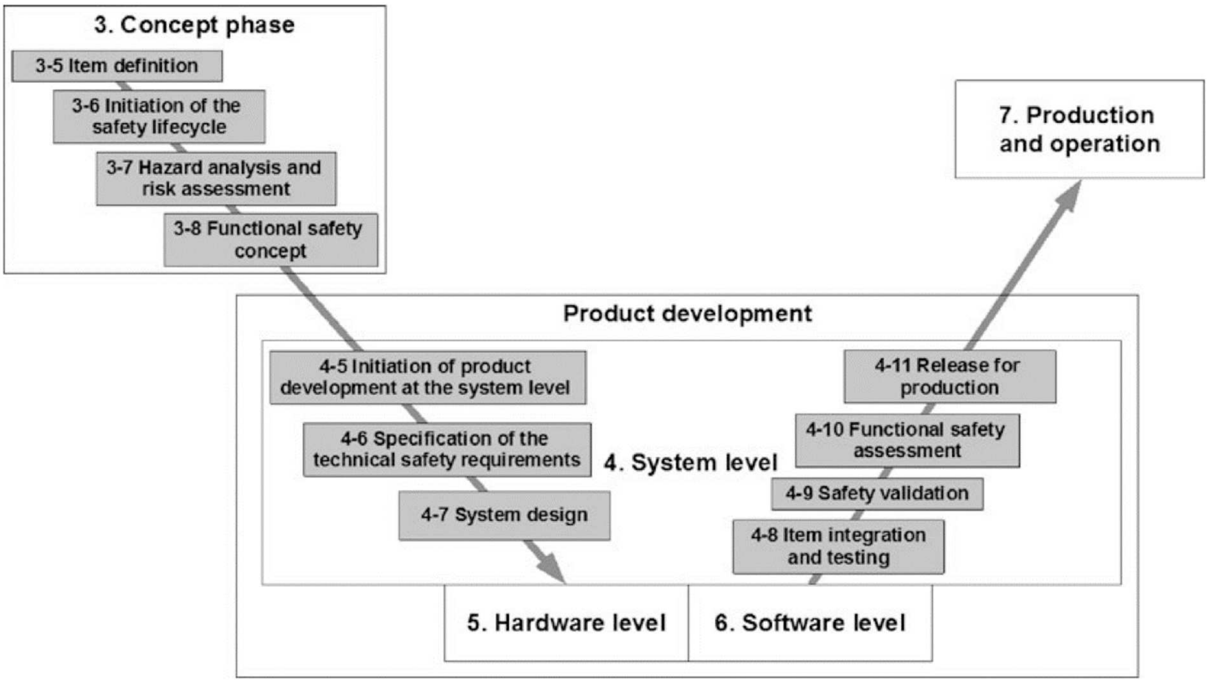

Figure 61: Overview of ISO 26262 acc. to [38, 41]

The concept phase can be subdivided in four different stages:

- Item definition
- Initiation of the safety lifecycle
- Hazard and risk assessment
- Functional safety concept

Item Definition

The first step in the concept phase of the ISO 26262 includes the definition of so-called items. The ISO 26262 defines an item as a system or an array of systems to which the ISO 26262 has to be applied. To define an item, a basic understanding of the considered system is necessary. The purpose and content of the item has to be described and functional requirements and non-functional requirements have to be defined. An item function (= functional requirement) is a function that a customer can experience. For every functional requirement a message sequence chain consisting of input, processing and output has to be provided as illustrated in Figure 62. [38, 42]

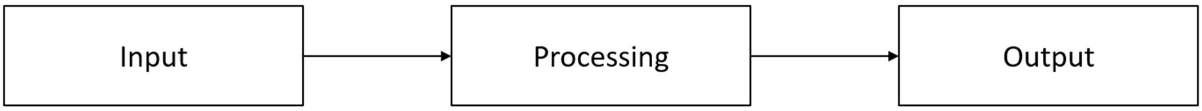

Figure 62: Message sequence chain for functional requirements

Available information like relevant laws, norms and standards applicable for the functional safety project have to be considered. In this context, interfaces and boundaries of the item, interactions with other items or elements and known operating modes, states and situations shall be described. [38, 42]

Initiation of the Safety Lifecycle

After defining the item, the safety lifecycle is initiated. A distinction must be made between a new development and a modification of an existing item. In case of a new development the whole ISO 26262 has to be implemented. If a modification of an item is the case, it has to be evaluated which parts of the safety lifecycle have to be applied and if phases of the safety lifecycle have to be adapted. [42]

Hazard and Risk Assessment

Based on the item definition, the hazard and risk assessment (HARA) is carried out. To perform the hazard and risk assessment according to ISO 26262, the scope of the item, a list of known hazards, the operating conditions and possible operating errors of the item have to be known. Already known safety mechanisms, like sensors are not taken into consideration. Without analysing the cause, possible functional defects are determined. The impacts of the errors are determined on vehicle level and for every known operating condition. Hazards are classified in severity, probability of exposure and controllability. [42]

The severity of the injury shall be assigned to one of the four severity classes, which are described in Table 19. [42]

Table 19: Classes of severity acc. to [42]

Class of severity	Description
S0	No injuries
S1	Light and moderate injuries
S2	Severe and life-threatening injuries (survival probable)
S3	Life-threatening injuries (survival uncertain), fatal injuries

Table 20 shows the classes of probability of exposure of a certain scenario. The probability of exposure regarding operational situations shall be assigned to one of the classes E0 – E4. [42]

Table 20: Classes of probability of exposure acc. to [42]

Class of probability of exposure	Description
E0	Incredible
E1	Very low probability
E2	Low probability
E3	Medium probability
E4	High probability

The classes of controllability are listed and described in Table 21. Controllability means the probability to regain control of a situation in case of a hazard. An assignment to one of the controllability classes C0 – C3 should be done.

Table 21: Classes of controllability acc. to [42]

Class of controllability	Description
C0	Controllable in general
C1	Simply controllable
C2	Normally controllable
C3	Difficult to control or uncontrollable

After the classification of the hazards, the ASILs are determined based on Table 22. The results are the values QM, ASIL A, ASIL B, ASIL C and ASIL D with ASIL D being the highest hazard class. QM stands for quality management, which means no further measures according to the ISO 26262 are necessary. If the result is a value between ASIL A and ASIL D, the next step is to determine a safety goal for those evaluated ASILs. Similar safety goals can be merged into one safety goal. In this case, the highest ASIL is assigned to the combined safety goal. Functional safety requirements for risk avoidance are derived from those safety goals. A verification review is done at the end to check if the HARA was carried out in a correct way. [42]

Table 22: ASIL determination acc. to [42]

Severity class	Probability class	Controllability class		
		C1	**C2**	**C3**
S1	**E1**	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	ASIL A
	E4	QM	ASIL A	ASIL B
S2	**E1**	QM	QM	QM
	E2	QM	QM	ASIL A
	E3	QM	ASIL A	ASIL B
	E4	ASIL A	ASIL B	ASIL C
S3	**E1**	QM	QM	ASIL A
	E2	QM	ASIL A	ASIL B
	E3	ASIL A	ASIL B	ASIL C
	E4	ASIL B	ASIL C	ASIL D

Functional Safety Concept

The functional safety concept specifies safety measures and safety mechanisms to comply with the safety goals. This is done in form of functional safety requirements. The safety requirements are allocated to the item's elements of the system architecture. The functional safety concept addresses fault detection and mitigation, transitioning to a safe state, mechanisms of fault tolerance, warning of the driver and arbitration logic. Every functional safety requirement should be described by operating mode, fault tolerant time interval, safe states, interval for emergency operation and functional redundancies. The last step of the functional safety concept phase is to verify it regarding its consistency and compliance with the safety goals. [42]

4.1.4 Application of ISO 26262 on the MH_2PS

The idea is to prepare input information for the development of a functional safety concept according to ISO 26262 for the MH_2PS. Figure 63 illustrates the schematic system architecture of the MH_2PS. The ISO 26262 approach was conducted with the help of Magna internal Excel spreadsheets. In order to not reveal internal information, only excerpts of the excel documents are written down in this thesis. It should be noted that during the definition of the functional requirements, the final operational strategy was not existent yet. The function “Electrical energy distribution” is based on the assumption that the system itself decides whether the battery or the consumer is supplied with electrical energy. Charging the consumer with the battery alone was not intended at that time.

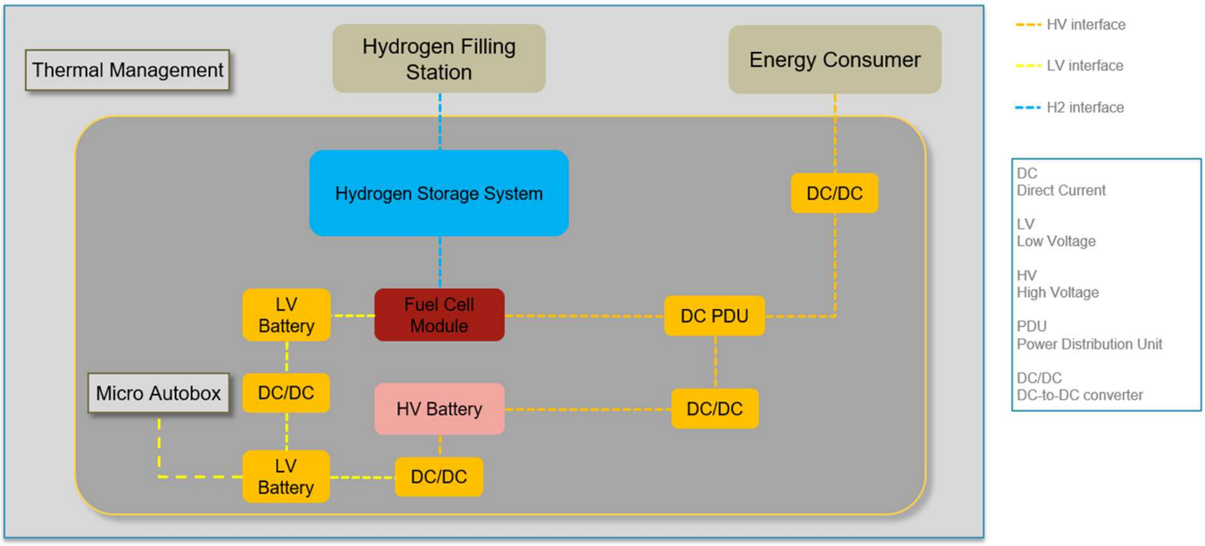

Figure 63: Schematic system architecture of the MH_2PS

At first a description of the item’s scope is given. Then the overall functions of the MH_2PS are determined and narrowed down to the functions covered by the ISO 26262 standard. The project title and the identification of the item are stated in Table 23.

Table 23: Specification of the project title and the item name

Project title	Master Thesis Safety Concept	
Identification of the item	Mobile Hydrogen Power Supply	MH_2PS

4.1.5 Scope of the Item

The item is able to provide electrical energy by converting the chemical energy of hydrogen into electricity with the help of a fuel cell. The proton exchange membrane fuel cell has a rated net power of 30 kW with an operating DC voltage range of 85 to 180 V and a current output of 0 to 300 A. The oxidant used for hydrogen conversion in the fuel cell is atmospheric air. Hydrogen is stored in gaseous state at 70 MPa in the hydrogen storage system. Depending on the control strategy, electrical energy is delivered directly to the HV Battery of an electric vehicle via a standardized connector for high power charging (CHAdeMO or CCS-Typ2) and/or stored in a HV Battery with a usable system energy capacity of 6.1 kWh in order to provide an additional output of electrical energy to the consumer. The HV Battery in the MH$_2$PS can only be charged by the fuel cell. The item is in a quasi-stationary position. Dynamic operation properties are not scope of the item. In an initial consideration on the course of the present master thesis, the following simplification have been defined: Hydrogen filling at the hydrogen filling station is not a scope of the item. Thermal management is not scope of the item. Battery management system is not scope of the item. Vehicle communication is not scope of the item.

4.1.6 Overall Functions of the MH$_2$PS

As stated in chapter 4.1.3 item functions (= functional requirements) have to be described. As a first step the overall functions of the MH$_2$PS were determined:

- Hydrogen storage (in the hydrogen storage system)
- Electrical energy storage (in the high voltage battery)
- Hydrogen conversion (by the fuel cell)
- Electrical energy distribution (by the power distribution unit)

Hydrogen Storage

ISO 26262 is a standard for functional safety of electrical and/or electronic systems. The message sequence chain of a function consists of input, processing and output. Regardless of the input and output the processing part “Storage of hydrogen”, illustrated in Figure 64, is not an electronically controlled sequence. As it is a mechanical procedure it is not covered by the ISO standard.

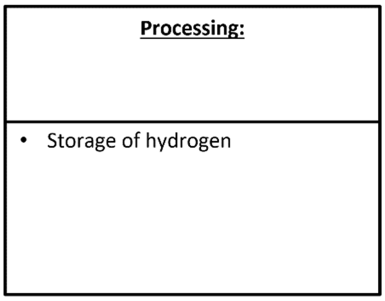

Figure 64: Hydrogen storage processing sequence

Electrical Energy Storage

Like “Hydrogen Storage” the item function “Electrical energy storage” is not covered by the ISO 26262 given the fact that the processing sequence “Storage of electrical energy”, illustrated in Figure 65, is not a mechatronic process but an electrochemical one.

Processing:
• Storage of electrical energy

Figure 65: electrical energy storage processing sequence

As both functions “Hydrogen storage” and “Electrical energy storage” are not covered by the ISO 26262, the two remaining functions covered by the standard are “Hydrogen conversion” and “Electrical energy distribution”.

4.1.7 Functional Requirements of the Item MH_2PS

The functional requirements of the item MH_2PS are listed in Table 24.

Table 24: Functional requirements of the item MH_2PS

Functional requirements/ List of item functions
Hydrogen conversion
Electrical energy distribution

Figure 66 illustrates the schematic system architecture of the item. The item function “Hydrogen conversion” is carried out by the fuel cell module, the item function “Electrical energy distribution” is carried out by the power distribution unit in combination with the DC/DC converters. The wide red line in the illustration below represents the boundaries of the item. The components inside the red line are considered by the item.

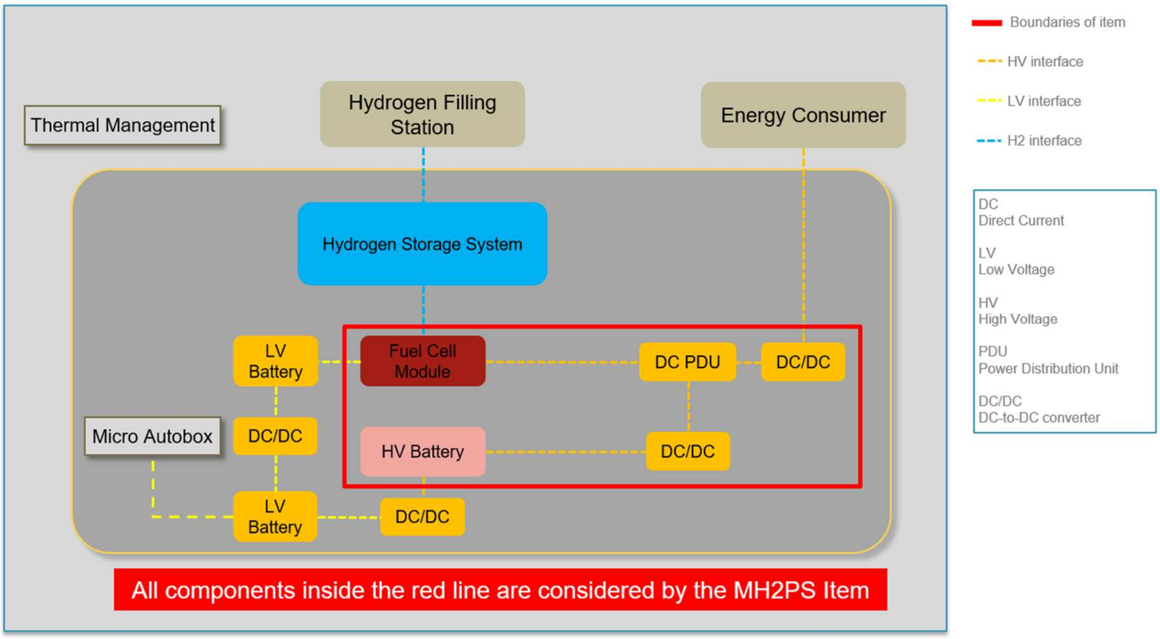

Figure 66: Schematic system architecture of the item MH_2PS

Functional Requirement: Hydrogen conversion

In Table 25 the function “Hydrogen conversion” is described.

Table 25: Description of the functional requirement hydrogen conversion

Functional requirement: Hydrogen conversion
Requested hydrogen coming from the hydrogen storage system is converted by the fuel cell to provide electrical energy. To start the process of energy conversion, following boundary conditions have to be fulfilled: Fuel Cell State: ON / power output Hydrogen Pressure: OK

The message sequence chain of the function “Hydrogen conversion” consists of input, processing and output as illustrated in Figure 67. The input factors are right state conditions of the fuel cell module, and the right conditions on the anode and cathode side. The processing sequence is the conversion of hydrogen. The output is the electrical energy requested by the power distribution unit.

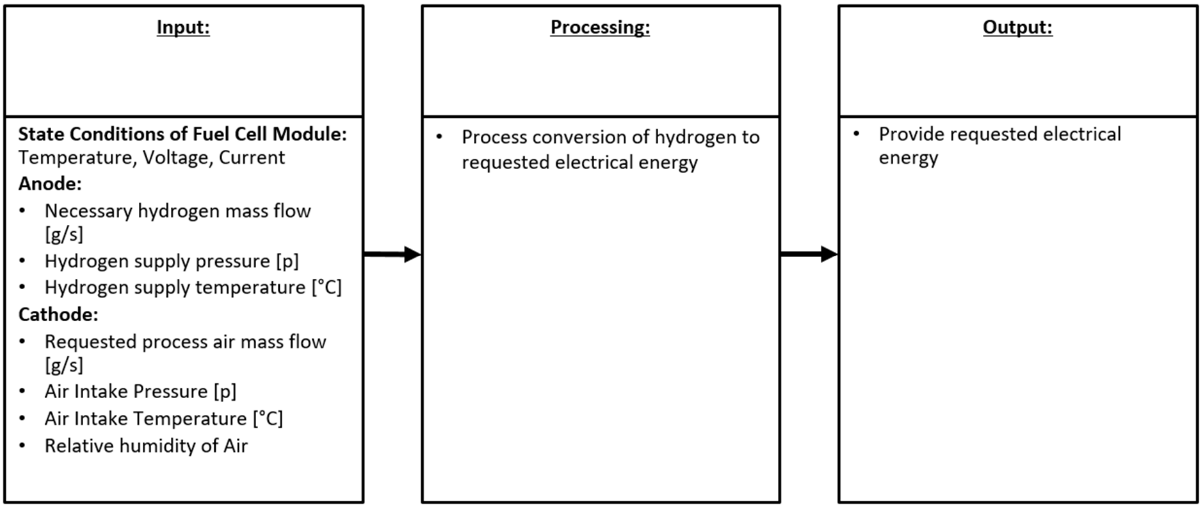

Figure 67: Hydrogen conversion function

Functional Requirement: Electrical Energy Distribution

Table 26 describes the function “Electrical energy distribution”.

Table 26: Description of the functional requirement Electrical energy conversion

Functional requirement: Electrical energy distribution
The possibility to distribute electrical energy is processed. Energy should be provided either to battery or consumer from different energy sources based on the processing of the relevant signals. Battery alone does not provide energy [at that time of development].

The message sequence chain of the function “Electrical energy distribution” is illustrated in Figure 68.

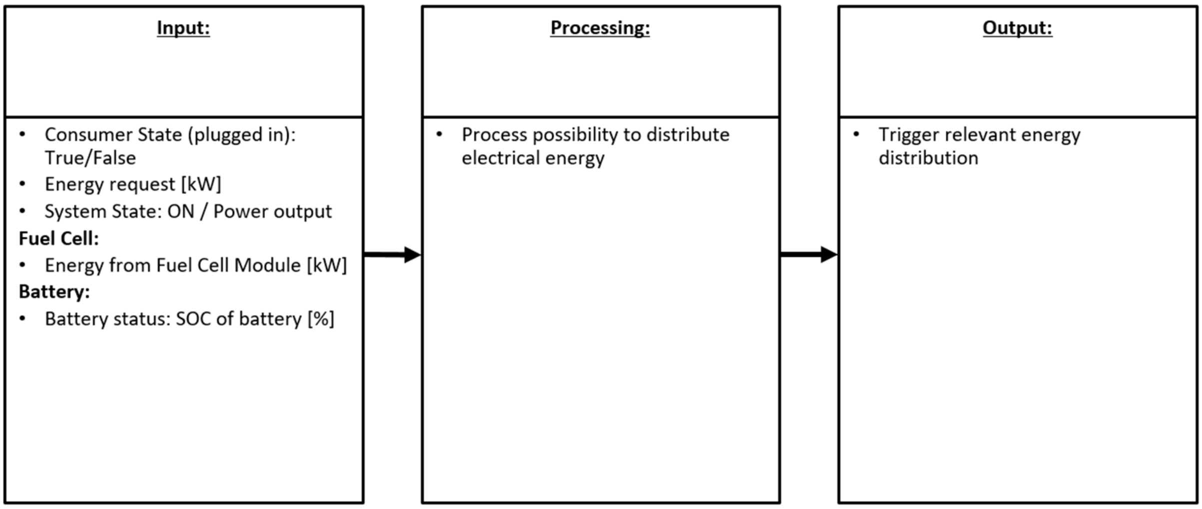

Figure 68: Electrical energy distribution function

In a next step of the development process according to ISO 26262, malfunctions have to be determined based on the defined functional requirements of the MH_2PS. Malfunctions serve as input for an upcoming HARA which is not part of this master thesis.

Operating Modes, States and Situations

In the course of the item definition, the intended operating modes, possible state and situations should be described if already known.

Operating modes in cars exemplary describe overall vehicle modes like “Sport mode” or “Eco mode”. In the MH_2PS finalised operating modes are not defined yet. They are dependent on the operational strategy which is yet to come.

States describe a possible state of the item itself like system on or system off. Table 27 lists possible states of the item MH_2PS.

Table 27: Possible item states

Item states
System start up
System standby
System off

Situations serve as relevant input for the HARA. Some possible situations of the item MH_2PS are listed in Table 28.

Table 28: Possible item situations

Item situations
Refuelling of hydrogen
Energy conversion in fuel cell
Electrical energy provision to supply battery
Electrical energy provision to consumer
Electrical energy provision to consumer and supply battery

5 Data Provision for the FMEA Process

In order to guarantee safety of the MH_2PS, possible hazards posed by the system have to be found. A typical procedure to evaluate possible errors in complex technical systems, the Failure Mode and Effects Analysis (FMEA) is applied. In addition to the FMEA process, various methodologies are available for this purpose. In this chapter, data for a FMEA is derived which might be performed in a subsequent step of the MH_2PS development project. The data collection is based on information given by the system, its components and the operating strategy. In addition to a short description of other methods, the FMEA process is described in more detail.

5.1 Methodologies for Identifying and Assessing Risks and Hazards

To ensure that a product is safe (definition of safety in chapter 3.1), an appropriate risk prevention has to be made. The engineers must prove that they fulfilled their obligations by assessing all hazards, hazardous situations and the risks associated with them. Only in this way they can release themselves from the accusation of negligence. There is no general applicability or compulsory procedure to assess risk objectively, instead there are a couple of methods for risk analysis. [37]

To identify hazards, their effects and causal factors, a hazard analysis can be performed. With the help of a hazard analysis, system risks and the significance of hazards can be determined. Based on these findings, safety design measures can be defined in order to eliminate or at least mitigate hazards. Systems, subsystems, components or facilities can be systematically examined by executing them. [43]

Inductive and Deductive Techniques

Hazard analyses can be divided into inductive and deductive methodologies. Inductive reasoning helps finding out, which system states can occur. Deductive reasoning means finding out how a particular system state, especially a failure state can occur. In Table 29, the characteristics of inductive and deductive analysis techniques are described. [43]

Table 29: Characteristics of inductive and deductive analysis techniques [43]

	Inductive	Deductive
Methodology	Bottom-up What if	Top-down How can
General characteristics	System subdivided into components Potential failures on component level Effects of potential failures	Identification of hazard comes first Definition of the cause of each hazard
Applicability	Smaller Systems Single point failure	All system sizes Complex systems Identification of hazards caused by multiple failures

Problems	Application to complex systems is difficult A lot of components have to be taken into account Difficult to consider failure combinations	Time consuming High data volumes Requires detailed system documentation
Examples	FMEA HAZOP	FTA ETA

Qualitative and Quantitative Techniques

Hazard analyses can also be divided into qualitative and quantitative techniques. Qualitative tools comprehensively describe all aspects, which are of significance for the safety of a system. All components which are safety relevant during a stochastic failure are detected. Qualitative tools also provide information about unwanted hazardous states especially about events, which refer to improper operation. Quantitative tools predict (numerically) the probability of occurrence of unwanted hazardous events or states. They analyse the extent of damage and quantify the risks related to them for humans and environment. The values allow a comparison of components and machines with each other. [37]

Table 30 summarises the differences between the two different approaches according to [43].

Table 30: Strength and weaknesses of qualitative and quantitative approaches [43]

Characteristic	Qualitative	Quantitative
Numerical values	no	yes
Subjective/Objective	subjective	objective
Difficulty	lower	higher
Complexity	lower	higher
Data	less detailed	more detailed
Technical expertise	lower	higher
Time required	lower	higher
Tools required	seldom	usually
Accuracy	lower	higher

Hazard Analysis Techniques

There are more than 100 hazard analysis techniques. A hazard analysis technique is a specific analysis methodology like for instance FMEA or FTA. Many techniques are used in special fields of applications. Hazard analysis techniques are always team-oriented as an interdisciplinary cooperation is important to find all relevant hazards. In this thesis, four common techniques used in the preliminary and detailed design phase are mentioned. The techniques and their attributes are listed in [43].

The failure mode and effects analysis (FMEA) is a bottom-up hazard analysis technique, which reviews as many components, assemblies, and subsystems as possible. Failure modes and their causes and effects are identified and analysed. Measures are defined to reduce risks. There are two different Types of the FMEA, the Design-FMEA used to analyse products and systems and the Process-FMEA used to analyse manufacturing processes of products and systems. [44, 45]

The hazard and operability study (HAZOP) is used to examine complex processes. Problems are evaluated that could risk personnel or equipment. It was initially applied when planning chemical or nuclear power plants. A complex system is broken down into simpler sections (nodes) that are individually analysed. [44]

The event tree analysis (ETA) is a bottom-up hazard analysis technique used to model a sequence of events. It is used to identify a system's consequence to an initiating undesirable event or a normal system operating command. It enables the assessment of the probability of the outcome, be it favourable or unfavourable. A ETA can be applied to a variety of systems, but was initially introduced to analyse nuclear power plants. [44]

The fault tree analysis (FTA) is a top-down hazard analysis technique. After determining an undesirable condition or event, the failure pathways of a system are traced to the faults that could have cause the undesirable event. This technique is used to analyse complex systems and commonly applied to high-energy systems like nuclear power plants. [44]

The techniques and a comparison of their attributes according to [43] and [46] are listed in Table 31.

Table 31: Common hazard analysis techniques and their attributes [43, 46]

Criterion	FMEA	HAZOP	ETA	FTA
Documentation	extensive	extensive	extensive	extensive
Required time	moderate	extensive	extensive	extensive
Team Leader Expertise	moderate	moderate	extensive	extensive
Quantitative/ Qualitative	qualitative/ quantitative	qualitative	qualitative/ quantitative	qualitative/ quantitative
Inductive/ Deductive	inductive	inductive	inductive	deductive
Level of detail	in-depth	moderate	moderate	moderate
Single/ Multiple failures	single	single	multiple	multiple
Life-cycle phase	preliminary/ detailed design	preliminary/ detailed design	preliminary/ detailed design	preliminary/ detailed design
Skills required	system safety engineering maths/ statistics	system safety engineering maths/ statistics	system safety engineering maths/ statistics	system safety engineering maths/ statistics

Unlike the other techniques, the FMEA is well established in the automotive industry according to a survey conducted by the VDA (Verband der Automobilindustrie). In this survey preventive QM methods are compared including the FMEA and the FTA. The results of the study are based on surveys conducted among automotive manufacturers and automotive suppliers. Figure 69 illustrates the results of the survey. [45]

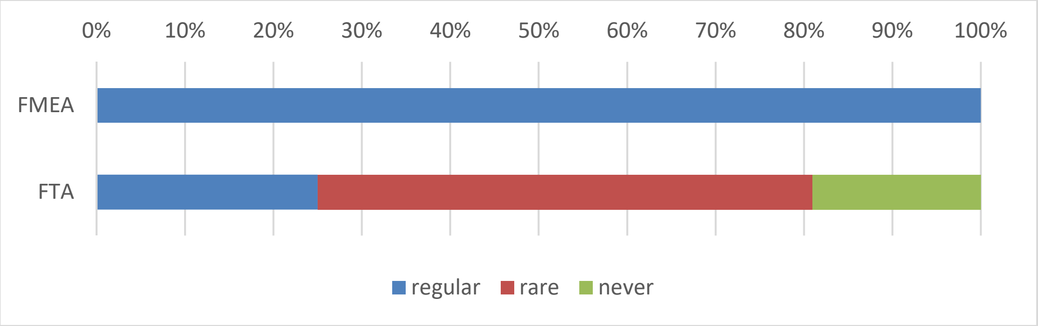

Figure 69: Frequency of use of FMEA and FTA in the automotive industry acc. to [45]

According to Popović [43] the bottom line is that it is not really important in the long run if a hazard analysis technique is inductive, deductive top-down or bottom- up. It is good to know that various techniques exist to identify hazards, but since a hazard analysis technique is a team approach it is important that the team conducting the hazard analysis is able to use and apply an appropriate technique correctly. [43]

As with most automotive suppliers, the FMEA methodology is well established at Magna Steyr. The team conducting the hazard analysis includes specialists from Magna Steyr and from Graz University of Technology. Both, the specialists from Magna Steyr and the specialists from Graz University of Technology, have experience in conducting a FMEA. Therefore, this technique is used and also described in more detail in this thesis.

If a HARA is executed in the course of the functional safety process according to ISO 26262, and an ASIL classification of malfunctions is done, conducting a FMEA is mandatory. The goal is to prove that all possible failures and failure roots leading to an ASIL related malfunction are covered by the functional safety concept.

5.2 Description of the FMEA Process

In the development of a product, a manufacturer has to ensure that a product is safe, by conducting an appropriate risk prevention. The FMEA provides a valuable support in this matter as it is a state of the art hazard analysis technique. It provides an effective documentation and knowledge base for potential failures and hazards and helps to lay down action strategies. Moreover, it might serve as a protective measure against damage claims. [40, 47]

5.2.1 Objectives of FMEA

The aim of the FMEA is the determination and assessment of potential hazards regarding their severity, occurrence and detection and laying down executing measures to avoid hazards and reducing risks. [45]

Conducting a FMEA helps in various ways:

- Increasing the functional reliability
- Proof of safety for approval application
- Establish a knowledge base
- Shorter development times
- Evidence in product liability case

The FMEA should be performed in an early stage of the product development process in order to be able to correct any failures at an early stage.

5.2.2 Types of FMEA

According to VDA [47], there are two different FMEA types, the Design-FMEA and the Process-FMEA as listed in Table 32.

The Design-FMEA considers the required functions of products and systems. If possible, systems, subsystems and components are structured on different levels in the FMEA. Possible deviations of the required functions are determined and measures to secure the functions are defined. [47]

The Process-FMEA considers processes for manufacturing products. Deviations of the process are taken into account and measures to ensure a safe process are defined. [47]

Table 32: Types of FMEA acc. to [48]

	Object of observation	Objective	Requirements	Implementation
Design-FMEA	Systems/Products (e.g. motor)	Ensuring functional efficiency, reliability and safety according to the specifications	Product concepts	After completion of the product concept
	Single components of a product	Ensuring design in accordance with specifications	Design documentation	After completion of the design documentation
Process-FMEA	Individual steps of a manufacturing process (e.g. grinding)	Ensuring faultless manufacturing of a product	Production plans	After completion of the production plan (also for already running production processes)

In further steps of the MH$_2$PS project, the Design-FMEA will be used as the manufacturing process of the MH$_2$PS is not relevant yet.

5.2.3 General Procedure for Performing an FMEA

The steps for performing an FMEA are listed in Table 33. Often, the structure of a system is not defined in an early development phase, but functions may already be known. Therefore, the functional analysis and the structural analysis can be performed in reverse order or at the same time.

Table 33: General procedure for performing a FMEA acc. to [40]

Process step	**Purpose**
Data collection	Information from: parts lists, specifications, regulations, benchmark results, lessons learned
Definition of scopes and depth of observation	Scope definition for instance by means of a block diagram
Structural analysis	Identify and structure elements as well as assign functions
Functional analysis	Link functions
Failure analysis	Assign and link failure modes
Action analysis	Documenting and evaluating the current status
Optimization	Optimization with further measures to minimize risk and asses the changed status

Figure 70 illustrates and sums up the FMEA process.

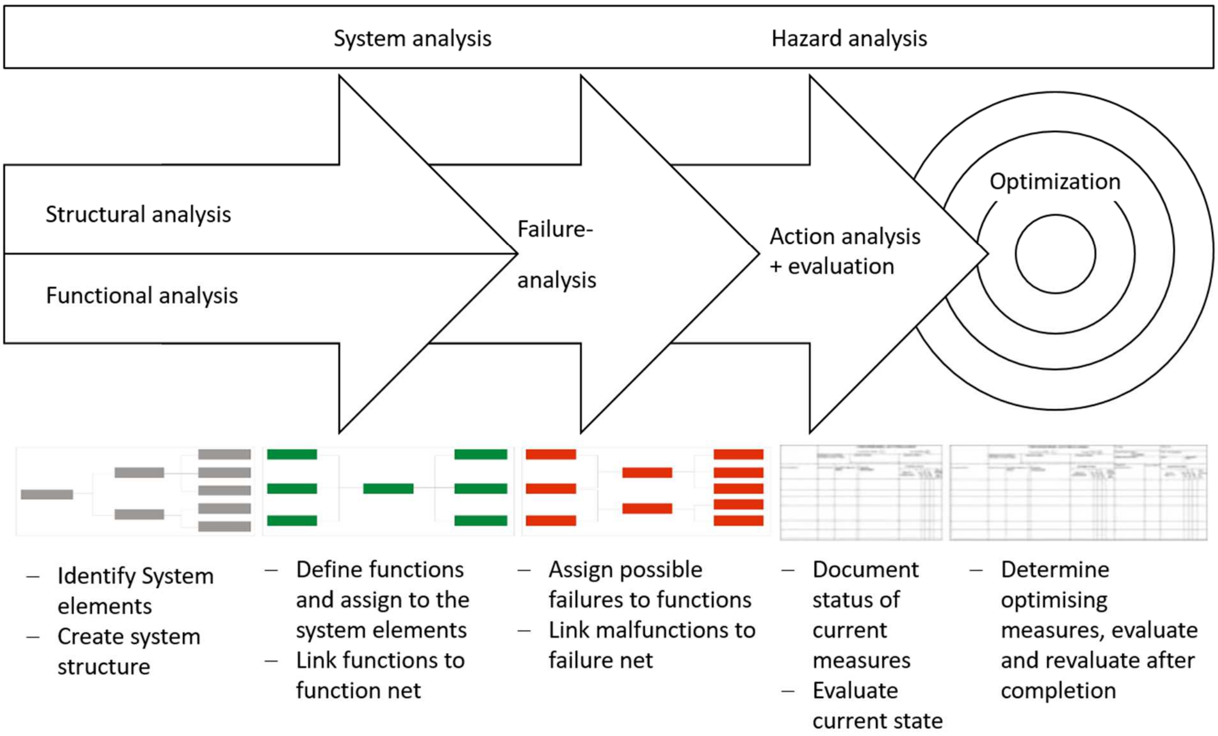

Figure 70: FMEA process acc. to [40]

5.2.4 FMEA Team Composition

The FMEA is commenced by the responsible project manager and conducted in a team. At first, a cross-departmental project team must be formed in which experts from different departments are represented. [40, 48]

The team consists of the members listed in Table 34.

Table 34: FMEA team composition acc. to [27]

Team member	Activities
Project leader	Decision to start the FMEA Specification of the responsible persons for the definition phase Assisting the collection of required information and documents Provision of all necessary tools and resources
Person responsible for conducting the definition phase	Procurement of necessary documents and information Coordination and organisation of the definition phase Block diagram (interface definition) Composition of the team Responsible for the results of the definition phase
FMEA-Moderator	Contributes to the team composition Contributes to establish a schedule Contributes to the invitation of the first team meeting for the analysis phase Contributes to the preparing of decision documents/ criteria
Team members	Contribute to the preparation of the FMEA (block diagram, interface definition, data collection, team formation) Provision of experience and expertise Active participation during FMEA-sessions

Requirements for Being a FMEA-Moderator: [40]

- Methodical expertise
- Social competencies
- Competencies in the areas of moderation, organisation, presentation, structured working and cross-linked thinking
- product and sector expertise is not required but beneficial

Criteria for all Team Members: [40]

- Expert knowledge about the scope of the FMEA
- Basic knowledge in conducting a FMEA
- Ability to work in a team

Composition of the Team: [40]

- Competent employees of the departments involved in the project (internal and external) from various departments (design/development, process planning, quality assurance, prototype/sample production etc.)
- If needed, additional experts from other fields like customer service, legal department, etc.

Organisational Functions within the Team

The organisational functions within the team are listed below in Table 35.

Table 35: Organisational functions within the FMEA team acc. to [40]

Team member	Organisational function within the team
Team leader	Responsible for the advancement of the FMEA Represents the team on the outside Decides the dates of the meetings, is responsible for the invitations to the meetings Decision preparation
Moderator	Responsibility of the FMEA does not lie with the moderator Responsible for the methodical approach Responsible for the work atmosphere Leading the FMEA process with the team leader Evaluating the results of the FMEA Encouraging measures Responsible for the clear and verifiable documentation Preparing of decision documents Creates evaluation catalogue
Time manager	Allotting time for the agenda points with the team leader Monitoring the progress Redistribution of the remaining time if necessary
Scribe	Summing up team decisions Documenting the results
Recorder	Writing the minutes (attendees, discussed issues, decisions, agreements, results, etc.) Collecting additional documents Handing out the minutes of the sitting

In times of online processing via data projector scribe and recorder are usually the same person. [40]

5.2.5 Structure Analysis

The objectives of a structure analysis in the design FMEA are: [40, 47]

- To give an overview of the product
- To enable modular construction (for reuse)
- Interface delimitation, description and observation
- Today's software tools often need a system structure first
- The functional structure is then embedded in this system structure

The system consists of individual system elements (SE) that are arranged hierarchically to describe the structural relationships. [40, 47]

According to the VDA, the following rules apply: [40, 47]

- The clear structured representation of the entire system is ensured by the fact that each system element exists only once.
- The structures arranged under each system element are independent substructures.
- The structuring also creates interfaces (physical connections existing in the system) at system elements of a substructure to system elements in other substructures.
- All functional relationships between the system elements, even across interfaces of the considered system structure, are to be described.
- There is always a structural element, even if it is derived from the function and cannot yet be specified more precisely.

In Figure 71 an example of a system structure is illustrated.

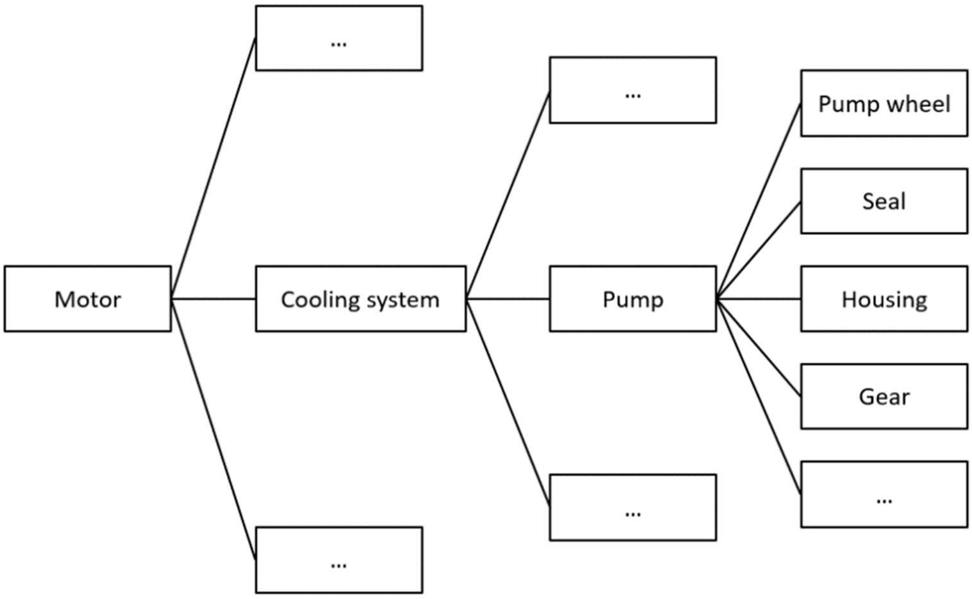

Figure 71: Example of a system structure down to component level acc. to [40]

5.2.6 Function analysis

In the function analysis, functions are assigned to system elements and a function structure is created. This demands comprehensive knowledge of the system and the environmental conditions of the system. [40, 47]

The objectives of the functional analysis according to VDA are: [40, 47]

- Overview of the functionality of the product/system
- Overview of the cause-effect relationships
- Verify against the specifications
- Basis for failure analysis

Definition of Functions

Each system element has different functions in the system as illustrated in Figure 72. To fulfil individual functions of a system element, the functions of other system elements are usually also required. [40, 47]

Functions should consist of a noun and a verb, for instance “generate torque” or “transmit force”. [40, 47]

- Functions are technical and country-specific requirements or design goals.
- Functions are unambiguous, concrete, verifiable and validable.
- The following must also be taken into account:
  - specifications
  - naturally presupposed expectations
  - foreseeable abuse

Functional Structures

The interaction of the functions of several system elements must be illustrated. This can be realized with a function tree. In order to create the functional structures of a system element, the functions involved must be considered. Sub-functions that describe a function are logically linked in the assigned function structure. In the structure, the level of detail of the functional structure increases to the right. The function to the right describes how the previous function is to be fulfilled. To go to the right for higher detailing, the question "How?" is asked. To check the plausibility of the links from right to left, "Why? Is asked. [40, 47]

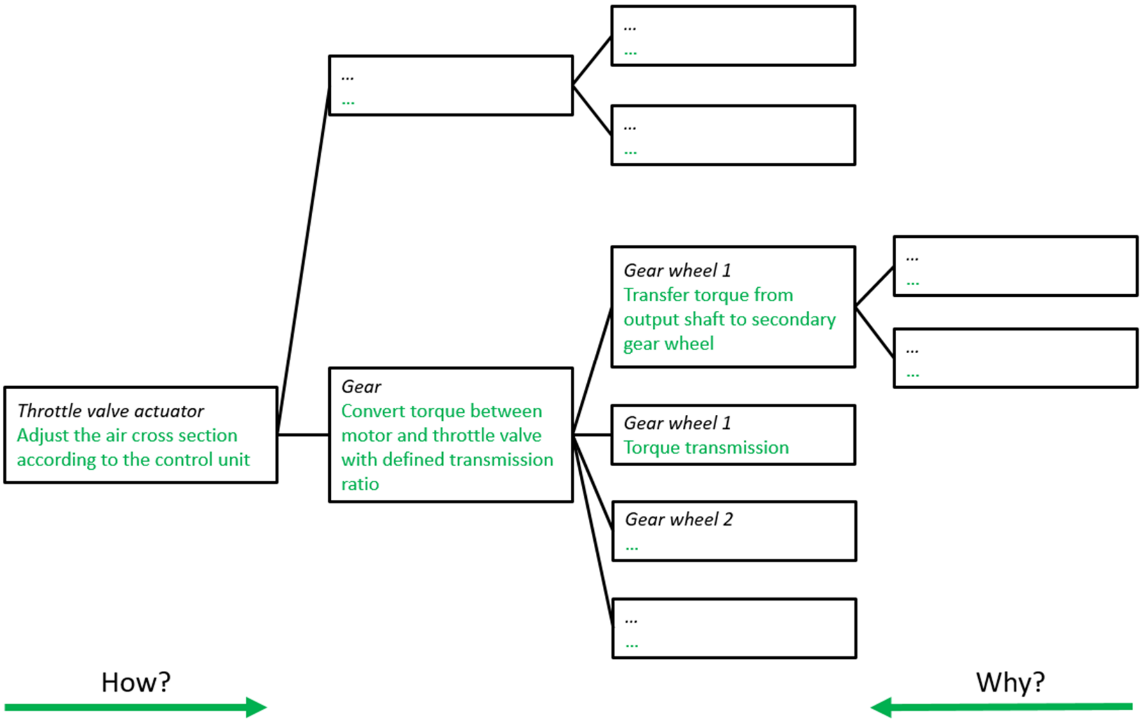

Figure 72: Example of a function structure acc. to [47]

5.2.7 Failure Analysis

In the failure analysis possible failure are determined. They are assigned to the system structure and to the functions. In a second step, the possible failures are linked to a failure tree. Failure analyses must be performed for all system elements or function groups considered in the FMEA. Possible failure modes are derived from the functions of the system for instance by a deviation of the specific nominal state of the function. [40, 47]

The description of the failures has to be unambiguous. “Part broken”, “device out of order” or “defective” are not sufficient descriptions to assign the failure. Several failure modes are usually assigned to one function. [40, 47]

Failure Tree

In the failure analysis, failure modes are derived from functions and failure trees are created as illustrated in Figure 73. In a failure tree, failure modes are linked to each other according to cause and effect. Depending on the focus, a failure can be a possible failure mode, a possible cause of the failure mode or a possible failure mode consequence. [40, 47]

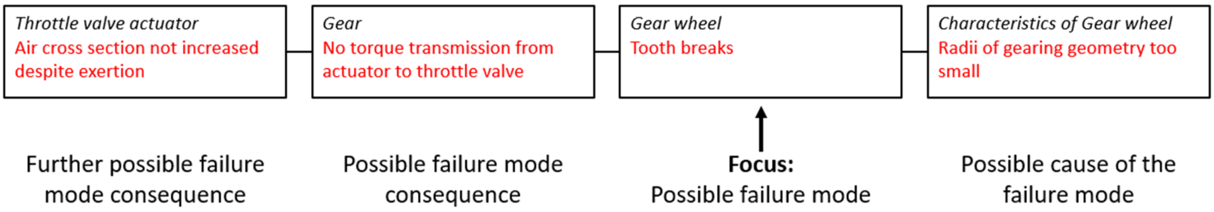

Figure 73: Failure tree using the example of a throttle valve actuator acc. to [47]

5.2.8 Action Analysis

The objectives of the measure analysis are the assignment of existing or already defined measures to the failures and to perform a risk assessment. [40, 47]

There are two different groups of actions, prevention actions and detection actions. [40, 47]

Prevention Actions

Prevention actions in the development serve the optimal system design, to minimize the probability of occurrence of possible failures. Prevention actions must be described clearly and comprehensibly, such as quality regulations or generally accepted rules. This can also be done by a reference to other documents, regulations or calculations. [40, 47]

Prevention actions using the example of an electric steering assistance system: [40, 47]

- Possible cause of failure: incorrect values from sensor
- Possible consequence: The driver's steering request is not fulfilled
- Direct prevention action: redundant design of the sensor
- Impact-limiting action: plausibility check

Detection Actions

Detection measures are used to find the possible causes of failures or their possible consequences or to confirm the prevention measures. Detection actions must be described clearly and comprehensibly. Detection Actions can be a burst test, an endurance test or a laboratory test. [40, 47]

Responsible Persons and Date

According to the VDA, each task is assigned to a person responsible and a date. The person responsible is responsible for the decision and implementation of the action. Deadlines must be set early enough to ensure the implementation before the product goes to the internal or external customer. Actions can have different statuses. They are listed in Table 36. [40, 47]

Table 36: Status of the action [40, 47]

Status of the action	Explanation
Unprocessed	Implementation of the action has not yet started.
In decision	The action is defined, but not yet decided.
In implementation	The action has been adopted but not yet fully implemented.
Completed	Action is completed, documented and evaluated.
Discarded	Rejected actions must be documented.

Evaluation of Causes

The risks associated with each cause of failure are assessed. All causes are assessed individually. The current status, the detection actions and their consequences are taken into account. [40, 47]

In order to perform a risk evaluation, the severity of the failure consequences for the customer (S), the probability that a failure cause occurs O, and the probability that a failure is detected D must be evaluated. The values range from 1-10, where 1 stands for "low risk" and 10 for "high risk". These three factors can be considered individually or combined in order to make prioritizations. By multiplying these three factors, the risk priority number (RPN) is obtained. The reaction threshold is made up of (S) and the risk priority number (RPN) and serves as a guideline to establish actions. The reaction thresholds must be agreed with the customer. [40, 47]

In case there are no other specifications, the Magna Steyr internal thresholds are valid:

(S) = 10 and RPN > 40

(S) < 6 and RPN > 100

(S) < 3 and RPN > 120

(S) = 3, 2, 1 and RPN > 150

The risk priority number is not precise enough to evaluate the risk level of an identified failure. Therefore, a risk matrix has to be made and analysed. If there are no other specifications, the risk matrix according to the VDA standard shall be used at Magna Steyr, as illustrated in Figure 74.

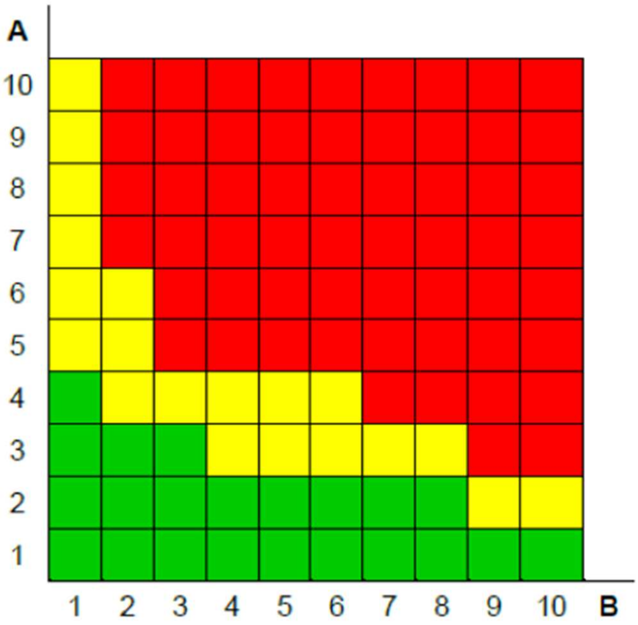

Figure 74: Risk matrix acc. to [47]

No further measures need to be taken in the green areas. In yellow areas it is not mandatorily needed to implement action. It must be decided within the team, if actions are taken or not. In red areas actions are mandatory.

5.2.9 Optimisation

The objectives of the optimisation are to determine the actions, which are necessary for improvement, to assess the risk and to check the effectiveness of the implemented measures and their documentation. If the outcome of the assessment is not satisfactory, new actions shall be proposed. [40, 47]

The optimization process is repeated until an acceptable result is achieved. The rejected actions remain documented in the FMEA to not use the same measures again. [40, 47]

5.3 General Hazards of the MH_2PS

As preparation for a FMEA, the key safety hazards of the MH_2PS concept are identified.

Combustion Hazards

Before addressing combustion hazards in combination with hydrogen, the principles of flammability shall be considered. In order to make an ignition possible the following factors need to be given: [49]

- The flammable chemical's concentration needs to be within its flammability limits.
- The oxidant needs to be present in the right concentration to put the chemical in its flammable range.
- There needs to be a thermal or electrical ignition source.

Table 2 lists the properties of hydrogen, including explosion and detonation limits, ignition temperature and minimum ignition energy. Due to the wide detonation and flammability range, a hydrogen leak is dangerous. The probability of hydrogen being present at levels that could result in a detonation or the chance of hydrogen being present at flammable levels is high. If the area is well ventilated, flammability is normally limited to the area where the hydrogen leak occurs. A problem appears in enclosed or partially confined spaces, because the flammability concentration might be present over a larger area. If hydrogen is ignited and if it is present within its flammability and detonability ranges, it can explode. In addition, hydrogen is a colourless and odourless gas (at normal pressure and temperature), hence there are no natural warning signals of its presence. [7, 49, 50]

Hydrogen can deflagrate (subsonic combustion) or detonate (supersonic combustion). Deflagration occurs if a hydrogen-air mixture is ignited in an unenclosed space. In this case, flames travel at subsonic speeds. This can cause a pressure wave, which can lead to injuries or damage surrounding structures. A detonation can occur in closed or partially confined areas if hydrogen is present in its detonation range. Usually, a hydrogen fire is not extinguished until its supply is shut off. A hydrogen flame is often nearly invisible and therefore difficult to detect. [49, 50]

High Pressure Hazards

Figure 12 provides an overview of density and volumetric energy density of hydrogen at different pressure levels and in different states. As hydrogen is a gas, the energy content per unit volume is low. Therefore, hydrogen in vehicles is either stored in compressed or liquefied form to achieve high energy densities. In the MH_2PS project, hydrogen is stored in compressed form in a type IV vessel at maximum

70 MPa. Along with the chemical energy stored in the hydrogen, the energy content of 1 kg hydrogen compressed to 70 MPa is about the equivalent of 0.6 kg of TNT. A sudden release of hydrogen can lead to injuries caused by the released energy and by the debris. Therefore, a failure of the vessel resulting in an explosive release of compressed hydrogen must be prevented. [7, 49, 50]

In order to prevent failure and to get a type-approval, vessels designed to contain compressed gaseous hydrogen have to undergo a series of tests listed in Table 37. [15]

Table 37: Applicable test procedures for hydrogen containers designed to use compressed (gaseous) hydrogen [15]

Type of test	Applicable to container type			
	I	II	III	IV
Burst test	✓	✓	✓	✓
Ambient temperature pressure cycle test	✓	✓	✓	✓
Leak-Before-Break performance test	✓	✓	✓	✓
Bonfire test	✓	✓	✓	✓
Penetration test	✓	✓	✓	✓
Chemical exposure test		✓	✓	✓
Composite flaw tolerance test		✓	✓	✓
Accelerated stress rupture test		✓	✓	✓
Extreme temperature pressure cycle test		✓	✓	✓
Impact damage test			✓	✓
Leak test				✓
Permeation test				✓
Boss torque test				✓
Hydrogen gas cycle test				✓

The minimum burst pressure of a 70 MPa type IV vessel is 2.25 times its nominal pressure hence 157.5 MPa. Given that vessels have to pass all these tests leads to the fact that using compressed hydrogen as a fuel has a similar level of safety as using conventional fuels like gasoline or diesel. [15, 49]

In the MH_2PS concept, hydrogen is stored and processed in compressed form by various components. If damaged, for instance due to a crash, those components have the potential for an uncontrolled release of hydrogen. A release of compressed hydrogen can occur in three primary modes, each having unique safety considerations: [50]

- Leakage
- Venting (blowdown)
- Component rupture

Leakage is a controlled release of hydrogen either through a crack or a hole and does not have a significant influence on the system's pressure. It can be stopped by plugging the hole, by blocking the hydrogen source or if the hydrogen flow upstream the leak is shut off with the help of a solenoid valve. Hydrogen's autoignition properties can lead to an ignition and fire at the leak's source. Through a leak, hydrogen can be released into enclosed areas like the housing of the MH_2PS or a garage. Due to being a light and active element, hydrogen usually dissipates quickly. If a leak remains undetected, a crack could increase in size and get more hazardous. [50]

A blowdown is a rapid release of compressed hydrogen. The gas is released through a relatively large opening. It leads to a rapid pressure reduction in order to defuel components or the whole hydrogen system. It is usually vented in a supersonic flow, which may cause an ignition and burn in form of a hydrogen "jet" or can collect in confined areas and form a combustible mixture. Unlike a hydrogen leakage, a blowdown often cannot be stopped. Usually a blowdown is allowed to progress until the tank system is empty and all hydrogen is released. Temperature pressure relief devices on compressed hydrogen vessels are specifically designed to blowdown the vessel in order to avoid explosive rupture of the vessel in case of a fire. [50]

Rupture is defined as a supersonic fracture of components. Due to rupture, a hazardous pressure wave is released. Hydrogen vessels have technical design requirements to prevent rupture. In case of a crash, there is still a probability of rupture of components, which contain compressed hydrogen. It can lead to an explosive release of fragments or debris. [50]

Electrical Hazards

Due to the fuel cell and its high voltage battery, the MH_2PS concept has hazardous levels of current and voltage, which can cause cardiac arrests or burns for the operator. To protect the operator, electrical systems are isolated from the rest of the system. If a crash occurs, insulation barriers may be degraded and can cause harm. [49, 50]

Fuel Cell Electrical Failure

Due to damage caused by a crash, internal shorts or arcing can occur in the fuel cell. It may damage the membrane of the fuel cell resulting in mixing of air and hydrogen, which can lead to an overheating situation and fire. A crash can also damage cables and connections potentially resulting in shorts and arcing. Therefore, technical standards for electrical systems of vehicles require safety interlocks, which are designed to prevent or mitigate such failures. An overheating situation could also be the result of insufficient cooling of the fuel cell. [50]

Battery Electrical Failure

The MH_2PS concept uses a battery for storage and supply of electrical energy. While hydrogen may be isolated from the battery room, a high voltage battery has the potential to suffer a chemical breakdown resulting in an outgassing of hydrogen and other hazardous chemicals, which have a potential to be ignited. Additionally, a damaged battery may leak and electrolyte can be released. [49, 50]

Fire Hazards

Many factors can cause a fire. The origin of a fire can be outside or inside the system. As the MH_2PS concept contains compressed hydrogen, fire represents an important potential hazard type of the system. It can lead to rupture of the hydrogen vessel releasing the energy within. Compressed hydrogen storage systems are designed to prevent rupture with the help of temperature pressure relief devices, which are thermally activated in order to blowdown the vessel and to avoid an explosive rupture. [49, 50]

Temperature pressure relief devices on compressed hydrogen vessels are specifically designed to blowdown the vessel in order to avoid explosive rupture of the vessel in case of a fire. [49, 50]

5.4 Derivation of Data for a FMEA Analysing the Compressed Hydrogen Path and the Fuel Cell Subsystem of the MH_2PS

As preparation for a planned FMEA process, the compressed hydrogen path and the fuel cell subsystem are divided into their key components, as far as they are known in this early stage of development. The information can be used to evaluate the compressed-hydrogen fuel cell system of the MH_2PS in order to identify and evaluate possible failure modes of components, their potential effects on overall system safety of the MH_2PS, and to define measures to reduce the risk. As first step in a FMEA analysing the compressed hydrogen path of the MH_2PS, the structure analysis is prepared. It is illustrated in Figure 76.

The preliminary layout is illustrated in Figure 75, the components are listed below in Table 38.

Table 38: Preliminary components of the compressed hydrogen path and fuel cell subsystem

Number	Component
I	**Filling Unit**
I.1	Filter
I.2	Filling Receptacle
S6	Refuelling Data Interface (RDI) Infrared Sensor
II	**Check Valve Filling Line**
III	**Vessel 70MPa**
IV	**On Tank Valve (OTV)**
IV.1	Refuelling Filter
IV.2	Mechanical Shut-off Valve
IV.3	Electric Shut-off Valve
IV.4	Defueling Filter
IV.5	Temperature Pressure Relief Device
IV.6	Mechanical Bleed Valve
IV.7	Excess Flow Valve
S1	Vessel Temperature
V	**Mechanical Pressure Regulator (MRP)**
V.1	Hydrogen Filter
V.2	Pressure Regulator

V.3	Low Pressure Relief Device
VI	**High Pressure Line**
VII	**Venting Line**
VIII	**Middle Pressure Line**
IX	**Service Port**
IX.1	Service Valve
IX.2	Quick Coupling
X	**System Shutoff Valve (SSOV)**
X.1	Shutoff Valve
X.2	Hydrogen Filter
Sensors:	
S2	High Pressure Sensor (HP)
S3	Middle Pressure Sensor (MP)
S4	Hydrogen Detector
S5	Hydrogen Detector
Interfaces:	
HSS - IF 1	Receptacle Filling Station
HSS - IF 2	Outlet Venting Line
HSS - IF 3	Interface to the Tank Control Unit (TCU)
Control Unit:	
C1	Refuelling Data Interface ECU (RDI ECU)
Fuel Cell Subsystem:	
Anode side:	
XI	Flow Meter
XII	Hydrogen Supply Shutoff Valve
S7	Hydrogen Pressure Sensor
Fuel Cell Stack Subsystem:	
XIII	Fuel Cell Module
XIV	Anode Recirculation Pump
XV	Purge Valve
XVI	
S8	Hydrogen Sensor
Cathode side:	
XVII	Air Filter
XVIII	Mass Flow Sensor
XIX	Air Compressor
XX	Humidifier/ Aftercooler

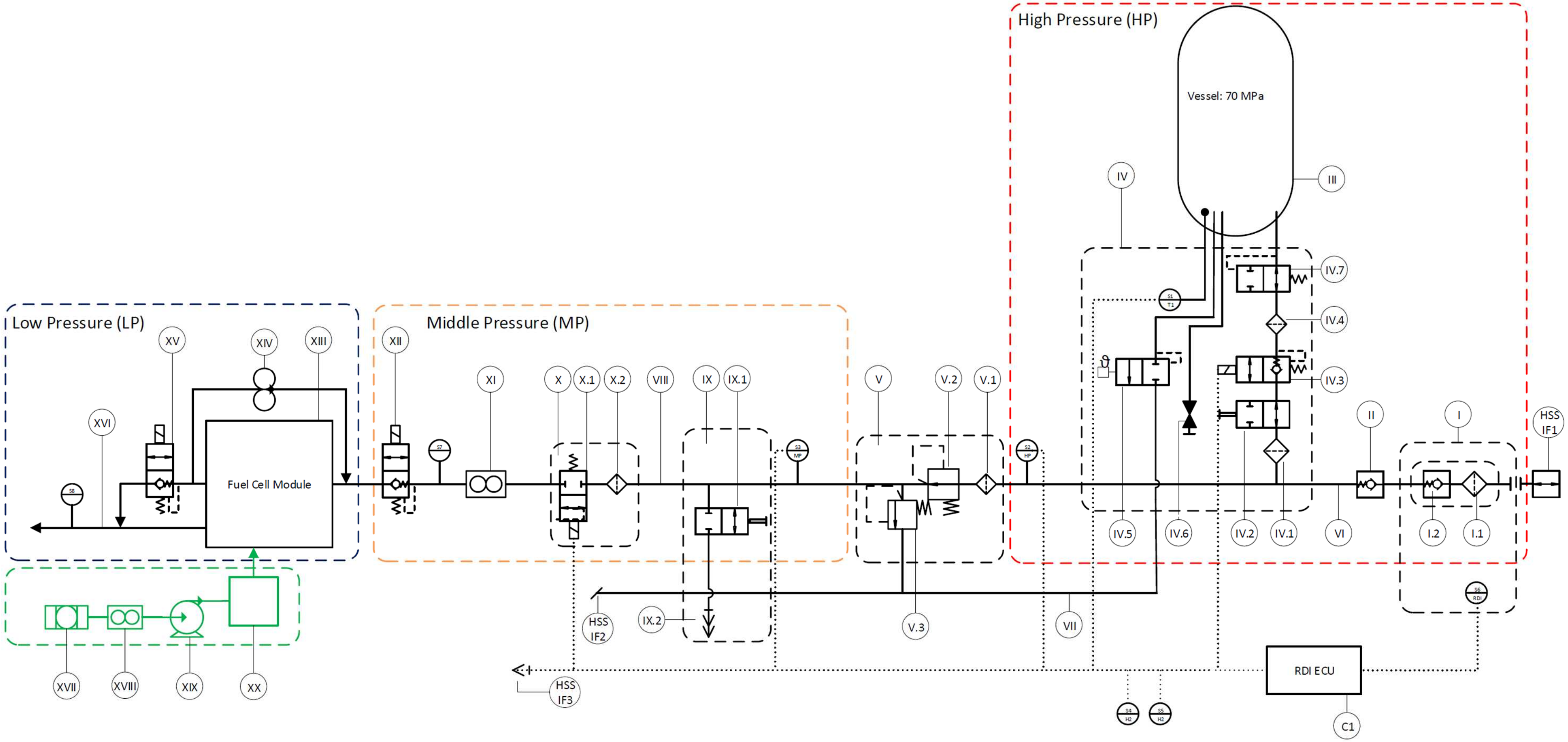

Figure 75: Preliminary layout of the compressed hydrogen path and fuel cell subsystem

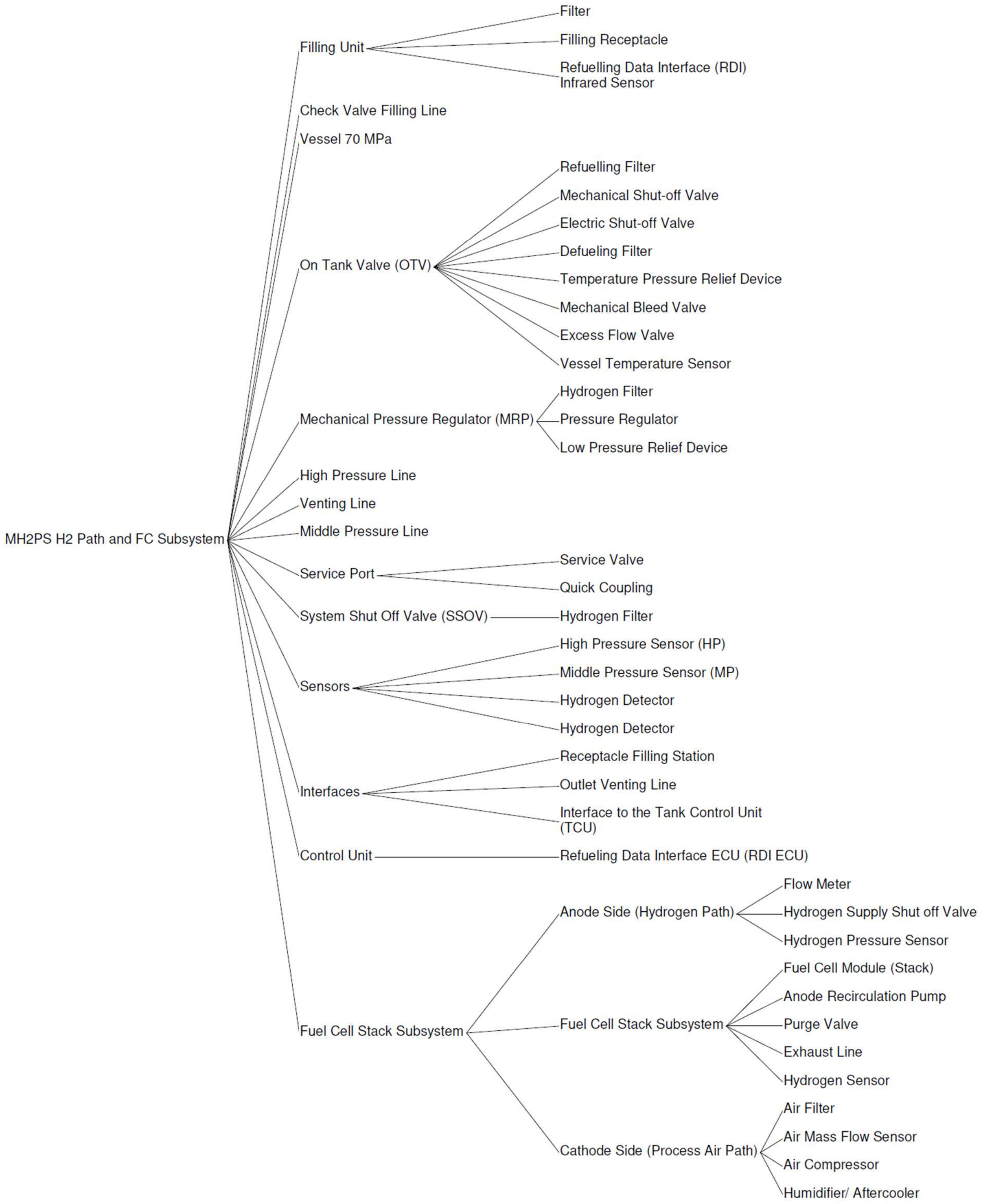

Figure 76: Structure analysis of the compressed hydrogen path and fuel cell subsystem

5.5 Derivation of Functions and Failures from Given Component Specifications

In order to find potential failures and to derive safety requirements for the MH_2PS concept, the manuals of the components, as far as they are available, have been examined. It is determined, which errors are addressed by the components and which have to be handled separately by the integrator. The information gathered will be used as input for the development of the control strategy, as preparation of a detailed specification sheet and as input data for a FMEA.

Table 39 provides a list of potential failures addressed in the manual of Ballard's fuel cell module, which will be integrated in the MH_2PS.

Table 39: Failure list of Fuel Cell Module FCveloCity MD30 [51]

Failure	**Effect**	**Integration manual**
Minimum current drawn from FCM is less than 20A	Integrator of FCM should set the current draw to zero and disable the MD_RUN signal	Integration manual Page 44: 20 A must be drawn from the fuel cell module by the integrator's DC/DC. If the integrator is unable to draw the allowable minimum current, the integrator should set the current draw to zero and disable the MD_RUN signal to cause the fuel cell module to enter the Standby State.
Reverse current to FCM	Results in shutdown of FCM	Integration manual Page 44: The fuel cell module system does not have a diode. Reverse current will be detected by a current transducer, and will result in a fault and shutdown. System integrator shall ensure that the DC/DC does not back-feed the fuel cell module.
Maximum total current output at the FCM system HV connections exceeds 300A	Triggers an alarm resulting in a shutdown of the FCM	Integration manual Page 43: The fuel cell module system does not have a fuse to limit the high voltage output current, but will alarm and shutdown if the high current limit is exceeded. The high voltage contactors will open as usual during the shutdown process.
Current drawn from FCM exceed I_ALLOW	Result: not known yet	The question has not yet been answered by the manufacturer. Remark: Strategy to handle the risk has to be elaborated during the safety concept development. Integration Manual Page 37: At any time, the drive system can draw less than I_ALLOW, and the air flow will adjust based on the measured current. The current drawn by the system must never exceed I_ALLOW to protect the fuel cell module.

Supply voltage (from 24V Battery) out of range	Result: not known yet	Integration manual Page 37: Minimum supply voltage is 23 V DC and maximum voltage is not to exceed 30 V DC.
No provision of 24V (~2A) for 15min after shutdown	Result: not known yet	Integration manual Page 37: 24 VDC (~2amps) must be provided for at least 15 min after shutdown.
Wrong CAN Customization Key	FCM stays in Locked Mode	Integration manual Page 36: Supplying +24 V to this input provides power to the fuel cell module system controller and the module will enter the Unlocked state (requires CAN customization key also be sent)
Safety Interlock Circuit OPEN	SSC_IN=0V	Integration Manual Page 38: This signal (SSC_IN) must be tied into the system’s safety interlock circuit such that this signal is dropped to 0 V if there is an Emergency Power Off (EPO) event.
Hydrogen leak inside FCM	Triggers an alarm resulting in the closing of the FCM's hydrogen supply valve	Integration manual Page 14: Hydrogen leaks, which develop within the fuel cell module will be detected by a hydrogen sensor located inside the fuel cell module. A high hydrogen sensor reading will trigger an alarm resulting in the closing of the fuel cell module hydrogen supply valve before an unsafe condition can exist. The responsibility for leak detection external of the fuel cell module rests with the system integrator.
Hydrogen leak in exhaust air outlet	A FCM shutdown will occur if an unsafe hydrogen concentration is detected	Integration manual Page 19: The process air exhaust outlet contains a hydrogen sensor that continuously monitors for the presence of hydrogen. A module shutdown will occur if an unsafe hydrogen concentration is detected by the hydrogen sensor.
Hydrogen leak in ventilation air outlet	A FCM shutdown will occur if an unsafe hydrogen concentration is detected	Integration manual Page 19: The ventilation air outlet contains a hydrogen sensor that continuously monitors for the presence of hydrogen. A module shutdown will occur if an unsafe hydrogen concentration is detected by the hydrogen sensor.

FCM reaches temperatures below 2°C	Results in possible freeze damage	Integration manual Page 15: The MD30 is susceptible to freeze damage. Unless the MD30 is equipped with the optional freeze protection system (see Section 10) and it is functional, the module should not be allowed to reach temperatures below 2°C.
FCM reaches temperatures above 50°C	Results in overheating of the FCM	Integration manual Page 23: The ambient temperature of the air compressor installation location shall not exceed 50°C.
Air Intake Pressure Drop - at the maximum expected air flow rate of 35 g/s (Total pressure drop allowed upstream of the air delivery system) exceeds 20mbar		Integration manual Page 22 The question has not yet been answered by the manufacturer. Remark: Strategy to handle the risk has to be elaborated during the safety concept development.
Maximum backpressure at FCM system process air exhaust exceeds 10mbar		Integration manual Page 22 The question has not yet been answered by the manufacturer. Remark: Strategy to handle the risk has to be elaborated during the safety concept development.

Table 40 lists potential failures found in the integration manual of the DC/DC converter Brusa BDC546.

Table 40: Failure list of DC/DC converter Brusa BDC546 [52]

Failure	Effect	Integration manual
The voltage permissible on LS is exceeded	Resulting current flow ignites the pyro-fuses and respectively leads to galvanic isolation of the fuel cell	Manual Page 14: Two inputs are set to the potential of the minus wiring system/terminal 31. The resulting current flow ignites the pyro-fuses and respectively leads to galvanic isolation of the fuel cell from the converter.
Invalid interlock signal sequence (internal/external)	Detection of the interlock error leads to an immediate shut down of the device.	Manual Page 29: The signal of the BDC546 can be evaluated via pin 19 of the control connector. An invalid signal sequence is regarded as error state and potential operation of the component is prevented by deactivation of the power stages. Manual Page 44: As the BDC546 itself is not part of the loop, it cannot be disconnected by the interlock loop. However, it can detect errors that are caused by external devices in the interlock loop. In case of an invalid signal sequence or missing interlock signal, the signal Interlock_In* is set and the error DC_Err_Interlock is returned via CAN. Detection of the interlock error leads to an immediate shut down of the device.

Temperature out of range	Power rating is reduced to protect the device from damage caused by overheating. Lowside current is reduced to 0 A at a temperature of 100°C.	Manual Page 15: This protective system is a self-protection feature of the BDC546. If the device reaches a defined temperature threshold, the power rating is reduced (derating) to protect the device from damage caused by overheating. The maximum permissible lowside current (400 A) will subsequently be reduced in proportion to the temperature increase until the temperature falls back to the target range. The module and choke temperatures are measured. Derating is activated if a temperature value of ≥ 95 °C is reached. The power or choke current is now reduced in stages to a temperature not lower than 115 °C (0 A). This means that the choke current is reduced by 20 A for every degree temperature increase. If a temperature sensor is defective, derating is activated at temperatures ≥ 80 °C for safety reasons, and, correspondingly, the lowside current is reduced to 0 A at a temperature of 100 °C.
Highside Overvoltage/ Lowside Overvoltage	Overvoltage shut-down functions at a specific voltage	Manual Page 61: The PARAM software provided by BRUSA is used for parameterization and configuration of BRUSA devices. PARAM provides access to the various parameters and functions of the BDC546 via CAN interface. This provides the possibility of individually adjusting parameters (e.g. overvoltage shut-down functions at a specific voltage).

Table 41 provides a list of potential failures taken from the integration manual of the DC/DC converter Brusa BSC624.

Table 41: Failure list of DC/DC converter Brusa BSC624 [53]

Failure	**Effect**	**Integration manual**
Interlock error (internal/external)	Results in an immediate shutdown of the device	Manual Page 47: The internal interlock identification works independently from the usage of the external interlock identification and it exclusively monitors whether or not the HV connector is properly connected. In the case of an error, the signal INTL_OC_int* is set and the error CRE_INTERLOCK is emitted via CAN. For safety reasons, the internal interlock identification cannot be deactivated. If one of the monitored connectors is not contacted correctly, the loop is open and the input current can no longer flow. If a threshold of approx. 15 mA is undercut, the signal INTL_OC_ext* is set, while the error CRE_INTERLOCK is emitted via CAN. The identification of the internal and external interlock error – provided that the latter is activated – leads to an immediate shut-down of the device.

Temperature out of range	Reduces the power rating (derating)/ Shutdown	Manual Page 14: This safety installation is a self-protection feature of the DC/DC converter. If the device reaches a defined temperature threshold, this reduces the power rating (derating) to protect the device from damage caused by overheating. Consequently, the maximum possible current is reduced proportionally to the temperature increase in order to avoid a further rise in the temperature. Via the CAN interface, the currently transferable current LVCUR_AVL is reported back. Here, it can be identified whether or not the device is in the derating mode. Generally, the device shuts down when the temperature of the switches of the buck / boost converter is >/= 81°C. If this temperature falls to </= 80°C, the device is 100% operable again. Here, no derating occurs but a direct shut-down of the device. With a shut-down of the device, the signal E_OVERTEMP is emitted. If the temperature at the windings of the HF power transformers reaches >/= 106°C, the current is reduced successively to a temperature value of < 131°C. At >/= 131°C, the device shuts down. If the temperature falls to </= 129°C, the device is operable again with reduced power according to the derating diagram. With a shut-down of the device, the signal E_OVERTEMP is emitted. If the temperature at the transformer stage switches reaches >/= 95°C, the current is reduced successively to a temperature value of >/= 120°C . At >/= 120°C, the device shuts down. If the temperature falls to < 120°C, the device is operable again with reduced power according to the derating diagram. With a shut-down of the device, the signal E_OVERTEMP is emitted.

HV – Overvoltage	Results in a shutdown of the device	Manual Page 15: The device provides the following possibilities for identifying an overvoltage at the HV side: Rapid HW overvoltage identification (immediate shut-down of the device if voltage > 470 V) Slow SW overvoltage identification (shut-down of the device if voltage > 456 V; automatic reactivation if voltage < 454 V) With a shut-down of the device, the signal E_HV_OVERVOL is emitted.
LV – Overvoltage	Results in a shutdown of the device	Manual Page 16: The device provides the following possibilities for identifying an overvoltage at the LV side: Rapid HW overvoltage identification (immediate shut-down of the device if voltage > 20 V) Slow SW overvoltage identification (shut-down of the device if voltage > 16.4 V; automatic reactivation if voltage < 16.2 V) With a shut-down of the device, the signal E_LV_OVERVOL is emitted.
HV – Undervoltage	Results in a shutdown of the device	Manual Page 16: The device provides the following possibilities for identifying undervoltages at the HV side: Immediate shut-down of the device if HV voltage < 215 V This error identification is deactivated for 3 s when starting the device in the boost mode. With a shut-down of the device, the signal E_HV_UNDERVOL is emitted.
LV – Untervoltage	Results in a shutdown of the device	Manual Page 16: The device provides the following possibilities for identifying undervoltages at the LV side: Immediate shut-down of the device if LV voltage < 7 V This error identification is deactivated for 5 s when starting the device in the buck mode. With a shut-down of the device, the signal E_LV_UNDERVOL is emitted.

Table 42 lists potential failures addressed in the integration manual of the power distribution unit Brusa PDU254.

Table 42: Failure list of Brusa PDU254 [54]

Failure	Effect	Integration manual
No 12V supply	Not ready for operation/ Safety Interlock Circuit open	Integration manual Page 31: The device is generally ready for operation as soon as a voltage of 12 V is applied to this pin.
Safety Interlock Circuit open	Main contactors are immediately opened	Integration manual Page 32: As soon as the interlock circuit is opened, this pin becomes inactive (= high). Now, the LV supply voltage is applied to this pin. Integration manual Page 33: As soon as the interlock circuit is opened, the relay (K) is de-energised again. As a result, the main contactors are immediately opened.
Overcurrent (over 300A)	Fuse is triggered	Integration manual Page 31: Fuse FWH-300 A / 500 VDC for main connections
Overvoltage (over 500V)	Fuse is triggered	Integration manual Page 31: Fuse FWH-300 A / 500 VDC for main connections
Voltage drop via interlock loop under 30V	Open safety interlock circuit	Integration manual Page 18: Max. permissible voltage drop via interlock loop
Max. ambient temperature exceeds +85°C		Integration manual Page 18: Max. ambient temperature +85°C
Min. ambient temperature exceeds -40°C		Integration manual Page 18: Min. ambient temperature -40°C

In Table 43 the potential failures found in the integration manual of the Samsung SDI Lithium-Ion battery are listed.

Table 43: Failure list of Samsung SDI P2-80 [32]

Failure	Effect	Integration manual
Exceed operating voltage limits	A short term exceedance of these limits does not damage ESS	Manual Page 27: During operation, each cell of the ESS stays within the upper operating voltage limit of 3.6V and the lower operating limit of 2.0V. Short term exceedance of these limits does not damage the ESS.
Specified isolation resistance limit reached	HV circuit is de-energized	Manual Page 28: The isolation monitor is implemented to check permanently the integrity of the isolation of all high voltage circuits. It measures alternately the actual isolation resistance between the positive high voltage pole and low voltage ground and between the negative high voltage pole and the low voltage ground. The HV circuit is de-energized as soon as a specified isolation resistance limit is reached. For ESS the entire high voltage circuit of the ESS and of the vehicle is monitored as long as the main relays are closed. When the main relays are open then only the high voltage circuits of the ESS are monitored. The high voltage circuits of the vehicle then are monitored by engaging an auxiliary relay.
Hazardous voltage Interlock Loop		Manual Page 27: A hazardous voltage interrupt circuit is included to prevent access to the HV bus when hazardous voltage is present. At the ESS the HVIL is located inside the service lid “HV Fuses” and also in the HV connector. Opening the service lid or disconnecting the ESS HV connector opens the interlock and results in de-energizing the HV circuit.

The upper limit of the voltage in the HV circuit exceeds 450V		Manual Page 56: Safety Instructions for vehicles installing the ESS: · HV-Interlock-Loop functionality: A short circuit of the HVIL outside the ESS is not detectable by the HVIL function of the ESS. · The upper limit of the voltage in the HV circuit shall not exceed 450V. · The wiring harness (wire cross section, insulation) to HV-components shall be designed with adequate dimensions and adequate fuse protection. · In case of crash the LV Signal CON+ of the ESS shall be switched off to interrupt the power supply of the main contactors.
Low isolation resistance on battery side	The battery pack is set into deep discharge mode	Manual Page 62: In case of a low isolation resistance on battery side, the battery pack is set into deep discharge mode where all the cells are discharged through the balancing resistors. · If the self-test of the isolation monitor fails, all error flags are set and 0Ohm/V will be output.
Overcurrent	Deactivation of the battery from the external HV-circuit via the fuse/ Main Contactor switches	Manual Page 101: Overcurrent Monitoring (OCM) performs a controlled, selective deactivation of the battery from the external HV-circuit via the fuse and the main-contactors if the current limits for normal operation are violated. Therefore, OCM protects the HV components from damage in overload situations. The deactivation strategy is performed by the BMU via timing-control of the Main Contactor switches. Moreover, both current directions are considered although high loads are mostly expected for discharge which is also the preferred orientation (current wise) of the relay-contacts switch mechanism. Deactivation limits are safely detected via a 2 channel (redundant) current measurement with respect to measurement tolerances.

Accumulated energy exceeds 925 Ah	Set to its safe state immediately by the sequential deactivation of the main contactors.	Manual Page 103: In case the accumulated energy exceeds 892Ah a warning is sent via CAN to the vehicle control unit. One second later the system is deactivated by first turning off the negative main contactor and afterwards the positive main contactor. In case the accumulated energy exceeds 925Ah the system will be set to its safe state immediately by the sequential deactivation of the main contactors. If the system has been deactivated due to excessive energy draw re-enabling is granted when the energy falls below 800Ah. The energy model will not reach the CAN warning boundary nor the immediate deactivation boundary in case of the current flow depicted in figure 70 in order to permit power control by SOP.
Main contactor welded		Manual Page 108: Contactor Diagnostics for Stuck At Faults (Contact Open or Closed) are performed and DTCs according to [14] are set. The status of the Stuck At Faults (Contact Closed) is provided on CAN (CAN_PNHV_BatCutSw_Err). Contactor welded evaluation for pos. and neg. main contactor is done by voltage measurement evaluation before contactor enabling is permitted. Therefore, the voltages across the positive and negative main contactor are checked against 14V to detect open contacts.
Main contactor dirty		Manual Page 108: Moreover, a contactor dirty detection is performed in parallel to the welded diagnosis. The dirty detection detects a high leakage current while all contactors are open. The status of the contactor can be read via the diagnostic job "Contactor Status" (22 D0 00) whereas the sequence described in figure 93 has to be executed to obtain meaningful values.

Abuse conditions	Manual Page 28: Due to safety measures (e.g., isolation, touch protection, potential equalization, etc.) the ESS is not dangerous within normal range of use. Risk of touching live parts can only be present when the ESS is mechanically, thermally or electrically abused or insufficient care is taken. Abuse conditions: · Temperature above 100°C · External short circuit · Internal short circuit · Severe mechanical shock or damage · Overcharge (at least one cell voltage above 3.8V) · Charge after deep discharge (at least one cell voltage below 1.5V) · Reversing the electrical system polarity

Based on the manuals of the individual components, functions and potential failures have been derived. They are summed up and illustrated in Figure 77.

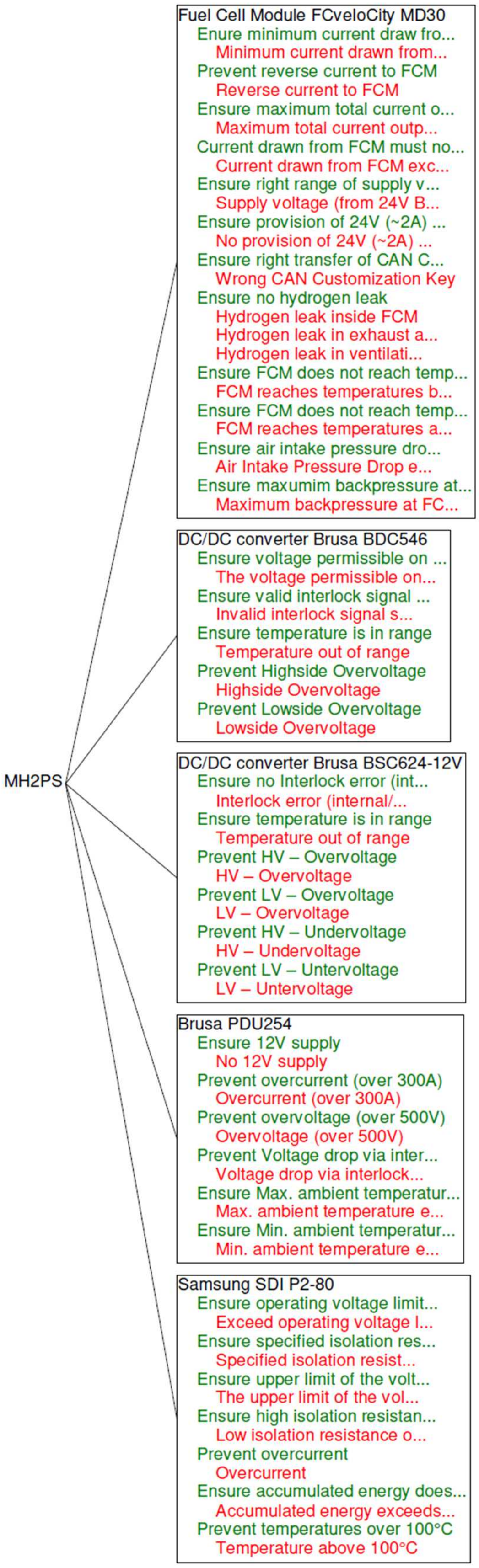

Figure 77: Possible functions and failures of components derived from their manuals

5.6 Derivation of Functions out of the Operating Strategy

Based on the operating strategy explained in chapter 2, an analysis of the function sequences of the individual operating modes is carried out.

5.6.1 Charge EV (Shot)

For operating mode “Charge EV (Shot)”, both options are analysed. On the one hand, electrical energy can be transferred from FCM to EV and on the other hand electrical energy can be transferred from FCM to EV and SB simultaneously.

Electrical Energy Provision from FCM to EV

Figure 78 illustrates the electrical energy provision from FCM to the EV. After a successful handshake with the EV, the operating mode “Charge EV (Shot)” can be selected. If the SOC of the SB is above its threshold value, or if not enough power can be drawn from the fuel cell, electrical energy from FCM is only transferred to the EV and not to the SB.

In order to process the electrical energy output of the FCM (I_out(FCM), U_out(FCM)), the control unit of the MH_2PS (VCU) needs information from the EV. The EV sends the SOC (SOC(EV)), the desired input voltage (U_in(EV)) and the desired input current (I_in(EV)) via CCS or CHAdeMO cable to the connector base of the MH_2PS. The information is then transferred to the VCU where the electrical energy output of the FCM is processed and sent to the FCM where the electrical energy conversion takes place. The power output of the FCM is transferred via power distribution unit (PDU) to the DC/DC converter BDC546 (consumer side). In the DC/DC converter, the output voltage of the FCM (U_out(FCM)) is converted to the desired input voltage of the EV (U_in(EV)). To process the conversion of the output voltage level from the FCM to the input voltage level of the EV, the VCU needs information from the EV, which is transferred to the VCU via connector base. After the voltage conversion in the DC/DC converter, the desired input voltage and input current is transferred to the EV via CCS or CHAdeMO cable.

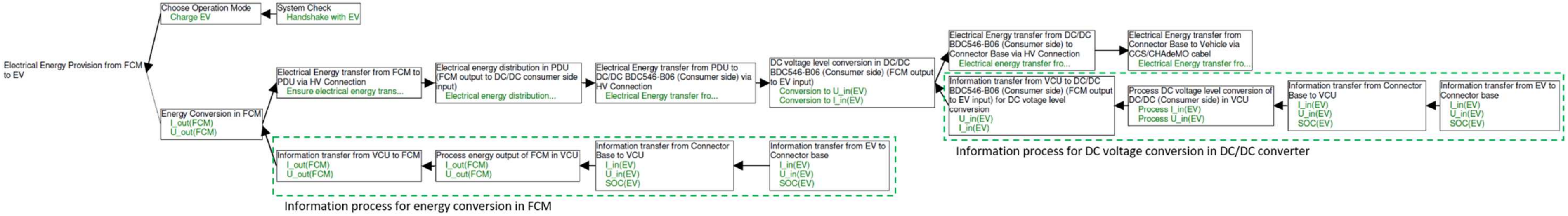

Figure 78: Electric energy provision from FCM to EV

Electrical Energy Provision from FCM to EV and SB

Figure 79 illustrates the electrical energy provision from FCM to the EV and SB. After a successful handshake with the EV, the operating mode “Charge EV (Shot)” can be selected. If the SOC of the SB is below its threshold value and if enough power can be drawn from the fuel cell, electric energy is transferred from FCM to EV and SB simultaneously.

In order to process the electric energy output of the FCM (I_out(FCM), U_out(FCM)), the control unit of the MH_2PS (VCU) needs information from the EV and the SB. The EV sends the SOC (SOC(EV)), the desired input voltage (U_in(EV)) and the desired input current (I_in(EV)) via CCS or CHAdeMO cable to the connector base of the MH_2PS. The information is then transferred to the VCU. The SB sends the SOC (SOC(SB)), the desired input voltage (U_in(SB)) and the desired input current (I_in(SB)) to the VCU. In the VCU, the electrical energy output of the FCM is processed based on the information input from EV and SB. It is sent to the FCM where the electrical energy conversion takes place. The power output of the FCM is transferred via power distribution unit (PDU) to both DC/DC converters BDC546 (consumer side and battery side).

In the DC/DC converter on consumer side, the output voltage of the FCM (U_out(FCM)) is converted to the desired input voltage of the EV (U_in(EV)). To process the conversion of the output voltage level from the FCM to the input voltage level of the EV, the VCU needs information from the EV, which is transferred to the VCU via connector base. After the voltage conversion in the DC/DC converter on connector side, the desired input voltage and input current is transferred to the EV via CCS or CHAdeMO cable.

In the DC/DC converter on battery side, the output voltage of the fuel cell module (U_out(FCM)) is converted to the desired input voltage of the SB (U_in(SB)). To process the conversion of the output voltage level from the FCM to the input voltage level of the SB, the VCU needs information from the SB, which is transferred from SB to VCU. After the voltage conversion in the DC/DC converter on battery side, the desired input voltage and input current is transferred to the SB, where the energy is stored.

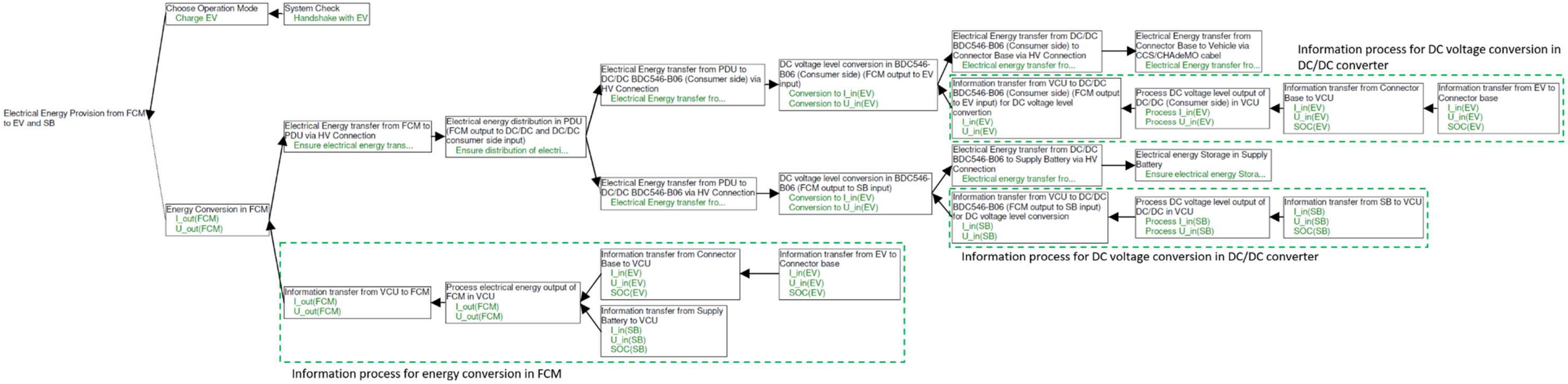

Figure 79: Electric energy provision from FCM to EV and SB

5.6.2 Charge EV (Shot-boost)

Figure 80 illustrates the electrical energy provision from FCM to the EV and SB. After a successful handshake with the EV, the operating mode “Charge EV (Shot-boost)” can be selected. If the SOC of the SB is above its threshold value and power can be drawn from the fuel cell, both FCM and SB provide electrical energy to the EV.

In order to process the electric energy output of the FCM (I_out(FCM), U_out(FCM)), the VCU needs information from the EV and the SB. The EV sends the SOC (SOC(EV)), the desired input voltage (U_in(EV)) and the desired input current (I_in(EV)) via CCS or CHAdeMO cable to the connector base of the MH_2PS. The information is then transferred to the VCU. The SB sends the SOC (SOC(SB)), the desired input voltage (U_in(SB)) and the desired input current (I_in(SB)) to the VCU. In the VCU the electrical energy output of the FCM is processed based on the information input from EV and SB. It is sent to the FCM, where the electrical energy conversion takes place.

For the electric energy output of the SB (I_out(SB), U_out(SB)), the VCU needs information from both, the SB and the EV. The EV sends the SOC (SOC(EV)), the desired input voltage (U_in(EV)) and the desired input current (I_in(EV)) via CCS or CHAdeMO cable to the connector base of the MH_2PS. The information is then transferred to the VCU. The SB sends the SOC (SOC(SB)), the possible output voltage (U_out(SB)) and the possible output current (I_out(SB)) to the VCU. Based on this information, the VCU processes the electric energy output of the SB. The power output of the SB is transferred to the DC/DC converter BDC546 (battery side). The DC/DC converter then converts the output voltage level of the SB to the output voltage level of the FCM.

The power output of the FCM and SB is transferred via PDU to the DC/DC converter BDC546 (consumer side). In the DC/DC BDC546 converter on consumer side, the output voltage of the FCM (U_out(FCM)) and SB (U_out(SB)) is converted to the desired input voltage of the EV (U_in(EV)) and transferred to the EV via CCS or CHAdeMO cable.

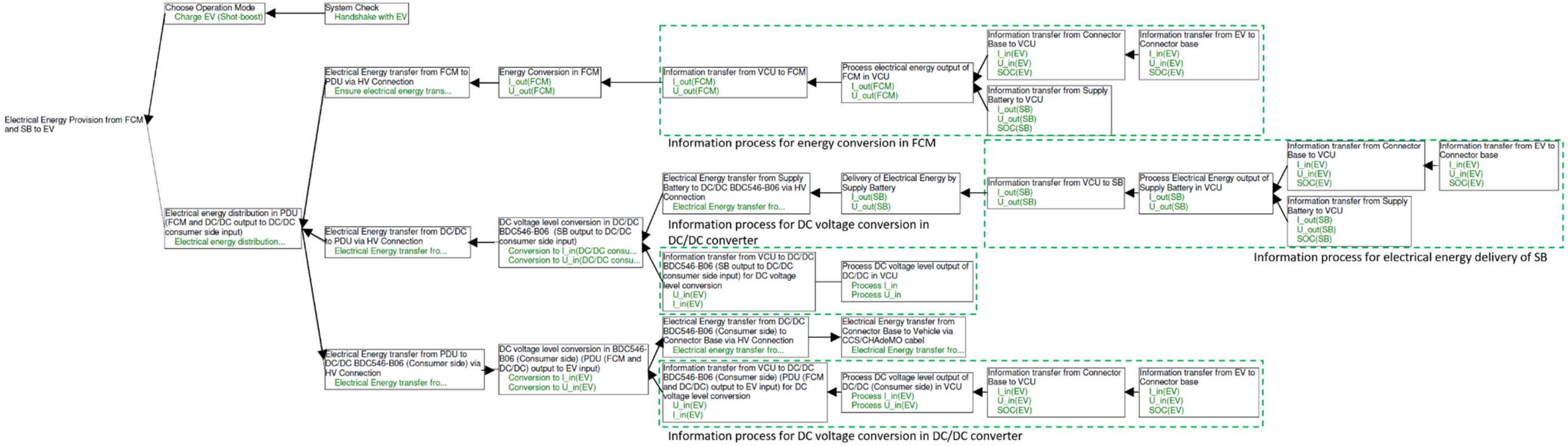

Figure 80: Electric energy provision from FCM and SB to the EV

5.6.3 Charge SB

Figure 81 illustrates the electric energy provision from FCM to the SB. If no EV is linked to the MH_2PS and the SOC of the SB is low, the operating mode "Charge SB" can be selected.

In order to process the electric energy output of the FCM (I_out(FCM), U_out(FCM)), the VCU needs information from the SB. The SB sends the SOC (SOC(SB)), the desired input voltage (U_in(SB)) and the desired input current (I_in(SB)) to the VCU. In the VCU, the electric energy output of the FCM is processed based on the information input from the SB. It is sent to the FCM, where the electric energy conversion takes place. The power output of the FCM is transferred via PDU to the DC/DC converter BDC546 (battery side).

In the DC/DC converter on battery side, the output voltage of the fuel cell module (U_out(FCM)) is converted to the desired input voltage of the SB (U_in(SB)). To process the conversion of the output voltage level from the FCM (U_out(FCM)) to the input voltage level of the SB (U_in(SB)), the DC/DC converter needs information, which is processed in the VCU. After the voltage conversion in the DC/DC converter on battery side, the desired input voltage and input current is transferred to the SB where the energy is stored.

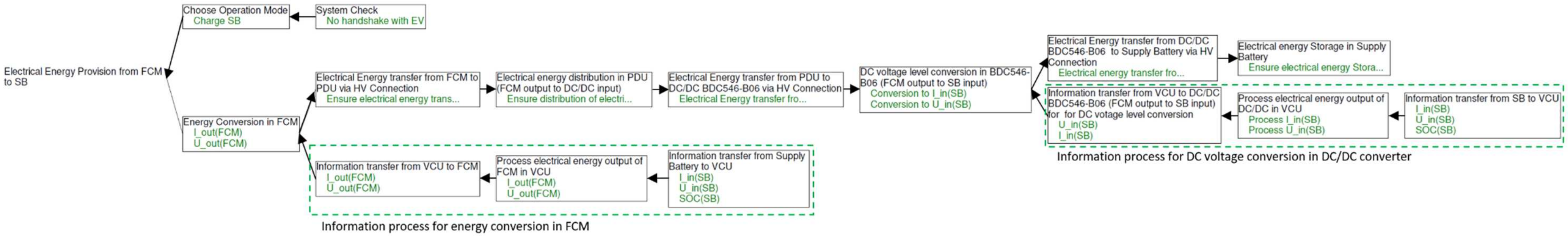

Figure 81: Electric energy provision from FCM to SB

5.6.4 Discharge SB

Figure 82 illustrates the electrical energy provision from SB to the EV. After a successful handshake with the EV, the operating mode “Discharge SB” can be selected. This may be necessary if no power can be drawn from the fuel cell or if in case of service reasons the supply battery needs to be discharged.

The EV sends the SOC (SOC(EV)), the desired input voltage (U_in(EV)) and the desired input current (I_in(EV)) via CCS or CHAdeMO cable to the connector base of the MH_2PS. The information is then transferred to the VCU. The SB sends the SOC (SOC(SB)), the possible output voltage (U_out(SB)) and the possible output current (I_out(SB)) to the VCU. Based on this information the VCU processes the electrical energy output of the SB. The power output of the SB is transferred to the DC/DC converter BDC546 (battery side). The DC/DC converter then converts the output voltage level of the SB.

The power output of the SB is transferred via PDU to the DC/DC converter BDC546 (consumer side). In the DC/DC BDC546 converter on consumer side, the output voltage of the SB (U_out(SB)) is converted to the desired input voltage of the EV (U_in(EV)) and transferred to the EV via CCS or CHAdeMO cable.

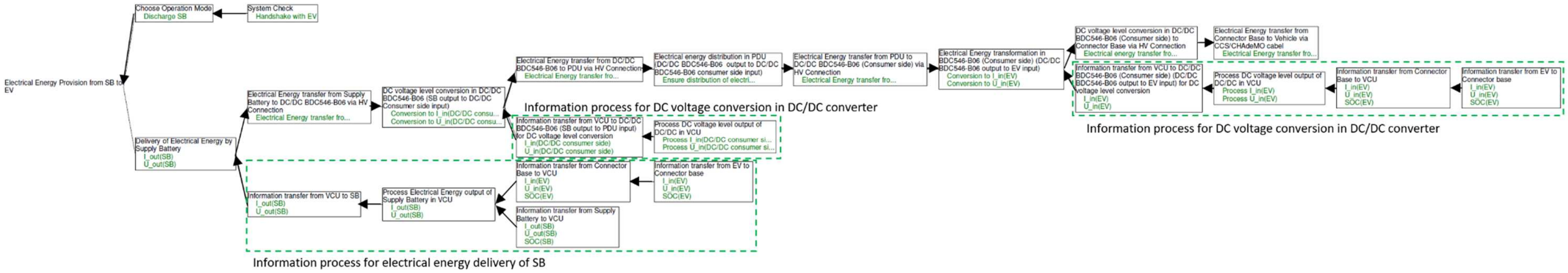

Figure 82: Electrical energy provision from SB to EV

6 Conclusion

Electric mobility is a key measure to decarbonise traffic. Battery electric vehicles have the potential of significantly reducing air pollution by having zero tail pipe emissions. However, major disadvantages of EVs are the relatively low driving range compared to a conventional automobile and a charging infrastructure that is still in an ascent stage of development. Another obvious drawback of EVs is that in case of an empty battery, the EV usually needs to be towed off to the next charging station, which is time-consuming and costly. Therefore, EV drivers try to avoid this situation by all means, which is negatively affecting the overall comfort and usability of EVs. By developing the MH_2PS system, Magna Steyr is taking an important step towards the solution of this challenging problem. The MH_2PS system is based on a commercial car trailer and is designed to provide zero emission mobile charging of EVs. It contains a compressed hydrogen storage system, a fuel cell module, a high voltage battery and high voltage power electronics. Naturally, high voltage and compressed hydrogen represent potential hazards that have to be considered in the development of the system's safety concept. In order to aid this development process, the overall objective of this thesis is to provide information and data for the functional and safe development of the MH_2PS system according to ISO 26262 as well as for an upcoming FMEA process.

As a first step in the concept phase of ISO 26262, the scope, items and functions have to be defined. The functional requirements of the MH_2PS-system are narrowed down to two functions. (1) “Hydrogen conversion”, which is carried out by a fuel cell module and (2) “Electrical energy distribution”, which is carried out by the power distribution unit in combination with DC/DC-converters. However, the early stage of development of the project did not allow a completion of the item definition and further development according to ISO 26262, as necessary information, e.g. the operating strategy of the MH_2PS, is not yet defined. Nonetheless, the development according to ISO 26262 can be continued in a later stage of the project based on the collected data in the present thesis.

Engineers in charge of the system's safety development need to determine and evaluate potential hazards and associated risks. The FMEA provides a valuable support in this matter. With the help of this tool, relevant risks can be analysed and state of the art measures for hazard prevention can be determined based on the intended functions and the expected product usage. One aim of the present thesis is to provide essential data for the FMEA. The FMEA process itself will be performed by Magna Steyr in an upcoming development stage.

Part of the data needed for the FMEA is concerned with the system's component interfaces. One such interface represents the compressed hydrogen path between the pressure vessel and the fuel cell. This thesis provides a design suggestion for this interface including a structural analysis of the relevant parts.

Furthermore, functions, possible failure modes and safety requirements of components need to be identified prior to the FMEA. Their potential effects on the overall system safety will be evaluated and measures to reduce the risk will be implemented in future project steps. To derive these functions, failure modes and safety requirements, the manuals of the system components are examined in the present work. The components used in the MH_2PS are customary and intended for the use in such a system environment. Therefore, selected safety relevant failure modes, e.g. the exceeding of operating voltage or current limits, are already addressed by the components themselves. These failures either result in a controlled shutdown of the component or in triggering a fuse. In the present work, it was determined, which failure modes fall into this category, and which of those need to be handled separately by the integrator.

Many potential failures in the system can be avoided by a suitable operating strategy. Another major focus in the future development of the MH_2PS has to be laid on the definition of a suitable operating strategy. For this purpose, the functional sequences of predefined individual operating modes are analysed and evaluated in view of critical aspects concerning the development of operation strategies.

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10 Appendix

BALLARD®

PUTTING FUEL CELLS TO WORK

FCveloCity®–MD

Fuel Cell Power Module for Heavy Duty Motive Applications

Description

Ballard's 30kW FCveloCity®-MD module was developed for use in zero-emission, battery dominant hybrid, heavy duty motive applications. The hydrogen fuelled power module is sized for smaller transit vehicles, and offers a low risk, versatile and easy installation solution for system integrators, with a design based on many years of transit experience, and backed by Ballard's unmatched expertise and experience.

Features

High Performance – robust PEM fuel cells deliver the route flexibility, range, gradeability and top speeds demanded by transit operators.

Flexible Integration – modular design with separate air sub-system enables flexible integration of components into the vehicle drive train and easy access for enhanced serviceability. The coolant pump is also included in the scope of supply.

High Temperature Operation – permits a smaller cooling package for integration flexibility and generates HVAC heating, significantly improving overall vehicle fuel economy.

High Pressure System – offers better performance, fuel efficiency and durability by preventing degradation of the fuel cell power module.

Fuel Efficiency – two to three times more efficient than CNG/diesel engines, fuel cell buses reduce overall fuel consumption.

Remote Diagnostics – wireless or direct connection provides access to performance data anytime on the road as well as in the service bay, enabling anticipation of required maintenance.

Proven Reliability & Durability – demonstrated through exceptional bus availability and fuel cell module lifetime, with >20,000 hours of operation of a fuel cell power module in the field without failure.

Safety features – Integrated safety system with ventilation fans, H2 sensors, and smoke detectors built into the module to ensure highest safety and ease of installation.

System Integration Flexibility – collaborating closely with the system integrator, Ballard supports the integration of a variety of drive systems to optimize the transit application.

Zero-emission – PEM fuel cell power module to meet the mandates set by policy makers to reduce transportation emissions.

Humidification - integrated humidification system is maintenance free and provides maximum system performance and durability through a wide range of environmental conditions.

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FCveloCity®-MD

PRELIMINARY PRODUCT SPECIFICATIONS

Technology	Fuel cell	Proton exchange membrane
Performance	Rated net power	30 kW
	Operating DC voltage range	85 - 180V
	Current	0-300 A
Physical	Dimensions (l x w x h)	900 x 480 x 375 mm[1]
	Weight	125 kg (fuel cell module)
Fuel	Type	Gaseous hydrogen
	Composition	As per SAE specification J2719
Operation	Oxidant	Air
	Stack coolant	50/50 pure ethylene glycol and deionized water WEG 60° to 70°C
	Fuel supply pressure	8 barg nominal
	Fuel flow rate	0.7 g/s maximum
Safety Compliance	Design Standards	ISO 6469-2:2009[2], ISO 6469-3:2009[2] and ISO 23273:2013[2]
	Enclosure	IP55
Monitoring	Control interface	CANbus
Emissions	Exhaust	Zero-emissions (no PM, NOx, SOx, CO or CO_2)
	Sound level	Less than 75 dBA

Options

Freeze protection
Ground fault monitor

[1] Freeze protection option adds 60mm in all dimensions
[2] Specific clauses within each standards

Sub-system

The FCveloCity®-MD includes a separate air-sub systems for simplified and flexible integration into the electric drive system. The air sub-system delivers air at a prescribed flow rate to the fuel cell stack to support the electrochemical reaction. Sub-system includes motor, controller, air compressor and a mass flow sensor.

BSC6 - Bidirectional Auxiliary Supply Converter

The most efficient and versatile alternator ever

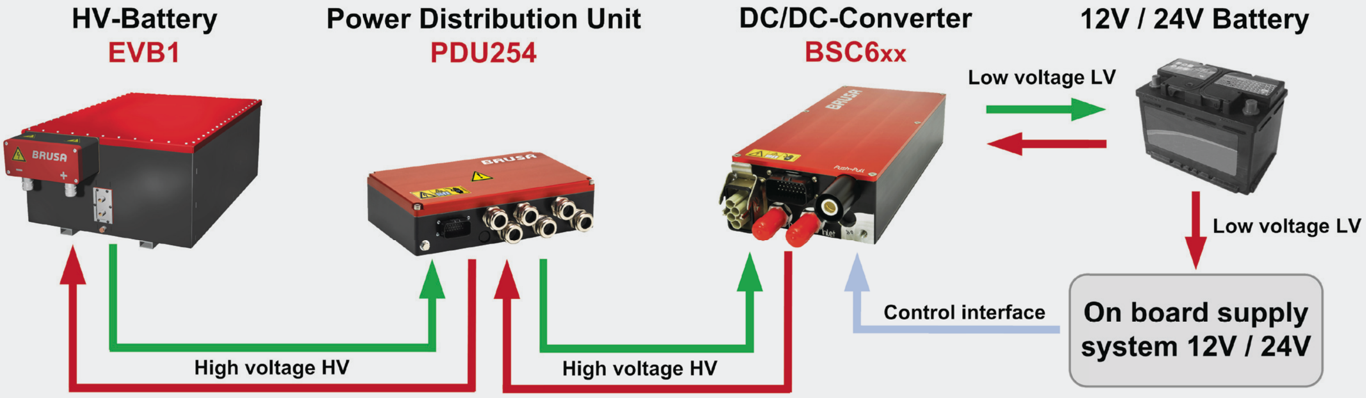
Features at a glance

- Bidirectional operation
- Resonant topology ensures very low switching losses and excellent EMC-behavior
- Very high efficiency (up to 96%)
- Very compact and lightweight
- Fully automotive compliant
- PARAM-tool offers comprehensive configuration options and diagnostic function
- Optional operation without CAN (CAN-less mode)

What makes it special - benefits through bidirectional operation

- In fuel cell applications it allows to start-up the fuel cell auxiliary circuits on the HV-side right from the 12 V / 24 V supply system
- Enables emergency recharge of traction battery via common jump-start-cable
- Increases availability of vehicle when traction battery system fails since the converter provides energy from the 12 V / 24 V supply system

Application example



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BRUSA

Specifications BSC6xx

High voltage side	BSC623-12V	BSC624-12V	BSC614-24V	BSC618-24V	BSC628-12V	
High voltage range	170 - 425	220 - 450	220 - 450	400 - 900	400 - 900	VDC

Low voltage side	BSC623-12V	BSC624-12V	BSC614-24V	BSC618-24V	BSC628-12V	
Nominal low voltage	14.0	14.0	28.0	28.0	14.0	VDC
Low voltage range	8 - 16	8 - 16	16 - 32	16 - 32	8 - 16	VDC

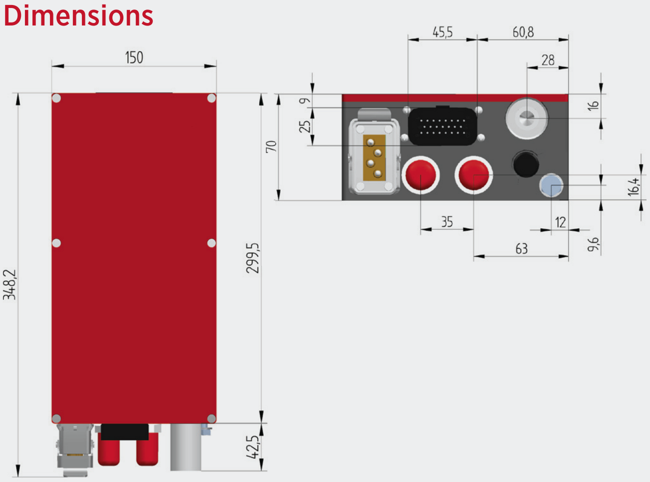
Performance	BSC623-12V	BSC624-12V	BSC614-24V	BSC618-24V	BSC628-12V	
Continuous low voltage current (@ $T_{coolant}$ = 65°C)	200	200	100	100	200	A
Max. low voltage current	250	250	125	125	250	A
Continuous power (@ nominal low voltage)	2.8	2.8	2.8	2.8	2.8	kW
Max. power (@ nominal low voltage)	3.5	3.5	3.5	3.5	3.5	kW
Efficiency typical (@ nominal voltage)	93.5	94.4	96.0	95.9	94.7	%
Switching frequency buck / boost stage	30 - 135	40 - 150	44 - 150	44 - 157	44 - 168	kHz
Switching frequency transformer stage	220	197	205	192	181	kHz

Control circuit	BSC623-12V	BSC624-12V	BSC614-24V	BSC618-24V	BSC628-12V	
Voltage range for signals of control connector (AUX)	7 - 32	7 - 32	7 - 32	7 - 32	7 - 32	V
High voltage signal range	0 - 480	0 - 480	0 - 480	0 - 960	0 - 960	V
Low voltage signal range	0 - 20	0 - 20	0 - 40	0 - 40	0 - 20	V
High and low voltage signal accuracy (referring to scale end)	+/- 1	+/- 1	+/- 1	+/- 1	+/- 1	%
Current signal range	+/- 25	+/- 25	+/-25	+/- 12.5	+/- 12.5	A
Current signal accuracy (referring to scale end)	+/- 3.5	+/- 3.5	+/- 3.5	+/- 3.5	+/- 3.5	%

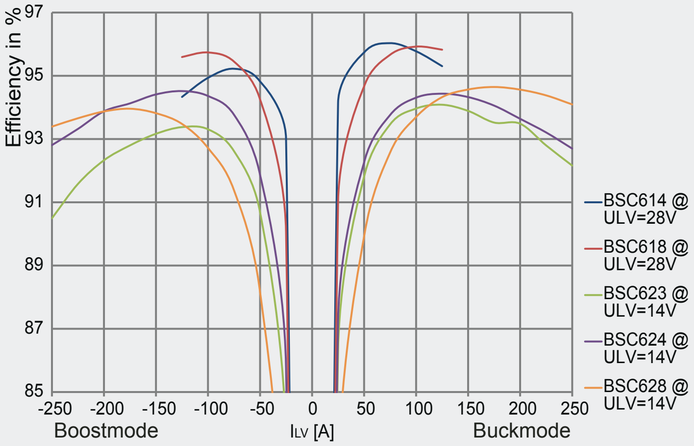
Mechanical data / Cooling system	BSC623-12V	BSC624-12V	BSC614-24V	BSC618-24V	BSC628-12V	
Weight	4.8	4.8	4.8	4.8	4.8	kg
IP - protection	IP65	IP65	IP65	IP65	IP65	---
Ambient temperature range (operation)	- 40 to + 85	- 40 to + 85	- 40 to + 85	- 40 to + 85	- 40 to + 85	°C
Coolant temperature range	- 40 to + 65	- 40 to + 65	- 40 to + 65	- 40 to + 65	- 40 to + 65	°C
Coolant flow rate	> 4	> 4	> 4	> 4	> 4	l / min
Pressure drop (@ nominal flow rate)	< 100	< 100	< 100	< 100	< 100	mbar

Galvanic insulation between high voltage circuit and low voltage circuit / user interface	BSC623-12V	BSC624-12V	BSC614-24V	BSC618-24V	BSC628-12V	
Test voltage (2 s)	2'700	2'700	2'700	4'000	4'000	VDC

Dimensions



Efficiency



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BDC546 - Bidirectional 750 V DC/DC-Converter

The new benchmark in power density

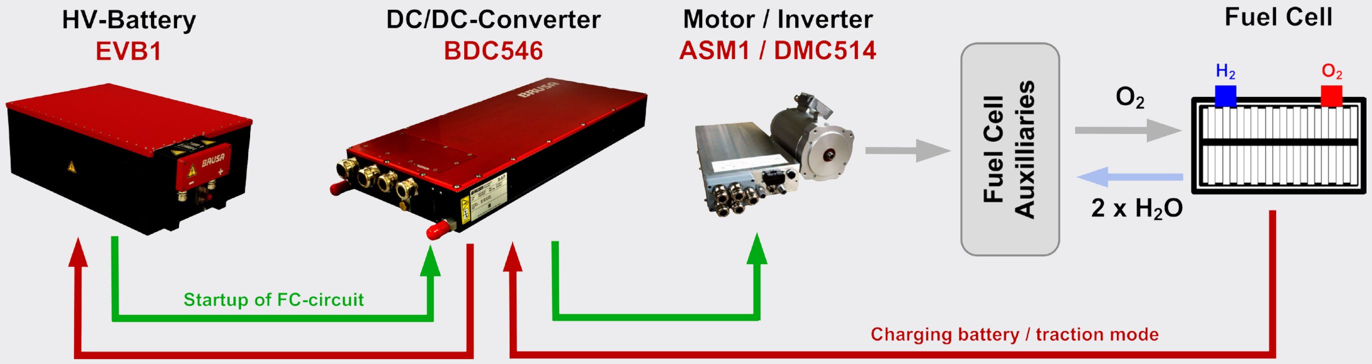
Features at a glance

- Resonant topology ensures very low switching losses and excellent EMC-behavior
- Very high efficiency (up to 99 %)
- Very high power density (6.4 kW / kg)
- Patented Liquid Pin© cooling system for optimal temperature behavior and performance
- Fully automotive compliant
- FPGA based very dynamic control loop

Unreached versatility

- In fuel cell applications, the bidirectional operation allows to start-up the fuel cell auxiliary circuits
- Adjustable regulators facilitate the implementation in a wide variety of applications
- In combination with a stationary transformer it makes up for a powerful yet sophisticated rapid DC-charging unit

Application example



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Specifications BDC546

Highside	BDC546	
Voltage range (full performance, highside must not be lower than lowside)	150 - 750	V_{DC}
Overvoltage (shut down of power stage)	800	V_{DC}
Max. voltage (no operation)	900	V_{DC}

Lowside	BDC546	
Min. voltage (start up)	0	V_{DC}
Voltage range (full performance)	50 - 600	V_{DC}
Overvoltage (shut down of power stage)	650	V_{DC}
Max. voltage (no operation)	900	V_{DC}

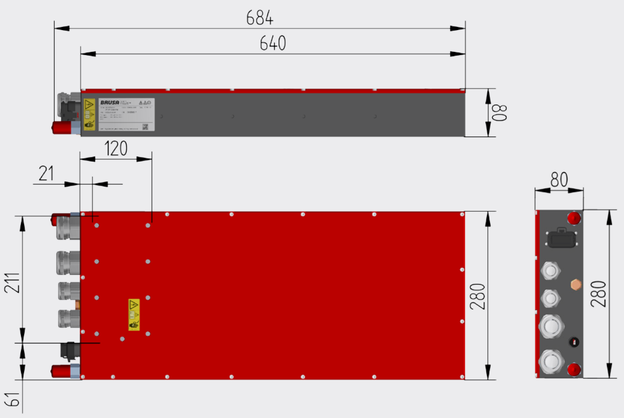
Performance	BDC546	
Continuous lowside current (@ $T_{coolant}$ = 60°C)	300	A
Max. lowside current	400	A
Continuous output power (@ U_{LS} = 600 V)	180	kW
Efficiency typical (in buck mode @ U_{HS} = 600 V, U_{LS} = 400 V, I_{LS} = 300 A)	98.9	%
Switching frequency	41	kHz

Control circuit	BDC546	
Voltage range for signals of control connector (AUX/clamp 30, Interlock, Enable/clamp 15)	9 - 16	V
Highside voltage signal range	0 - 1'020	V
Lowside voltage signal range	0 - 828	V
Highside and lowside voltage signal accuracy (1V or 1% of measured value, whatever is bigger)	+/- 1	V / %
Highside and lowside current signal range	+/- 400	A
Highside and lowside current signal accuracy (1A or 1% of measured value, whatever is bigger)	+/- 1	A / %

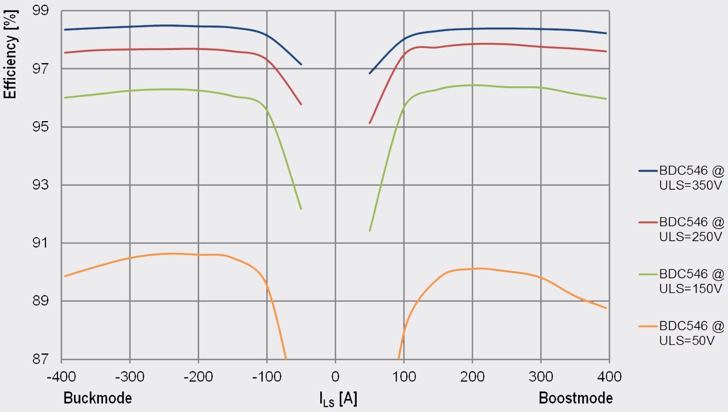
Mechanical data / Cooling system	BDC546	
Weight	25.2	kg
IP - protection	IP6K6, IP6K7	---
Ambient temperature range (operation)	- 40 to + 85	°C
Coolant temperature range	- 40 to + 65	°C
Coolant flow rate	> 15	l / min
Pressure drop (@ 15 l/min, $T_{coolant}$ = 25°C)	< 250	mbar

Galvanic insulation between high voltage circuit and user interface	BDC546	
Test voltage (2 s)	3'000	V_{DC}

Dimensions



Efficiency



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PDU254 - Power Distribution Unit

Simple, safe, multi-functional und compact

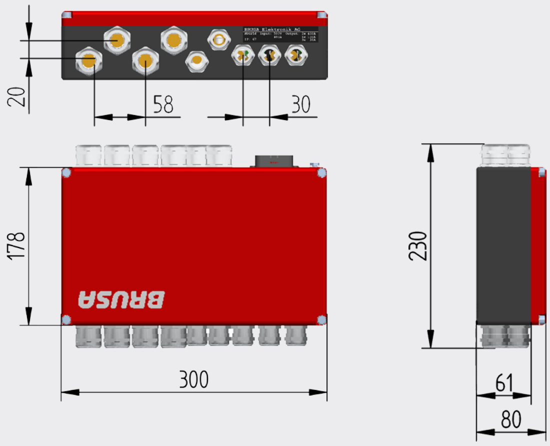
Safety first

- Active HVIL (HV - Interlock) with back signaling and HV - activation
- Isolated shorting link for shorting of the HV - circuit (e.g. for installation works)
- All pole fusing of all connected components

Advanced technology

- Possibility of parallel connection of two PDU available (cascading)
- Compact and lightweight design
- Connection of two HV - batterys possible
- 2 connections 300 A (fused) for inverter (e.g. DMC5)
- 1 connection 100 A (fused) for range extender (RXT) or DC fast charge
- 3 connections for more peripherals (e.g. charger, climatic - compressor, DC / DC converter etc.)

Dimensions



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Specifications PDU254

Electrical data

	PDU254	
Operating voltage	200 - 500	V
Max. switching current of contactors	6	A
Voltage for control signals (Pin = high)	7 - 15	V
Interlock current	10	mA
Voltage for interlock generator	- 48	V
Allowed voltage drop over interlock loop max.	30	V
Recommended cable cross - section for main connection 300 A and cascading	50	mm^2
Recommended cable cross - section for Range - Extender or DC - fast charge	25	mm^2
Recommended cable cross - section for small electric consumers (up to 24 A)	4	mm^2

Performance data at + 25°C

	PDU254	
Allowed peak current for max. duration 10 s	400	A
Continuous current: BATT - connection 1 + 2 to DMC - connection 1 + 2	300	A
Continuous current: BATT - connection 1 + 2 to RXT - connection	100	A
Continuous current: BATT - connection 1 + 2 to NLG - / BSC - / AUX - connection	20	A

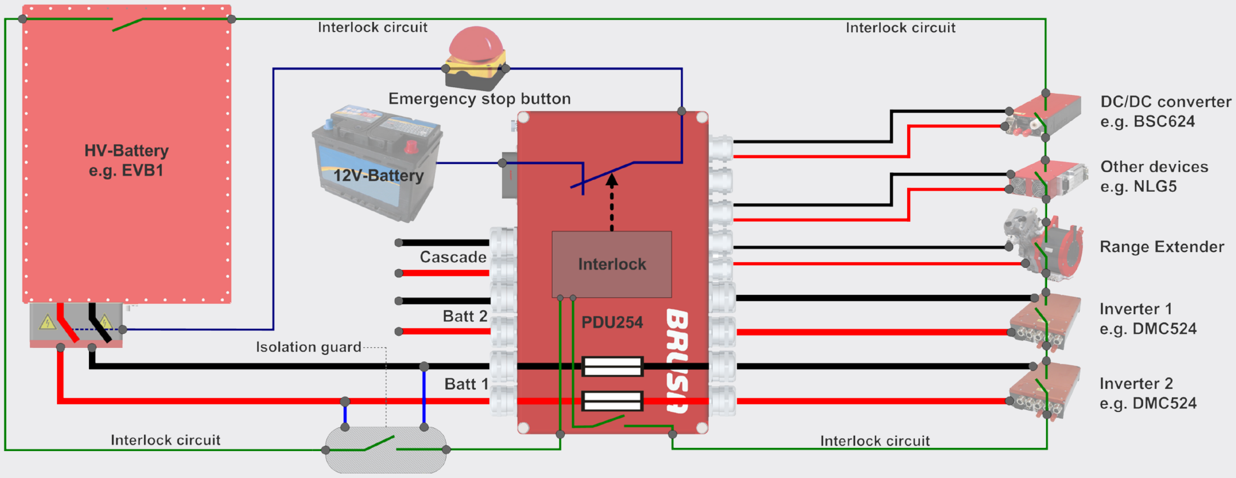
Mechanical data

	PDU254	
Material	AlMgSi1	---
Housing volume	4.16	l
System weight (incl. fuses)	3.9	kg
Weight fuse 300 A	200	g
Weight fuse 100 A	90	g
Weight fuse 20 A	10	g
IP - protection	IP68	---
Waterproof pressure equalizing membrane	yes	---

Thermal

	PDU254	
Ambient temperature min.	- 40	°C
Ambient temperature max.	+ 85	°C

Schema



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