EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

Techno-economic evaluation of hydrogen refueling stations with trucked-in gaseous or liquid hydrogen

Thomas Mayer[1*], Malte Semmel[1], Artur Bauer[2], Martin Guerrero-Morales[2], Karla Maria Schmidt[1], Jörg Wind[1]

[1]*Daimler AG, Neue Str. 95 - 73230 Kirchheim/Teck-Nabern – Germany, *thomas.ma.mayer@daimler.com*

[2]*NuCellSys GmbH, Neue Str. 95 - 73230 Kirchheim/Teck-Nabern – Germany*

Abstract

Fuel Cell Electric Vehicles have the potential of a greenhouse gas and air pollutants free mobility without compromising comfort compared to vehicles with combustion engine. In this study hydrogen refueling stations (HRS) with liquid and gaseous supplied hydrogen were investigated based on technical requirements and lifetime cost minimization aspects, including boil-off electrification via fuel cell of liquid stations. For both concepts, energy consumption including boil-off losses (at liquid HRS) or standby losses (at gaseous HRS), initial investment costs and specific hydrogen costs were calculated depending on ambient temperature, station capacity as well as station utilization. For highest possible accuracy the thermophysical properties were embedded by using a database from the National Institute of Standards and Technology (NIST). As a result, the investment costs, energy consumption (at high utilization) and specific costs of liquid supplied stations are lower than for gaseous supplied stations. A large liquid supplied station with 6 dispensers causes station costs of 0.47 € per kilogram dispensed compared to 0.93 € per kilogram dispensed (CGH_2). As liquefaction of hydrogen causes high energy consumption and costs, for a holistic comparison of both concepts, conditioning (compression vs. liquefaction) and transportation needs to be considered as well. Considering the entire hydrogen chain, liquid hydrogen causes higher energy consumption than gaseous hydrogen.

1 Introduction

Several hydrogen supply concepts like centralized production with pipeline, truck transportation or onsite-production are feasible for the supply of hydrogen for FCEVs. Because of the current relevance, liquid and gaseous trucked-in hydrogen refueling stations are analyzed in this study. To fill a car within 3 minutes with a pressure up to 87.5 MPa [1], hydrogen needs to be preconditioned at the HRS and a communication between HRS and FCEV via an infrared interface is necessary. Due to material requirements the temperature of the vehicle storage is limited to 85°C. To ensure a filling time of 3 minutes without exceeding the temperature limit, hydrogen is conditioned to the range from -33°C to -40°C [1] before filling the car. Different concepts and designs for compression, storage and thermal management are possible.

In the gaseous case, hydrogen can either be compressed directly from the low- or medium-pressure storage into the vehicle tank (so-called ‘boosting’) or compressed into a high pressure storage followed by an overflow process into the car. To reduce the energy consumption for the second case, the high pressure storage can be divided into several storage-vessels with different pressure levels (cascade-storage-system). In case that hydrogen is delivered and stored as a liquid, it needs either to be evaporated and compressed or directly compressed in the liquid phase with a pump. There are different approaches to handle the unavoidable hydrogen boil-off (evaporation caused by heat input from environment).

Existing research studies investigate either only parts of a refueling station [2-4] or a complete compressed gaseous hydrogen (CGH_2) refueling station [5-7]. In our simulation both concepts (CGH_2 and LH_2) are simulated and compared with each other. In the first step, layouts are techno-economically optimized based on lifetime costs (including boil-off use approaches) with current and projected performance indicators as well as cost data. In the second step, the optimized HRSs are analyzed in terms of energy consumption, investment and specific hydrogen cost.

2 State of Knowledge

2.1 Thermodynamics

The present paper uses common definitions of a thermodynamic system and its properties, thermodynamically defined by physical state variables (see [8], [9]). Furthermore the first and second law of thermodynamics as well as the law of conservation of mass are utilized and presumed to be known (for further information see [10], [11], [12]).

Effective compression energy was calculated by multiplying isentropic compression energy with the isentropic efficiency [13]:

$$w_{t,12} \approx \eta \, \frac{\kappa}{\kappa - 1} \, R_i \, T_1 \, \bar{Z} \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right] \tag{2.1}$$

η	isentropic efficiency
$w_{t,12}$	specific compression energy $[\frac{J}{kg}]$
R_i	specific gas constant $[\frac{J}{kg\,K}]$
$\bar{Z}$	averaged compressibility factor [-]
κ	isentropic exponent [-]

Heat transition between pressure vessels and environment was calculated quasi-stationary using a constant heat transfer coefficient. However heat transition between liquid hydrogen heat exchanger and environment was calculated transient using the one-dimensional heat conduction equation for a cylindrical temperature distribution [14]:

$$\frac{\partial T}{\partial t} = \frac{a}{r} \frac{\partial}{\partial r} \left(r \, \frac{\partial T}{\partial r} \right) \tag{2.2}$$

a	temperature conductivity $[\frac{m^2}{s}]$
r	radius $[m]$

Aiming representative calculations hydrogen is treated as real gas. For this purpose various approximations such as the van der Waals correction, gas equation with compressibility factor or virial coefficient calculation can be found in literature [12]. Leachman et al. [15] suggest equations of state (EOS) explicit in the Helmholtz free energy. Due to the high accuracy all hydrogen state calculations of this study are premised on the database of ‘National Institute of Standards and Technology’ (NIST) [16].

2.2 Hydrogen Refueling Station Performance Requirements

A significant advantage of H_2-powered vehicles over battery electric vehicles (BEV) is the duration of the refueling time. With a filling time of about three minutes, FCEVs receive their complete range-regeneration in the same magnitude as conventional vehicles [17]. For this purpose the guideline SAE TIR J2601 specifies a standardized refueling profile at defined fueling qualifications [1]. Varying refueling conditions (e.g. ambient temperature or initial onboard storage system pressure) influences the fueling process, because restrictive process requirements like safety aspects have to be adhered. Aiming at short refueling times, a significant pressure difference between onboard tank and HRS storage is necessary. Compression heat as well as hydrogen’s negative Joule-Thomson coefficient (in the relevant temperature/and pressure range of the refueling process) leads to heat generation during refueling. To ensure the stability of composite liner materials, the upper temperature limit inside the onboard vessel amounts 85°C. In order to satisfy this limit and simultaneously fulfill a vehicle refueling within three minutes, hydrogen is pre-cooled to temperatures ranging between -33°C and -40°C, before filled into the vehicle. After the filling process, the hydrogen in the vehicle tank is much warmer than ambience. The cool down of filled H_2 to ambient temperature results in an isochoric expansion. To prevent described underutilization of installed 70 MPa vessels, H_2 inside the FCEV is compressed to pressure levels higher than operating pressure (up to 87.5 MPa) [18]. Dependent on the ambient temperature the HRS must provide a pressure ramp according to SAE TIR J2601 [1]. The higher ambient temperature, the lower is the required pressure ramp. So refueling times of 3 minutes are feasible up to temperatures of about 10°C. In case of 34°C ambient temperature, the refueling time is about 6 minutes.

2.3 Existing Models

As currently most OEMs favor FCEV with 70 MPa onboard storage tanks [19] various studies investigate technological concepts of CGH_2 refueling and involved components. Hereby for example Cebolla et al. [20], Guo et al. [5], Hosseini et al. [21], Striednig et al. [22], Xiao et al. [2] or Yang [23] examine the refueling process and its thermodynamic behavior, including temperature analysis and prediction of pre-fueling temperature needed. Conceptual differences of single buffer storage in comparison to cascade storage systems are analyzed by Farzaneh-Gord et al. [3]. Additionally Serdaroglu et al. [4] survey the influence of environmental conditions on an external storage facility.

As a techno-economic analysis of hydrogen refueling, Nistor et al. [24] present a thermodynamically significantly simplified simulation (e.g. by using Van der Waals state equations or setting a fixed energy consumption value for cooling) of a complete CGH_2 refueling station with onsite hydrogen generation. Reddi et al. [6] also expand the observation on the whole hydrogen refueling station. Tube trailer refueling, pressurizing unit and high pressure storage vessels as well as the interdependency of the modules were reviewed and also valued economically. Rothuizen et al. [7, 25] established a dynamic HRS simulation model to predict a thermodynamically efficient high pressure storage design (number of tanks, volume and pressure level).

Although hydrogen refueling stations with trucked in LH_2 which process liquid hydrogen to compressed gaseous hydrogen for filling 70 MPa applications exist already (e.g. in Detmoldstrasse in Munich, Germany [26]), studies on described layout are rare. Petitpas et al. [27], Brown et al. [28] and Elgowainy [29] however examine HRS concepts with LH_2 input and CGH_2 output, but study energy-intensive architectures, where liquid hydrogen is first evaporated, then compressed in the gaseous phase and afterwards refrigerated in order to fulfill refueling demands. More efficient configurations (see chapter 3.2), like provided for example by the Linde Group [26], use cryogenic pumps for low-energy compression starting in the liquid phase, hence the systems require less power for thermal management.

To the authors' knowledge, a complete energetic study of gaseous and liquid supplied hydrogen refueling stations with influencing ambient parameters as well as varying utilization cases, has not been conducted. Especially the representative comparison of both technological concepts, reached by evaluating the energy consumption of HRS and implemented components – using a dynamic simulation model based on the stations thermodynamics – has not been investigated.

3 Dynamic simulation model

3.1 Simulation Methodology

In order to investigate both technologies, compressed gaseous as well as liquid HRS, a dynamic simulation is created. In contrast to previous work, the present paper compares the architectural concepts with the same underlying influences as station utilization or ambient conditions. Therefore both configurations were modeled and simulated in various scenarios.

To evaluate the energy consumption of refueling concepts the thermodynamics of specified components are elaborated to facilitate the generation of a complete hydrogen refueling station, aggregating analyzed parts and functionally linking individual sub-modules. As a result, the dynamic simulation allows the exploration of different station configurations under varying and individually modifiable influencing parameters.

The simulation is functionally constructed as backward simulation. Instead of modelling the vehicle tank the simulation complexity is reduced by using predefined profiles for the refueling mass flow, provided and considered as representative by the standard SAE J2601 [1]. Thus, the HRS component modules use the required mass flow as calculation input. Furthermore, related thermodynamic properties are identified. Hydrogens thermophysical properties are embedded by using a database from NIST [30].

3.2 Station layout CGH_2 and LH_2

The given system inputs of the hydrogen refueling station models are: required hydrogen mass flow, pressure, refueling temperature and HRS layout parameters. Figure 1 and Figure 2 show the simulated station architectures with information flow, containing the required H_2 amount or details, considering the state variables of communication components, as well as the evoked H_2 mass flow with related thermophysical properties.

Gaseous trucked-in HRS

In this study, the concept with a 5MPa low-pressure storage is investigated. Besides this concept, also low-pressure storages with higher pressure are possible. Beneficial is the lower electrical energy consumption – due to lower compression ratios- whereas higher costs for the storage itself are disadvantageously. The capacity of the storage is determined by fulfilling the requirement to serve the station one day with hydrogen at full utilization (see "Friday fueling amount" [1] in Figure 3, chapter 5) incl. a safety buffer of 20% while not coming below a minimum pressure of the compressor (0.5MPa). For compression, a 5-stage compressor (e.g. Linde IC-90, [31]) with cooling after each stage is applied. The compression process of each stage is calculated isentropic with an isentropic efficiency. The high number of compression stages and the cooling after each stage approaches the overall compression process towards an isothermal compression. The precooling temperature in the simulation is exactly the current temperature of the high-pressure storage that is currently filled. This assures the same temperature of the high-pressure storage after a depletion and filling process (excepting small differences due to heat input from ambient). The high-pressure storage system consists of 3 storage tanks - with different capacities and maximum pressures - that are intelligently interconnected (for more information regarding such a "cascade storage system", see [3]). The car filling process starts by depleting the high-pressure storage with the lowest pressure. As soon as vehicle storage pressure and HRS storage pressure approach each other, the storage with next higher pressure continues the filling process etc. The advantage of splitting one big storage to several storages and depleting one by one is

---

[1] Highest amount of hydrogen is fueled on Friday

that the first storages can be depleted below final car storage pressure. Thus, a higher amount of hydrogen can be filled into the car storage with an identical total capacity of the cascade storage. Thus the capacity of a “cascade storage system” can be lower. The effect of lower maximum pressure of the first storage results in lower compression energy, lower cooling demand due to a less severe Joule-Thomson effect, lower specific storage costs (per mass) but also in higher required capacities because of the smaller gap between storage pressure and target pressure. Thus external effects like electric energy consumption of the compressor, electricity prices and storage costs influence the best configuration. Therefore, the configuration is optimized including these influencing parameters (see chapter 4).

When refilling the cascade storage system the pressure vessel with the highest maximum pressure is being refilled first. This guarantees the highest possible supply reliability. Each vessel is being filled until its initial mass. To avoid exceeding of the maximum pressure the compressor’s outlet temperature is set to the temperature in the vessel. As temperature inside the vessel decreases during depletion - and only rises back to original temperature as soon as the vessel is being refilled - the heat transfer from the environment leads to a small rise of the temperature. To minimize this effect to an insignificant level, each pressure vessel is coated with a thin insulation shell. The outflowing hydrogen is cooled down (see chapter 2.2). by a cooling system consisting of a chiller unit and a heat exchanger. The heat exchanger in form of an aluminum block with a high thermal capacity is hold at -50°C.After filling a car, temperature of the block goes up and the chiller unit has time to restore the block until the next car comes. So the chiller unit can be downsized compared to a concept without a thermal storage. Standby-losses caused by heat input into aluminum block and dispensing line are included in the model. The electricity consumption caused by the periphery like payment unit is neglected.

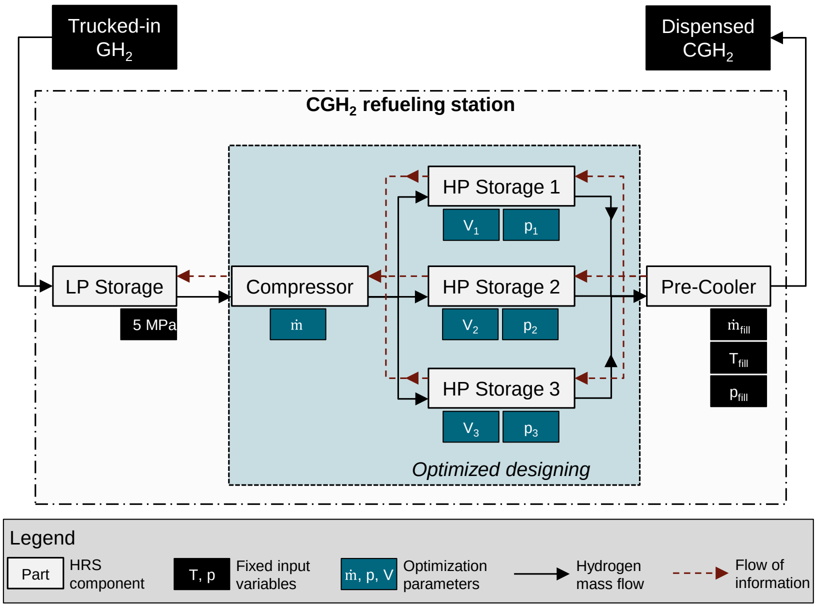

Figure 1: Schematic of a hydrogen refueling station with trucked-in gaseous hydrogen.

Liquid trucked-in HRS

The configuration of a LH_2-HRS is similar to the CGH_2-HRS as illustrated in Figure 2Figure 6. The main differences are the H_2 storing condition in liquid form, H_2 heat up before filling the high pressure storages and the mixing of cold and warm H_2 by a control valve to target temperature before filling the car.

Stored liquid hydrogen is assumed to be in thermodynamic equilibrium and thus boiling at a temperature of about -253°C. Heat input from ambient leads to evaporation and pressure increases. The maximum pressure in this study is set to 0.35 MPa. To avoid pressures above 0.35 MPa, so called “boil-off” hydrogen is let out of the storage and used in a fuel cell to generate electricity. The liquid hydrogen pump compresses the liquid hydrogen to pressures up to 90 MPa (> 87.5 MPa to ensure an overflow process into the car storage). This process is assumed to be isentropic. After compression the supercritical hydrogen need to be warmed up until at least -40°C (minimum temperature of car filling process). Therefor an air heat exchanger is used due to the cost-free heat input. The length of the heat exchanger is set by fulfilling the requirement to permanently (back-to-back refueling) warm-up hydrogen to -40°C at ambient temperature of -10°C. For temperatures below -10°C an electric heater warms-up hydrogen after the heat exchanger to -40°C. Icing, resulting from air condensation is neglected in the model. The high-pressure storage is modelled identically to the high-pressure storage of the gaseous delivered HRS as the functionality is the same. The electricity consumption caused by the periphery like payment unit is neglected (same for gaseous delivered stations).

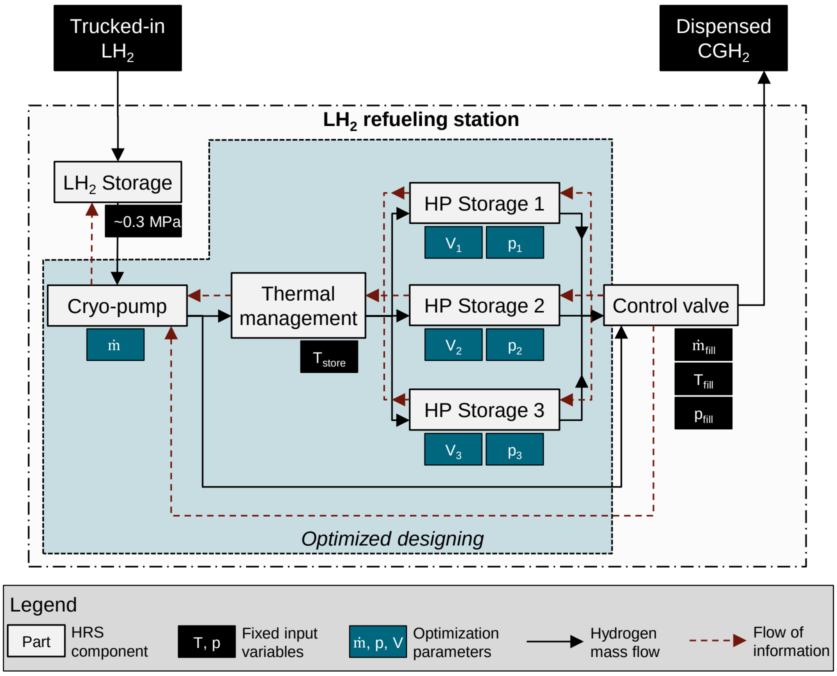

Figure 2: Schematic of a hydrogen refueling station with trucked-in liquid hydrogen.

4 HRS Design and Cost Calculation

Before doing the simulations, the stations need to be grouped into different sizes. H_2-Mobility [32] divides the stations into 4 groups with different capacities and performance specifications. The smallest station ("Very Small") is able to conduct 2.5 refuelings per hour with 5.6kg and one back-to-back refueling (handling time of 3 min. between refueling). The midsized stations ("Small" and "Medium") are able to refuel max. 6 cars per hour and one back-to-back refueling per fueling position. The "small" HRS has 1 and the "Medium" HRS has 2 refueling positions. The "Large" HRS is able to permanently fill a car back-to-back [32]. In this study stations with 1 until 6 dispensing positions are investigated. Because of convenience reason for customers (no waiting time due to unavailability of the station) a maximum capacity of 10 vehicles per hour (6 minutes per customer considering refueling and paying time) and dispensing position are assumed. Thus H_2-Mobility performance requirement for Station "Large" [32] are applied to all stations from 1 until 6 dispenser".

For both concepts (liquid and gaseous delivered hydrogen) a detailed cost analysis is done. Table 1 shows the applied methodologies to calculate investment and operational costs for different station sizes. Maintenance costs are calculated as cost surcharge on the components. In the Appendix the input data for the cost calculation can be seen.

Components		Investment Costs	Operational Costs
Compression	LH_2-Pump	Scaling according to throughput (power function)	Electricity costs (consumption from simulation)
	CGH_2-Compressor		
Storage	LH_2-Storage	Scaling according to surface (fixed height-diameter ratio)	Boil-off losses: Scaling according to surface (fixed height-diameter ratio)
	Low-Pressure-Storage	Scaling according to capacity (linear)	-
	High-Pressure Cascade Storage System	Scaling according to pressure (power function) and capacity (linear)	-
Thermal Management	Electric Heater	Scaling according to number of dispensers (linear)	Electricity costs (consumption from simulation)
	Air Heat Exchanger		-
	Inverter	Scaling according to electric power resulting from boil-off electrification	-
	Fuel Cell Stack		H_2-Consumption: See boil-off costs / Electricity generation: Reduces net electricity consumption (if negative, feeding grit → revenues: spot price)
	Fuel Cell Periphery		
	Precooling System – Refrigeration unit	Scaling according to throughput (power function)	Electricity costs (consumption from simulation)
	Precooling System – Aluminim heat exchanger	Scaling according to number of dispensers (linear)	Standby-losses: Electricity costs (consumption from simulation)
Dispenser	-		-
Container, Pipework etc.	-	Cost surcharge on main components	-

Table 1: Cost calculation methodology of HRS.

HRS design optimization

Main drivers for investment costs are the compressor (CGH_2) or pump (LH_2) and cascade storage system and for operational costs the electricity consumption of the compressor/pump. In this study the HRS is designed in a way to minimize lifetime costs (investment, interest, electricity consumption) of the system “compressor (CGH_2) or pump (LH_2) – high pressure cascade storage”. Due to simulation time reasons the design optimization is not done by simulating 20 years. Only one refueling process with 5.6 kg is conducted.

The pressure of the low-pressure storage is a main factor of electricity consumption of the CGH_2 station. As there is only one refueling process considered in the optimization, a representative average pressure value of the low pressure storage is required. When simulating a whole day, pressure in the storage decreases from 5 MPa to 0.5 MPa during the day. The compression energy needed in this case can now be converted to an average compression energy which is necessary for one single representative refueling process. By using this average compression energy for one refueling process and equation (2.1), the corresponding average pressure can be calculated. This value represents an average pressure of the low pressure storage in order to neither under- nor overestimate the required compression energy in the optimization model.

The electricity consumption for one refueling with 5.6 kg is projected to the hydrogen amount refuelled over HRS lifetime (4.6 kg per refueling, see chapter 5). Therefore the optimization is conducted at ambient temperature of 10°C, which is approximately average temperature over the year in Germany. The other main reason for taking 10°C is due to performance requirements. Taking higher temperatures, the refueling process itself takes longer [1] and high-pressure storage capacity requirements lowers as the compressor can refill the storage with more hydrogen during refueling. For temperatures lower than 10°C, the high-pressure storage capacity requirements are lower as hydrogen density (at same pressure) is smaller than at 10°C. To ensure the permanent readiness of the station, the station pressure after each refueling must be at least 87.5 MPa (highest possible vehicle pressure according to standard SAE J2601 [1]) and all high pressure storage vessels need to be refilled after the time for paying and exchanging the vehicle. Therefore, a lifetime of 20 years and an interest rate of 6.3% p.a. is assumed (see Appendix). The optimization consisting of seven parameters (capacities and max. pressure of three high pressure storages and compressor throughput) and one constraint (min. 87.5 MPa end pressure in the last vessel of the cascade storage system) determines the HRS design. The boundary conditions of all high-pressure storages are 5 kg until 50 kg (step size 5 kg) for capacity and 20 MPa until 90 MPa (step size 10 MPa) for maximum pressure.

Optimization results

The optimization results show, that a compressor/pump throughput of 56 kg/h (10 vehicles per hour with 5.6 kg) leads to minimal total costs. Thus, a “booster-principle” is more expensive. Using such a principle, the hydrogen is compressed directly into the car tank within the 3 minutes refueling time and no high-pressure storage system is necessary. In case of CGH_2 and LH_2, the max. pressure of storage one is 50 MPa while the max. pressure of storage two and three is 90 MPa (see Table 2). The max. capacities differs in case of CGH_2 and LH_2. The gaseous delivered station achieves a cost minimum with capacities of 20 kg (vessel 1), 10 kg (vessel 2) and 20 kg (vessel 3). The LH_2 HRS requires capacities of 15 kg for each vessel.

	Max. throughput compressor/pump	High-pressure storages		
		Number	Max. pressure (MPa)	Max. capacity (kg)
CGH_2	56 kg/h	1	50	20
		2	90	10
		3	90	20
LH_2	56 kg/h	1	50	15
		2	90	15
		3	90	15

Table 2: Compressor/Pump – Cascade storage optimization results.

5 Modell Application and Results

Refueling profiles

To compare liquid and gaseous trucked-in HRS systematically, the described simulation model is applied for different utilizations and temperatures. First of all, a “full-utilization” needs to be defined. The max. hydrogen mass filled per hour is calculated by assuming an average amount of 4.6 kg per refueling according to ‘H2A Hydrogen Delivery Infrastructure Analysis Model’ [33]. The average fueling capacity per day is calculated based on the same study. Therefore refueling profiles of 387 gasoline refueling stations (operated by Chevron Corporation) were analyzed in terms of starting times and refueling quantities. Average refueling profiles for each day of the week measuring the share of daily transactions for each hour are shown. Moreover the average share of weekly sales are shown for each day of the week [33]. The hour with highest share of weekly transactions (Friday, from 3 to 4 p.m.) with 1.20% is defined as full capacity. Figure 3 shows the average daily fueling profile, Friday fueling profile and corresponding hydrogen fueling amounts for stations with 1 dispenser.

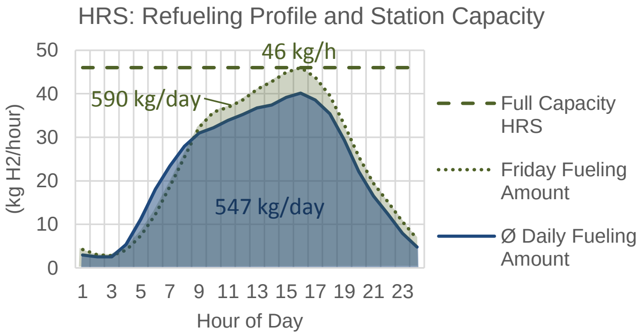

Figure 3: Typical Refueling Profile (Source: [33], applied to Hydrogen Refueling Station with 1 Dispenser).

For stations with more than 1 dispenser, the numbers of Figure 3 needs to be multiplied with the number of dispensers. Refueling profiles for utilizations below 100%, the avg. daily fueling profile and corresponding hydrogen amount is reduced accordingly.

Specific energy consumption

The simulation model described above is demonstrated using different utilizations and ambient temperatures. The simulations are done by simulating one complete day with the above mentioned refueling profiles. In case of HRS with gaseous stored hydrogen, the pressure level of the low-pressure storage has high impact on electricity consumption for compressing hydrogen into the cascade system. To make a fair comparison, the pressure drop over the simulation time needs to be identical for each utilization. Additionally the same refueling profile needs to be applied. Fulfilling both requirements together needs a methodological model adaption. The size of the low-pressure storage is adapted by multiplying with the utilization. This ensures that the pressure storage at the end of the day is the same for each simulation day. The result of the simulations for utilizations from 2% until 100% and for the temperatures -10°C, +12°C and 34°C can be seen in Figure 4.

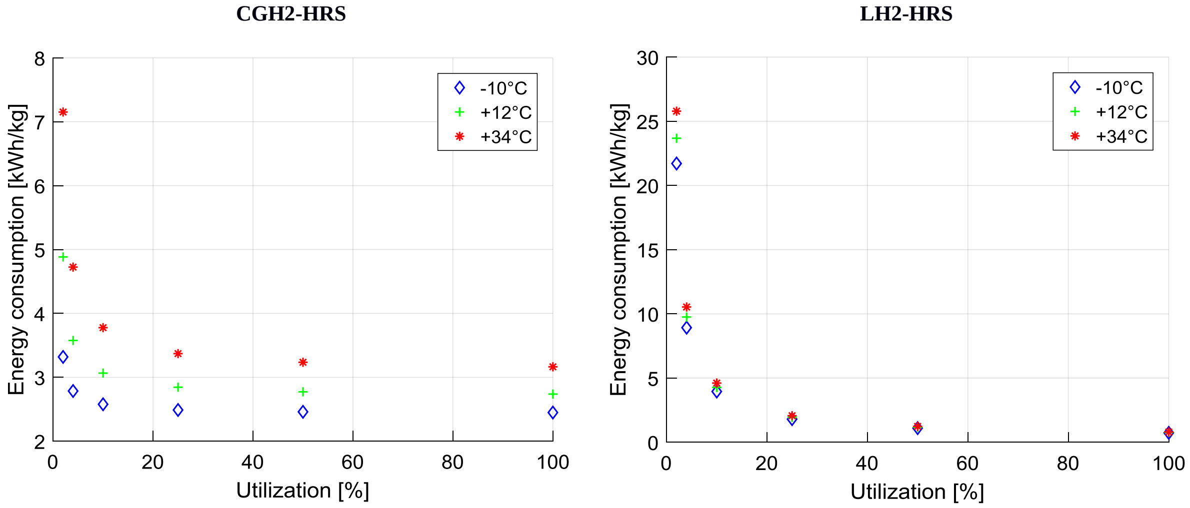

Figure 4: Specific energy consumption of gaseous (left side) and liquid (right side) delivered refueling stations.

While the ambient temperature has a high impact on the electricity consumption of gaseous delivered stations, the impact is very slight in case of liquid delivered stations. The low impact in case of liquid delivered stations is due to the slight relative change in the difference temperature between storage (about -253°C) and ambient temperature (-12°C until +34°C). The relative temperature difference at gaseous delivered stations (about -50°C) and ambient temperature (-12°C until +34°) is much bigger. Energy consumption of liquid delivered stations is significantly lower than for gaseous delivered stations at high utilizations. Compressing liquid hydrogen with an already high density demands relative low energy. At low utilizations, energy consumption is significantly higher than for gaseous delivered stations. This is due to higher boil-off energy losses[2] (LH_2) compared to standby-losses of gaseous delivered stations. This effect becomes insignificantly low at high utilizations. At 100% utilization gaseous delivered stations consume from 2.4 kWh/kg (-10°C) to 3.2 kWh/kg (+34°C). In contrast liquid delivered stations consume 0.4 kWh/kg (-10°C until +34°C) at 100 % utilization.

HRS investment costs and specific hydrogen costs

The low-pressure storage of the CGH_2 refueling stations is limited to a refueling capacity of 1.500 kg (reached with three dispensers). This is due to the limited capacity of truck trailers delivering gaseous hydrogen (currently about 1.100 kg at 50 MPa) plus a 400 kg buffer to compensate fluctuations in delivery times. The liquid storage (LH_2 refueling stations) is not limited as the truck capacity is about 3.5 tons.

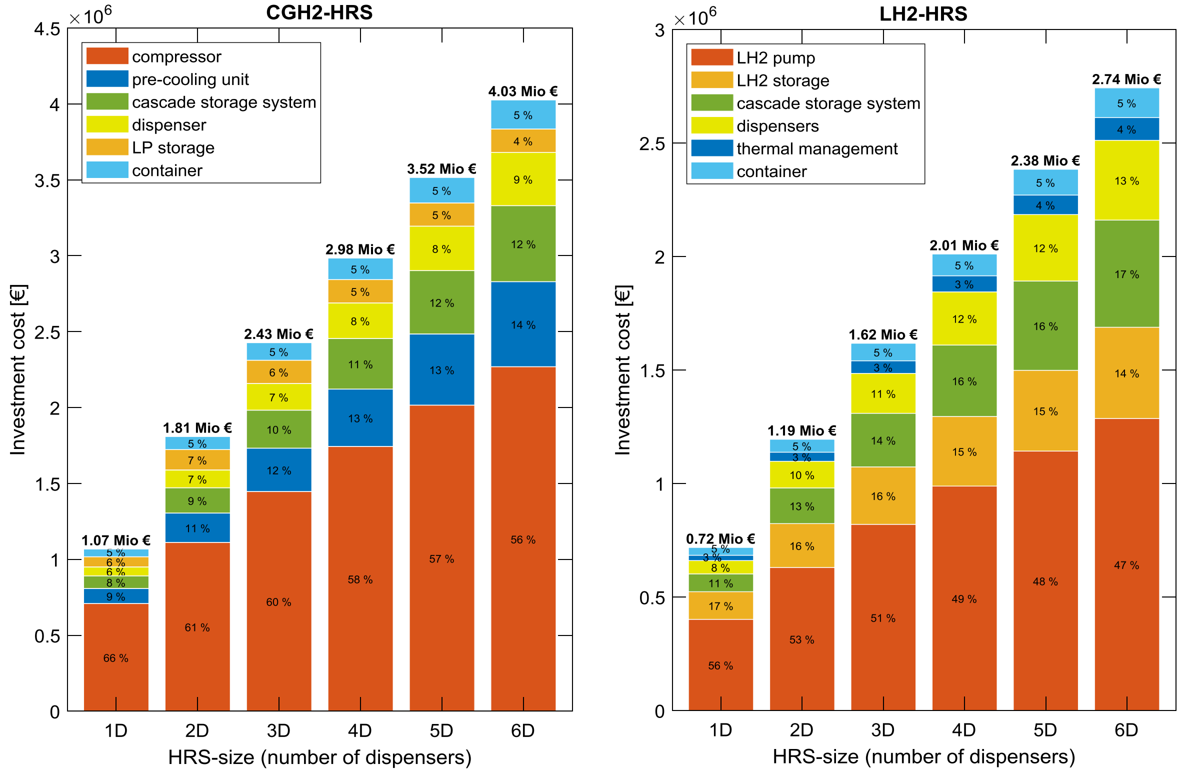

Figure 5: Investment costs of gaseous (left side) and liquid (right side) delivered refueling stations.

Figure 5 shows the investment costs of gaseous and liquid delivered refueling stations from 1 to 6 dispensers and the cost share divided into the main components. The current (base year: 2015) investment costs of CGH_2 refueling stations are higher than for LH_2 refueling stations. This is mainly caused by the compressor

---

[2] Calculated with higher heating value of hydrogen

compared to the technical simpler and cheaper liquid pump. Another reason is the cheap thermal management (L H_2) compared to cost expensive precooling system.

The specific hydrogen costs, illustrated in Figure 6, are very sensitive to the station utilization. The cost range of CGH_2 refueling at 100 % utilization is from 0.92 €/kg (6 Dispenser) to 1.26 €/kg (1 Dispenser). In contrast the cost range of the LH_2 refueling stations is from 0.47 €/kg (6 Dispenser) to 0.73 €/kg (1 Dispenser). At very low utilization (2 %) the refueling station costs range from 26.41 €/kg to 43.11 €/kg (CGH_2) resp. from 20.84 €/kg to 34.47 €/kg (LH_2).

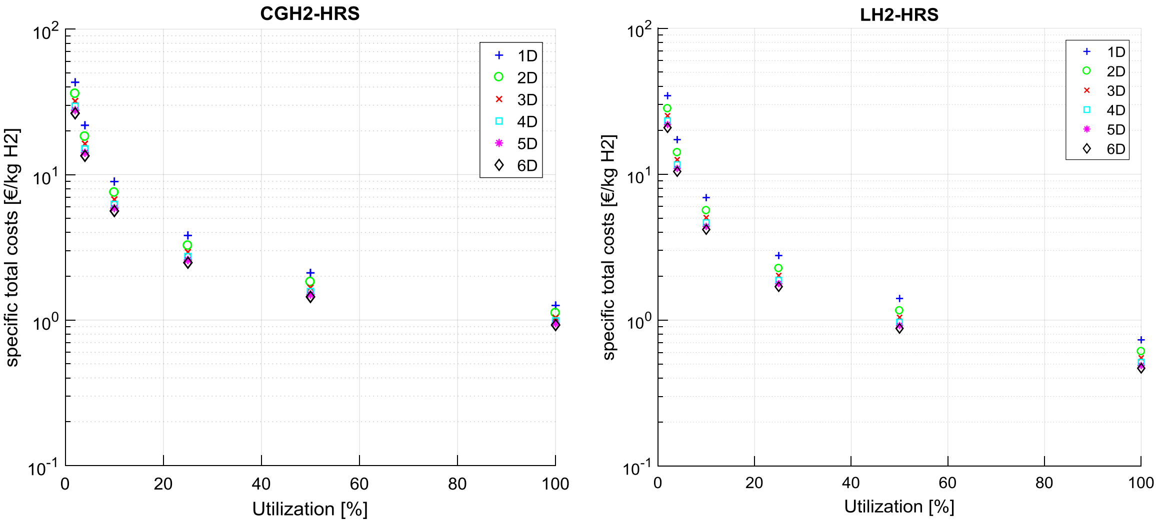

Figure 6: Specific refueling station costs of gaseous (left side) and liquid (right side) delivered stations.

Despite significantly higher energy consumption of LH_2 refueling stations (see Figure 4) at low utilization, specific hydrogen station costs are even lower due to lower investment costs and generating electricity with a fuel cell by using the boil-off hydrogen.

6 Conclusions

Liquid delivered HRS have several advantages compared to gaseous delivered stations. The investment costs, energy consumption and specific costs are lower at high utilization. Large stations with 6 dispensers cause station costs of 0.47 € per kilogram dispensed compared to 0.93 € per kilogram dispensed (CGH_2). The reason for the cost effectiveness of liquid delivered hydrogen stations is the already high density of liquid hydrogen and the low temperature (about -253°C). The high density of liquid hydrogen requires only slight volume changes when pumping to 90 MPa which leads to lower energy demand and lower technical requirements (esp. installation space) as well as costs compared to a gaseous hydrogen compressor. The thermal management of liquid delivered stations is significantly cheaper because heat from ambient can be taken to warm-up hydrogen instead of cooling down to -40°C (CGH_2). Also transportation is cheaper due to higher energy density resulting in higher delivery quantities per truck. But the advantage of liquid hydrogen at the station site is a disadvantage at the production site. The liquefaction of hydrogen needs significantly more energy (currently about 8 kWh/kg for large-scale liquefiers [34]) than the compression into a trailer (about 1 kWh/kg at 500 bar). Therefore LH_2-transportation is more beneficial because hydrogen transportation capacity per trailer in liquid (ca. 3,500 kg) is higher than in gaseous (ca. 1 t at 500 bar) state. Transportation of gaseous hydrogen to the fueling stations uses currently about 1.8 kWh/kg compared to 1.1 kWh/kg for liquid hydrogen (30l/km truck fuel consumption, 37.4 MJ/l HHV for diesel, see [35] for truck routes calculation methodology). With increasing numbers of production/liquefaction facilities and refuelling stations, the energy use for both transportation paths will decrease. Taking these numbers, the gaseous hydrogen pathway causes currently an energy demand at theoretically 100% station utilization between 5.2 and 6 kWh/kg, depending on the ambient temperature. Ceteris paribus for liquid hydrogen, the energy demand rises up to 9.5 kWh/kg. Thus, the gaseous pathway has a significant advantage concerning the total energy consumption. The economically advantageousness of the entire pathways depends on various factors like electricity costs (production site vs. station site), investment costs etc.

Acknowledgments

This work was supported by the Institute of Energy Economy and Application Technology, Technical University of Munich (TUM). The authors especially would like to thank Professor Dr.-Ing. Ulrich Wagner for his help and his valuable input.

References

[1] Society of Automotive Engineers (SAE). J2601: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles. Surface Vehicle Standard. 2014.

[2] Xiao J, Bénard P, Chahine R. Charge-discharge cycle thermodynamics for compression hydrogen storage system. International Journal of Hydrogen Energy. 2016;41:5531-9.

[3] Farzaneh-Gord M, Deymi-Dashtebayaz M, Rahbari HR, Niazmand H. Effects of storage types and conditions on compressed hydrogen fuelling stations performance. International Journal of Hydrogen Energy. 2012;37:3500-9.

[4] Serdaroglu G, Khzouz M, Gillott M, Shields A, Walker GS. The effect of environmental conditions on the operation of a hydrogen refuelling station. International Journal of Hydrogen Energy. 2015;40:17153-62.

[5] Guo J, Xing L, Hua Z, Gu C, Zheng J. Optimization of compressed hydrogen gas cycling test system based on multi-stage storage and self-pressurized method. International Journal of Hydrogen Energy. 2016;41:16306-15.

[6] Reddi K, Elgowainy A, Sutherland E. Hydrogen refueling station compression and storage optimization with tube-trailer deliveries. International Journal of Hydrogen Energy. 2014;39:19169-81.

[7] Rothuizen E, Mérida W, Rokni M, Wistoft-Ibsen M. Optimization of hydrogen vehicle refueling via dynamic simulation. International Journal of Hydrogen Energy. 2013;38:4221-31.

[8] Stephan P, Schaber K, Stephan K, Mayinger F. Thermodynamik - Grundlagen und technische Anwendungen: Springer Vieweg; 2013.

[9] Geller W. Zustandsgrößen. Thermodynamik für Maschinenbauer: Grundlagen für die Praxis. Berlin, Heidelberg: Springer Berlin Heidelberg; 2003. p. 13-27.

[10] Stephan P. B2 Berechnungsmethoden für Wärmeleitung, konvektiven Wärmeübergang und Wärmestrahlung. In: Vdi, editor. VDI-Wärmeatlas. Berlin, Heidelberg: Springer Berlin Heidelberg; 2013. p. 23-36.

[11] Rönsch S. Anlagenbilanzierung in der Energietechnik: Springer Fachmedien Wiesbaden; 2015.

[12] Wesselak V, Schabbach T, Link T, Fischer J. Thermodynamische Bewertung Regenerativer Energiewandlungen. Regenerative Energietechnik: Springer Berlin Heidelberg; 2013. p. 741-850.

[13] Tietze V, Stolten D. Thermodynamics of Pressurized Gas Storage. Hydrogen Science and Engineering : Materials, Processes, Systems and Technology: Wiley-VCH Verlag GmbH & Co. KGaA; 2016. p. 601-28.

[14] VDI. VDI-Wärmeatlas. Berlin, Heidelberg: Springer Berlin Heidelberg; 2013.

[15] Leachman JW, Jacobsen RT, Penoncello SG, Lemmon EW. Fundamental equations of state for parahydrogen, normal hydrogen, and orthohydrogen. Journal of Physical and Chemical Reference Data. 2009;38:721-48.

[16] National Institute of Standards and Technology NIST. Thermophysical Properties of pure Substances and Mixtures. 2010.

[17] Mohrdieck C, Venturi M, Breitrück K, Schulze H. Mobile Anwendungen. In: Töpler J, Lehmann J, editors. Wasserstoff und Brennstoffzelle Technologien und Marktperspektiven. Berlin, Heidelberg: Springer Vieweg; 2014. p. 59-111.

[18] Schnell P. Refueling Station Layout. Hydrogen Science and Engineering : Materials, Processes, Systems and Technology: Wiley-VCH Verlag GmbH & Co. KGaA; 2016. p. 891-916.

[19] Elgowainy A, Wang M. Sustainable Vehicle Fuels, Well-to-Wheel Analysis. In: Ehsani M, Wang F-Y, Brosch GL, editors. Transportation Technologies for Sustainability. New York, NY: Springer New York; 2013. p. 911-38.

[20] Ortiz Cebolla R, Acosta B, de Miguel N, Moretto P. Effect of precooled inlet gas temperature and mass flow rate on final state of charge during hydrogen vehicle refueling. International Journal of Hydrogen Energy. 2015;40:4698-706.

[21] Hosseini M, Dincer I, Naterer GF, Rosen MA. Thermodynamic analysis of filling compressed gaseous hydrogen storage tanks. International Journal of Hydrogen Energy. 2012;37:5063-71.

[22] Striednig M, Brandstätter S, Sartory M, Klell M. Thermodynamic real gas analysis of a tank filling process. International Journal of Hydrogen Energy. 2014;39:8495-509.

[23] Yang JC. A thermodynamic analysis of refueling of a hydrogen tank. International Journal of Hydrogen Energy. 2009;34:6712-21.

[24] Nistor S, Dave S, Fan Z, Sooriyabandara M. Technical and economic analysis of hydrogen refuelling. Applied Energy. 2016;167:211-20.

[25] Rothuizen E, Rokni M. Optimization of the overall energy consumption in cascade fueling stations for hydrogen vehicles. International Journal of Hydrogen Energy. 2014;39:582-92.

[26] Reese W. Weiterentwicklung der Kryopumpentechnologie. Status Referenzmesssystem. NIP Vollversammlung. Berlin, Deutschland: Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie; 2015.

[27] Petitpas G, Aceves SM, Gupta N. Vehicle refueling with liquid hydrogen thermal compression. International Journal of Hydrogen Energy. 2012;37:11448-57.

[28] Brown T, Stephens-Romero S, Scott Samuelsen G. Quantitative analysis of a successful public hydrogen station. International Journal of Hydrogen Energy. 2012;37:12731-40.

[29] Elgowainy A. Hydrogen Infrastructure Analysis in Early Markets of FCEVs. IEA Hydrogen Roadmap- North America Workshop. Bethesda, USA: Argonne National Laboratory, DOE; 2014.

[30] NIST. Thermophysical Properties of Fluid Systems. National Institute of Standards and technology, http://webbook.nist.gov/chemistry/fluid/ [Accessed: 09.05.2016].

[31] Reese W, Heisterkamp T. Weiterentwicklung von H2 Betankungstechnologien. NIP Vollversammlung. Berlin2013.

[32] H2-Mobility. 70MPa Hydrogen Refuelling Station Standardization Functional Description of Station Modules. https://www.now-gmbh.de/content/5-service/4-publikationen/4-nip-wasserstoff-und-brennstoffzellentechnologie/h2mobility_hrs_functional_description.pdf [Accessed: 30.12.2015].

[33] Nexant Inc. H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Nr. DE-FG36-05GO15032. 2008.

[34] NREL. Hydrogen Pathways. Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios. Denver2013.

[35] Mayer T, Haiber A, Berger J, Hopmann S, Wind J. Hydrogen Refuelling Station Network and Route Optimisation of Trucked-in Hydrogen in Germany. Poster at 7th World Hydrogen Technologies Convention. Prague2017.

[36] U.S. Department of Energy. Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. 3.2 Hydrogen Delivery. 2015.

[37] Pratt J, Terlip D, Ainscough C, Kurtz J, Elgowainy A. H2FIRST Reference Station Design Task. Project Deliverable 2-2. 2015.

[38] U.S. DRIVE. Hydrogen Delivery. Technical Team Roadmap. 2013.

[39] Pehnt M. Energieeffizienz. Berlin Heidelberg: Springer-Verlag; 2010.

[40] Bohne D. Wärme – und Kälteversorgungsanlagen. Technischer Ausbau von Gebäuden: Und nachhaltige Gebäudetechnik. Wiesbaden: Springer Fachmedien Wiesbaden; 2014. p. 185-331.

[41] Reddi K, Elgowainy A, Rustagi N, Gupta E. Impact of hydrogen refueling configurations and market parameters on the refueling cost of hydrogen. International Journal of Hydrogen Energy. 2017;42:21855-65.

[42] Wei M, Lipman T, Mayyas A, Chien J, Chan SH, Gosselin D, et al. A Total Cost of Ownership Model for Low Temperature PEM Fuel Cells in Combined Heat and Power and Backup Power Applications 2014.

[43] Statista. Jährliche Entwicklung des Wechselkurses des Euro gegenüber dem US-Dollar von 1999 bis 2016 (in US-Dollar). https://sta.cir-mcs.e.corpintra.net/statistik/daten/studie/200194/umfrage/wechselkurs-des-euro-gegenueber-dem-us-dollar-seit-2001/ [Accessed: 18.09.2017].

[44] KPMG. Kapitalkostenstudie 2016. Wertmessung – quo vadis? 2016.

[45] Hirschberg HG. Handbuch Verfahrenstechnik und Anlagenbau. Berlin Heidelberg: Springer; 1999.

[46] Fraunhofer ISE. Monatliche Börsenstrompreise in Deutschland im 2015. https://www.energy-charts.de/price_avg_de.htm?year=2015&price=nominal&period=monthly [Accessed: 21.09.2017].

[47] Netze BW. Preise und Regelungen für die Nutzung des Stromverteilnetzes der Netze BW GmbH. Gültig ab 1. Januar 2016. https://www.netze-bw.de/media/geteilte-medien/docs/veroeffentlichungspflichten/entgelte/preise-und-regelungen-gueltig-ab-01.01.2016.pdf [Accessed: 31.12.2015].

[48] EEG. Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2014), zuletzt geändert am 29.06.2015. Berlin2015.

[49] Konzessionsabgabenverordnung. Verordnung über Konzessionsabgaben für Strom und Gas (Konzessionsabgabenverordnung - KAV). Berlin2006.

[50] Stromsteuergesetz. 2015.

Appendix

Techno-economic input data

Component		Value	Source	Explanation
Liquid H_2 Storage	Investment Costs	6,600,000 USD	[36]	3,500 m³
Liquid H_2 Storage	Fixed height-diameter ratio	4	Assumption	$\mathrm{Height} = 4\mathrm{xdiameter}$
Liquid H_2 Storage	Boil-Off Losses	4 kg/d	[26]	Reference: 400 kg LH_2-Storage, Ambient temperature 290 K
Liquid H_2 Storage	Lifetime	30 a	[36]	Value from LH_2-Trailer
H_2-Compressor	Throughput-dependent investment costs	$\mathrm{IC}(\mathrm{TP}) = 51{,}901 * \mathrm{TP}^{0.6494}$ in USD	Calculated from [37]	Small quantity purchase prices (see “New HRSAM”), TP=Throughput in kg/h
H_2-Compressor	Isentropic efficiency	73 %	[38]	
H_2-Compressor	Electrical efficiency	Electric engine: 95 %, Power electronics (98%)	Electric engine: [39], Power electronics (Assumption)	Electric engine: based on “IE2-requirments” (> 100kW), Overall efficiency: 93%
H_2-Compressor	Maintenance	8 % of invest. costs per year	[36]	
Liquid H_2 Pump	Investment costs	650,000 USD	[36]	100kg/h
Liquid H_2 Pump	Investment costs scaling exponent	0.6494 (exponent)	See H_2-Compressor	Scaling factor (power function) assumed to be same as for gaseous compressor
	Lifetime	10 a	[36]	
	Isentropic Efficiency	58 %	Calculated from [26]	
	Maintenance	8 % of invest. costs per year	See H_2-compressor	Due to lack of data, values from compressor are taken

Type IV Pressure Storages (20-90 MPa)	Pressure-dependent investment costs	$\mathrm{IC}(p) = 343.06 * e^{0.002005*p}$	Data from several sources at different pressures	Power function regression with p = max. storage pressure
Pre-Cooling System	Efficiency factor	0.35	[40]	Conservative approach (minimum value)
Pre-Cooling System – Chiller unit	Investment costs	$\mathrm{IC}(P) = 6{,}558.3 * \mathrm{TP}^{0.8665}$ in USD	Calculated from [41]	P = Power in refrigeration tons
Pre-Cooling System – Aluminium block	Investment costs	$\mathrm{IC}(P) = 5{,}955 * P + 2{,}128.5$, in USD	Calculated from [41]	P = Power in kW
	Temperature	-50°C	Assumption	
Electric Heater	Efficiency	100 %	Simplification	
Air Heat Exchanger	Length	55 m	Calculated	
Fuel Cell Stack	Investment costs	1,621 €/$\mathrm{kW_{el}}$	[42]	
	Lifetime	20,000 h	[42]	
	Degradation	10 % performance loss per 20,000 h	[42]	
Fuel Cell Periphery	Investment costs	1,385 €/$\mathrm{kW_{el}}$	[42]	
	Lifetime	20 a	Assumption	
Dispenser	Investment costs	65,000 USD	[36]	1 hose per dispenser
Several components	Maintenance	2 % of invest. costs per year	[24]	Excepted compressor, pump and high-pressure storage
Container, piping etc.	Investment costs	5 % cost surplus on overall inv. costs	Own Assumption	
Exchange Rate	EUR per USD	1,11 EUR-USD	[43]	
Interest rate		6.3 %	[44]	
Refrigeration tons	kW per RT	3.5168	[45]	

Electricity price	Electricity price (spot market)	31.20 €/MWh	[46]	
	Costs, taxes and duties		[47-50]	

Authors

Thomas Mayer is a researcher at Daimler AG and analyses fuel chains from Well to Tank. His research focuses mainly on hydrogen chains, especially on hydrogen transportation and refueling station analyses. He studied 'Business Administration' (B. Sc.) at Albstadt-Sigmaringen University and 'Automotive Engineering and Management' (M.Sc.) at University of Duisburg-Essen. His Bachelor´s thesis, published by 'Int. Journal of Hydrogen Energy', was a 'Feasibility study of 2020 target costs for PEM fuel cells and lithium-ion batteries'. In this work, a new two-factor experience curve approach was developed. In his Master´s thesis, awarded by 'Deutsche Gesellschaft für Elektrische Straßenfahrzeuge', he created a Business-Case model for hydrogen - used in Fuel Cell Electric Vehicles - in Germany. Currently he is a doctoral candidate at Technical University of Munich. His thesis deals with a techno-economic evaluation of fuels with focus on hydrogen.

Malte Semmel is a student of Karlsruher Institute of Technology (KIT). He finished his studies in "Chemical Engineering" (B.Sc) while focusing on energy- and environmental engineering. He completed his Bachelor's thesis, a 'systemic evaluation of hydrogen refueling station concepts for the decarbonized energy supply of road traffic' in cooperation with the NuCellSys GmbH. He refined the dynamic simulation model technically as well as adding the cost model to it. Currently he works at NuCellSys GmbH as a member of the department of "Fuel cell development and H_2 Infrastructure" and is continuing his studies in "chemical engineering" (M. Sc) since KIT in April 2017.

Artur Bauer graduated from the Technical University of Munich (TUM) in 2016. Focusing during his university education on renewable energy systems and alternative drive concepts he analysed battery electric vehicles and hydrogen driven systems. He finished his studies in 'Energy and Process Engineering' (M.Sc.) by completing his Master's thesis, an 'Energetic valuation of hydrogen refueling stations with trucked-in compressed gaseous and liquid hydrogen' in cooperation with the NuCellSys GmbH. Built simulation model which calculates the energy consumption of different HRS architectures and included components, serves as base for the examinations presented in this paper.

Martin Guerrero-Morales has concluded the M.Sc. program "Energy Science and Technology" at the Ulm University in 2017. He also graduated from the University of Guanajuato (Mexico) and obtained his B.Sc. degree in Chemical Engineering in 2012. He wrote his master's thesis "Systematic evaluation and simulation of hydrogen refueling stations for automobile application" in cooperation with the NuCellSys GmbH. He developed an operating strategy and assessed the energy consumption of the hydrogen refueling stations depending on ambient temperature and station utilization. Currently he works as a developer engineer at the department of R&D of Fuel Cells at ElringKlinger AG.

Karla Maria Schmidt is a Master student in Mechanical Engineering at Darmstadt University. In 2015 she graduated from Esslingen University and obtained her Bachelor degree in Mechanical Engineering. Currently she works on her Master's thesis on the "analysis of hydrogen refueling stations with on-site hydrogen production through electrolysis / steam reforming of natural gas" in cooperation with Daimler AG, as a member of the department of "Fuel cell development and H_2-Infrastucture". The aim of her work is to add the on-site production of hydrogen to the dynamic simulation model.

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