



Life cycle assessment of MHP (Mobile Hydrogen Powersupply), an off-grid system to charge battery electric vehicles

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Abstract

Purpose The paper introduces MHP (Mobile Hydrogen Powersupply), an off-grid fuel cell electric system to recharge (stranded) BEVs, and discusses MHP from the life cycle perspective. The LCA shows the effects of system architecture, charging efficiency, hydrogen supply routes, and the predicted electric vehicle recharging demand on global warming potential and energy consumption and further gives recommendations to optimize the assessed environmental impact.

Methods Demand scenarios of mobile recharging assistances due to BEVs, stranded with an uncharged battery, are predicted for Austria and the greater Vienna area. The introduction of MHP follows the discussion of system architecture, operation strategy, and energetic charging efficiency. The LCA follows the guidance of the ISO 14040 standard and applies the Circular Footprint Formula. The functional unit is 1 kWh of electrical energy, balanced at the charging interface. The system boundary includes raw material extraction, production, transport of resources and products, use, and end of life management. The hydrogen supply is modeled representatively for Austria. The selected impact categories are global warming potential and cumulated energy demand. The data originate, among others, from GEMIS Austria, GREET2, and ProBas.

Results and discussion Environmental impacts vary between 0.40 and 1.58 kg CO₂eq/kWh-el and 4.95 to 7.68 kWh/kWh-el in the life cycle. In production and end of life processes, the hydrogen storage system leads to the highest weight-specific GWP and CED of MHP sub-systems due to the large share of CFRP. The efficiency of the MHP system is directly reflected in the use phase's environmental impacts. The impact of MHP cooling efficiency, charging efficiency, and operation strategy on GWP and CED is below 12%. The CED primarily originates from hydrogen production. If the hydrogen supply route is mostly renewable and generates minor GWP, the MHP efficiency has only a small impact on the life cycle's GWP and the production and end of life processes gain importance.

Conclusions Optimized material selection and lightweight construction reduce the life cycle impact. Further, the paper demonstrates that hydrogen supply significantly affects MHP's environmental impact. Therefore, besides optimizing the production and end of life processes, implementing a renewable hydrogen infrastructure and providing renewable energies and fuels must be strongly accelerated.

Keywords Life cycle assessment (LCA) · Mobile Hydrogen Powersupply (MHP) · Battery electric vehicles (BEVs) · Off-grid charging · Charging infrastructure · Fuel cell · Hydrogen

1 Introduction

The regulations of the European Union on climate and health protection have a substantial impact on future powertrains. Increasing shares of sustainable powertrains and fuels in the

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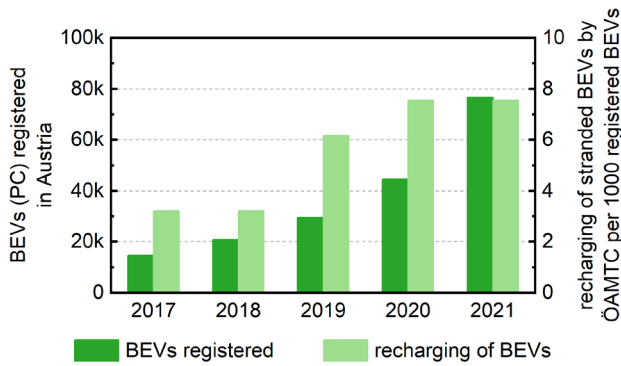


Fig. 1 Development of registered BEVs in Austria and roadside assistances to recharge BEVs by ÖAMTC

European vehicle fleet are expected. With the increasing number of battery electric vehicles (BEVs) and the limited range (especially at low ambient temperatures), the demand for mobile battery recharging devices for stranded vehicles rises (Storandt and Funke 2012; Budde Christensen et al. 2012). Figure 1 shows the development of the registered BEVs—personal cars (PC)—in Austria and the annual roadside assistances to charge BEV batteries by ÖAMTC (Austrian Automobile, Motorcycle, and Touring Club).

In 2021, the ÖAMTC performed 7.5 roadside assistances due to discharged batteries (hence mostly user errors) per 1000 registered BEVs, see Fig. 1. With the increasing spread of the mass-produced BEV, more and more drivers are also not technology-savvy. Thus, a growing ratio can be expected.

This paper discusses MHP (Mobile Hydrogen Power-supply), an off-grid fuel cell electric system to recharge (stranded) BEVs, from the life cycle perspective. First, demand scenarios of mobile recharging assistances due to BEVs, stranded with an uncharged battery, are predicted for Austria and the greater Vienna area for the next ten years. Further, a literature review discusses off-grid charging infrastructure systems. The introduction of MHP follows the discussion of system architecture, operation strategy, and

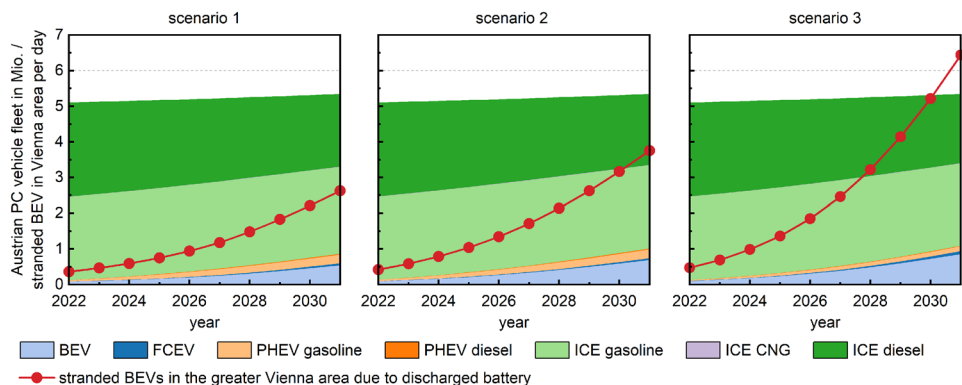
energetic charging efficiency. Different conventional and regenerative routes are set up and balanced for the hydrogen supply of the life cycle assessment’s (LCA) use phase. The LCA shows the effects of system architecture, charging efficiency, hydrogen supply routes, and the predicted MHP-demand scenarios on global warming potential and energy consumption. Recommendations to optimize the assessed environmental impact conclude the paper.

2 Forecast of the Austrian BEV fleet and demand for recharging stranded BEVs

Based on Bruckmüller and Tober (2021), Fig. 2 shows scenarios for the future development of the PC vehicle fleet in Austria. In scenario 2, the estimation of future new registrations and the renewable fuel share is based on the legal regulations of CO₂ fleet goals and fuel blending goals of 2021. This results in 0.58 million BEVs in 2030. With 5.30 million PCs, this is approximately 11% of the fleet. Scenario 3 sets the boundary conditions to accelerate the market penetration of BEVs and FCEVs (fuel cell electric vehicles). The BEV share in 2030 is about 13% (0.71 million). Scenario 1 assumes a higher penetration of synthetic fuels. This leads to increased fractions of PHEVs (plug-in hybrid electric vehicles), hybrid, and ICE vehicles (internal combustion engine). Scenario 1 assumes a BEV share of about 8% (0.45 million) in 2030. The ICE powertrain fractions of Fig. 2 also include hybrid powertrains that cannot be charged externally.

The greater Vienna area is a typical European metropolitan region and provides representative boundary conditions for the LCA. Figure 2 shows the estimation of daily stranded BEVs in the area of the Vienna ÖAMTC bases. These estimations are based on the ÖAMTC roadside assistance statistics of 2021 and conservatively assumed growth rates of scenario 1: 0% p.a., scenario 2: 1% p.a., and scenario 3: 3% p.a. It is predicted that in 2030 daily between 2.2 and 5.2 BEVs will stand due to an uncharged battery. Scenario 2 predicts over a 10-year period from 2022 to 2031, a total of

Fig. 2 Development of Austrian PC fleet with prediction of stranded BEVs in the greater Vienna area due to discharged battery



6422 stranded BEVs in Vienna. Scenario 1 leads to 4544, and scenario 3 leads to 9803 cases. For Austria, the comparable predictions result in between 9.3 and 21.7 BEVs that will strand daily 2030. Over a 10-year period, between 18960 and 40904 BEVs will stand.

3 Solutions for off-grid charging

Different solutions for off-grid charging are presented in the literature (Afshar et al. 2020; Huang et al. 2015). A variant is the utilization of a mobile battery like Cui et al. (2018) propose or a combination of battery and ultracapacitor (Atmaja and Amin (2015)) to recharge the BEV battery. Yet, the main drawback of these technologies is the long recharging time of the mobile battery, which leads to significant downtimes and, hence, inflexible application periods, as well as an additional loading of the power grid. Moreover, the limited capacity of the battery restricts the refueling events of BEVs, as Cui et al. (2020) argue.

4 Life cycle perspective of BEV charging in literature

There is, however, a lack of life cycle perspective in mobile BEV charging systems. To the best of the author's knowledge, no previous published studies are available that investigate impacts from a life cycle perspective, i.e., how system structure and operation strategy affect the use phase or how materials affect impacts upstream and downstream from the use phase.

Life cycle energy demand and the environmental impact of on-grid charging infrastructure have already been discussed in the literature. Nansai et al. (2001) analyzed the installation of BEV charging infrastructure in Japan and found that the life cycle carbon emissions of the charging infrastructure, including storage batteries, are responsible for 16% of the total emissions in a BEV's life, powered with Japanese electricity mix. Zhang et al. (2019) projected the environmental life cycle impact of different charging systems in China for 2020 to 2040. They predict that home chargers have the lowest cumulative energy demand and global warming potential (GWP), followed by public AC chargers, public DC chargers, and public AC and DC chargers, due to differences in materials and charging technologies. They found that the average chargers account for less than 2% of the GWP in a BEV's life. Traut et al. (2012) proposed an optimization model to minimize the annual lifecycle GWP and costs from the PC fleet of conventional, hybrid, plug-in hybrid electric vehicles (PHEV), and BEVs. Two charging modes were compared: home charging and additional workplace charging. The results show that additional workplace charging reduces the GWP by up to 21%

if the grid offers low-carbon electricity. The impact of the charging infrastructure (without storage batteries) is thereby less than 3% of the GWP of a BEV's life if the US-electricity mix is applied. Marmioli et al. (2019) assessed the life cycle of constructing and maintaining an electrified road (e-road) equipped with an inductive charging system. These e-roads seem to lead to almost double impact compared to a traditional road. McLaren et al. (2016) analyzed the use phase carbon emissions of charging BEVs and PHEVs depending on charging scenario (at home or workplace), time restriction, and carbon intensity of the grid. They argue that workplace charging leads to the lowest emissions. BEVs achieve lower emissions in one out of five scenarios (due to a low-carbon grid) than highly efficient PHEVs. Xu et al. (2020) examined the life cycle GWP of electricity generation and BEV batteries in Europe in 2050 for different charging strategies: uncontrolled, unidirectional controlled, and bidirectional charging (vehicle-to-grid). They found that uncontrolled charging increases the electricity production from controllable sources like natural gas slightly. The emissions are lowest for bidirectional charging due to the increasing use of electricity from renewable energy sources. Thereby, the impact on the lifecycle emissions of the enhanced battery degradation due to the bidirectional charging is outperformed. Burchart-Korol et al. (2020) analyzed the life cycle impact of the highly diversified energy production in the European Union countries (2015–2050) on BEV charging. They show a generally lower environmental impact from charging BEVs in countries with a high share of electricity generated from regenerative energy sources.

In contrast to the works cited, most studies on alternative powertrains exclude the energy infrastructure, as Bothe and Steinfort (2020) show in their meta-analysis of LCA studies. They estimate the energy infrastructure effect on 5 to 8% of the overall emissions and recommend considering GWP resulting from energy infrastructure. Also, Chester and Horvath (2009) suggest considering infrastructure in the LCA of passenger transportation next to fuel production and supply chains.

5 Mobile BEV charging system MHP

The solution proposed in this paper is to use a hydrogen fuel cell (FC) supplied from a high-pressure tank in addition to a high-voltage battery (HVB) to recharge stranded BEVs. In this way, the system can store more energy, provide more refueling events to stranded BEVs, and reduce the downtimes due to the fast hydrogen refueling process. This system is called Mobile Hydrogen Powersupply (MHP).

MHP is designed as a trailer (see Fig. 3) so that a conventional breakdown service vehicle can tow MHP to the site of operation.



Fig. 3 MHP: CAD rendering of MHP and photo of MHP charging a BEV

5.1 System architecture

Figure 4 shows the system architecture of MHP. A 30 kW-el polymer electrolyte membrane FC converts the electrical power from hydrogen, supplied by the 4.1 kg 700 bar storage system. The air supply system supplies ambient air to the FC using a compressor. As a galvanic element, the FC provides electrical energy and emits water vapor from atmospheric oxygen and hydrogen. The exhaust gas, composed mainly of atmospheric nitrogen and water vapor, is released into the ambient air through the exhaust system.

In addition, an HVB with a capacity of 8 kWh (6.1 kWh usable) is available for start-up and shut-down and as a supplementary power source. The DC-voltage of HVB and FC is converted via the power electronics and directed to auxiliary consumers and the DC-charging interface CCS. The 3-phase AC-charging interface Type 2, with an optional adapter for Tesla vehicles, is supplied through an inverter. As a result, MHP fits all relevant BEV charging interfaces

on the European market. Thereby, the maximum charging power is above 20 kW, regardless of the charging interface.

MHP is operated and monitored via a human-machine interface (HMI) designed as a touch screen. The low voltage system supplies auxiliary consumers like FC BoP (balance of plant), fans and pumps of the cooling system, the system control unit, and the HMI. The liquid-cooled components are divided into two cooling circuits. Heat exchangers transfer the thermal power to the ambient air.

5.2 Operation strategy

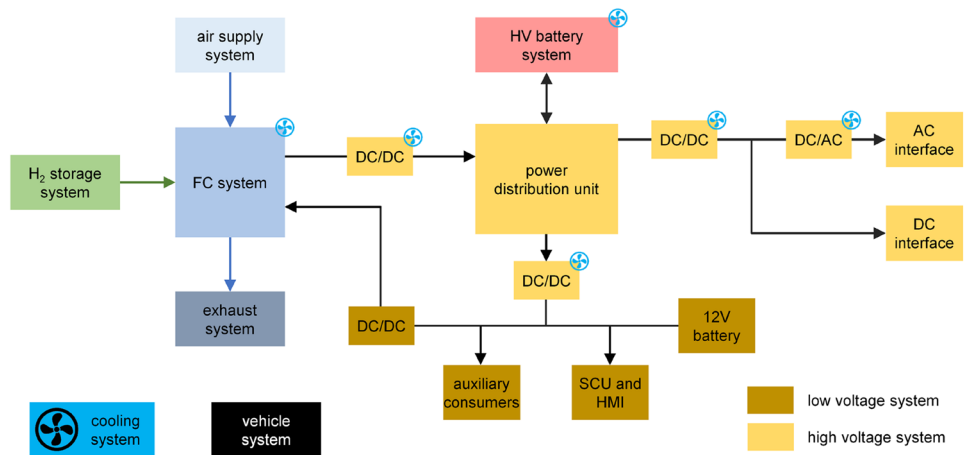
The operational process of MHP is divided into three successive phases: start-up, charging, and shut-down. During transport, MHP is deactivated. MHP is switched on at the operation site and enters the start-up phase. The operator can select via the HMI which operation strategy is to be applied to charge the BEV and the amount of charging energy.

MHP has two sources of power: HVB and FC. The system architecture allows parallel and, by timing the processes, serial operation, see Fig. 5.

Parallel operation strategy FC and HVB power the charging interfaces and auxiliary consumers individually or jointly. The charging interfaces and auxiliary consumers are supplied only by the FC in standard charging mode. If FC operation is not possible or is disadvantageous, the HVB can power the system alone. After completing the charging phase, the operator can select whether to charge another BEV or shut-down the system. In the shut-down phase, the FC recharges the HVB.

Serial operating strategy FC and HVB are connected virtually in series. The HVB provides the energy for charging the BEV and supplying the auxiliary consumers. In the shut-down phase, the FC then recharges the HVB. The serial operating

Fig. 4 MHP: system architecture with sub systems



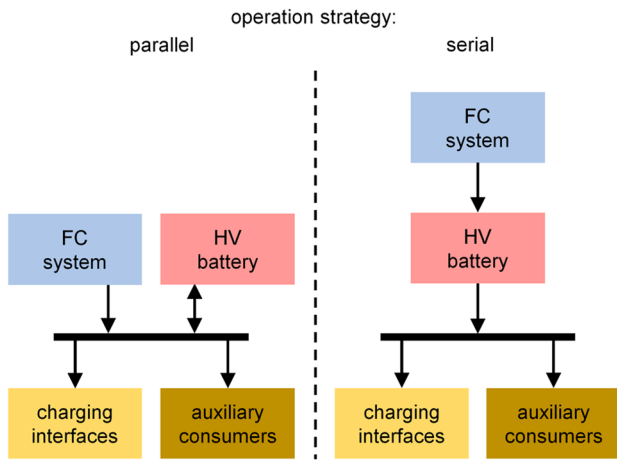


Fig. 5 MHP: parallel/serial operation strategy

strategy has the disadvantage of limiting the amount of energy available for the charging process to the capacity of the HVB.

5.3 System efficiency

The efficiency of the BEV charging process depends on various parameters. Figure 6 shows efficiency maps depending on the ambient temperature and the charging power for the parallel and the serial operation strategy of a complete BEV DC charging process with 5 kWh charging energy. These efficiency maps are based on FC test bench measurements, thermal system simulations in GT-Power, and the component's technical documentation, including electrical power consumption and efficiency. The start-up time is 2 min and the shut-down time 3 min, independent of the operating conditions.

Parallel operation strategy The maximum efficiency is achieved at 6.7 kW charging power and low ambient temperatures. The FC efficiency is highest in the low to middle power range. With increasing power, the FC efficiency decreases due to rising losses. In a very low power range, the BoP power demand decreases the FC efficiency, see O'Hayre et al. (2016) or Klell et al. (2018). This correlation is visible since the FC provides the charging power when using the parallel operating strategy. As the ambient temperature increases, the electrical power consumption of the thermal system's fans and pumps rises. For example, the electrical fan power at 22 kW charging power and 40 °C ambient temperature is approximately 1 kW. This leads to decreasing charging efficiencies with increasing outside temperatures. The efficiency of the HV components increases towards their rated power. The high charging power reduces the charging time. The shorter charging time decreases auxiliary consumers' energy share. However, the FC efficiency characteristic outweighs these effects. Consequently, the charging efficiency is 6.9% below the maximum at high charging power and high ambient temperature.

Serial operation strategy The FC charges the HVB with maximum efficiency independent of the BEV charging power. Thus, the serial operation strategy's efficiency map is decoupled from the significant FC influence. The HV components' efficiency rises with increasing charging power, and the auxiliary consumers' energetic share reduces. Thus, the charging efficiency increases. The highest efficiency is achieved at high charging power and low ambient temperature. With rising ambient temperatures, the system efficiency decreases due to the increasing power demand of the thermal system.

Despite the charging and discharging of the HVB, the serial operating strategy's maximum efficiency is 1% higher

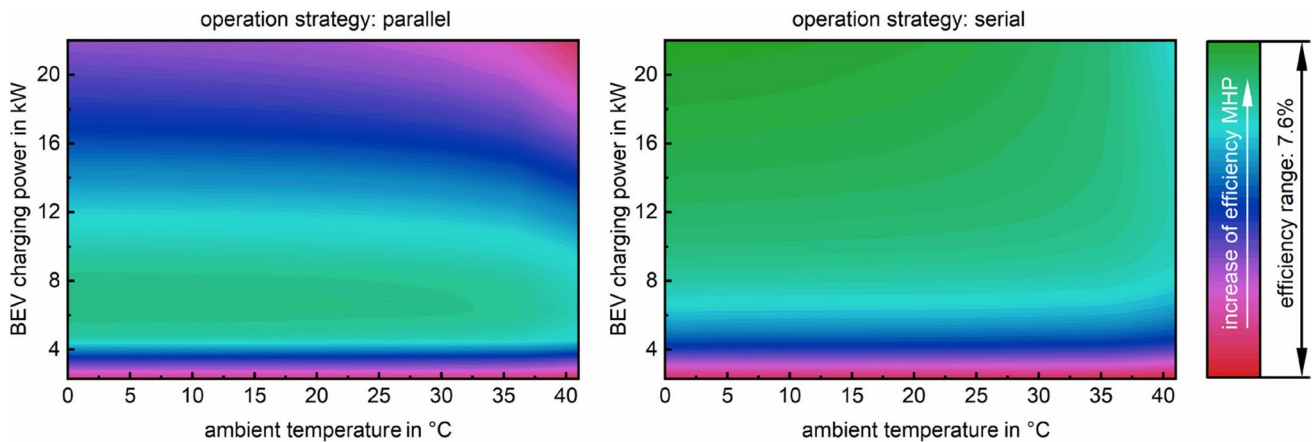


Fig. 6 Serial and parallel operation strategy: efficiency map depending on ambient temperature and charging power of a complete BEV DC charging process with 5 kWh

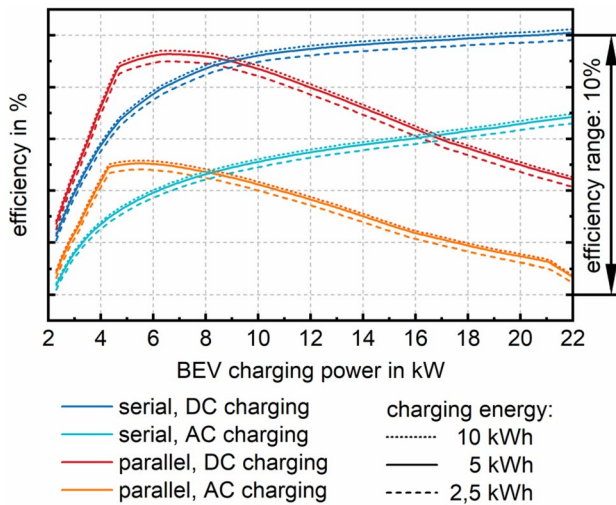


Fig. 7 Charging efficiency: effects of operation strategy, charging energy and charging interface at 20 °C ambient temperature

than the parallel operation strategy’s maximum. This has several reasons: The fuel cell works at high efficiency regardless of the operation strategy. The maximum efficiency of the serial operating strategy is at a higher charging power than the maximum of the parallel operation strategy. Thus, the HV components operate at higher efficiencies, and the auxiliary consumers’ power demand is less significant due to the reduced charging time. In addition, the HVB has low charging and discharging losses.

Figure 7 shows, at a constant ambient temperature of 20 °C, the effects of operation strategy, charging energy, and charging interface on the charging process efficiency as a function of charging power.

With rising charging energy, the efficiency of the charging process also rises because start-up and shut-down processes are proportionally less significant. AC charging leads to a reduced charging process efficiency compared to DC charging. This is due to the additional energy conversion via the DC/AC inverter, see Fig. 4. In the map, serial DC charging achieves the maximum charging efficiency, and parallel AC charging the lowest at high charging powers in each case. The difference in efficiency is thereby 10%. From an efficiency point of view, charging the BEV via the DC interface is always recommended.

6 Methods LCA: goal and scope

MHP is assessed with the guidance of the ISO 14040 standard, see ISO (2021a, b). The Circular Footprint Formula (CFF), according to the European Commission (2017), is applied for the end of life management. This LCA aims to present the life cycle impact of the application of one MHP by an Austrian breakdown service with varying hydrogen supply routes in the greater Vienna area. The life cycle impacts resulting from production and end of life phases are analyzed for the MHP system setup. Based on these findings, environmentally relevant system improvements are determined and implemented. The use phase focuses on the life cycle impact of hydrogen supply and MHP parameterization.

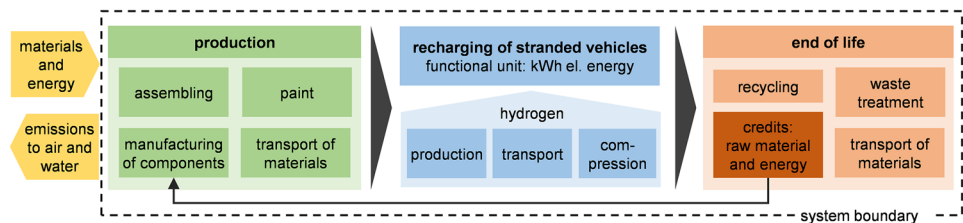
There are two reasons for carrying out the study: First, according to the UN, it is crucial to reduce primary energy consumption and CO₂ emissions, especially for transport systems, to meet the Paris Agreement, see UNEP (2017). MHP was developed from scratch and is new to the market. Therefore, under these conditions, LCA is particularly relevant to assess the life cycle impact and give recommendations for the application and evolution of MHP. Secondly, the fraction of BEV will rise, and recharging stranded vehicles will become more common. Thus, the environmental assessment of BEVs should consider the effects of recharging. This publication can provide a source for this aspect of e-mobility and contribute to the research field.

The target audience of this publication are developers of transport systems (focus FC and BEV) and researchers and decision-makers in hydrogen, energy, and mobility systems.

The system boundary includes the entire life cycle of MHP: raw material extraction, production, transport of resources and products, use, and end of life management. Figure 8 shows the product system with system boundary.

The vehicle space frame construction with paintwork and assembly of the complete MHP system takes place in Graz, Austria. Components and raw materials are purchased worldwide. Their production in the individual producer countries, packaging, and transport to Austria are considered in the model. Typical and country-/region-specific conventional logistic systems describe the transport processes of components and materials. The energy required for production and end of life is divided into electrical energy, thermal energy, and gas. The country-specific energy mixes are considered.

Fig. 8 Product system with system boundary



In the use phase, the charging of stranded BEVs due to an empty battery in the greater Vienna area, Austria, is modeled. The BEV is charged as far as needed to leave the breakdown location quickly and to be able to reach the next free stationary charging station. The modeling assumes that the BEV has to cover an average of 20 km to the next charging station. The energy required for this is based on the BEV chassis dynamometer measurements by Tober (2016). An average energy requirement of 25 kWh/100 km is estimated. This results in the charging energy per BEV of 5 kWh. MHP's system and charging efficiency are modeled corresponding to Section 5. The hydrogen supply of the hydrogen refueling station for 700 bar storage systems is modeled for representative Austrian fossil and renewable routes. Hydrogen production, transport by truck or pipeline, and compression for transport and refueling are the modules of the hydrogen supply route.

In the end of life phase, MHP is disassembled as far as possible, and materials are processed individually. The Circular Footprint Formula (CFF), according to the European Commission (2017), is applied to model end of life management.

The ILCD handbook by the European Commission et al. (2011) is the base of the applied cut-off criteria. However, components that contribute less than 1% to the total mass and are not relevant for the life cycle impact can be cut off. The total cutoff mass must not exceed 5% of the total MHP mass.

Capital goods for the products' manufacture and infrastructures like roads and railways are not within the system boundary. The transport of MHP from the production site in Graz to the deployment site in Vienna and the transport to the disassembly site are very short and, therefore, not considered. Also excluded from system boundaries are the routes to the stranded BEVs and the hydrogen refueling stations. This assumption allows the study to be independent of the breakdown service vehicle's powertrain system.

The production of MHP is balanced for the year 2022. In recent years, the development of FCEVs and BEVs has been progressing very dynamically. Components and production methods are constantly optimized. Therefore, considering the quality of the data source, the focus is on data as up-to-date as possible with suitable regional allocation for the balancing. The modeling of hydrogen supply routes applies current Austrian framework conditions and the ones expected for 2030.

The lifespan and operational life of MHP are ten years. This assumption is a conservative estimate. Scenario 2 of the fleet development (see Fig. 2) provides the number of operations. Over the MHP lifespan from 2022 to 2031, 6422 BEV charges are predicted for the greater Vienna area. Including the charging energy of 5 kWh, this results in a total provided energy of 32.11 MWh. The functional unit is 1 kWh of electrical energy, balanced at the charging interface.

Life cycle impact assessment Global warming potential (GWP) and cumulated energy demand (CED) are the selected impact

categories. Thereby, the MHP system can be analyzed, and recommendations, also of a general nature, can be derived for the energetic and environmental optimization of this and similar systems. Due to these objectives, other transport-related aspects (like acidification, ecotoxicity, photochemical ozone creation potential, or mineral extraction) were not the focus of this research. The time horizon is assumed to be 100 years. The data originate from GEMIS Austria by IINAS and Umweltbundesamt (2018), GREET2 by Argonne National Laboratory (2021), ProBas by Umweltbundesamt (2015), and cited literature.

To protect the intellectual property of the involved partners, it is not possible to describe details of the chosen components and production phases. Therefore, no detailed bill of material is published further on.

7 Results of MHP life cycle assessment

This section contains the result of the life cycle inventory and the life cycle impact assessment. It is divided into production with end of life management, hydrogen supply routes of the use phase, cumulated life cycle, and sensitivity analysis.

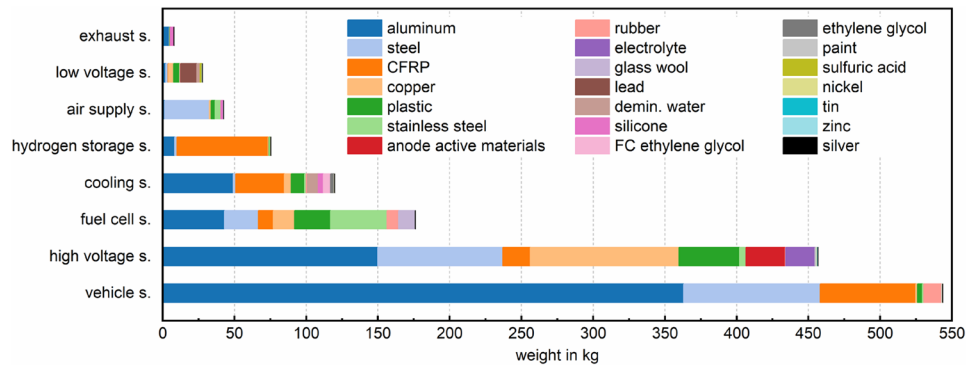
7.1 Production and end of life

The analysis of MHP's production and end of life processes is split into the sub-systems shown in Fig. 4. Figure 9 contains the masses of these systems and the respective material shares.

MHP weighs a total of approx. 1500 kg. The balance sheet lists 1450 kg, which fulfills the 5% cutoff criteria. The vehicle system includes the trailer, storage compartments, and cover (outer skin of MHP) and is the heaviest system (544 kg). The trailer mainly consists of aluminum and steel. The cover is a custom production from CFRP. HVB, power electronics, filters, and the HV harness are combined in the high voltage system. Thereby the HVB weighs the most: 112 kg. Hydrogen is fed to the FC from the 700 bar hydrogen storage system, consisting of a CFRP tank (64 kg), valves, and piping. The two circuits of the cooling system cool the FC and HV components. The heat exchangers are aluminum; hoses are silicone; the enclosure of the heat exchangers for cooling airflow guiding is a custom production from CFRP. The low voltage system (27 kg) contains the components and harness for low voltage power distribution, control units, HMI, and 12 V battery. Weight-balanced across all systems, aluminum (622 kg), steel (242 kg), CFRP (194 kg), and copper (130 kg) are the most common materials used in MHP.

Essential are GWP and CED of CFRP. According to Das (2011), CFRP components cause GWP of 47.9 kg-CO₂eq/kg and CED of 291 kWh/kg. Witik et al. (2013) show 78% lower GWP and, on average, 75% reduced CED by secondary material, compared to virgin material. The GWP and CED of paint are estimated from the work of Papisavva et al. (2001). The impacts of the tires originate from Krömer et al. (1999). The recycling

Fig. 9 Life cycle inventory: masses and material share of MHP sub-systems



processes' GWP and CED impacts of materials less than 30 kg in total accounted are assumed to be 86% of the respective virgin materials. The FCEV analysis in scenario 2020 of the European Commission et al. (2020) is the basis for deriving this assumption. This approach defines 123 kg of materials, which equals about 8% of the total MHP mass. Apart from this, all other GWP and CED impacts for production and end of life processes are from the GEMIS, GREET, and ProBas databases. The material-specific parameters to calculate the CFF originate from the European Commission (2018) database and the European Commission et al. (2020) LCA. If CFF parameters are not available in these databases, own conservative assumptions are applied. The energy demand of MHP production is estimated based on Volkswagen's sustainability report—see Volkswagen (2021)—and results in 0.80 kWh electric energy, 0.42 kWh thermal energy, and 0.29 kWh gas per kg material used. The GWP and CED of production's energy demand, packaging materials, and transport processes originate from GEMIS.

Figure 10 shows the analyzed systems' category indicator results for production and end of life processes. These GWP and CED results are presented absolute and scaled to the functional unit and sub-system masses. The assessed production impacts include materials, transportation, packaging, and energy demand. The end of life process includes transportation, recycling, and waste treatment of components and packaging materials.

The production of MHP accounts for 17.78 t-CO₂eq. About 4.98 t-CO₂eq can be recovered through end of life management, resulting in 12.81 t-CO₂eq. All transport processes contribute 0.27 t-CO₂eq. The total CED amounts to 68.97 MWh, including 17.98 MWh recovered. The hydrogen storage system leads to the highest weight-specific GWP and CED due to the large share of CFRP (hydrogen tank). The cooling system and vehicle system also show relatively high specific GWP and CED. Figure 9 reveals that CFRP is used extensively as cover in the vehicle system and air guiding in the cooling system. Both systems also have high aluminum fractions, which strongly negatively impacts the category indicator results with a specific GWP of 12.67 kg-CO₂eq/kg and a CED of 44.34 kWh/kg.

Based on these findings, a second, from an environmental perspective, improved version of MHP—called MHP 2.0—was

designed on paper. The aim was to employ low-threshold potentials. Figure 11 illustrates the mass balance and material share.

The focus is on avoiding CFRP and reducing weight. The CFRP airflow guiding (cooling system) and the cover (vehicle system) are substituted by aluminum. The aluminum components lead to a weight increase of 20% compared to the CFRP components. Regarding the purchased components hydrogen tank, HVB, and FC, CFRP is crucial for functionality. Thus, substitution is not possible. Design measures and a lighter air compressor (air supply system) lower the weight of MHP 2.0 by 34 kg. This results in adding 119 kg of aluminum and reducing 100 kg of CFRP. In total, MHP 2.0 is 14 kg lighter compared to MHP.

Figure 12 shows the systems' category indicator results of MHP 2.0. In total, production results in a GWP of 14.20 t-CO₂eq and a CED of 61.66 MWh. End of life management compensates for 5.61 t-CO₂eq and 19.42 MWh, resulting in a total of 8.60 t-CO₂eq and 42.24 MWh. Compared to the base version, this is a 33% reduction of GWP and a 39% reduction of CED. The vehicle system and cooling system show the most significant reductions due to CFRP substitution. The hydrogen storage system continues to have the highest weight-specific GWP and CED, now followed by the FC system.

7.2 Use phase: hydrogen supply routes

The assessment of the use phase includes different fossil and renewable hydrogen supply routes. The purpose of these routes is to represent the possible Austrian hydrogen mix at hydrogen refueling stations (HRS) in Austria (AT) during the MHP application. The routes consist of production, transport, and compression for transport and refueling MHP at a HRS.

The assessment includes seven hydrogen production sources, excluding processes where hydrogen is a byproduct. The respective GWP and CED are included in Table 1. The GWP of coal gasification (CG) is taken from Burmistrz et al. (2016). Based on Guang et al. (2019), the CG's CED is estimated. Steam methane reforming (SMR) of natural gas is currently the primary hydrogen source worldwide. The respective

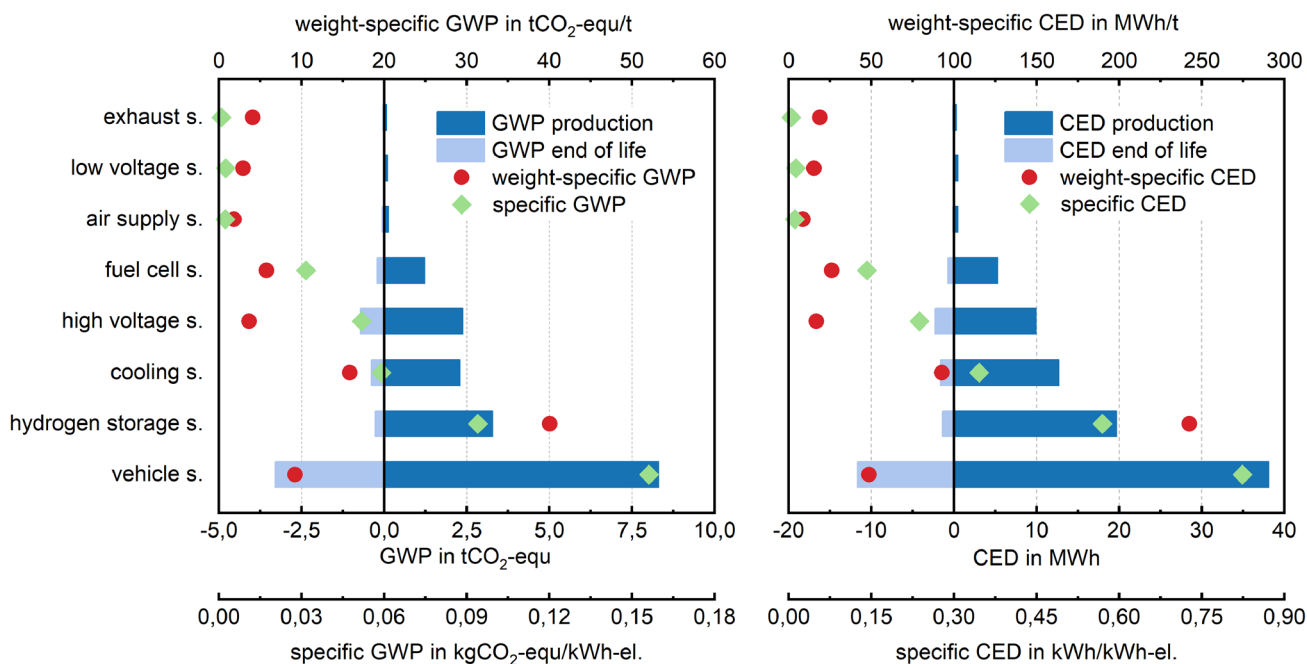


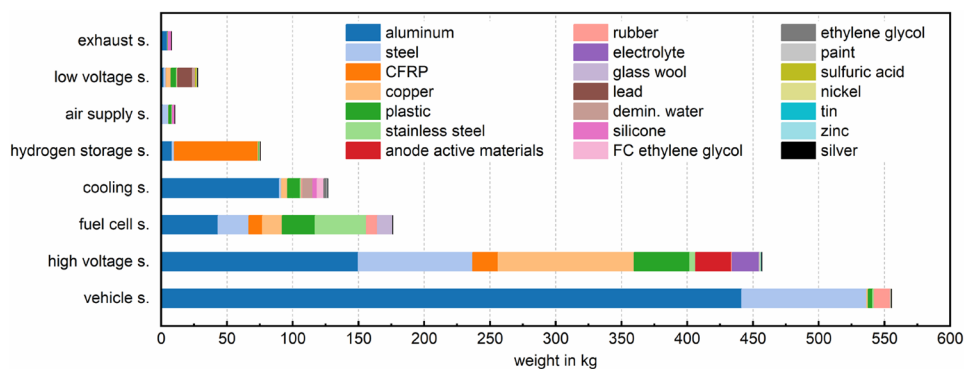
Fig. 10 Life cycle impact assessment: production and end of life, split in sub-systems

GWP and CED impacts of 2019 are estimated according to Jungmeier et al. (2019). SMR of natural gas with a CO₂ capture and storage system (SMR-CCS) leads to relatively low fossil GWP, but at the same time to very high CED, see Dufour et al. (2012). Jungmeier et al. (2019) is a source to estimate GWP and CED impacts for electrolytic hydrogen supply, powered by varying electric energy sources: wind, solar, and hydro. Sustainable forest residues are an input material for biomass gasification (BG). According to Wulf and Kaltschmitt (2018), the respective GWP is estimated and according to Weinberg and Kaltschmitt (2013) the BG's CED.

The HRS supply is balanced for transport by truck and pipeline. ICEs or FCs power the assessed heavy trucks. GWP and CED impacts of the ICE truck come from GEMIS. The FC truck's GWP origin from Simons and Azimov (2021) and the scaled CED from GEMIS. According to the data of

Adolf et al. (2017), the modeling includes two truck trailer technologies: a standard tube trailer with a payload of 500 kg at 200–250 bar and a container trailer with an increased payload of 1000 kg at 500 bar. Trucks have to drive the return from HRS to hydrogen production site unloaded; therefore, in contrast to pipeline transport, the double distance specific impacts from truck transport arise. With these assumptions, hydrogen transport by ICE truck at a payload of 500 kg results in 4.72 kg-CO₂eq/tkm and 19.69 kWh/tkm and by FC truck in 1.12 kg-CO₂eq/tkm and 12.87 kWh/tkm, based on the distance between HRS and production site. For the hydrogen pipeline transport, GWP of construction and operation, apart from electrical energy, originates from Wulf et al. (2018), and CED is scaled from GEMIS. This results in 0,34 kg-CO₂eq/tkm and 1,20 kWh/tkm. The hydrogen compression work for transport and refueling (at 900 bar)

Fig. 11 Life cycle inventory: masses and material share of MHP 2.0 sub-systems



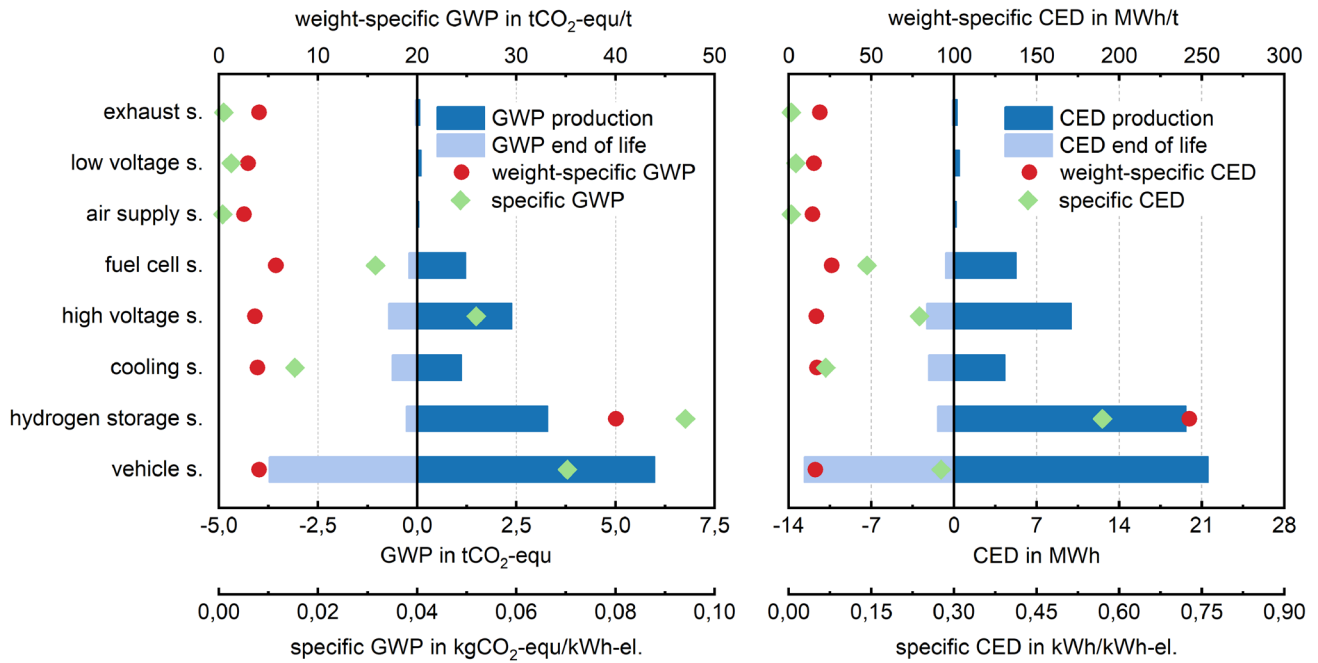


Fig. 12 Life cycle impact assessment: production and end of life, split in sub-systems, MHP 2.0

is calculated by isothermal compression. The compressor efficiency amounts to 65%. The electrical power supply efficiency is estimated to be 66%. Umweltbundesamt (2020) is the source of electricity supplies' GWP. Austrian electricity mix (AT electricity mix) leads to 0.26 kg-CO₂eq/kWh, and renewable electricity to 0.02 kg-CO₂eq/kWh.

Table 2 contains the parameterization the hydrogen supply routes. The global hydrogen mix route is based on the worldwide hydrogen production in 2020 of the global hydrogen review of IEA (2021), excluding hydrogen as a byproduct. The announced pledges route is also extracted from IEA (2021) and assumes the full implementation of all currently announced pledges. The net zero emissions route originates as well from IEA (2021) and assumes a development to achieve net-zero emissions in 2050. The hydrogen mix of announced pledges and net zero emission routes are assumed to correspond to the development in 2030.

In the electrolysis route, solar-powered electrolysis is the only hydrogen source. An exemplary plant is SolHub by Fronius, a combined unit that includes photovoltaics, electrolysis, and HRS, see BMK, Klima und Energiefonds (2020). According to the current Austrian government program, Austria should be climate neutral by 2040 at the latest, see Bundeskanzleramt Österreich (2020). According to the Austrian hydrogen strategy of BMK (2022), the government intends to introduce renewable hydrogen with a focus on hard to decarbonize sectors, including transport. Since an exact path is not public, the AT-traffic hydrogen mix route is assumption-based for the year 2030. In the biomass gasification route, BG, supplied with sustainable forest residues, is

the only hydrogen source. A role model for this path can be the BioH2Modul of the FCTRAC project, which includes gasification, purification, compression, and supply of the HRS, see Gubin et al. (2022).

Figure 13 shows the GWP and CED category indicator results of assessed hydrogen supply routes. The global hydrogen mix route leads to the highest GWP: 17,12 kg-CO₂eq/kg-H₂. The hydrogen production by SMR-CCS leads to relatively low GWP but is very energy-intensive, which is reflected in the high CED. The net zero emissions scenario owns the highest share of CCS-SMR, resulting in the highest CED of 95.75 kWh/kg-H₂. The lowest GWP and CED result from the BG route with 2.27 kg-CO₂eq/kg-H₂ and 63,04 kWh/kg-H₂. Decentralized hydrogen supply—as in the case of electrolysis and BG—shows an environmental impact

Table 1 GWP and CED of hydrogen production

Hydrogen production	GWP in kg-CO ₂ eq/kg-H ₂	CED in kWh/kg-H ₂
Coal gasification (CG)	21.7	86.42
Steam methane reforming (SMR)	12.82	63.27
Steam methane reforming with CO ₂ capture and storage (SMR-CCS)	3.77	121.94
Electrolysis wind	0.73	79.92
Electrolysis solar	3.66	66.66
Electrolysis hydro	0.43	66.66
Biomass gasification (BG)	2.23	59.61

Table 2 Hydrogen supply routes: parametrization of production, transport, and compression

Hydrogen supply route	Hydrogen production	Transport system	Transport distance	Electricity mix
Global hydrogen mix	74% SMR 25% CG 1% SMR-CCS	ICE truck, payload 500 kg	300 km	AT mix
Announced pledges scenario	32% CG 32% SMR 22% CCS-SMR 5% electrolysis wind 5% electrolysis solar 5% electrolysis hydro	50% ICE truck payload 1000 kg 50% FC truck, payload 1000 kg	200 km	50% AT mix 50% renewable
Net zero emissions scenario	35% SMR-CCS 13% CG 13% SMR 13% electrolysis wind 13% electrolysis solar 13% electrolysis hydro	33% ICE truck, payload 1000 kg 33% FC truck, payload 1000 kg 33% pipeline	200 km	50% AT mix 50% renewable
Electrolysis	Electrolysis solar	Pipeline	1 km	Renewable
AT-traffic hydrogen mix	30% electrolysis wind 30% electrolysis solar 20% SMR-CCS 15% BG 5% electrolysis hydro	33% ICE truck, payload 1000 kg 33% FC truck, payload 1000 kg 33% pipeline	200 km	Renewable
Biomass gasification	Sustainable forest residues	Pipeline	1 km	Renewable

reduction compared to the centralized routes also due to the almost complete omission of transport efforts. Production leads to the largest share of environmental impacts for all hydrogen supply routes. Renewable energy and renewable fuels further decrease the GWP impact of transport and compression.

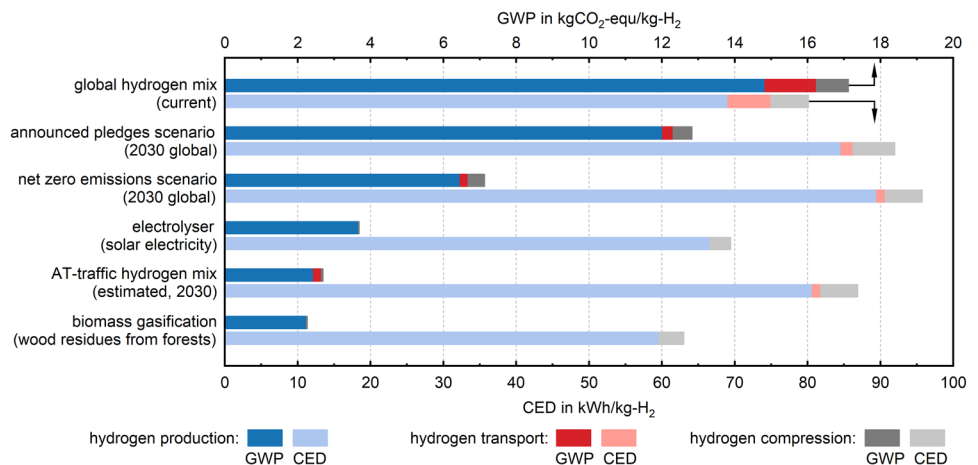
7.3 Full life cycle with sensitivity analysis

The life cycle combines the environmental impacts of production, use, and end of life phases. Scenario 2 of the Austrian PC fleet development (see Fig. 2) delivers the use phases' boundary condition: 32.11 MWh of electrical charging energy. Figure 14 contains the environmental impact of MHP depending

on the hydrogen supply route, charging type, operation strategy, and system setup. The charging power is always 20 kW and the ambient temperature 20 °C.

The highest life cycle environmental impacts result from parallel AC charging with the basic system setup and the global hydrogen supply route: 1.58 kg-CO₂eq/kWh-el and 7.68 kWh/kWh-el. In absolute terms, this amounts to 50.76 t-CO₂eq and a CED of 246.60 MWh. In combination with the high-efficient serial DC charging (see efficiency map, Fig. 7) and MHP 2.0, the BG route leads to the lowest environmental impacts: 0.40 kg-CO₂eq/kWh-el and 4.95 kWh/kWh-el. This corresponds to a 75% reduction in GWP and 36% in CED.

Fig. 13 Hydrogen supply routes: GWP and CED for production, transport, and compression



The MHP system efficiency, characterized by charging type and operation strategy, is independent of the hydrogen supply route directly reflected in the use phase's environmental impacts. With the present boundary conditions, the CED primarily originates from the use phase – in detail: from hydrogen production. Thus, high efficiencies of hydrogen supply route and MHP system cause low life cycle CED. For the global and the BG hydrogen routes (extremes), serial DC charging reduces the life cycle CED by approximately 11% compared to parallel AC charging.

The hydrogen supply route is crucial for the GWP of the use phase and, thus, the life cycle. If the hydrogen supply route causes minor GWP, such as the AT-traffic or BG route, the MHP efficiency has only a small impact on the life cycle's GWP. The production and end of life processes gain importance in this case. For example, the BG hydrogen supply route with serial DC charging, combined with MHP 2.0 shows a 25% GWP reduction compared to MHP. Figures 10 and 12 contain the individual GWP and CED life cycle impacts of the MHP sub-systems.

7.4 Boundary condition impact: cooling/charging efficiency, operation strategy, and Austrian PC fleet

The system analysis in Section 5 demonstrates clear influences of ambient temperature, charging power (Fig. 6), and operating strategy (Fig. 7) on efficiency. Figure 15 shows the effect of ambient temperature, and Fig. 16 that of charging power on GWP and CED for 5 kWh DC charging with the serial and parallel operating strategy for the AT-traffic hydrogen mix.

With increasing ambient temperature, the system efficiency decreases at an accelerated rate. This decrease results from the cooling system's rising power demand and increases GWP and CED. The efficiency curve depending on BEV charging power (see Fig. 7) mirrors in GWP and CED. The effects of cooling/charging efficiency and operation strategy are minor for sustainable hydrogen supply. The reduction potential by optimal boundaries is approximately 10% for CED and 4% for GWP, considering the AT-traffic hydrogen mix. Their influence increases if the use phase gains relevance (by conventional hydrogen supply).

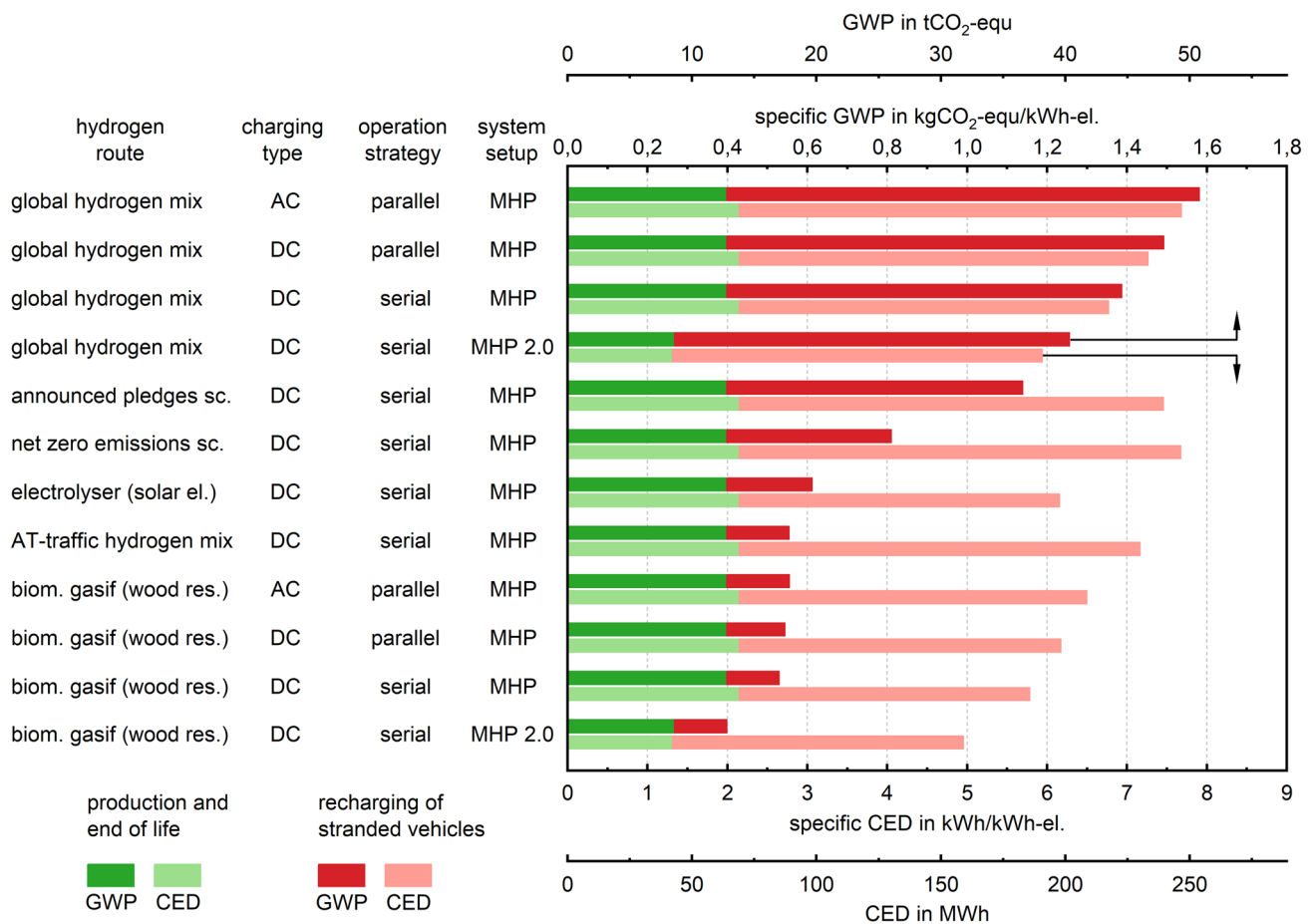


Fig. 14 LCA of MHP: GWP and CED

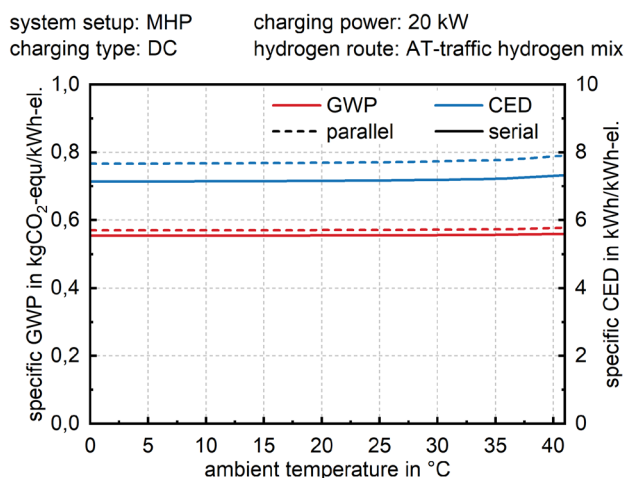


Fig. 15 LCA of MHP: impact of ambient temperature

Applying the global hydrogen supply route shows a reduction potential of approximately 10% for CED and 10% for GWP.

The PC fleet’s future development and, thus, the fundamental demand for recharging stranded BEVs is strongly dependent on the legal boundary conditions and road users’ acceptance. For the AT traffic hydrogen supply route combined with MHP and 20 kW serial DC charging at 20 °C ambient temperature, the effect of different PC fleet developments on the MHP life cycle impact is analyzed. Figure 17 contains GWP and CED as a function of charging energy, or more specifically, applications of MHP in the greater Vienna area, based on the PC fleet development scenarios 1–3 (see Fig. 2).

With increasing MHP application numbers, the specific GWP and CED decrease. Scenario 1, with a total of 4544 BEV charged, results in 0.71 kg-CO₂eq/kWh-el and 8.03 kWh/kWh-el. Scenario 3, with more than a doubling of operations to 9803, leads to 0.41 kg-CO₂eq/kWh-el and 6.41 kWh/kWh-el.

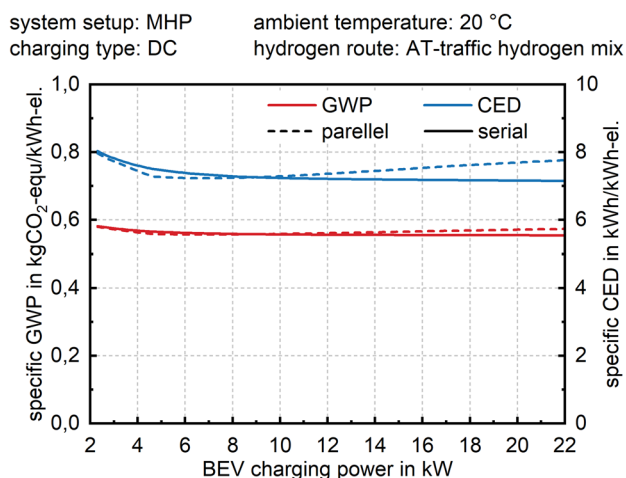


Fig. 16 LCA of MHP: impact of charging power

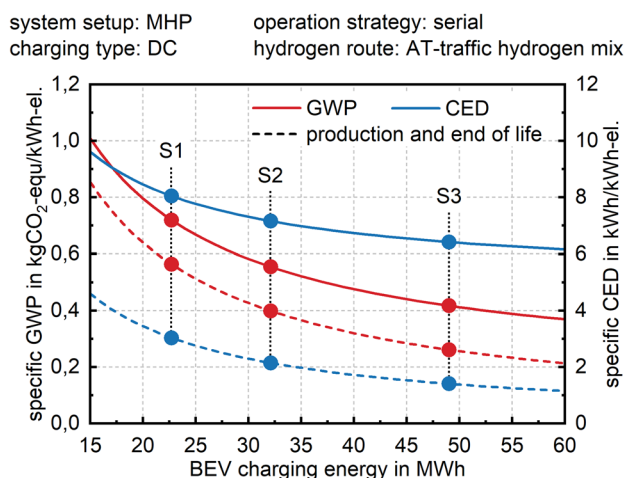


Fig. 17 LCA of MHP: impact of PC fleet development

The impacts of the production and end of life phase significantly influence the GWP for all three scenarios. Therefore, the specific GWP decreases considerably with increasing BEV charging numbers. The opposite is the case for CED: the main share results from the use phase. The specific CED reduces slightly with increased charging energy.

8 Conclusion and outlook

This paper introduces MHP—Mobile Hydrogen Powersupply—an off-grid fuel cell electric system to recharge (stranded) BEVs, and discusses MHP from the life cycle perspective. A polymer electrolyte membrane FC and a HVB are the power sources. The maximum charging power is above 20 kW.

The system architecture allows parallel and serial operation of FC and HVB. In parallel operation, the maximum efficiency is directly dependent on the FC’s efficiency map. The maximum is in the low to middle power range. In serial operation, the HVB powers the loads and the FC recharges the HVB efficiently. The HV components’ efficiency rises with increasing charging power, and the auxiliary consumers’ energetic share reduces. Thus, the highest efficiency is achieved at the highest charging power. With rising ambient temperature, the power consumption of the thermal system rises and the efficiency decreases. Due to the additional energy conversion, AC charging leads to reduced efficiency compared to DC.

MHP was assessed with the guidance of the ISO 14040 standard and the application of the Circular Footprint Formula. The LCA aimed to present the life cycle impact of the MHP application by an Austrian breakdown service with varying MHP parameterization and hydrogen supply routes. The functional unit is 1 kWh of electrical energy, balanced at the charging interface.

MHP weighs a total of approx. 1500 kg. The most common materials are weight-balanced, aluminum, steel, CFRP, and copper. The production and end of life result in 12.81 t-CO₂eq. The total CED amounts to 68.97 MWh. The hydrogen storage system leads to the highest weight-specific GWP and CED due to the large share of CFRP (hydrogen tank). Apart from the vehicle system, the hydrogen storage system has the highest absolute GWP and CED, surpassing the high voltage and fuel cell system. MHP 2.0 was designed on paper and achieved a 33% reduction of GWP and a 39% reduction of CED.

The highest life cycle environmental impacts result from parallel AC charging with the basic system setup and the global hydrogen mix supply route: 1.58 kg-CO₂eq/kWh-el and 7.68 kWh/kWh-el. In combination with the most efficient serial DC charging and the MHP 2.0 system setup, the biomass gasification route leads to the lowest environmental impacts: 0.40 kg-CO₂eq/kWh-el and 4.95 kWh/kWh-el. The efficiency of the MHP system is independent of the hydrogen supply route directly reflected in the use phase's environmental impacts. The impact of MHP cooling efficiency, charging efficiency, and operation strategy on total GWP and CED is below 12%. The CED primarily originates from hydrogen production. Thus, high efficiencies cause a low life cycle CED. The hydrogen supply route is crucial for the GWP of the use phase. If the hydrogen supply route generates minor GWP, the MHP efficiency has only a small impact on the life cycle's GWP and the production and end of life processes gain importance. With increasing MHP application numbers, the specific GWP and CED decrease.

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Author contribution Conceptualization: Johannes Konrad; Methodology: Johannes Konrad; Formal analysis and investigation: Johannes Konrad; Writing—original draft preparation: Johannes Konrad; Writing—review and editing: Axel-Oscar Bernt, Peter Hofmann; Supervision: Peter Hofmann; Project management: Axel-Oscar Bernt.

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Data availability To protect the intellectual property of the involved partners, it is not possible to describe details of the chosen components and production phases in the publication. For further insight, please contact the corresponding author.

Declarations

Ethics approval The work reported in this paper does not involve humans and/or animals.

Conflict of interest The authors declare no competing interests.

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