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Integrated environmental and economic assessment of current and future fuel cell vehicles

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Abstract

Purpose Light-duty vehicles contribute considerably to global greenhouse gas emissions. Fuel cell vehicles (FCVs) may play a key role in mitigating these emissions without facing the same limitations in range and refueling time as battery electric vehicles (BEVs). In this study, we assess the environmental impacts and costs of a polymer electrolyte membrane fuel cell system (FCS) for use in light-duty FCVs and integrate these results into a comparative evaluation between FCVs, BEVs, and internal combustion engine vehicles (ICEVs). **Methods** We conduct a detailed life cycle assessment (LCA) and cost assessment for the current state of the technology and two future scenarios for technological development. We compile a detailed and consistent inventory for the FCS by systematically disassembling and integrating information found in cost studies. For the vehicle-level comparison, we use

models to ensure that vehicle size, performance, and fuel consumption are unbiased between vehicle types and consistent with the scenarios for technological development.

Results and discussion Our results show that FCVs can decrease life cycle greenhouse gas emissions by 50 % compared to gasoline ICEVs if hydrogen is produced from renewable electricity, thus exhibiting similar emission levels as BEVs that are charged with the same electricity mix. If hydrogen is produced by natural gas reforming, FCVs are found to offer no greenhouse gas reductions, along with higher impacts in several other environmental impact categories. A major contributor to these impacts is the FCS, in particular the platinum in the catalyst and the carbon fiber in the hydrogen tank. The large amount of carbon fiber used in the tank was also the reason why we found that FCVs may not become fully cost competitive with ICEVs or BEVs, even when substantial technological development and mass production of all components is assumed.

Conclusions We conclude that FCVs only lead to lower greenhouse gas emissions than ICEVs if their fuel is sourced from renewable energy, as is the case with BEVs. FCVs are an attractive alternative to ICEVs in terms of vehicle performance criteria such as range and refueling time. However, the technological challenges associated with reducing other environmental impacts and costs of FCVs seem to be as large, if not larger, than those associated with the capacity and costs of batteries for BEVs—even when not taking into account the efforts required to build a hydrogen infrastructure network for road transportation.

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1 Introduction

With around one billion passenger vehicles in use, automobiles contribute substantially to global greenhouse gas (GHG) emissions and air pollution (Pollet et al. 2012). In the EU27 states, approximately 18 % of the GHG emissions came from road transport in 2009 (Hill et al. 2011). In the USA, it was 28 % in 2012, of which almost two thirds were emitted by personal light-duty vehicles (EPA 2014). Hydrogen-based fuel cell vehicles (FCVs) are regarded as a potential substitute for fossil-based internal combustion engine vehicles (ICEVs) that could lower the environmental impacts of transportation. Compared to battery electric vehicles (BEVs), FCVs do not exhibit the disadvantages of short driving range and long refueling time, making them more functionally equivalent to ICEVs than BEVs (Thomas 2009).

Early prototypes of FCVs were developed during the 1960s, and hundreds of millions of dollars have been spent on their development since (NRC 2011). The US Department of Energy (DOE) has been funding the development of fuel cells for vehicle applications for years, although their focus has recently broadened to stationary applications (Andress et al. 2012). Recent models include the Honda FCX Clarity, the Mercedes Benz F-Cell, and the Hyundai ix-35-FCV (also known as Tucson). While some manufacturers have seemingly reduced their efforts in the past 2 years, others have presented the first fully commercial FCVs: Hyundai announced an updated version of the ix-35, and Toyota unveiled the Mirai FCV at the end of 2014. Due to limited availability of hydrogen infrastructure, however, such vehicles can only be operated where corresponding regional projects are in place. Another reason for the absence of commercial success is the costs; the Honda FCX Clarity was estimated to cost around USD 120,000–140,000 to produce (Ohnsman 2008). Therefore, one of the main objectives of the second phase of the Hydrogen Joint Technology Initiative (FCH JTI) by the European Union is to reduce the costs of fuel cell systems (FCSs) for transport applications by a factor of 10 (European Commission 2013). A major contributor to these costs is the platinum on the catalyst layer of the fuel cell stack. Platinum, along with other uncommon materials used in the stack, also raises concerns regarding the environmental impacts of fuel cell production.

The DOE has funded two detailed cost analyses for FCSs (Sinha et al. 2008; James et al. 2010); a comparison between these two studies has been done as well (Marcinkoski et al. 2011). Further cost assessments of FCSs are provided by the International Energy Agency (Giorgio Simbolotti 2007) and consultancies (McKinsey & Company 2010; Bernhart et al. 2013), and a quantitative literature review was conducted in 2008 (Werhahn 2008). Some reports have incorporated cost assessments of FCSs in order to assess life cycle costs of FCVs and compare them against ICEVs (Kromer and

Heywood 2007; Bandivadekar et al. 2008; McKinsey & Company 2010). However, these reports usually do not consider the life cycle costs at the current, low production volumes, instead focusing on costs at mass production.

Several studies dedicated to the comparison of environmental impacts of FCV exist (Sørensen and Roskilde 2000; Pehnt 2002; Zamel and Li 2006; Schafer et al. 2006; Kromer and Heywood 2007; Bandivadekar et al. 2008; Simons and Bauer 2011a; Hwang et al. 2013; Bartolozzi et al. 2013; Bauer et al. 2015). The differences in scope and underlying assumptions of these studies lead to a large variety in results (Nordelöf et al. 2014). Most assessments focus on the fuel cycle; production and disposal of the vehicles are only accounted for roughly. These life cycle stages are particularly relevant for the FCS, where a variety of uncommon materials such as platinum, tetrafluoroethylene products, fibers, and resins are used. In addition, the fuel consumption is often based on rough literature estimates or manufacturer values and may not reflect the state of technology represented in the powertrain inventories and the chosen vehicle size. Furthermore, fuel consumption estimates often neglect the energy consumption of auxiliaries (lights, ventilation, cooling, and heating). Technological development is rarely included as well, implying that a technology that is still in major development (FCVs) is compared to a mature technology (ICEVs). Finally, impact categories other than climate change are frequently not discussed, making the identification of environmental trade-offs difficult. Results for life cycle carbon emissions range from approximately 90 g CO_{2,eq}/vehicle-kilometer (vkm) (Bandivadekar et al. 2008) to about 220 g (Simons and Bauer 2011a) when hydrogen is produced by steam methane reforming (SMR). Such results are often difficult to compare, as parameters such as the lifetime driving distance and the vehicle size or class vary greatly between studies.

The study presented in this paper aims to provide a consistent and detailed assessment of the environmental impacts and costs of FCVs over their entire life cycle and to compare the results to those for BEVs and ICEVs. The geographical scope focuses on Europe, an assumption that is particularly relevant for fuel and electricity costs, as they can differ considerably between regions. Because of the lack of detailed material inventories for FCSs in existing literature, the first goal of this study is to compile such an inventory and to conduct an assessment of the environmental impacts and costs associated with current and future FCSs for automotive applications. Based on these findings, the second goal is to conduct a comparative assessment of the environmental impacts and costs of FCVs, BEVs, and ICEVs. To overcome some of the issues in existing literature, we (a) use the high level of detail found in cost studies of FCS to compile new inventories for the environmental assessment; (b) tightly integrate the inventories for costs and environmental impacts, thus allowing direct

comparisons between costs and environmental impacts on a component level; (c) assess both the current state of technology, as well as the prospective development until 2030, for two technological development scenarios; (d) use models to calculate the fuel economy of all vehicles and the size of various drivetrain components, ensuring consistency between different vehicle types and scenarios; and (e) assess the influence of parameters that tend to vary between studies, such as the lifetime driving distance, vehicle class and the life of critical components such as the fuel cell stack in FCVs, and the battery in BEVs.

2 Methods

2.1 Life cycle assessment

The environmental impacts were quantified using the life cycle assessment (LCA) approach, which is a method to calculate environmental impacts of goods and services, covering their complete production and value chains. We base our LCA on the ISO standards (ISO:14040 2010). Additionally, specific LCA guidelines for the assessment of BEVs (Del Duce et al. 2013) and FCVs (Masoni and Zamagni 2011) were taken into account. The environmental impacts were assessed for the entire life cycle of the vehicles, including vehicle production and disposal, a well-to-wheel assessment of the fuels, fuel combustion, non-exhaust emissions during use due to tire, road, and brake wear, as well as road provision and maintenance.

The ecoinvent database v2.2 (ecoinvent 2010) was used for background life cycle inventory (LCI) data. For the life cycle impact assessment (LCIA), the ReCiPe method (Goedkoop et al. 2008), as implemented in the LCA software SimaPro v7.2.3 (PréConsultants 2011), was used. In addition to the climate change impact by GHG emissions, four other impact categories were analyzed: terrestrial acidification, human toxicity, photochemical oxidant formation, and particulate matter (PM) formation. Results for all other ReCiPe midpoint categories are presented in the supplementary material. In our case, terrestrial acidification is composed of SO₂, NO_x emissions, and ammonia emissions, as well as (to a lesser extent) emissions of other sulfur oxides. Human toxicity is composed of emissions of almost 300 toxic substances, with manganese, arsenic, antimony, lead, selenium, and mercury being among the most important ones. The most contributing photochemical oxidants are NO_x, non-methane volatile organic compounds (NMVOC), SO_x, and CO. Other organic compounds such as toluene, pentane, and butane contribute as well. To PM formation, SO₂ and NO_x (via formation of secondary particles) contribute about as much as direct particulate emissions below a 10-μm diameter.

2.2 Life cycle costs

The costs of the vehicles were assessed as life cycle costs from the perspective of the vehicle owner. Generally, life cycle costing is similar to the evaluation of total costs of ownership (TCO), although the latter typically includes prepurchasing costs (Ellram 1995). The overall approach is similar to an LCA: The costs are evaluated for the entire vehicle life cycle, including all relevant components and their value chains.

Economies of scale are reported to have a major influence on FCS component costs (Sinha et al. 2008; James et al. 2010; Law 2011). Therefore, these costs were assessed for three different production volumes: 200 vehicles (or systems) per year, 1000 per year, and 500,000 per year. The impact of production volumes on LCIs for the LCA was not modeled, since we expect a minor impact on LCI data compared to the impact on costs. Discount rates were not applied to future costs. While this approach is not in line with many cost studies, it resolves two caveats of using a discount rate for costs: (a) It prevents inconsistencies with the environmental impact assessment, where discount rates are not generally recommended and not applied (Yuan et al. 2015) and (b) it prevents a bias due to the omission of vehicle leasing and financing, where costs are paid over time (and would be discounted), as opposed to paying the vehicle costs upfront (which would not be discounted). All costs were compiled in USD₂₀₁₄. A conversion factor of 1 €=\$1.15 was used where necessary to convert cost information given in € to USD.

The costs were modeled to only include the purchasing price of the vehicle and fuel costs. Disposal costs were excluded because they are usually not assigned to the owner of the vehicle. Insurance costs, taxes, and maintenance costs were excluded because they would obscure the costs of vehicle production and fuel consumption, which were of primary concern in this study. In addition, insurance costs, maintenance costs, and taxes depend more on factors related to the vehicle owner and region where the car is driven than on the powertrain technology itself.

2.3 Scenarios

The costs and environmental impacts were assessed for three different scenarios: The “current” scenario refers to the state of technology implemented in recently produced FCV (2011–2014) and a production volume of FCSs of 200 units per year and manufacturer. This volume corresponds to the volume of small-series FCV such as the Mercedes Benz F-Cell and the Honda Clarity FCX. As discussed, the impact of the production volume was only modeled for FCS costs. It was not modeled for other component costs or for the LCIs. The first future scenario, “2030 conservative,” assumes a slow technical development and a slow production volume increase of FCSs to 1000 vehicles per year. The second future scenario,

“2030 optimistic,” includes a more optimistic development of vehicle technology and a production volume increase of FCSs to 500,000 per year. A volume of 100,000–500,000 is generally considered to be mass production (NRC 2011), and 500,000 is the highest volume considered in several cost studies (Sinha et al. 2008; Werhahn 2008; James et al. 2010). Therefore, the 2030 optimistic scenario represents a “fully mature technology” comparison between FCVs, BEVs, and ICEVs.

Toyota is planning to produce up to 3000 units/year of its upcoming Mirai FCV, meaning that the 2030 conservative production levels may already be reached in 2016. As we based the current scenario on vehicles that had already been in production at the time of this study, we did not consider Toyota’s plans in the current scenario. However, we show cost results for all nine possible combinations of technological development (current, 2030 conservative, and 2030 optimistic) and production volume (200, 1000, and 500,000/year) in Sect. S4 in the Electronic Supplementary Material.

The emission and energy intensity of all background processes (production and distribution of all materials, generation and distribution of electricity, electricity mixes for specific regions, and production and distribution of fuels) were not modified for future scenarios. The same is true for fuel and electricity prices. Assessing these price changes would have been outside the scope of this study and is associated with substantial uncertainty. The only exception is the efficiency of the production of hydrogen using electrolysis, which was increased for the future scenarios.

Therefore, changes between scenarios in the environmental impacts and costs of non-fuel cell system components only stem from a lower material consumption (such as fuel consumption per kilometer driven or the amount of material per kilowatt of engine) or a decrease in reference flow (such as the required engine power in kilowatts to maintain acceleration performance) but not from changes in mass-specific costs or inventories. For the FCS components, changes can also be caused by material replacements (for instance, stainless steel instead for graphite in bipolar plates), and changes in costs can additionally be caused by economies of scale, as all material and process costs were defined for three different production volumes.

2.4 Modeling the fuel cell product system

The functional unit of the FCS was defined as “one polymer electrolyte membrane (PEM) FCS with 80 kW nominal power and a hydrogen tank of 5.6 kg usable capacity, for use in light-duty vehicles.” Mapping the results to a reference flow such as 1 kW is omitted, because this would not allow a combined assessment of the fuel cell stack (which scales almost linearly with system power), the balance of plant (which only scales partially with system power), and the hydrogen tank (which does not scale with system power but with tank capacity).

Figure 1 depicts the modeled product system of the FCS. The system is split into three major subgroups: the stack (the actual fuel cells that convert the chemical energy of hydrogen into electrical energy), the balance of plant (which handles fuel input and output, air, heat, and water), and the hydrogen tank. Hydrogen was assumed to be stored on board in gaseous form in a single 700-bar carbon fiber hydrogen tank. The inventories of the fuel cell stack components are either modeled by m_{2a} (active area of the fuel cell stack) or m_{2t} (total area, i.e., active area plus inactive border). The fuel cell balance of plant components are modeled as scaling linearly with FCS power for a default power of 80 kW or as a fixed-size piece that does not scale with power. The hydrogen tank is modeled for a reference case of a single tank with a net capacity of 5.6 kg hydrogen and was assumed to scale linearly with storage capacity.

The amount of active area and total area per kilowatt of (gross) fuel cell output was determined using an electrochemical fuel cell model and validated using existing literature. The

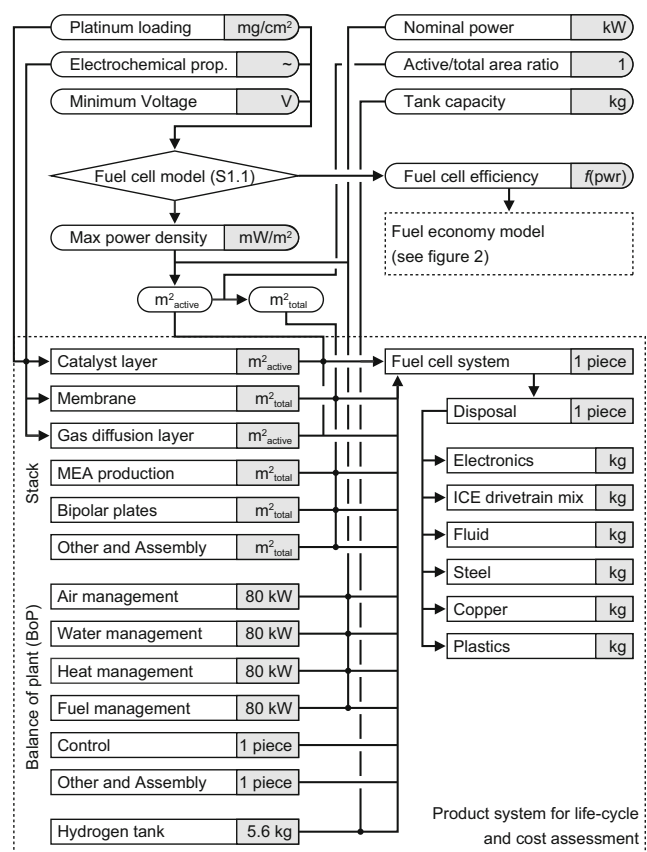


Fig. 1 Framework of analysis and flow of information for the fuel cell system (FCS). Boxes within the product system boundary represent product system components. Boxes outside the product system boundary (with round corners) represent parameters that are used directly or indirectly (via other parameters) to scale product system components according to the unit of their respective reference flow (shaded box)

same model was used to determine the efficiency curves of the FCS, which were used to determine the fuel economies of FCV for the second part of this study. More information on this procedure can be found in Sect. S1.1 of the Electronic Supplementary Material. Explicitly modeling the FCS allowed us to obtain reasonable estimates for the power density and efficiency of the FCS that are consistent with the corresponding assumptions about the technological development of the materials in all scenarios.

For compiling the component inventories, the amount of materials (in kg) per reference flow of that specific component was defined for each scenario and each individual component. Each material was then affiliated with a certain cost at each production volume (corresponding to the three scenarios), a suggested LCI process for production, a suggested LCI process for disposal, a recycling rate, and a production waste factor. For instance, the “gasket” material required for the membrane electrode assembly was defined to be $0.26 \text{ kg/m}^2_{\text{total}}$ in the current scenario, $0.24 \text{ kg/m}^2_{\text{total}}$ in the 2030 conservative scenario, and $0.18 \text{ kg/m}^2_{\text{total}}$ in the 2030 optimistic scenario. It was set to costs of \$65/kg at a production level of 200 units per year (for the current scenario), \$51.5/kg at a production level of 1000 units per year (for the 2030 conservative scenario), and \$43.5/kg at a production level of 500,000 units per year (for the 2030 optimistic scenario). It was associated with the “polysulphide, sealing compound, at plant/RER” process fromecoinvent for production and the “disposal, plastics, mixture, 15.3 % water, to municipal incineration/CHU” for disposal, assuming no recycling. A waste factor of 0.36 was set (meaning that $1/(1-0.36)-1 = 56\%$ more of this material is required in production than the amount per $\text{m}^2_{\text{total}}$ indicated above).

The same procedure was used for each material, and all major processing steps (such as stamping and coating), with the exception that no recycling rates, waste factors, or disposal processes need to be associated with processing. In addition, a markup was set for each component, lifting the overall price by the respective amount. We used markup estimates of 36 % for the added value of membrane electrode assembly (MEA) production, 25 % for the bipolar plates and other stack materials, 15 % for the hydrogen tank, and 0 % for all other components. These values are based on (James et al. 2010) and represent the lowest bound of possible values.

The inventories for the balance of plant components and the hydrogen tank were assembled in the same manner. As most of these components (such as filters, pipes, coolers) consist of relatively common materials with a similar composition as the respective components in combustion engine drivetrains, corresponding proxy processes were used. A more detailed assessment of these components was found unnecessary, as their impact is relatively low in all impact categories.

The composition (i.e., the list, amount, and costs of all materials and processes required for each component) for the current inventory was derived from detailed cost studies of FCSs (Sinha et al. 2008; James et al. 2010, 2011; Sinha 2010; James 2012). Waste factors were based on (James et al. 2010; Bernhart et al. 2013). The projections for the two future scenarios were based on according literature. Table 1 summarizes the assumptions regarding technology and materials that guided the compilation of the inventories. The full specific inventories can be found in the Electronic Supplementary Material in Tables S5, S6, and S7. The resulting final inventories after combining specific inventories with the “amount” of each component needed can be found in the Electronic Supplementary Material in Tables S11, S12, S13.

Notably, the platinum group metals (PGMs) loading in the current scenario was assumed to be considerably higher (0.4 mg/cm^2 of platinum) as in several existing studies, which often use $0.15 \text{ mg}_{\text{PGM}}/\text{cm}^2$ (James et al. 2010; Sinha 2010; Simons and Bauer 2015). With current technology, the power density at these low loadings would lead to too low a power density, which is required to be at least around 1000 mW/cm^2 to meet of vehicle size constraints (Martin 2010; Debe 2012). This is especially true once degradation of the fuel cell during its lifetime is taken into account (Debe 2012). The recently announced Toyota Mirai (2015/2016 model) is reported to use about 40 g of platinum (Cobb 2014). Assuming a nominal power of the FCS of 100 kW at a power density of 1000 mW , this corresponds to $0.4 \text{ mg}_{\text{Pt}}/\text{cm}^2$. Based on our electrochemical model and literature indicators (Rabis et al. 2012; Barbir 2013), the loading was decreased considerably for future scenarios (0.20 and 0.10 g/cm^2), with simultaneous improvements in power density and efficiency. Non-precious metal catalysts are in development as well, but their performance is still very far from being competitive with PGM-based catalysts (Othman et al. 2012). Therefore, such catalysts are not considered here.

2.5 Modeling the vehicle product system

The functional unit of the vehicle comparison was defined as “driving 150,000 km in a five-seat compact car (class C), using the most recent technology, with the same moderate acceleration performance of 12 s from 0 to 100 km/h, driving on the New European Driving Cycle (NEDC), with average auxiliary use (including heating and cooling).” The reference flow was set to 1 vkm of driving. Note that some of these definitions were changed in the course of a sensitivity analysis, which is discussed later.

Figure 2 shows all system components that were modeled for the vehicle comparison and the corresponding information flows. The FCVs were modeled as hybrids, meaning that electric power is delivered from both the FCS and a battery. The inventories of the powertrain components, which include an

Table 1 Key assumptions for the fuel cell system

Parameter/component	Current	2030 Conservative	2030 Optimistic	Source
Production volume (affects costs only)	200 per year	1000 per year	500,000 per year	
Stack				
Catalyst layer ^a	0.4 mg/cm ² Pt in Pt/C particles	0.2 mg/cm ² Pt in Pt/C particles, higher specific activity ^a	0.1 mg/cm ² Pt in Pt/C particles, even higher specific activity ^a	Model, (Martin 2010; Debe 2012; Martin et al. 2012; Cobb 2014)
Membrane ^a	Perfluorosulfonic acid (PFSA/Nafion®) with expanded polytetrafluoroethylene (ePTFE) backbone and sulfuric acid side chains, 25 μm	Thickness reduced to 17.5 μm, improved performance and temperature	Polybenzimidazole (PBI), 12.5 μm, even further improved performance and temperature, much lower costs	(James et al. 2010; Barbir 2013)
Gas diffusion layer ^a	0.28-mm non-woven carbon substrate macroporous layer with 0.04-mm microporous layer of PTFE and carbon black	0.15-mm non-woven carbon substrate macroporous layer with 0.04-mm microporous layer of PTFE and carbon black	0.08-mm non-woven carbon substrate macroporous layer with 0.02-mm microporous layer of PTFE and carbon black	(James et al. 2010), Future values are assumptions.
Bipolar plates	1.5-mm-thick injection-molded graphite plates (3 mm combined), injection-molded coolant gaskets	0.152-mm-thick stainless steel plates, coated with TiN, screen-printed coolant gaskets	0.120-mm-thick stainless steel plates, coated with TiN, screen-printed coolant gaskets	(James et al. 2010; Karimi et al. 2012; Barbir 2013)
Balance of plant				
Air management	Compression-expansion-motor unit for operation at 2 bar	Improved compression-expansion-motor unit for operation at 2 bar	Improved, smaller compression-expansion-motor unit for operation at 1.5 bar	(Sinha et al. 2008; James et al. 2010; Barbir 2013)
Water management	Humidifier using PFSA (Nafion®) tubes	Simple humidifier without Nafion®, operating temperature above 373 K	No humidifier and precooler necessary	(Sinha et al. 2008; James et al. 2010; Barbir 2013)
Heat management	Radiator and antifreeze liquid	Smaller unit due to higher operating temperature	Even smaller unit	(Sinha et al. 2008; James et al. 2010; Barbir 2013)
Performance				
Peak efficiency in % (LHV)	58	62	64	Model
Efficiency at rated power in % (LHV)	48	50	52	Model
Power density at rated power (mW/cm ²)	1060	1310	1625	Model
Hydrogen tank				
Hydrogen tank	700-bar single gaseous tank	700-bar single gaseous tank, 15 % lower material consumption	700-bar single gaseous tank, 30 % lower material consumption	(Hua et al. 2011; Law 2011)

The detailed inventories can be found in the Electronic Supplementary Material in Table S5, S6, S7 (specific inventories), and Table S11 (total inventories). Details on the fuel cell system model are available in Sect. S1.1

^a Improvements in the performance of the MEA components contributed to a simultaneous increase in system efficiency, increase in power density, and decrease of the platinum loading on the catalyst layer. The membrane for the 2030 optimistic scenario (PBI) should be regarded as a proxy for a future, almost-ideal technology

electric motor (FCVs and BEVs) or an internal combustion engine (ICEVs), power electronics, transmission, differential, and further subcomponents, were split into two parts: a part that scales linearly with powertrain system power and a part that does not scale. The glider contains all components that are common for both vehicle types. Unlike some components of the FCS, no additional markups and waste factors were applied to the components depicted in Fig. 2, as they are already accounted for in the respective prices and inventories. However, a final markup of \$5000 was applied to all vehicles to account for research and development, marketing, and final distribution costs.

The reference flows that determine the scaling of various components include the power of the FCS (for FCVs), the peak power of the electric motor (for FCVs and BEVs), the rated power of the combustion engine (for ICEVs), and the power of the power battery (for FCVs). It can be argued that a consistent scaling of these components does not necessarily take place, but the scaling does allow for a functionally consistent assessment and comparison of the different vehicles. Similar approaches to modeling the fuel economy and drivetrain size have been used in other studies (Kromer and Heywood 2007; Bandivadekar et al. 2008; Bauer et al. 2015). The reference flows are derived from parameters such as desired acceleration and vehicle mass, using physical relationships. Details on this procedure

can be found in Sect. S1.2 of the Electronic Supplementary Material.

Drivetrain components that do not belong to the FCS were not modeled in detail, as we focused on the modeling of the FCS for this study. Instead, existing inventories and information from literature were used. While the continuous power requirement usually determines the size of the battery for FCVs, the driving range (capacity) determines the size of the battery for BEVs. We therefore distinguish between power and energy batteries. The power density (for FCVs) and energy density (for BEVs) of the batteries are available in Table 2 and were based on Kalhammer et al. (2007) and Duleep et al. (2011). In the current scenario, the battery is modeled as a lithium-ion (lithium nickel cobalt aluminum oxide) battery. For the 2030 scenarios, the energy density of the battery is assumed to correspond to the predictions for silicon lithium batteries (Duleep et al. 2011). However, the LCIs of lithium nickel cobalt aluminum oxide batteries were used to model the material composition of the batteries in all scenarios, as other inventories were not available in ecoinvent v2.2. In addition, the uncertainties affiliated with the inventories of lithium-ion batteries themselves (Ellingsen et al. 2014) may be larger than the potential error introduced by using a lithium-ion-based proxy process to model the future batteries. Mass-specific costs for all batteries were based on (Kalhammer et al. 2007) and are assumed to decrease by about 25 % in the 2030

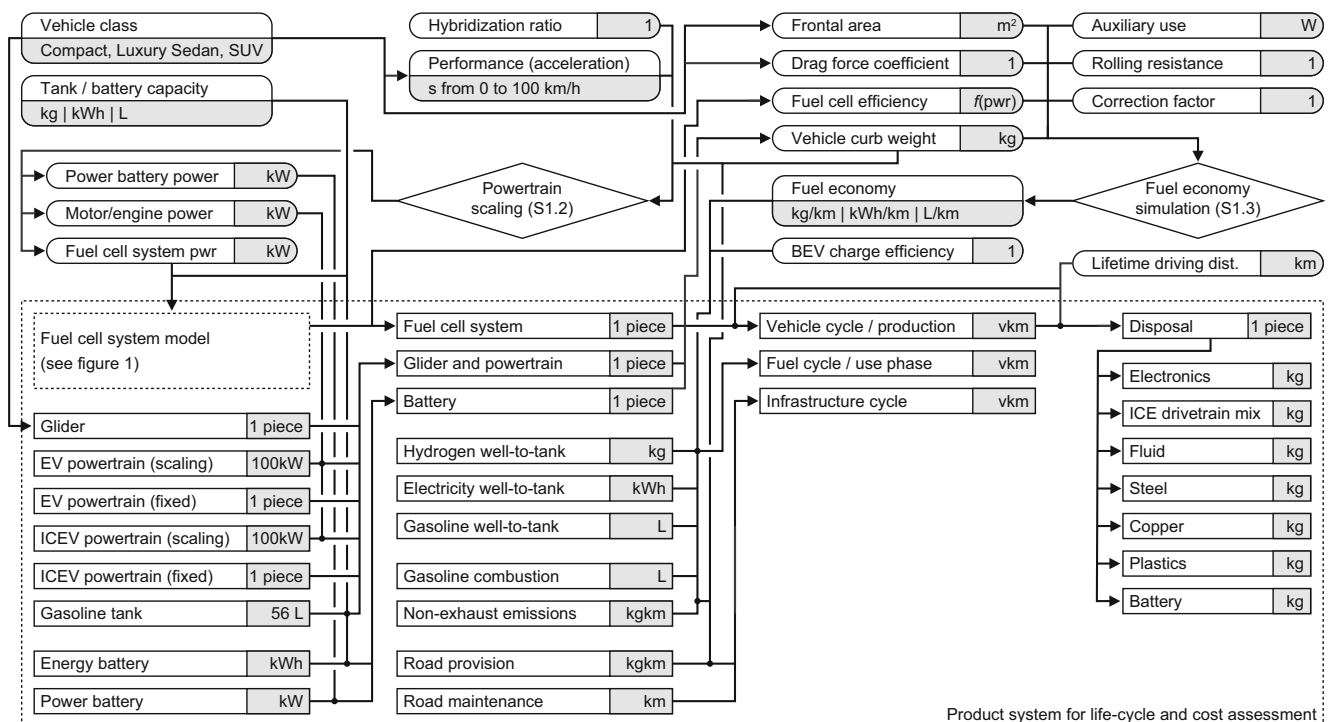


Fig. 2 Framework of analysis and flow of information for the entire vehicles. Boxes within the product system boundary represent product system components. Boxes outside the product system boundary (with

round corners) represent parameters that are used directly or indirectly (via other parameters) to scale product system components according to the unit of their respective reference flow (shaded box)

conservative scenario and by about 45 % in the 2030 optimistic scenario. Due to considerable technological hurdles, more advanced battery technologies (such as lithium-sulfur and lithium-air) may not reach maturity until 2030 (Bruce et al. 2011) and were therefore not considered.

The fuel economies of the vehicles were simulated using ADVISOR (Markel et al. 2002) for the NEDC, using the inputs from the FCS and powertrain scaling calculations (see Fig. 2). The average use of auxiliaries such as lights, heating, and cooling for a central European climate were included in the fuel economy simulation. The efficiency of certain components, including the headlights and the heat pumps for heating and cooling, were assumed to improve in the future. This resulted in average electrical auxiliary loads of 1100 W (current), 917 W (2030 conservative), and 721 W (2030 optimistic) for FCVs and BEVs, and 500/417/293 W for ICEVs. The values for ICEVs are lower because the vehicles can be heated for free in winter using waste heat from the combustion engine. On the other hand, the electricity for auxiliaries has to be gained from mechanical energy using an alternator. Its efficiency was assumed to be 55 %. Finally, a penalty of 10 % was added to all calculated fuel economies, to account for more demanding driving patterns than the official NEDC cycles. Table 2 shows the outputs of the vehicle configuration models that were used to scale the respective components for the LCA-life cycle cost (LCC) model.

For the fuel economy simulation, internal parameters of ADVISOR that determine the efficiency of the combustion engine (for ICEVs) and the efficiency for the battery (for FCVs and BEVs) were calibrated to match the reported fuel economy in the NEDC of the 2015 VW Golf VII and the 2015 Nissan Leaf (before taking into account auxiliaries and the aggressive driving penalty). Parameters such as vehicle mass and power were adjusted before the calibration to match these cars. The efficiency characteristics of the FCS were modeled explicitly, instead of using a calibration approach (see Sect. S1.1 in the Electronic Supplementary Material). For modeling fuel economies in the 2030 scenarios, the efficiency parameters of the combustion engine (for ICEVs), fuel cell system (for FCVs), and auxiliaries (all vehicles) were adjusted. In addition, all cars benefit from a decrease in vehicle mass and an improvement in aerodynamics. Further details can be found in Table 2 and in Sect. S1.3 and Table S2 in the Electronic Supplementary Material. Overall, we modeled a decrease in fuel consumption by 17 % (2030 conservative) and 31 % (2030 optimistic) for ICEVs (see Table 2). These efficiency increases are in line with predictions found in literature (Kromer and Heywood 2007; Schafer et al. 2009). BEV energy consumption was modeled to decrease by 15 and 28 %, respectively, and FCV fuel consumption was modeled to decrease by 18 and 30 %.

The costs and LCIs for the vehicle components depicted in Fig. 2 were based on literature values. As with the FCS inventories, the mass of each component was defined for each scenario and associated with a certain cost per mass. The detailed specific inventories are available in Table S8 in the Electronic Supplementary Material.

2.6 Fuel production and costs

The LCI of hydrogen was based on existing literature (Simons and Bauer 2011b), both for the current scenario as well as for 2030. However, all background processes (such as electricity production) were kept at the state of the current scenario, consistent with the approach to the vehicle modeling. As production pathways, local production at the refueling station by SMR and electrolysis from two different electricity sources (UCTE mix and wind) were considered. Other production methods such as coal gasification and solar thermal ZnO/Zn water splitting were omitted, because local production is not currently done with these technologies. Considering a centralized production would have required a detailed cost assessment of the distribution system, which was outside the scope of this study. As in (Simons and Bauer 2011b), the efficiency of hydrogen production from electrolysis was increased from 58.5 to 66.7 % in 2030 and the efficiency of hydrogen production from SMR was set to a constant 67 % (both including compression and storage). For the BEV, a charging efficiency of 90 % was assumed, meaning that the overall electricity consumption was set to be 11 % higher than the modeled fuel economy of the BEV.

The prices of hydrogen were based on (Ramsden et al. 2009) but were adjusted using our own (industrial) natural gas and electricity prices. These prices, as well as the prices of gasoline (for ICEVs) and residential electricity (for charging BEVs), were calculated as inflation-adjusted 7-year averages from 2007 to 2014 using data for Germany (Federal Statistical 2014).

The determination of fuel prices is made more complicated by the issue of taxation. In Germany, an energy tax equivalent to 0.0248 €/MJ_{Gasoline,LHV} and 19 % value-added tax (VAT) are imposed on gasoline. Several taxes and the VAT affect the electricity price for consumers as well. The German taxes on electricity (without VAT) amount to a total of approximately 0.022 €/MJ_{electricity}, although they serve different purposes than the energy tax on gasoline. In order to ensure some degree of consistency between the prices of the three types of fuels, a fuel tax equivalent to the gasoline tax in Germany on a per-MJ basis was added to the production costs for hydrogen (0.0248 €/MJ_{LHV} or \$3.42/kg_{Hydrogen}) to determine the final hydrogen price, and a 19 % VAT was applied as well.

The resulting energy carrier prices are \$1.83/L (\$6.93/gallon) for gasoline, \$0.303/kWh electricity for charging BEVs, \$17.1/kg for hydrogen from electrolysis, and \$9.34/kg for hydrogen from SMR. For the 2030 scenarios, the hydrogen

Table 2 Key assumptions and model outputs for the entire vehicles, for a compact car about the size of a VW Golf, Mercedes-Benz B-Class, or Ford Focus

Parameter	Unit	FCV			BEV			Gasoline ICEV		
		Current	2030 Con	2030 Opt	Current	2030 Con	2030 Opt	Current	2030 Con	2030 Opt
Powertrain										
Active area of fuel cell stack	m ²	9.1	5.9	4.0						
Total area of fuel cell stack	m ²	14.0	9.1	5.3						
FCS nominal power	kW	85	72	62						
Motor/engine (peak) power	kW	102	86	74	100	90	81	84	78	73
Total amount of platinum ^a	g	36.4	11.8	4.0	0	0	0	1.5	1.4	1.2
Rest of vehicle										
Battery power	kW	28	24	21						
Battery and energy density of batteries	kW/kg, kWh/kg	1.2	1.5	2.5	0.11	0.14	0.19			
Fuel capacity (usable)	kg, kWh, L	5.6	5.0	4.5	25	30	35	56	45	40
Vehicle curb weight ^b	kg	1537	1292	1117	1501	1352	1208	1198	1117	1045
Vehicle purchasing price	\$	74,460	27,110	16,350	37,180	24,500	15,580	20,060	22,110	14,880
Fuel										
Fuel consumption ^c (energy equivalents)	kWh/100 km	35.0	28.8	24.3	16.8	14.3	12.1	52.6	53.7	36.3
Fuel consumption ^c (mixed units)	kg/100 km, kWh/100 km, L/100 km	1.05	0.86	0.73	16.8	14.3	12.1	5.88	4.88	4.06
Fuel consumption ^{c,d} (US units)	MPG(e)	60	73	86	125	146	173	40	48	58
Effective range	km	535	576	616	149	209	289	951	920	987
Hydrogen production efficiency (electrolysis/SMR) ^f	%	58.5/67	66.7/67	66.7/67						
Fuel price (including fuel tax and VAT)	\$/kg, \$/kWh, \$/L	17.1/ 9.34 ^f	15.9/ 9.34 ^f	15.9/ 9.34 ^f	0.303	0.303	0.303	1.83	1.83	1.83
Exhaust emissions standard								EURO VI	EURO VI	EURO VI

Details about how these parameters were obtained can be found in the Electronic Supplementary Material, Chap. S1.2 and S1.3 and Tables S1 and S2. *FCS* fuel cell system, *LHV* lower heating value, *2030 Con* 2030 conservative scenario, *2030 Opt* 2030 optimistic scenario

^a The decreased amount of platinum in ICEVs is not explicitly modeled but comes from the decreasing drivetrain mass, as the material mix of the ICE drivetrain is kept constant. For area-specific platinum loadings in FCVs, see Table 1

^b Curb weight does not include the cargo mass of 100 kg, which was added for fuel economy simulation

^c Fuel consumption is based on a simulation using the New European Driving Cycle (NEDC) and accounts for the energy consumption of auxiliaries and a 10 % penalty for aggressive driving patterns. Fuel consumption of BEVs does not yet include the 10 % losses during charging

^d US values are not necessarily comparable to EPA-reported adjusted MPG ratings available to consumers in the USA, because different assumptions regarding auxiliaries and aggressive driving and a different driving cycle are used

^e Efficiencies are indicated against the lower heating value (LHV) of hydrogen. Include electricity consumption for compression to 700 bar and storage

^f The first number refers to the price of hydrogen produced with electrolysis, the second to steam methane reforming (SMR). Prices include a fuel tax of \$3.4/kg (equivalent to the fuel tax on gasoline in Germany on a per-MJ basis) and 19 % VAT

price for electrolysis was lowered to \$15.9/kg due to an assumed improvement in the efficiency of electrolysis. Without the energy-based tax and VAT, the hydrogen costs would have been \$11.0/kg, \$4.43/kg, and \$9.93/kg, respectively. A case where all energy carrier prices are determined by production costs only is explored in the sensitivity analysis (Table 3).

Note that the approach of a constant per-MJ tax implies that per *distance* driven, ICEVs will be taxed more than FCVs and FCVs will be taxed more than BEVs. This is because ICEVs require more energy per kilometer driven than FCVs and

FCVs require more energy per kilometer driven than BEVs. Also, this data is not fully representative of all of Europe, but it provides a reasonable approximation for most European countries. For many other countries, including the USA, they are not representative. We added a case to the sensitivity analysis where fuel prices are based on US prices (see Table 3). Finally, it should be noted that we assumed the electricity price to be independent of the electricity mix considered (UCTE and wind), as a detailed estimation and projection for technology-specific electricity prices was outside the scope

Table 3 Overview of the parameters used in the sensitivity analysis

Variable parameter	Default value	Alternative value(s)	Applied to	Affects
Class ^a	Compact car	Luxury sedan SUV	All types All types	LCA and costs LCA and costs
Lifetime driving distance	150,000 km	241,400 km (150,000 mi)	All types	LCA and costs
Life of the fuel cell stack and energy battery	Last entire life	2 fuel cells per life (FCVs) 2 batteries per life (BEVs)	FCVs and BEVs	LCA and costs
Platinum price	10-year average (\$45/g or \$1400/oz)	\$100/g (\$3110/oz)	FCVs only	Costs only
Fuel prices	Baseline ^b : H ₂ (electrolysis current) \$17.1/kg H ₂ (electrolysis 2030) \$15.9/kg H ₂ (SMR) \$9.34/kg Electricity \$0.303/kWh Gasoline \$1.83/L	USA ^c : H ₂ (electrolysis current) \$7.59/kg H ₂ (electrolysis 2030) \$7.04/kg H ₂ (SMR) \$4.11/kg Electricity \$0.127/kWh Gasoline \$0.83/L No taxes ^d : H ₂ (electrolysis current) \$11.0/kg H ₂ (electrolysis 2030) \$9.93/kg H ₂ (SMR) \$4.43/kg Electricity \$0.164/kWh Gasoline \$0.74/L	All types	Costs only

ICEV internal combustion engine vehicle, BEV battery electric vehicle, FCV fuel cell vehicle, SMR steam methane reforming

^a The vehicle class affects drag coefficient, frontal area, glider mass, and desired acceleration performance. The specific values can be found in the Electronic Supplementary Material, Tables S2 and S8

^b Inflation-adjusted average prices for gasoline (ICEV), residential (BEV), and industrial (electrolysis) electricity and industrial natural gas (SMR) from 2007 to 2014 in Germany. Hydrogen prices include a fuel tax of \$3.4/kg (equivalent to the fuel tax on gasoline in Germany on a per-MJ basis) and 19 % VAT

^c The 10-year inflation-adjusted average prices in the USA. All prices include corresponding US taxes. Hydrogen prices include the same tax as gasoline in the US on a per-MJ basis

^d The tax-free prices are based on the German prices (baseline case) but without any taxation added to any energy carrier

of this study. In addition, it can be argued that wind (and other renewables) will only reach a high penetration if they are close to being cost-competitive with the average generation costs of the current electricity mix.

Ecoinvent processes were taken for the LCI of gasoline production and for vehicle maintenance. The processes for gasoline combustion and evaporation were taken from literature (Simons 2013). LCI for non-exhaust emissions from tire, road, and brake wear as well as LCI for road construction and maintenance were taken from the same source. In all scenarios, the ICEV were assumed to conform to the EUROVI emission standard, which became effective for all newly sold cars in the European Union in September 2014. The detailed specific inventories are available in Table S9 in the Electronic Supplementary Material. The resulting inventories after combining specific inventories with the amount of each component (in this case, fuel consumption) needed can be found in the Electronic Supplementary Material in Table S11.

2.7 End of life

The recycling of vehicles consists of preparing the materials for treatment by dismounting, shredding and separation, and

preparing the components and materials for reuse, recycling, or disposal (Del Duce et al. 2013). Disposal processes for the drivetrains were available from the corresponding datasets used for modeling the production of the drivetrains (De Haan and Zah 2013). For the disposal of the glider, a standard ecoinvent process for vehicle disposal was taken. For the FCS and the hydrogen tank, the materials were assigned to one of five categories: plastics, aluminum, antifreeze liquid, electronics for control units, and cables. A more specific overview of the disposal processes used can be found in Table S10 in the Electronic Supplementary Material.

Consistent with ecoinvent v2.2 and the available disposal processes, a cutoff approach was chosen for the recycling of materials. As a consequence, the emissions originating from recycling processes and reconditioning are not accounted for. Instead, these emissions are allocated to the (future) secondary materials. At the same time, no emission credits from recycling of materials at the end of life stage are granted.

The decision to use a cutoff approach for recycling, along with using ecoinvent v2.2 inventories, is particularly relevant for the case of platinum. The ecoinvent dataset for the market mix of platinum assumes the use of 95 % primary platinum and only 5 % secondary (i.e., recycled) platinum. If the real

share of secondary platinum was higher, the affiliated emissions due to the platinum use in the fuel cell catalyst would be lower. The same was true if a burden-shifting approach was used for accounting for recycling, and the recycling rates of platinum group metals in the fuel cell catalyst could be assumed to be reasonably high. Therefore, the approach chosen in this study is conservative and likely yields an upper bound of the “true” emissions resulting from the use of platinum group metals in FCS.

2.8 Sensitivity analysis

For the current and the 2030 optimistic scenario, a sensitivity analysis was conducted (Table 3). Lifetime and vehicle class (which influences the vehicle cycle and fuel consumption) were chosen because they often vary among LCA and cost studies and were found to have an impact on the conclusions drawn from comparative LCAs (Hawkins et al. 2013). Note that the vehicle class affects several other parameters: glider mass, desired acceleration performance, drag coefficient, and frontal area. The impact of the luxury class vehicle on the per-kilogram production costs of the glider and the final markup was not considered, however. Fuel prices and platinum price were chosen for the sensitivity analysis because they represent major cost uncertainties, and it was worth analyzing how large their influence on results would be in relation to the total life cycle costs. Fuel cell lifetime and energy battery lifetime were chosen because there still is considerable uncertainty as to whether these components would last for an entire vehicle lifetime of 150,000 km (or even 150,000 mi).

3 Results

3.1 Assessment of the FCS

The life cycle impact and cost results for the FCS (Fig. 3) show that the catalyst accounts for a large share of overall emissions in terrestrial acidification, human toxicity, photochemical oxidant formation, and PM formation. The main causes are the emissions originating from the mining of platinum. Because the platinum loading on the catalyst is assumed to decrease in the future, the emission intensity of the catalyst decreases in the 2030 conservative and optimistic scenarios, but it remains substantial.

The impact of platinum mining on GHG emissions and FCV costs is much lower. In the case of GHG emissions, components that contain tetrafluoroethylene (the membrane and the humidifier in the current scenario) or carbon fiber (the hydrogen tank) contribute equally or more to GHG emissions than the catalyst. For costs, the high costs of platinum are easily outweighed by the high production costs for the low production volume in the current scenario. While these costs

can be expected to decrease considerably in the future scenarios, both due to technological development as well as due to an increased production volume, the platinum loading (per active stack area) and the stack area decrease as well. Therefore, the platinum itself contributes only 3 % to overall FCS costs in the 2030 optimistic scenario, assuming a platinum price of \$50/g and a platinum loading of 0.10 mg/cm². In the current scenario, it is 6 % (at \$50/g and 0.4 mg/cm²).

For most environmental impact indicators, the balance of plant plays a minor role. The only exception is human toxicity, where the control electronics and wires lead to a considerable amount of manganese, arsenic, selenium, and zinc emissions from the treatment of sulfidic tailing at the end-of-life stage. The environmental impacts of most other balance of plant components, such as filters, tubes, and radiators, were modeled with an ICEV powertrain proxy processes. The material mix of this process (mostly steel and aluminum and some plastics) does not lead to substantial emissions in any environmental impact category. For costs, the balance of plant was found to be more important than for environmental impacts. In the 2030 optimistic scenario, the balance of plant resulted in higher overall costs than the stack.

Overall, the hydrogen tank is the most important component in terms of costs and GHG emissions. In the 2030 scenarios, its share among GHG emissions and costs of the entire FCS is between 40 and 60 %. The primary reason is the large amount of carbon fiber (assumed to be 66 % of the tank by weight in all scenarios).

3.2 Contribution of FCS emissions and costs to the vehicle life cycle

Compared to the overall FCV life cycle, the FCS is of limited importance in terms of climate change (Fig. 4). While it does add between 33 % (current scenario) and 15 % (2030 optimistic) to GHG emissions of the vehicle cycle, the impact of the fuel cycle (hydrogen production and distribution) dominates GHG emissions. The FCS only contributes a major share to overall life cycle GHG emissions when hydrogen is produced from a clean source (such as wind). This is not true for some of the other environmental impact categories, especially PM formation and terrestrial acidification. There, the FCS contributes 60 % to the overall life cycle emissions from FCVs. As shown in Fig. 3, this major source of this contribution is the platinum in the catalyst. Therefore, this contribution decreases substantially in the future scenarios, where much less platinum is used.

In terms of costs, the FCS dominates life cycle costs in the current scenario. As the production volume is increased and the fuel cell technology is developed, the costs of FCS decrease by more than an order of magnitude (note that the decrease here is disproportional compared to Fig. 3, because the future FCVs are assumed to be lighter, and thus require a less powerful FCS to reach the same acceleration

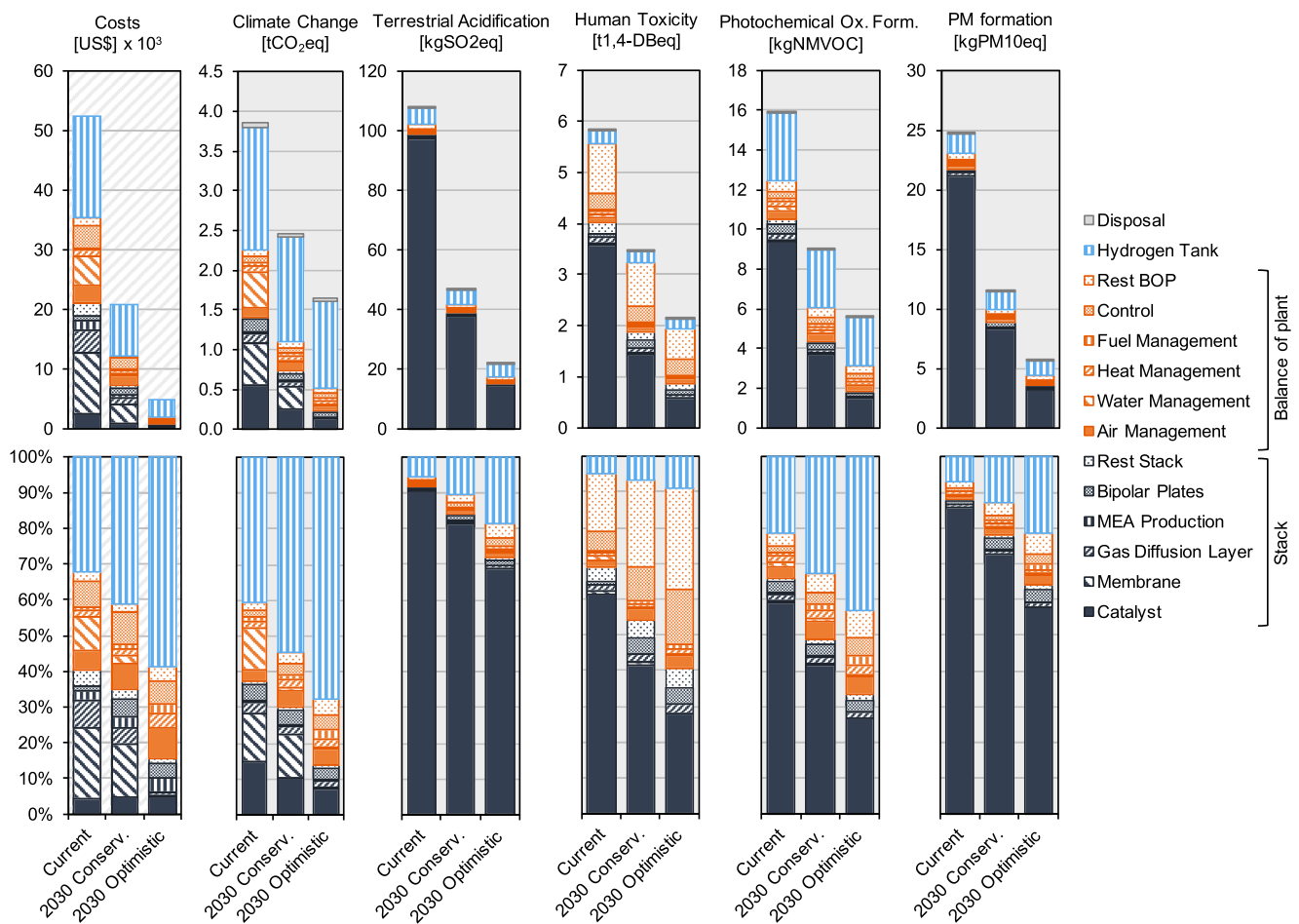


Fig. 3 Costs and environmental impacts of a 80 kW fuel cell system (FCS) with a 5.6 kg hydrogen tank, for the three scenarios, in absolute (*top*) and relative (*bottom*) contributions of each part. *BOP* balance of plant. *MEA* membrane electrode assembly

performance). However, the FCS remain a major contributor to costs even in the 2030 optimistic scenario, where it comprises about 22 % of the total vehicle costs and 11–14 % of the total life cycle costs including hydrogen.

3.3 Comparing FCVs to ICEVs and BEVs

The comparison of FCVs to gasoline ICEVs and BEVs depends largely on the hydrogen production pathway. If hydrogen is produced from natural gas using SMR, FCVs were found to produce slightly more GHG emissions during their lifetime than ICEVs in the current scenario and about the same amount in the 2030 optimistic scenario. A similar conclusion holds when comparing FCVs to BEVs that are charging with electricity from the UCTE electricity mix (594 gCO₂eq/kWh). When hydrogen is produced with electricity using the UCTE electricity mix, FCVs result in higher GHG emissions than BEVs or ICEVs. Only when hydrogen is produced with electricity from a very clean source such as wind, FCVs exhibit a significant GHG reduction potential compared to ICEVs. Depending on the scenario, this reduction amounts to 46 % – 53

%. The GHG emissions of BEVs using electricity from wind generation were only slightly lower than the one from FCVs; the lack of a FCS in BEVs and the lower fuel consumption are offset by emissions from the battery production.

In most other environmental impact categories, FCVs do not seem to offer any reduction potential compared to ICEVs. In terrestrial acidification, human toxicity, and PM formation, they even lead to increases in emissions in all scenarios. This is partly due to emissions from the production of the FCS and partly due to emissions from hydrogen production. As is the case of GHG emissions, the impact of the latter can be mitigated considerably when hydrogen is produced from a clean source.

Our study also finds that FCV manufacturers will find it difficult to make FCVs fully cost competitive to ICEVs. The costs of the electric motor and other electrical components already by themselves offset the cost reductions due to the lack of an ICE. The potential decrease in operating costs (when hydrogen is produced from SMR) cannot outweigh, however, the added costs of the FCS. BEVs were found to become almost fully cost competitive with ICEVs over their

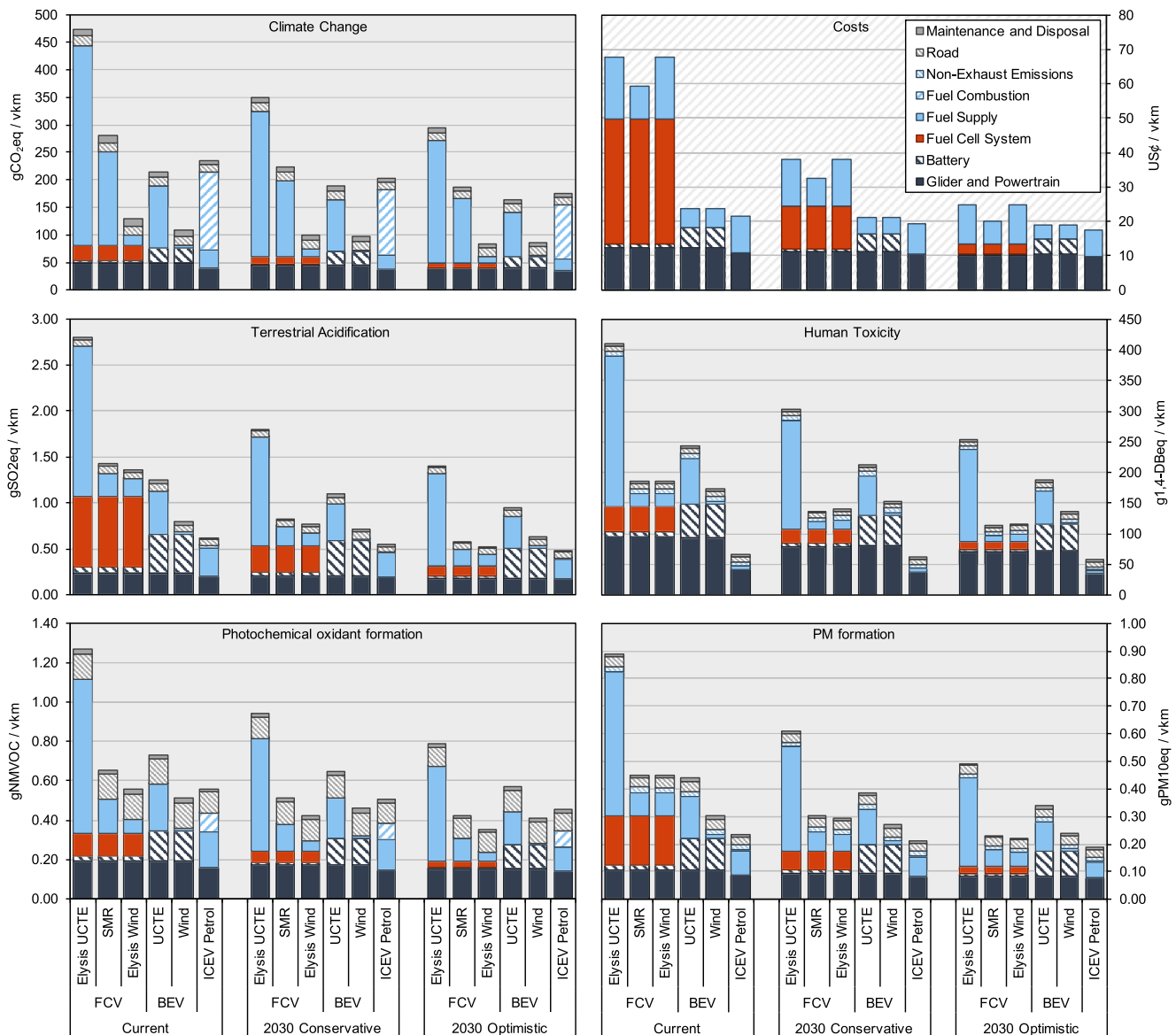


Fig. 4 Costs and environmental impacts of fuel cell vehicles (FCVs), battery electric vehicles (BEVs), and gasoline combustion engine vehicles (ICEVs) in comparison, for the three scenarios. SMR steam

life cycle, given a certain progression of technological development and costs of the batteries.

3.4 Sensitivity analysis

The sensitivity analysis (Fig. 5) shows that the vehicle class has a very large impact on life cycle costs and GHG emissions, especially when the acceleration performance is increased (as done for the “luxury” class). For FCVs, the influence of the vehicle class on costs and GHG emissions was almost as large as the difference between the current and the 2030 optimistic scenarios. For BEVs and ICEVs, it was even larger. The lifetime driving distance was found to have a

methane reforming, Elysis electrolysis. The results of all remaining impact categories are available in the Electronic Supplementary Material

considerably impact as well, because the costs and emissions of the vehicle cycle are “allocated” across a larger amount of km traveled. As for the fuel price, ICEVs and FCVs were found to be more sensitive to fluctuations than BEVs because the fuel costs represent a higher share of their total costs. A doubling of the platinum price was found to only have a marginal impact on FCV life cycle costs, given that it only contributes 2 % or less to overall FCS costs. The impact of component life (a replacement of the fuel cell stack) had a much lower influence on results in the 2030 optimistic scenario than in the current scenario. The impact of component life (the battery) for BEVs, on the other hand, was consistently high in both cases.

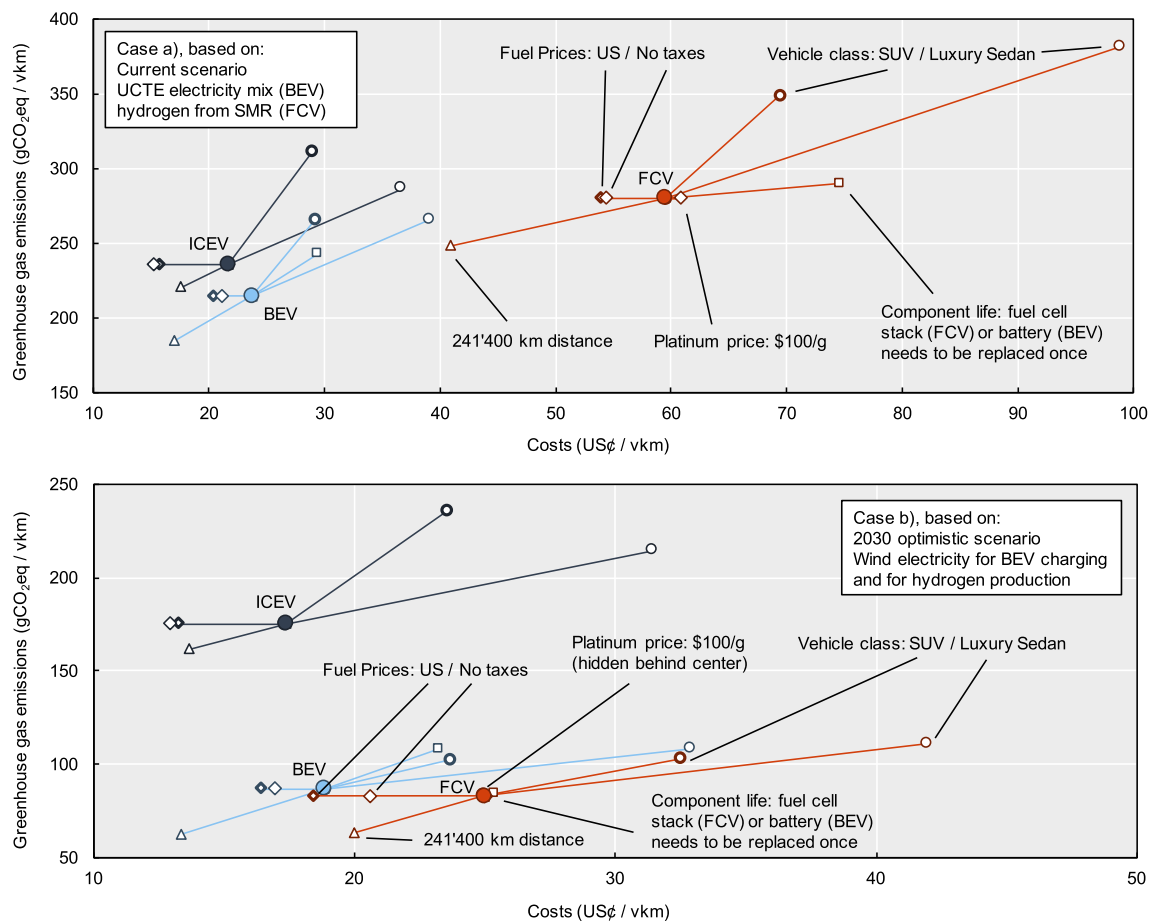


Fig. 5 Sensitivity of greenhouse gas emissions and costs of fuel cell vehicles (FCVs), battery electric vehicles (BEVs), and internal combustion engine vehicles (ICEV) against the parameters listed in Table 3, based on the current scenario with BEVs operated using

electricity from the UCTE mix and FCVs operated using hydrogen from SMR (*top*) and based on the 2030 optimistic scenario with BEVs operated using electricity from wind and FCVs operated using hydrogen produced with electrolysis from wind electricity (*bottom*)

4 Discussion

We found that a substantial amount of the environmental impacts of FCS are caused by platinum. With a share of primary platinum of 95 % on the general market in ecoinvent v2.2, the emissions due to the production of platinum shown here may be overestimated. Some literature suggest a share of secondary platinum of at least 15 % (UNEP 2011; Butler 2012; Alonso et al. 2012). In theory, it is feasible to recycle platinum to a high degree (Handley et al. 2002; McKinsey & Company 2010) in the order of at least 75–80 % yield (Pehnt et al. 2003; DOE 2008). Since a cutoff approach was used to treat recycling, the assumption that platinum will be recycled to a high degree at the end of the fuel cell life would not have changed our results considerably. However, the results do illustrate that efforts regarding the use of platinum should focus not only on decreasing its use in the stack but also on ensuring a high recycling rate. Apart from lowering the environmental impacts of the fuel cell production, recycling may also mitigate the supply risk and price volatility (Bernhart et al. 2013). This is especially important because a high market penetration

of FCVs could increase the global demand of platinum considerably. A study found that even if the platinum loading is decreased substantially, a light-duty vehicle fleet with 50 % FCVs would have a considerable impact on the global platinum price (Sun et al. 2011).

Another key material was found to be carbon fiber. Its use in hydrogen tanks meant that the tank dominated costs and GHG emission impacts in the 2030 optimistic scenario. As recycling of carbon fiber to a material of similar quality was not found to be feasible, efforts will have to focus on cutting down the use of carbon fiber in the hydrogen tank. In the long term, this may prove even more important than cutting down the amount of platinum in the catalyst in order to mitigate the GHG emissions and reduce the costs of FCSs.

When comparing FCVs to BEVs and gasoline ICEVs, we confirmed that a substantial reduction in FCV GHG emissions can only be achieved when hydrogen is produced from low-carbon sources, which is possible using electrolysis powered by electricity from low-carbon sources (or solar thermal processes, which were not considered in this study). If hydrogen

is produced from SMR, we found that no GHG emissions are reduced compared to an efficient gasoline ICEV.

The finding that FCVs operated with hydrogen that is produced from SMR do not have lower GHG emission than ICEVs contradicts several previous studies. The discrepancies between the results of our study and previously published results can be traced back to the fact that we (a) included of all important parts of the product system (we included the full vehicle cycle, modeled the FCS in detail, and only used proxy processes for FCS components at a very low level); (b) made sure that the most important sources of energy consumption are fully accounted for, especially those that differ systematically between technologies (we modeled the use of auxiliaries for the fuel consumption); (c) made sure that the functional unit is exhaustive and does not allow for systematic bias between technologies except for range and refueling time (we included vehicle size and acceleration performance into our functional unit and used models to ensure that all vehicles were treated equally with respect to these factors); and (d) made sure that different technologies are compared based on a similar state of technological development (since the FCV technology represented the state-of-the-art, we based our ICEV model on state-of-the-art combustion engines with high efficiencies). Additional sources for discrepancies may lie in the efficiency of hydrogen production (we assumed 58.5 % for electrolysis and 67 % for SMR for the current scenario, including compression and storage), and the lifetime distance driven (if 150,000 mi are used instead of 150,000 km, emissions and costs from the vehicle cycle are less important; see also Fig. 5).

In terms of costs, we found that substantial progress in the technology and manufacturing of FCSs is necessary to reach the same life cycle costs as ICEV. Economies-of-scale effects alone are not sufficient to reach this goal. It should be noted that maintenance costs (which were not considered in this study) may be lower for FCVs and BEVs than for ICEVs, but it is unlikely that these differences fully outweigh the cost differences between FCVs and ICEVs as presented here. Also, consumer may have a higher sensitivity to upfront costs than operating costs, making the higher vehicle costs of FCVs even more relevant.

Fig. 4 shows that FCVs emit more GHG when hydrogen is produced from electricity using the UCTE mix than BEVs when charged with the same electricity. This is because FCV consume 2.5–3.5 times as much electricity per kilometer as BEVs (almost twice as much for tank-to-wheel energy and 1.35 to 1.5 for well-to-tank). This fact is particularly important when considering the potential indirect consequences of the increase in electricity demand on the power sector. If the amount of renewables in the electricity mix is assumed to be limited, and if these limiting factors can be assumed to persist even when the demand increases, a higher demand will lead to non-renewable electricity generation plants being added to the

mix. In that case, the renewable electricity used in BEV or FCV is “cannibalized” from the general grid. At the same time, a solid hydrogen infrastructure or a large amount of BEV batteries connected to the grid may provide the opportunity for storage of electricity, benefiting the development and extension of electricity generation from renewable sources. The evaluation of such effects and relationships call for consequential LCAs, as opposed to the attributional approach used in this study (Lund et al. 2010; Earles and Halog 2011; Zamagni et al. 2012).

Based on the results in Fig. 4, we also found that switching from an ICEV-based fleet to a FCV-based fleet may induce environmental burden shifts; that is, it may lead to lower environmental impacts in some categories but higher impacts in others. It should be pointed out, however, that the environmental impacts in categories other than climate change are highly uncertain. In some cases, the emissions of certain components in certain categories can be traced back to a few pollutants from a single process, as it was discussed for the case of treatment of sulfidic tailing from the end-of-life stage of some electrical components. Also, the real-world emissions from ICEVs may be higher than what the EURO VI standard mandates, although this problem has been found to be larger for diesel ICEVs than for gasoline ICEVs (Ligterink et al. 2013). Finally, this assessment does not fully take into account the location of the emissions. Shifting from tailpipe emissions to rural emissions of the same type may have additional benefits that we have not accounted for. Other impacts such as noise have not been assessed as well.

Other ICE drivetrain options, such as diesel engines and hybrid electric vehicles, were not considered. With current technology, they would lead to lower use-phase GHG emissions and, likely, to lower overall GHG emissions as well. However, they are unlikely to reach the “bottom line” of GHG emissions achieved by FCVs and BEVs, and diesel engines promise lower efficiency improvements in the near future than gasoline engines (Kromer and Heywood 2007; Bandivadekar et al. 2008; Yazdanie et al. 2014; Bauer et al. 2015).

Finally, we would like to point out that the functional unit of this study, the amount of emissions per (vehicle-)km, does not fully correspond to the ultimate goal of limiting the environmental impacts of transportation. Decreasing the number of total vehicle kilometers traveled (for instance due to modal shifts to less energy-intensive systems, such as public transportation), increasing occupancy rates, and promoting car sharing may be other effective measures. An ICEV driven by three people has similar or lower GHG emissions per kilometer than a similarly sized BEV driven by one person, even when the BEV is charged with pure wind power (when taking into account emissions from the entire vehicle life cycle).

5 Conclusions

The results of this study emphasize that a shift to electric vehicles must be accompanied by a cleaner power sector. If that is the case, FCVs have the potential to reach similar levels of GHG emissions per kilometer as BEVs while not being subject to the same limitations in range and refueling time. FCVs with hydrogen from SMR, on the other hand, were found to have no notable benefits compared to ICEVs in any environmental impact category, including climate change. Also, FCVs use about three times as much electricity per distance driven than BEVs when hydrogen is produced with electrolysis. This may make it substantially to provide a considerable amount of electricity from renewable sources.

Platinum and carbon fiber were found to be the most important sources of environmental impacts in the FCS. For platinum, a combined effort to decrease the load and increase recycling rates may reduce these impacts considerably. For carbon fiber, recycling will be difficult. Therefore, a reduction of material use and a simultaneous increase in production efficiency will need to take place. This is not only important for reducing GHG emissions but also costs. Overall, FCVs will only become cost competitive with ICEVs and BEVs if very large progress is made in cutting down the costs of the FCS.

Finally, this study exemplifies how some of the common issues related to LCA methodology for assessing vehicles can be dealt with. This includes removing various systematic biases between technologies by including secondary functional parameters such as the state of technology, acceleration performance and vehicle class into the functional unit, and modeling the inventories accordingly. In addition, the integrated approach to compose the FCS inventories by systematically disassembling the information found in cost studies ensured a high degree of consistency between the cost and LCA results, and enabled comparisons of environmental impacts and costs at the component level.

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Conflict of interest The authors declare that they have no conflict of interest.

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