Background report

The environmental burdens of passenger cars: today and tomorrow

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Contents

1. Introduction

The environmental performance of electric and conventional vehicles has been prevalent in the recent literature (Bauer, Hofer, Althaus, Del Duce, & Simons, 2015; Ellingsen, Hung, & Strømman, 2017; Ellingsen, Singh, & Strømman, 2016; Peters, Baumann, Zimmermann, Braun, & Weil, 2017; Romare & Dahllöf, 2017), and also the press (Ferroni & Reichmuth, 2017; Irle, 2017; Kristensson, 2017; Leuthard, 2017; Mock, 2017; Tietge et al., 2016). Depending on the input assumptions and calculation methodologies used, results can vary widely. Furthermore, these results are often taken out of context, leading to confusion for decision makers and consumers who read reports with conflicting conclusions from opaque sources. The goal of this report is to provide a complete, fair, and open analysis of the environmental performance of different modern passenger car types operating in Switzerland today and in the mid-term future. We use the methodology of Life Cycle Assessment (LCA) to ensure that the complete environmental performance of each vehicle type is considered. We further consider uncertainty in all input parameters and examine the largest sources of variability in results, while striving for transparency.

Technologies such as battery and fuel cell electric vehicles are still in their infancy and are expected to improve significantly in the coming years. Moreover, the performance of conventional combustion vehicles is also improving rapidly due to policy pressure to reduce exhaust emissions of CO_2 and other health related substances. For this reason we consider both current (2017) and future(2040) technology levels. As the future structure of the Swiss electricity sector is uncertain, we also include three electricity scenarios from the Swiss Energy Perspectives (Prognos, 2012) to charge electric cars and produce hydrogen in the future. We also consider electricity from specific generation technologies such as hydro power, photovoltaics (PV) and natural gas power plants, since these show potential variability of charging electricity in Switzerland.

We build on the work of the THELMA[1] project, funded through the CCEM, as well as research performed at the Paul Scherrer Institut within the framework of the Swiss Competence Centers for Energy Research (SCCER) in Mobility, Supply of Electricity, and Heat and Electricity Storage[2].

2. Methods

We perform our calculations using a jupyter notebook, programmed in python. Interested readers are welcome to contact the authors to receive a copy of the calculation files. We provide a complete list of input parameters in Appendix A.

2.1. Life cycle assessment

LCA is a methodology that compiles inventories of all environmentally relevant flows (such as emissions, natural resource use, energy and material demand as well as waste) of a products' or services' entire life cycle, from resource extraction to end-of-life and calculates their contribution to known areas of environmental concern, such as climate change, primary energy use, or human health impacts due to fine particulate formation or ground level ozone formation.

[1] https://www.psi.ch/ta/thelma
[2] https://www.kti.admin.ch/kti/en/home/unsere-foerderangebote/foerderprogramm-energie.html

We perform attributional LCA according to the ISO standards ISO 14040 and 14044 (ISO, 2006a, 2006b) and use the ecoinvent v3.4 database with the system model “allocation, cut-off by classification” (Wernet et al., 2016). The LCA calculations are performed using the Brightway2 software package (Mutel, 2017). The goal of our study is to compare the life cycle environmental impacts of passenger cars with production years 2017 (current) and 2040 (future). We include the entire life cycle of the vehicle (from raw material production to end-of-life and recycling) and energy chain (from well-to-wheel) and use a ‘cradle-to-grave’ system boundary. The functional unit of the study is the vehicle kilometer travelled, averaged over the entire lifetime of the car. Except where explicitly stated, the inventories used for our life cycle assessment are taken from the ecoinvent 3.4 database for Swiss or European conditions where available and global averages otherwise. We present midpoint results for four environmental impact categories:

Climate change represents the contribution to global climate change due to the emission of all greenhouse gases. These results are presented in the units of kg CO_2 eq. We use the characterization factors from the most recent IPCC report with the 100 year time horizon (Stocker et al., 2013), as implemented in ecoinvent v3.4.

Cumulative energy demand represents the consumption of primary energy from fossil, nuclear and renewable sources. It is quantified with the unit of MJ using characterization factors as implemented in ecoinvent v3.4.

Photochemical oxidant formation quantifies the formation of ground level ozone due to the reaction of NO_x with non-methane volatile organic compounds (NMVOC). It is quantified in the unit of kg NMVOC calculated using the ReCiPe 2008 methodology with the hierarchist perspective (Goedkoop et al., 2013).

Particulate matter formation considers the human health impacts of fine particles in the air that can enter the lungs. This includes both primary and secondary particulates as is quantified in the unit of kg PM_{10} eq using the ReCiPe 2008 methodology with the hierarchist perspective (Goedkoop et al., 2013).

2.2. Vehicle Modelling

Vehicles considered

We consider all passenger car powertrain variants deemed relevant for current and future operation in Switzerland.

Internal Combustion Engine Vehicles (ICEV) are vehicles that use an internal combustion engine operating with diesel **(ICEV-d**), petrol (**ICEV-p**) or compressed natural gas (**ICEV-g**) as fuel to provide power to the wheels. Future ICEV are assumed to be mild hybrids with a small 48 V battery. Internal combustion engines can also operate using synthetic gas (**SNG**) as fuel. SNG is produced by using electricity to produce hydrogen via electrolysis, which is then converted to synthetic methane using carbon dioxide that is directly captured from ambient air.

Battery Electric Vehicles (**BEV**) are vehicles that use an electric motor to provide power to the wheels, with electrical energy coming from lithium ion batteries that are recharged from the electricity grid.

Hybrid Electric Vehicles (**HEV**) are vehicles powered by an internal combustion engine that operates in combination with an electric motor to provide power to the wheels. A battery is used for short term energy storage. Though it cannot be charged from the external electricity grid, it allows the combustion engine to be smaller and to operate more efficiently. All energy comes from the combustion of petrol (**HEV-p**).

Plug-in Hybrid Electric Vehicles (**PHEV**) are vehicles that use an electric motor to provide power to the wheels, with electrical energy coming from a battery that is recharged from the electricity grid. When the energy in the battery runs out, a small combustion engine fueled by petrol is used in hybrid configuration until the battery can be recharged. We show results for average driving which contains estimates for the share of driving in each mode based on the all-electric range of the vehicle (Plötz, Funke, & Jochem, 2017). When data are shown for PHEV in all electric mode, we use the abbreviation **PHEV-e**. For data specific to combustion mode, we use the abbreviation **PHEV-c**. When data are shown for average conditions, we use the abbreviation PHEV.

Fuel Cell Electric Vehicles (**FCEV**) are vehicles that use an electric motor to provide power to the wheels, with electrical energy coming from the operation of a fuel cell which uses hydrogen (H_2) as fuel. A battery is used for short term energy storage. Though it cannot be charged from the external electricity grid, it allows the fuel cell to be smaller and to operate more efficiently. All energy comes from the oxidation of hydrogen.

Treatment of uncertainty

We develop a Monte Carlo analysis based calculation structure that allows the use of uncertain input values for all parameters. For each parameter we define the most likely value as well as the lowest and highest values expected. We define the uncertainty distribution for each input parameter using these three values to create a simple triangular distribution. When calculating the performance of each vehicle and powertrain type, we calculate the most likely performance using the most likely value for each parameter. In order to estimate the distribution of the results we also calculate thousands of other results for each vehicle type using input parameter values randomly sampled from the uncertainty distributions. This distribution is shown in the results using box plots.

We are careful to define only the basic design parameters for each vehicle, and calculate all dependent parameters based on these input values. For example, vehicle energy consumption is not defined as an input parameter, but is rather calculated based on input values such as the vehicle mass, driving patterns, aerodynamic characteristics, and rolling resistance.

We note that the uncertainty results here consider only variation in foreground parameters and do not consider uncertainty in the background database or life cycle impact assessment methods. For simplicity we also do not consider variation in the driving patterns of the vehicle, though this is certainly also relevant.

General vehicle description

In order to compare vehicle powertrain types as fairly as possible, we consider the base vehicle as a common platform for all powertrain types. This common platform is referred to here as the glider, which contains all components of the vehicle that are not specific to the powertrain or energy storage components, and includes components such as chassis, tires, seats, etc. All vehicles are assumed to have the same uncertainty distributions for parameters such as glider size, lifetime, driving characteristics, cargo load, heating and cooling demand etc. The most important of these characteristics are summarized in Table 1. The most likely values correspond to average Swiss operating conditions.

The glider base mass parameter is defined based on typical vehicle glider masses that correspond to different vehicle sizes, ranging from mini-sized cars to SUVs based on a typical steel chassis. An additional parameter is defined for the amount of lightweighting that is included in the vehicle design using high strength steel to replace regular steel and thus reduce weight (Geyer, 2017).

The most likely values correspond to a medium sized car, which is roughly the equivalent of a VW Golf. Table 1 summarizes some of the most important input parameters. All input parameters are assumed to be independent and are sampled separately, with the exception of vehicle frontal area which is assumed to vary with vehicle mass, though uncertainty parameters are defined to include all vehicle shapes and weights commonly found on the road.

Table 1 Most Important common vehicle parameters Sources: a: Authors own calculation or estimate, b: (Hirschberg et al., 2016), c: (Geyer, 2017), d: (Transportation research board, 2006).

		Current (2017)			Future (2040)			
Parameter	**unit**	**Most Likely**	**Lowest**	**Highest**	**Most Likely**	**Lowest**	**Highest**	**Source**
Lifetime distance	1000 km	180	80	300	180	120	400	a
Glider base mass	kg	1200	600	2000	1175	550	1900	a, b
Frontal area	m^2	2.06	1.45	3.10	2.04	1.42	3.01	a, b
Lightweighting	%	10	0	20	10	0	25	c
Power to mass ratio	W/kg	60	40	100	60	40	100	b
Aerodynamic drag coefficient		0.31	0.3	0.35	0.295	0.264	0.35	b
Rolling resistance coefficient		0.010	0.007	0.012	0.009	0.006	0.012	a, d
Heating demand	W	300	200	400	285	180	400	a, b
Cooling demand	W	300	200	400	285	180	400	a, b
Total cargo mass	kg	155	60	610	155	60	610	a

Vehicle energy demand

Vehicle energy demand is calculated by assuming that the vehicle follows a fixed velocity versus time profile, and calculating the mechanical energy demand at the wheels required to follow this driving cycle, based on parameters for vehicle weight, rolling resistance and aerodynamic properties (Bauer et al., 2015; Hirschberg et al., 2016; Hofer, 2014). Additionally, the energy consumption due to auxiliaries such as heating and cooling, lighting and control functions as well as the potential for recuperative braking are considered where applicable for the specific drivetrain. Finally, the efficiency of all drivetrain components can be included in the calculation to determine the tank-to-wheel energy consumption of the vehicle. We use this methodology to model energy consumption because it allows us to endogenously calculate energy consumption based on variable input parameters upon which energy consumption strongly depends. These specific parameters are discussed in the following section.

We calculate vehicle energy consumption using the driving pattern defined by the Worldwide harmonized Light vehicles Test Cycle (WLTC). This driving cycle is selected because it attempts to model real world driving patterns, which is a common criticism of the New European Driving Cycle (NEDC) (Tietge et al., 2016).

In order to calibrate our model, we also calculate vehicle energy consumption according to the New European Driving Cycle (NEDC) with the non-essential auxiliary energy demands turned off, which represents how current vehicle energy consumption values are reported (Tietge et al., 2016). We compare these results to energy consumption and CO_2 emission monitoring data for all new cars sold in Europe (European Environment Agency, 2017) and find good correspondence. When we recalculate energy consumption results using the WLTC and consider auxiliary energy demand, our results are roughly 25% higher than the reported values. We compare these vehicle energy consumption results to other data sources with different driving patterns (Alessandrini, Orecchini, Ortenzi, & Villatico Campbell, 2009; Büchi et al., 2007; De Cauwer, Van Mierlo, & Coosemans, 2015; Gennaro, Paffumi, Martini, Manfredi, & Scholz, 2014; González Palencia, Furubayashi, & Nakata, 2012; Graham, 2005; Grunditz & Thiringer, 2016; Huo, Yao, He, & Yu, 2011; Karner & Francfort, 2007; Kouridis et al., 2017; N. Ligterink, Kadijk, Van Mensch, Hausberger, & Rexeis, 2013; N. E. Ligterink & Eijk, 2014; Mellino et al., 2017; Ntziachristos et al., 2014; Plötz et al., 2017; Tietge et al., 2016) and also find reasonable correspondence, though uncertainty is high in the literature values due to the variability of vehicle sizes, production years and driving cycles used.

Our modelled energy consumption results represent of current average passenger vehicles of different sizes operating in real world conditions.

Vehicle modelling details

In the following section we discuss assumptions regarding the components and environmental flows that have largest impact on the results: lithium ion batteries, fuel cells, hydrogen tanks, tailpipe emissions, and auxiliary power demand due to heating and cooling (Bauer et al., 2015; Ellingsen et al., 2016; Helmers & Weiss, 2016; Hirschberg et al., 2016; Nordelöf, Messagie, Tillman, Ljunggren Söderman, & Van Mierlo, 2014; Simons & Bauer, 2015). We also discuss the share of electric versus combustion powered driving for PHEV. We include the complete list of input values in Appendix A, and a summary of the most relevant assumptions and calculation results in Table 2.

Table 2 Summary of vehicle modelling results

Parameter	Current			Future		
	Most likely	**Lowest**	**Highest**	**Most likely**	**Lowest**	**Highest**
Curb mass (kg)						
ICEV-d	1380	756	2354	1340	697	2227
ICEV-p	1357	760	2316	1319	680	2213
ICEV-g	1434	819	2380	1383	735	2310
HEV-p	1372	766	2337	1301	674	2179
PHEV	1470	846	2413	1353	722	2262
BEV	1595	834	2627	1554	780	2581
FCEV	1570	823	2967	1462	723	2634
Tank to wheel energy (MJ/km)						
ICEV-d	2.19	1.41	3.73	1.55	0.95	2.49
ICEV-p	2.43	1.55	4.11	1.58	0.98	2.78
ICEV-g	2.71	1.74	4.40	1.73	1.14	2.93
HEV-p	1.41	0.94	2.46	1.17	0.71	1.92
PHEV-c	1.76	1.14	3.16	1.41	0.84	2.58
PHEV-e	0.68	0.47	1.10	0.56	0.37	0.93
PHEV	1.03	0.56	2.27	0.76	0.43	1.69
BEV	0.70	0.48	1.15	0.60	0.39	0.97
FCEV	1.28	0.83	2.20	1.00	0.62	1.75
Tank to wheel efficiency (%)						
ICEV-d	23.2	20.5	27.4	28.1	25.0	32.8
ICEV-p	20.8	18.2	24.9	27.2	22.8	30.2
ICEV-g	19.2	16.9	23.2	25.5	21.1	28.4
HEV-p	28.1	25.0	31.2	30.5	27.4	36.2
PHEV-c	23.8	20.3	28.1	26.5	22.7	33.1
PHEV-e	63.6	55.8	73.2	67.6	59.1	77.2
BEV	63.6	55.8	73.2	67.6	59.1	77.2
FCEV	33.6	28.6	39.5	38.3	32.3	46.8
Range (km)						
ICEV-d	656	302	1189	775	430	1640
ICEV-p	524	235	923	669	344	1217
ICEV-g	512	275	866	641	317	1272
HEV-p	753	406	1305	724	373	1610
PHEV-c	602	309	1035	603	309	1467
PHEV-e	51	17	120	67	22	179
BEV	173	54	406	439	129	998
FCEV	468	188	893	601	231	1146
Battery size (kWh)						
BEV	42.0	15.9	87.8	91.0	29.3	186.7
PHEV	12.0	5.0	22.2	13.0	5.6	31.7
Utility factor (share of distance driven in all electric mode)						
PHEV	0.67	0.25	0.90	0.77	0.35	0.90

Lithium ion batteries

The most important component of BEV are the lithium ion batteries used for energy storage, as they are responsible for a significant share of vehicle costs, mass and production impacts (Hirschberg et al., 2016). We assume that the future battery mass in BEV will remain roughly the same as in current vehicles. However, the energy storage density is expected to improve significantly in the future, greatly increasing the energy stored and extending the vehicle range between charging. We assume that the battery mass in future PHEV will decrease so that the average all electric range remains roughly constant.

Current batteries are expected to have a lifetime of 100000-300000 km (most likely value 150000 km) after which they are replaced and recycled (Konecky & Anderman, 2016). Future batteries are expected to have a lifetime distance of 150000-350000 km (most likely value 200000 km). We indirectly consider a battery 'second life' in this study: When a vehicle's battery reaches its end-of-life before the car is retired, the battery is replaced. However, if the car is retired before this replacement battery is expired, the battery is assumed to be used elsewhere, and only the used fraction of the battery is allocated to the car. In short, we assume that it is possible to use 1.2 or 2.3 batteries over the lifetime of a BEV, but never less than one complete battery.

The Life Cycle Inventory (LCI) for lithium ion battery production are based on primary data from (Ellingsen et al., 2014). According to the currently available literature, the largest contributing factor to the environmental burdens of lithium ion battery production is the electricity consumption during the assembly process, though the actual amount of energy required is still under debate as the production facility analyzed in Ellingsen et al. (2014) was not operating at full capacity (Ambrose & Kendall, 2016; Blomgren, 2017; Dunn, Gaines, Kelly, James, & Gallagher, 2015; Ellingsen et al., 2017; Hall & Lutsey, 2018; Peters et al., 2017). Furthermore, the electricity consumed per kilogram of battery is expected to reduce greatly in the future as manufacturing ramps up. Thus, we include battery cell electricity consumption as an uncertain parameter that ranges from 6-30 kWh / kg battery cell (most likely 24 kWh / kg) for current batteries and 6-24 kWh / kg battery cell (most likely value 15 kWh / kg battery cell) for future batteries.

Lebedeva, Persio, and Boon-Brett (2017) show that globally, 41% of Li-ion battery cells are currently produced in China, with roughly 20% each produced in Japan, Korea and the USA. According to personal communication with Marco Piffaretti from Protoscar (Piffaretti, 2018), no car manufacturers that have models available in Switzerland are currently using battery cells produced in China. Thus, we assume a battery production electricity mix corresponding to : 34% Japan, 29% each Korea and USA, and 8 % Europe. This average electricity mix has a life cycle carbon content of 672 g CO_2 eq/ kWh. If only renewable electricity were to be used during battery production, climate change impacts per unit battery would be reduced by roughly half compared to this average electricity mix.

All other aspects of lithium ion battery production per kilogram are assumed to remain constant in the future. We note however, that as the energy stored per kilogram battery is greatly increasing, the environmental burdens per kilowatt hour stored will still greatly decrease.

Figure 1 shows uncertain input values and results for batteries for BEV and PHEV. The bars show the most likely values, while the whisker plots show the maximum and minimum values. The whisker plot box contains 50% of the values, while the horizontal line within the box represents the mean.

Electricity consumption is responsible for slightly more than half of the climate change and primary energy demand and roughly one third of the photochemical oxidant and particulate matter formation due to current battery production. This contribution will decrease in the future due to reduced electricity consumption. The rest of the environmental burdens of battery production are mostly due to the production of the metals and other materials that are used in batteries.

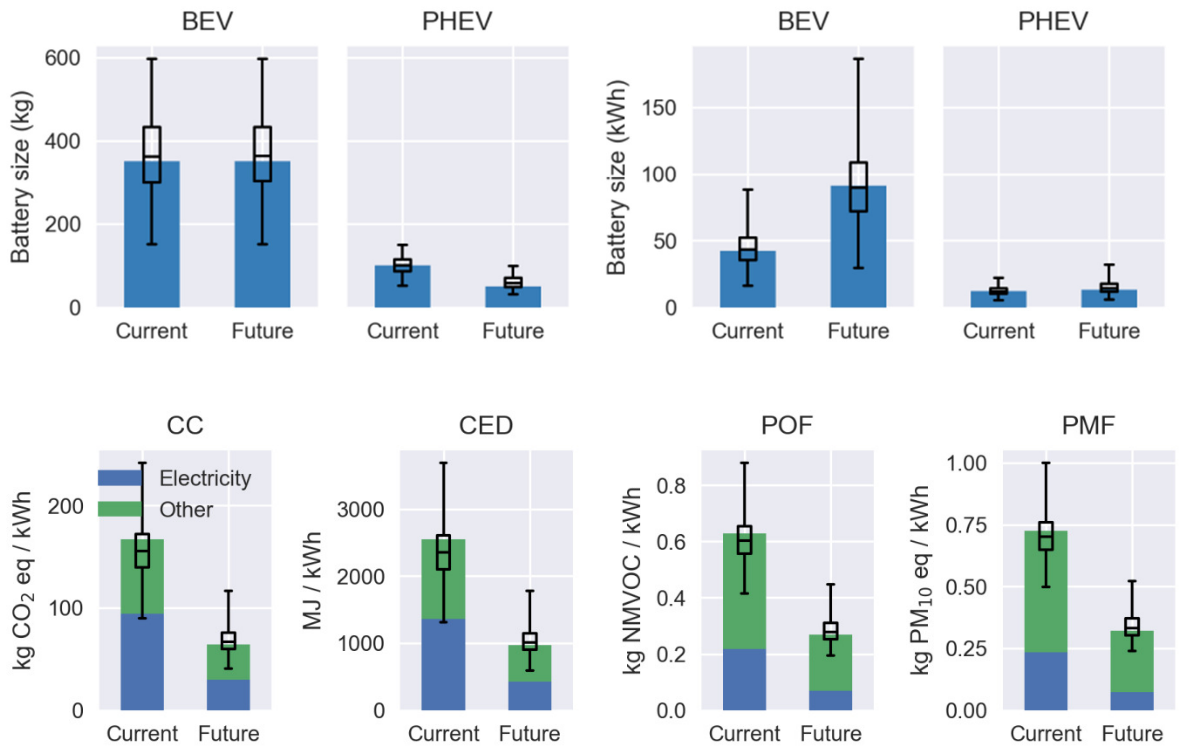

Figure 1 Energy storage battery size in kg (top left) and in kWh (top right), and environmental burdens of battery production (bottom), with emissions due to direct electricity consumption shown separately. Current: 2017; Future: 2040; CC: Climate change; CED: Cumulative energy demand; POF: Photochemical oxidant formation; PMF: Particulate matter formation.

Lithium ion batteries are also used for power applications in HEV, FCEV and future ICEV, though they are much smaller than the batteries used in BEV and contribute much less to the overall environmental impacts of the vehicle. We model power optimized lithium ion batteries in HEV, FCEV, and future ICEV with the same LCI that we use for energy optimized lithium ion batteries used in BEV and PHEV. We assume a current power density of 0.9- 1.5 kW /kg (most likely value 1 kW / kg), increasing to a range of 1- 1.7 kW / kg (most likely value 1.2 kW/kg) in the future (Konecky & Anderman, 2016).

Fuel cells

The most important component in a fuel cell vehicle in terms of cost, performance and environmental burdens is the fuel cell, with its efficiency and platinum loading being particularly important (Hirschberg et al., 2016; Miotti, Hofer, & Bauer, 2015; Simons & Bauer, 2015). We assume that FCEV use a Polymer Electrolyte Membrane (PEM) fuel cell designed in a hybrid configuration with a power-optimized lithium ion battery used to help meet peak power demands. Thus, the fuel cell is sized to have a maximum power output of 60-90% (most likely value 75%) of total vehicle power. Current fuel cell stacks are expected have efficiencies of 50-57% (most likely value 53.5%), with an own consumption due to pumps and internal losses of 10-20% (most likely value 15%), improving to 52-63% (most likely value 57%) stack efficiency with own consumption of 8-15% (most likely value 12.5%) in the future.

Our LCI model for PEM fuel cells is taken from the 2020 values published by Simons and Bauer (2015), which has a power area density of 800 mW / cm^2, and is comparable to currently available fuel cell vehicles. We consider uncertainty, as well as future improvements in fuel cell design by holding the fuel cell stack LCI per unit active area constant, and scaling according to different power area densities. Current fuel cell stacks are modelled to have a power area density of 700-1100 mW / cm^2 (most likely value 900 mW / cm^2), improving to 800-1200 mW / cm^2 (most likely value 1000 mW / cm^2) in the future.

We assume Simons' and Bauer's platinum loading of 0.125 mg / cm^2 of fuel cell active area to remain constant for varying power area density. Thus, as we scale the power area density of the fuel cell, the platinum loading for current fuel cells varies from 0.114-0.178 g/kW (most likely value 0.139 g/kW) and 0.104-0.156 g/kW (most likely value 0.125 g/kW) for future fuel cells. These values are consistent with values available in the literature (Bauer et al., 2015; Miotti et al., 2015; Simons & Bauer, 2015; US Department of Energy, 2017a, 2017c).

Very little data exists regarding actual fuel cell lifetimes in passenger cars. We lean on the assumptions from previous LCA studies (Bauer et al., 2015; Miotti et al., 2015; Simons & Bauer, 2015), targets from the US Department of Energy (US Department of Energy, 2017a, 2017c), and reports from fuel cell bus projects (Leslie Eudy, Matthew Post, & Jeffers, 2016a, 2016b; Lozanovski, Horn, & Ko, 2016) to make the assumption that current fuel cell systems are replaced and recycled after their lifetime of 100 000-300 000 km (most likely value 150 000) km, improving to 150 000-350 000 km (most likely value 200 000 km) in the future. We make the same assumptions for the second life of fuel cells that we make for replacement batteries as discussed above.

Hydrogen storage tanks

Hydrogen storage is assumed to be in 700 bar tanks made of an aluminum cylinder wrapped in carbon fiber with stainless steel fittings. The composition of the tank is assumed to be: 20% aluminum, 25% stainless steel, and 55% carbon fiber (of which 40% is resin, and 60% is carbon cloth).

Per kilowatt hour of hydrogen storage, hydrogen tanks are assumed to weigh between 0.55 and 0.6 kg (most likely value 0.57 kg), improving to 0.45-0.55 kg (most likely value 0.5 kg). These values are consistent with current values available in the literature and commercially available tanks (Hua et al., 2010; Luxfer, 2017; Mahytec, 2017; Ordaz, Houchins, & Hua, 2015; US Department of Energy, 2017b).

Vehicle exhaust emissions

Tailpipe operating emissions from combustion engines are included using data from HBEFA 3.3 (2017). Emissions of CO_2 and SO_x and linked to vehicle fuel consumption results. For other emissions, we use the average emissions per kilometer for EURO 6 vehicles in average Swiss driving conditions for the current most likely values and make the simple assumption that the lowest likely values are half of these values, and the highest likely values are double these values. We assume that all emissions from future vehicles will be reduced by 50% compared to current values. We remark that a vehicle with emissions twice as high as the current average would be quite comparable to a vehicle with designed according to the EURO 3 emission standard.

In light of the recent discovery that real NO_x emissions from EURO 6 diesel cars can be significantly higher than regulatory limits, we increase the upper limit for NO_x emissions from diesel powertrains to 1 g / km according to a report from the ICCT based on measurements in Germany (Bundesministerium für Verkehr und digitale Infrastruktur, 2016; Mock, 2017). The HBEFA 3.3 has already been updated to consider increased NO_x emissions from Euro 6 diesel powertrains, so we use this value (0.085 g/km) as the most likely value, which only slightly higher than the regulatory limit of 0.08 g/km.

Auxiliary energy consumption due to heating and cooling

We assume that all current vehicle types, on average over the whole year, have a thermal power demand on average of 200-400 W (most likely value 300 W) for each heating and cooling of the cabin. For future vehicles this thermal power demand is reduced to 180-400 W (most likely value 285 W). However, the actual increased load on engine or battery varies for each powertrain. For example, heat demand for combustion and fuel cell vehicles is supplied using waste heat from the powertrain, and thus poses no additional demand on the engine or fuel cell. Conversely, current BEV use energy directly from the battery to provide heat. We assume that future BEV will use heat pumps and novel concepts such as localized cabin heating to reduce the power demand on the battery to 30-100% (most likely value 80%) of the cabin heat demand. Cooling demands are assumed to be met by an air conditioner with a coefficient of performance between 0.83 and 1.25 (most likely value 1) for all powertrain types, increasing to 1-2 (most likely value 1.25) in the future. For BEV cooling load is assumed to draw directly on the battery, while for the other powertrain types the efficiency of the engine or fuel cell is also taken into account.

Plug in hybrid electric vehicle operation mode

Because PHEV can operate in combustion mode (energy supply from the internal combustion engine) or in all electric mode (energy comes from the onboard battery), assumptions must be taken to define the share of driving in each mode. We use the concept of a utility factor which is defined as the lifetime average ratio of distance driven in all electric mode to the total distance driven, which has been shown to generally correlate with the all-electric range of the vehicle (Plötz et al., 2017; Riemersma & Mock, 2017). We fit a logarithmic curve to the vehicle ranges and utility factors reported by Plötz et al. (2017) and determine the equation (minimum and maximum values are 0 and 0.9 respectively):

$$Utility\ factor = 0.385 * \ln(All\ electric\ range) - 0.845$$

Figure 2 shows the variation in utility factor versus battery size for PHEV in a hexbin plot. This plot shows uncertainty information in that the darker an area of the plot is, the more likely the outcome in the uncertainty analysis.

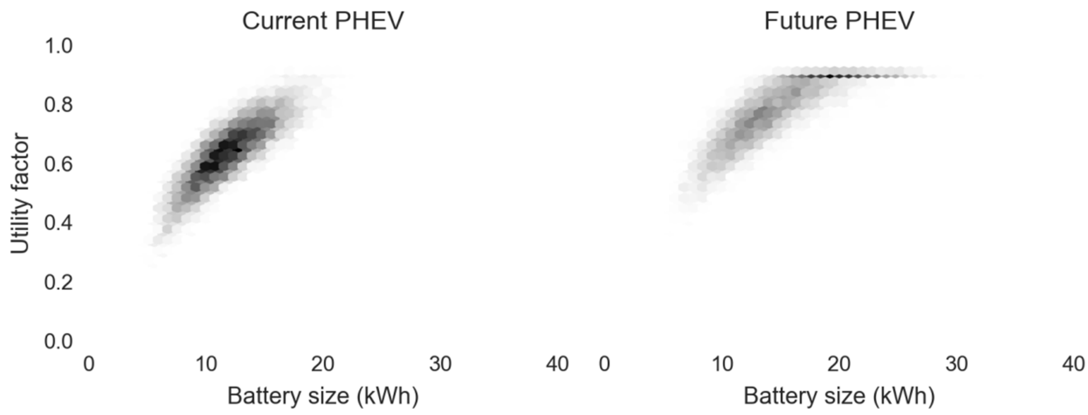

Figure 2 Plug in hybrid electric vehicle utility factor versus battery size for current (2017) and future (2040) vehicles. The grey scale represents the uncertainty in the value, darker areas show more likely values.

2.3. Vehicle energy supply

Electricity supply used to charge current BEV is assumed to be the current low voltage Swiss consumption electricity mix[3]. For the future electricity supply, we use three scenarios from the Swiss Energy Perspectives defined by Prognos (2012). We consider the best and worst cases to be the New Energy Policy with Renewables (CH-NEP-E) and the Business as usual with natural gas power plants (CH-BAU-C) (German: Weiter Wie Bisher (WWB)), respectively. As a base case we take the Political measures scenario with natural gas power plants (CH-POM-C). In all three future electricity scenarios, there is a small component of European average electricity as an import in 2040. For the BAU and POM scenarios we consider a business as usual electricity mix for Europe (life cycle carbon content 420 g CO_2/kWh), while in the NEP scenario we use an electricity mix corresponding to a climate protection scenario for Europe (life cycle carbon content 159 g CO_2/kWh). These two electricity mixes are taken from the SSP2 storylines as implemented by the IMAGE integrated assessment models (Riahi et al., 2017; Stehfest, van Vuuren, Bouwman, & Kram, 2014; van Vuuren et al., 2017). We also include electricity sourced from single technologies: hydro (Swiss hydroelectricity from reservoir power plants), solar photovoltaic (Swiss slanted-roof installations with multi-crystal silicon), natural gas (German combined cycle natural gas plants), or nuclear (Swiss pressure water reactor) are also included. Losses and emissions associated with converting high voltage to medium and low voltage electricity have been applied according to average Swiss conditions.

Hydrogen supply at 700 bar is assumed to be produced either with electrolysis[4] using the above electricity sources (medium voltage), or with Steam Reforming of Methane (SMR). LCI data for electrolysis is taken from Zhang, Bauer, Mutel, and Volkart (2017), while LCI data for SMR is taken from Simons and Bauer (2011). Electrolysis and compression are assumed to require 58 kWh electricity per kilogram of hydrogen produced (Zhang et al., 2017).

Fossil fuel supply chains for petrol and diesel are taken directly from the ecoinvent database for Swiss conditions, which does not include biofuel in the mix. Supply of compressed natural gas is also

[3] According to ecoinvent v3.4, system model "allocation, cut-off by classification" (Wernet, Bauer et al. 2016).
[4] Electricity consumption for electrolysis amounts to 55 kWh/kg hydrogen.

taken from ecoinvent, but is assumed to be a mixture of 90% fossil based gas and 10% biogas, as is currently sold at Swiss gas stations. For simplicity, we still refer to this mixture as "fossil" natural gas in the figures. We further consider the production of synthetic natural gas (SNG) based on the power-to-gas (P2G) process as described in Zhang et al. (2017). We use only the simple case of CO_2 being directly captured from the ambient air, as it avoids allocation issues (see related discussion in Zhang et al. (2017)). In Zhang et al. (2017), 0.50 kg of hydrogen are required to produce one kilogram of methane.

The well-to-tank environmental impacts of all energy chains are shown in Figure *3* to Figure 6 per kilowatt hour of energy delivered to the vehicle. The impacts per kilowatt hour of fossil energy provided are comparatively low, as these results do not include the environmental burdens associated with combustion of the fuel. The supply of synthetic gas, and hydrogen have generally higher impacts than the supply of electricity due to their lower system efficiencies, especially when based on electricity with higher environmental impacts per kilowatt hour, such as natural gas combined cycle power plants.

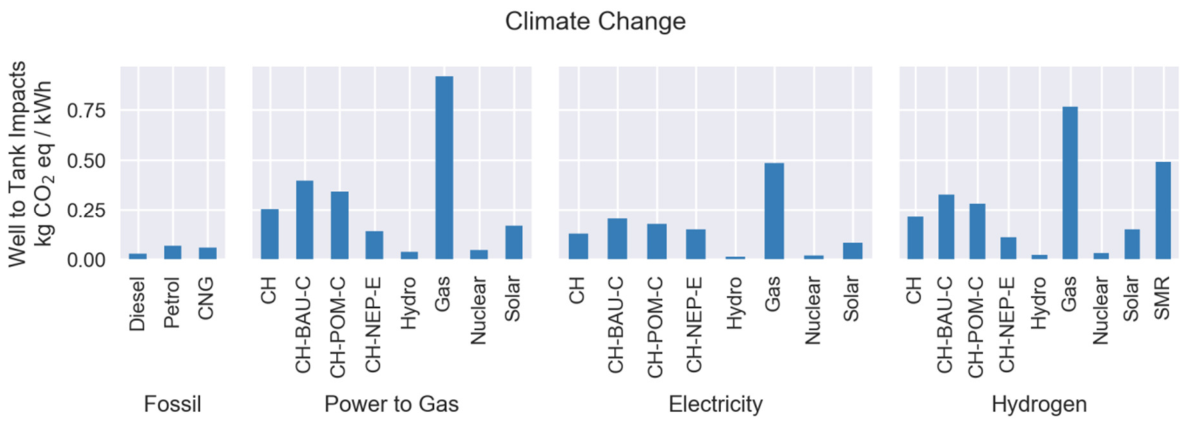

Figure *3* Well-to-tank climate change results for all energy chains

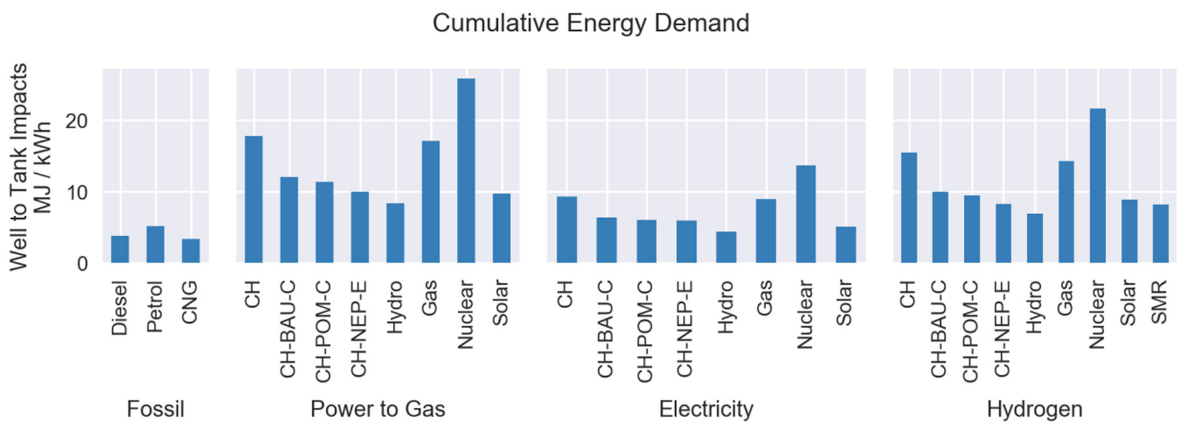

Figure 4 Well-to-tank cumulative energy demand results for all energy chains

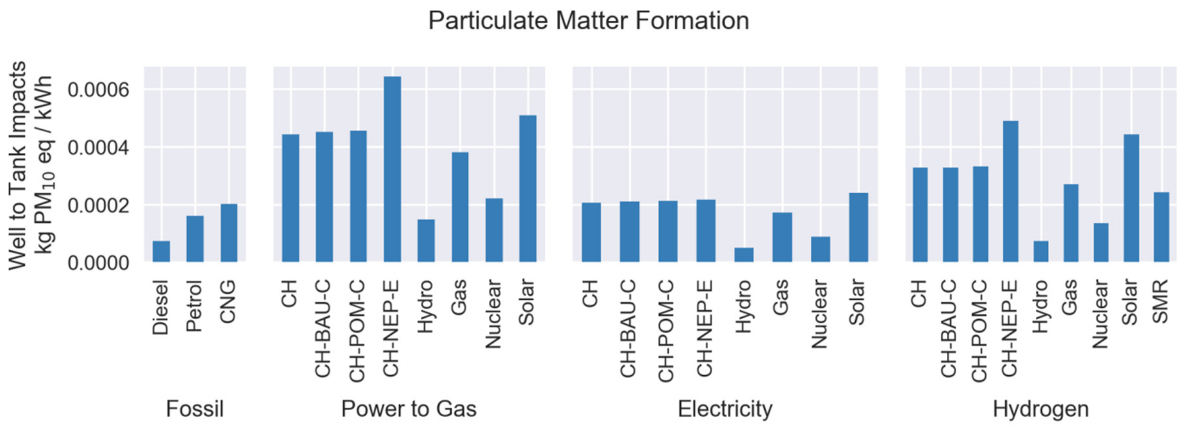

Figure 5 Well-to-tank particulate matter formation results for all energy chains

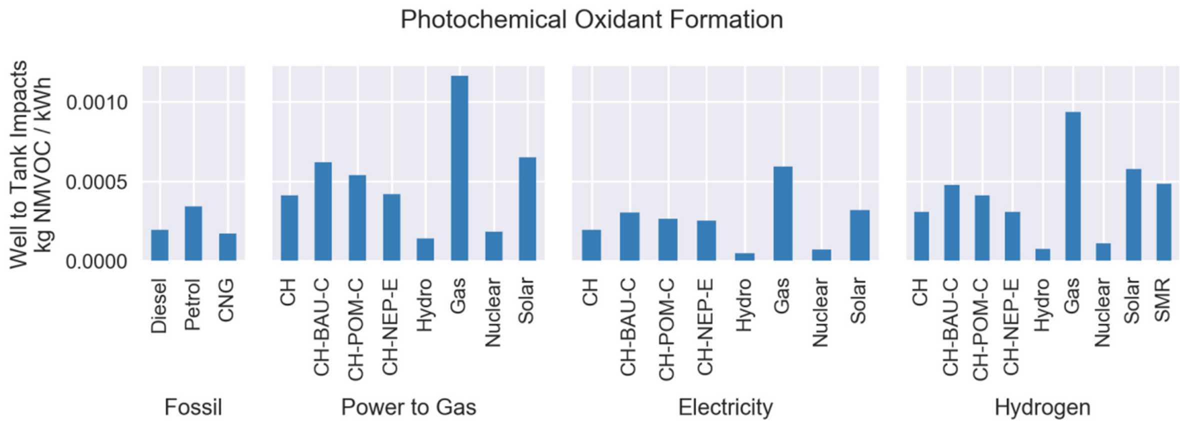

Figure 6 Well-to-tank photochemical oxidant formation results for all energy chains

3. Results and Discussion

In this section we present results for all powertrains. We first examine the vehicle mass and energy consumption in section 3.1, followed by LCA results in section 3.2, and sensitivity results to key parameters in section 3.3. We present results for global sensitivity analysis in the appendix.

Understanding figures with uncertainty:

Where bar chart results are presented with error bars, the bar chart represents the most likely result, calculated with the most likely value of all input parameters. The box plot represents the uncertainty of this value: the whiskers show the maximum and minimum values, while the box contains 50% of the results. The horizontal line within the box shows the mean result, which is usually similar to, but not the same as the most likely value, as the triangular distributions of the input values are not always symmetrical. Results presented in the fact sheet correspond to the most likely values.

3.1. Vehicle mass and energy consumption

Figure 7shows mass results for all powertrains, broken down into categories for glider, powertrain and energy storage devices. As mentioned in the methods chapter, the most likely value corresponds to a medium size car, with a curb weight of around 1400 to 1500 kg. There is, however, a large range of car sizes included in the results, ranging from very small cars on the order of 700 to 800 kg up to rather large cars and SUVs with curb weights on the order of 2300 to 2600 kg. While some of the variation in mass result is due to variations in vehicle power and energy storage size, the vehicle class by far dominates this variability.

In general, future vehicles are assumed to be lighter per class than current vehicles, due to technology improvements and replacement of steel with stronger or lighter materials. We have not included the fact that the average vehicle size has tended to increase over time and assume that the future cars will be similar in size to current cars. We find that conventional combustion vehicles tend to be the lightest, with hybrids slightly heavier, plug-in hybrids heavier yet, and battery and fuel cell vehicles tending to have the highest curb weights of all vehicles. While this trend will continue in the future, it is likely to become less pronounced as the weight of batteries, fuel cells and hydrogen tanks decrease.

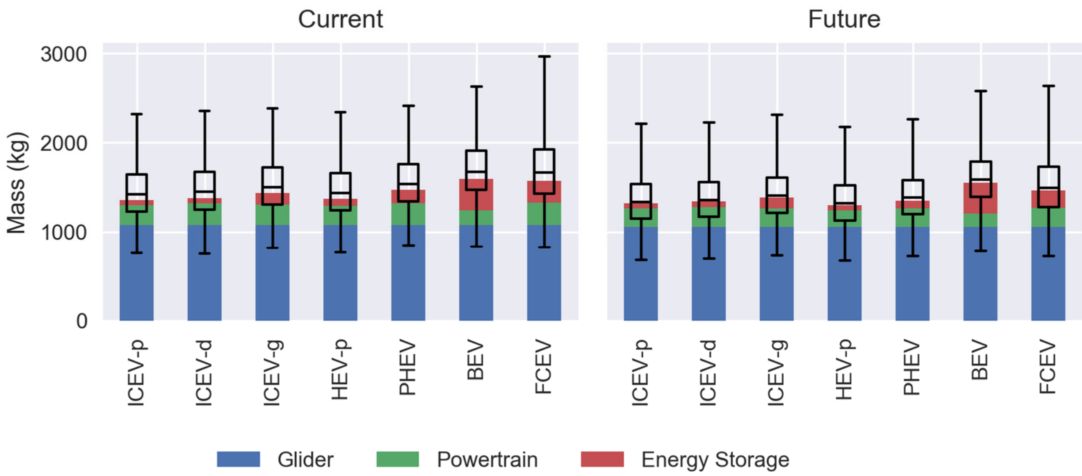

Figure 7 Vehicle mass for different powertrain technologies. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

Figure 8 shows results for vehicle tank-to-wheel energy consumption. We include two common units for measuring energy consumption: kilowatt hours per 100 km are shown on the left y axis, while liters of gasoline equivalent per 100 km are shown on the right y axis. As with vehicle curb mass shown above, the majority of the variation in vehicle energy consumption for each powertrain type is due to vehicle size. We examine this relationship in more detail in Figure 20. The bar chart results in Figure 8 are broken down into the origin of the energy consumption. Energy demand at the wheel due to aerodynamic and rolling losses, as well as kinetic energy demand are very similar for all vehicle types. Recuperated and braking energy are negative. Powertrains with recuperative braking have lower braking losses as this energy can be recuperated to recharge the battery. Future combustion engine vehicles are assumed to be mild hybrids; they can recuperate some braking energy, but not as much as strong hybrids or BEVs as their battery size is limited.

The largest differences between powertrain types are due to the tank-to-wheel efficiency of each powertrain, which is listed in Table 2. As conventional combustion engines have the lowest efficiencies, they have the highest overall energy consumption. PHEV operating in electric mode and BEV are found to have the lowest energy consumption, followed by FCEV and HEV.

Future vehicles are expected to have reduced energy consumption. The largest gains are expected for conventional vehicles due mostly to mild hybridization of the engines. Fuel cell vehicles are also expected to improve significantly due to gains in stack efficiency and reductions in energy consumption by the balance of plant. BEV tank to wheel efficiency is not expected to increase substantially, as it is already very high.

As discussed in section 2.2, we have calibrated these results to both manufacturer claims about energy consumption (by modifying our energy consumption model to reflect official testing conditions) and also more realistic driving conditions, and are confident that they represent real world vehicle consumption rather well.

We note that these figures show tank-to-wheel energy consumption, meaning that they do not include charging losses for BEV and PHEV-e, which would represent a 10 to 20% increase, or roughly 1 to 2 kWh per 100 km. These losses are included in the LCA results shown in section 3.2.

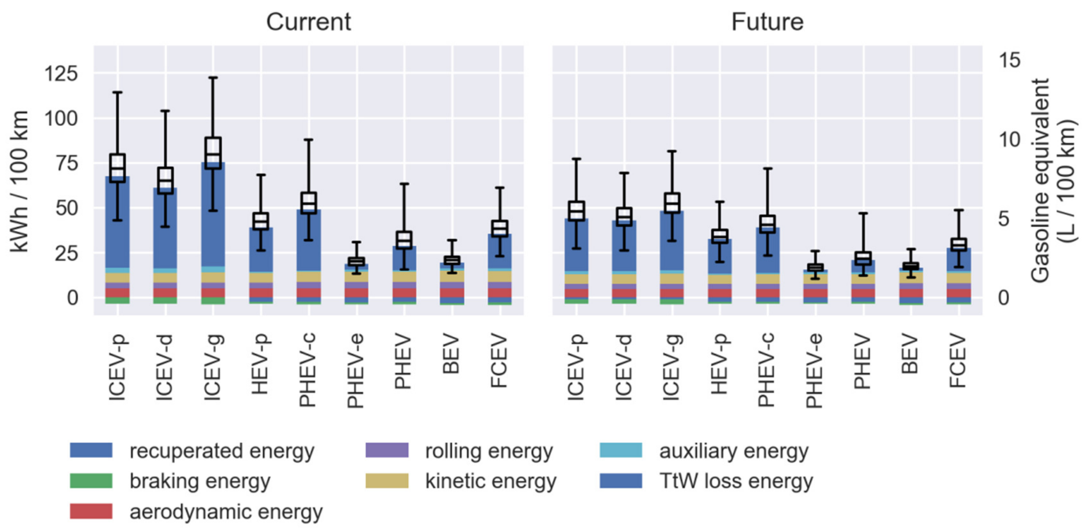

Figure 8 Vehicle tank-to-wheel energy consumption results, current (left) and in year 2040 (right). Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

3.2. Life cycle assessment results

In this section we present LCA results. For each impact category we show results for current and future vehicles separately, due to the large number of powertrain and energy chain combinations.

Results are shown in 5 panels. The first panel on the left shows results for ICEV-d (conventional diesel vehicles), ICEV-p (conventional petrol vehicles), and HEV-p (hybrid cars with petrol fuel). The next panel shows results for ICEV-g (compressed natural gas fueled vehicles). We show results for fossil natural gas (which contains 10% biogas as is the Swiss standard) and also synthetic natural gas, produced with different electricity sources and CO_2 captured from ambient air. The middle panel shows results for PHEV (plug-in hybrid electric vehicles) with the share of kilometers driven in electric and combustion mode calculated according to the vehicles electric range as discussed in section 2.2. Results for climate change are presented for separately for electric and combustion operating modes in Figure 11 and Figure 12. The different bars show the electricity sources used to charge the battery. The fourth panel shows results for BEV (battery electric vehicles) for different electricity sources. Finally, the fifth panel shows results for FCEV (fuel cell electric vehicles). The SMR scenario shows results for hydrogen produced via the steam reformation of methane. The other cases show results for hydrogen produced via electrolysis with different electricity sources. The different electricity sources are described in 2.3. Results are split into contributions from different parts of the vehicle and its life cycle (shown in different colors) as follows:

- **Road** represents construction and maintenance of road infrastructure in Switzerland and is allocated by vehicle gross weight.
- **Glider** represents manufacturing, maintenance and end-of-life of common vehicle components;
- **Powertrain** represents manufacturing, maintenance and end-of-life of powertrain specific components such as motors, power batteries, electrical converters, charging components and fuel cells.
- **Energy Storage** represents manufacturing, maintenance and end-of-life of energy storage components such as fuel tanks and batteries.
- **Energy Chain** represents supply of energy carriers used for vehicle operation.
- **Direct Emissions** represents exhaust and non-exhaust emissions from vehicle operation.

Figure 9 and Figure 10 show climate change results for current and future vehicles, respectively. The variance in results for each powertrain is, as is the case for vehicle mass and energy consumption, due mostly to the size of the vehicle, though the vehicle lifetime is also extremely important. This is examined further in Figure 19. Other parameters such as tank to wheel efficiency, battery size, and fuel cell size are also of importance as can be seen in the global sensitivity analysis results in Appendix B.

We find that future vehicles with all powertrain types will have lower climate change impacts than current vehicles due to technological improvements and efficiency gains. We further find that BEV, PHEV, FCEV and even ICEV-g operating with synthetic natural gas have the potential to greatly reduce the climate change impacts of passenger cars compared to conventional petrol and diesel cars, though only if low carbon sources of energy are used. Such sources of energy include hydro, wind, nuclear and solar photovoltaics. If electricity sources with higher carbon content are used, the efficiency of the entire energy chain becomes greatly important. When using the average Swiss electricity mix (which has a comparatively low carbon intensity due to high shares of hydro and nuclear power), BEV and PHEV outperform hybrid vehicles and FCEV have similar performance to HEV. ICEV-g vehicles operating with synthetic natural gas sourced from Swiss average electricity perform worse than HEV and worse than even conventional diesel vehicles. If one considers that natural gas combined cycle power plants to be the electricity supply that will be at least partially used to meet the additional demand of e-mobility in case of substantial expansion, we find that current BEV and PHEV have similar climate change performance to HEV, while FCEV no longer provide climate benefits in this scenario. In general, we find that PHEV operating in electric mode have lower climate change impacts than BEV, due to the reduced impacts of battery production as well as lower mass. PHEV operating in combustion mode perform slightly worse than regular hybrids due to increased mass and slightly lower drivetrain efficiencies. If batteries were produced using renewable energy, such as in the Tesla Gigafactory, climate change contributions for BEV would be reduced by roughly 20 g CO_2 eq/ km in the most likely case.

When future performance is considered, the same conclusions and technology ranking generally hold. However, uncertainty in these conclusions is higher due to the slightly higher carbon content of the future Swiss electricity mix, greatly improved combustion vehicles, and the general uncertainty of future technology performance predictions.

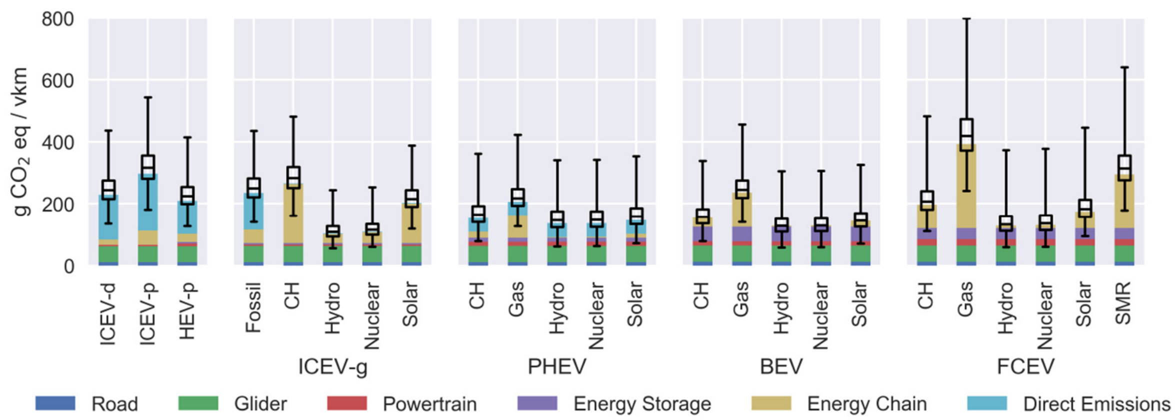

Figure 9 Vehicle climate change results for current vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

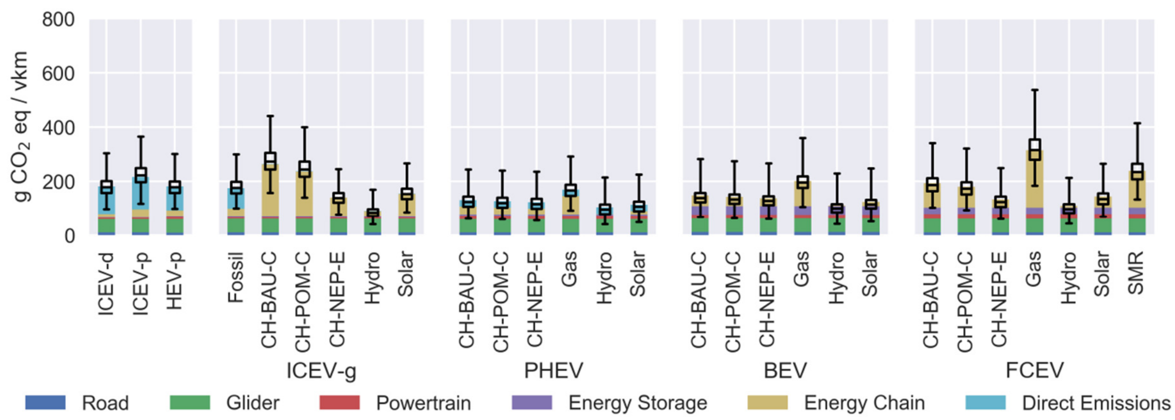

Figure 10 Vehicle climate change results for future vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

Figure 11 and Figure 12 show the same results as above, but only for PHEV in (left) only combustion mode, (middle) only electric mode, and (right) average operating mode. As expected, results for all electric mode are slightly better than pure BEV, due to the smaller batteries, while results for combustion mode are slightly worse than normal HEV, due to the additional batteries and slightly more complex drivetrain.

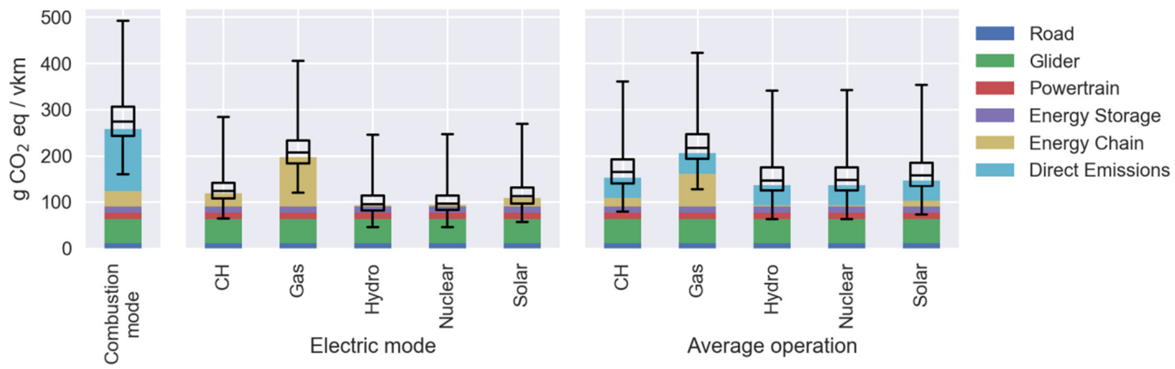

Figure 11 Vehicle climate change results for current PHEV vehicles with for different operating modes. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

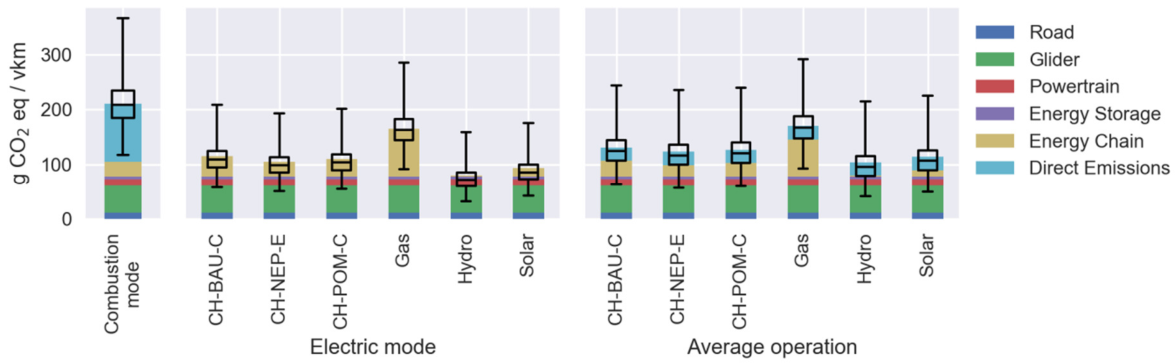

Figure 12 Vehicle climate change results for future PHEV vehicles with for different operating modes. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

In Figure 13 and Figure 14 we show cumulative energy demand results for current and future vehicles respectively. This indicator considers both renewable and non-renewable energy sources, though each energy source is included with a different conversion factor, which makes comparison across different primary energy types difficult. Despite this, meaningful conclusions for this indicator may still be made for similar energy chains for different powertrains. Here the inefficiency of using electricity to produce hydrogen, and especially synthetic natural gas becomes most clear compared to battery electric vehicles. Climate protection goals demand a great expansion of renewable electricity sources, which in Switzerland could prove difficult. Use of these resources should not be wasted in long energy conversion chains except where it is absolutely necessary.

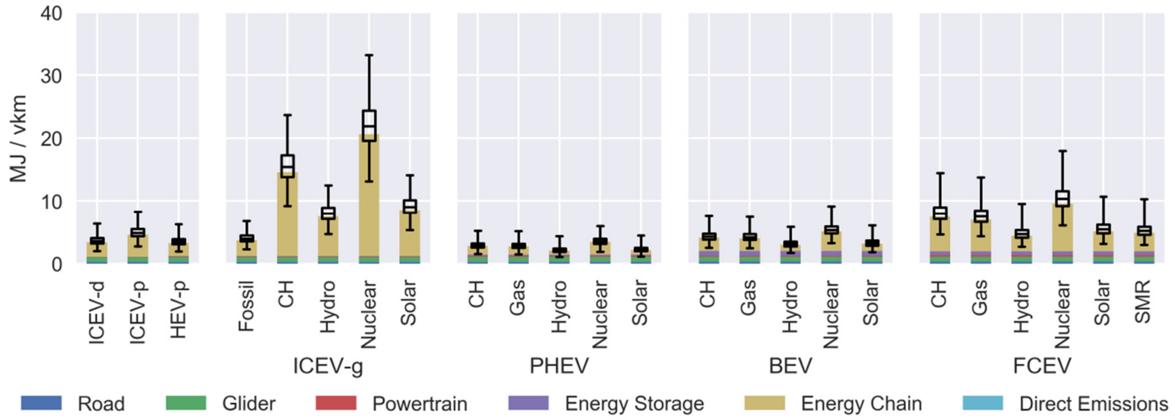

Figure 13 Vehicle cumulative energy demand results for current vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

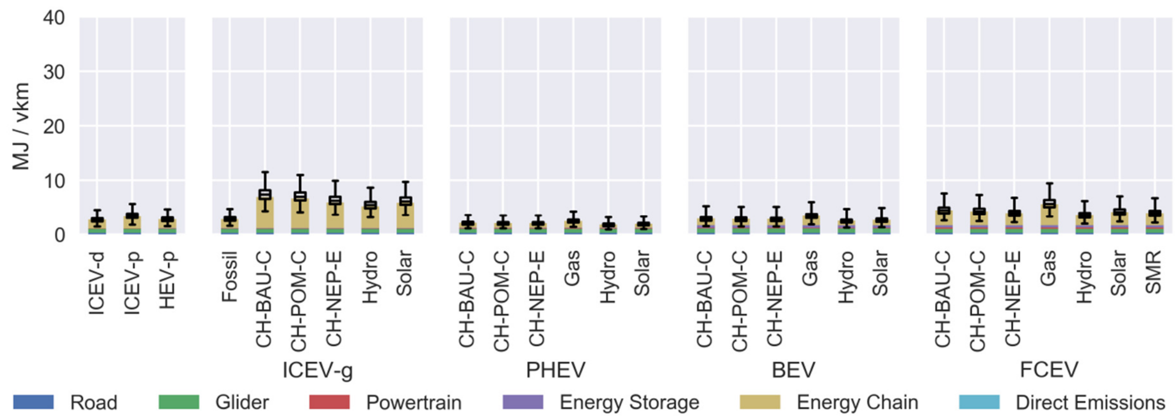

Figure 14 Vehicle cumulative energy demand results for future vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

In Figure 15 and Figure 16 we show results for current and future vehicle particulate matter formation respectively. The majority of impacts in this category are due to the upstream processes related to producing the vehicle and the energy. We note that the combustion vehicles considered here are have Euro 6 level emission control technologies, which generally have rather low amounts of direct pollutant emissions, with the exception of NO_x emissions from some Euro 6 diesel vehicles. Older combustion vehicles have significant direct emissions of primary particulate matter as well as substances that lead to the formation of secondary particles.

Results are quite comparable for all powertrain types and energy scenarios. BEV and FCEV are found to have larger uncertainties due to the variation in battery size. Significant particulate matter emissions come from the electricity used in battery production which highlights the importance of not only improving the environmental performance of vehicle operation, but also of global supply chains.

Despite the fact that all powertrains have roughly similar results in this category, it should be pointed out that life cycle assessment applies equal characterization factors to emissions in all locations, regardless of population density. Thus, even though all powertrain types are found to have similar LCA scores, it is likely that the true human health impacts of powertrains with zero direct tailpipe emissions are lower than conventional vehicles when operating in densely populated urban environments.

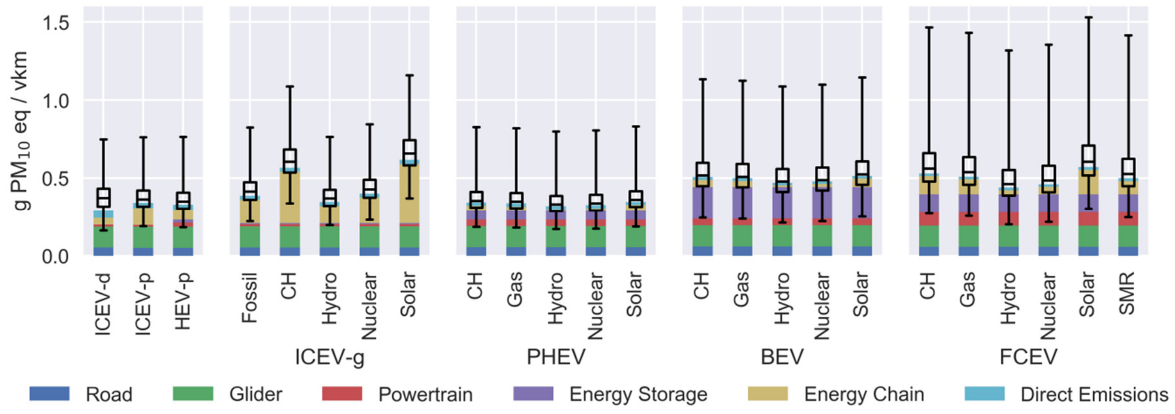

Figure 15 Vehicle particulate matter formation results for current vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

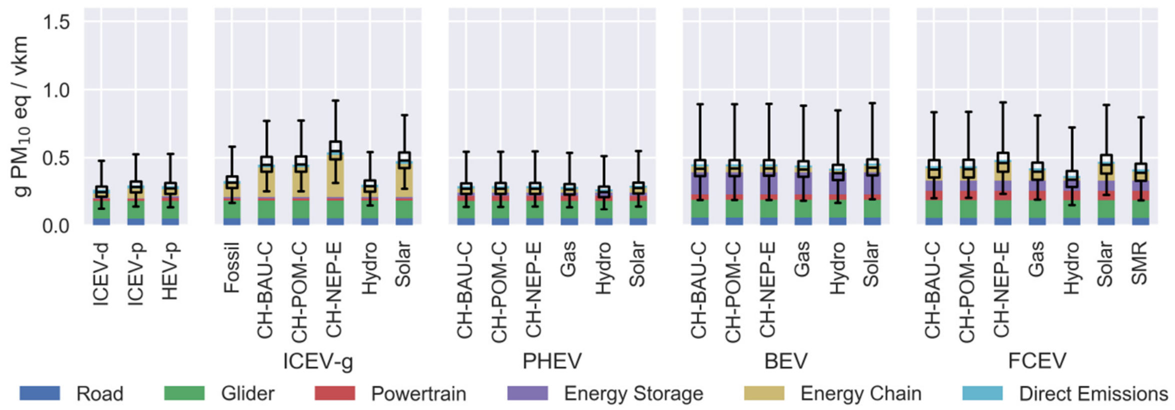

Figure 16 Vehicle particulate matter formation results for future vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

Figure 17 and Figure 18 show results for current and future vehicles in the photochemical oxidant formation (summer smog) impact category. As with particulate matter formation, results in this category for older combustion vehicles are dominated by direct tailpipe emissions. However, as emission control technologies have improved and tailpipe emissions reduced, the majority of burdens are now due to the upstream processes of producing the vehicle and energy. The majority of the uncertainty in this category is due to variations in vehicle size. One exception to this is for current ICEV-d vehicles which have recently been discovered to have much higher NO_x emissions in real driving conditions than in test conditions. We have included real world driving test emission levels for some of the worst offenders as the high bound in our uncertainty assessment, which is seen to shift the mean result by nearly 20%. However, even these elevated photochemical oxidant formation results for diesel cars are not greatly different than results for other powertrain types, which all show rather similar performance.

It should be noted that, similar to particulate matter formation, the location of these emissions is extremely important and this cannot be captured by generic life cycle assessment. The NO_x

emissions from diesel cars that are emitted in highly populated urban areas are likely much worse in terms of impacts on human health than similar emissions from other vehicle types which are in the upstream process in less populated areas, however LCA cannot make this distinction and thus weights all emissions equally.

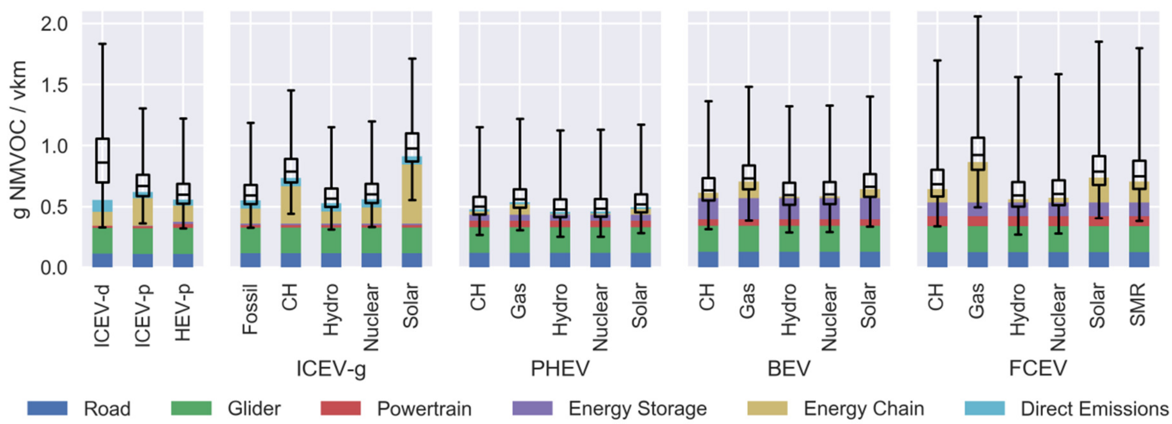

Figure 17 Vehicle photochemical oxidant formation results for current vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

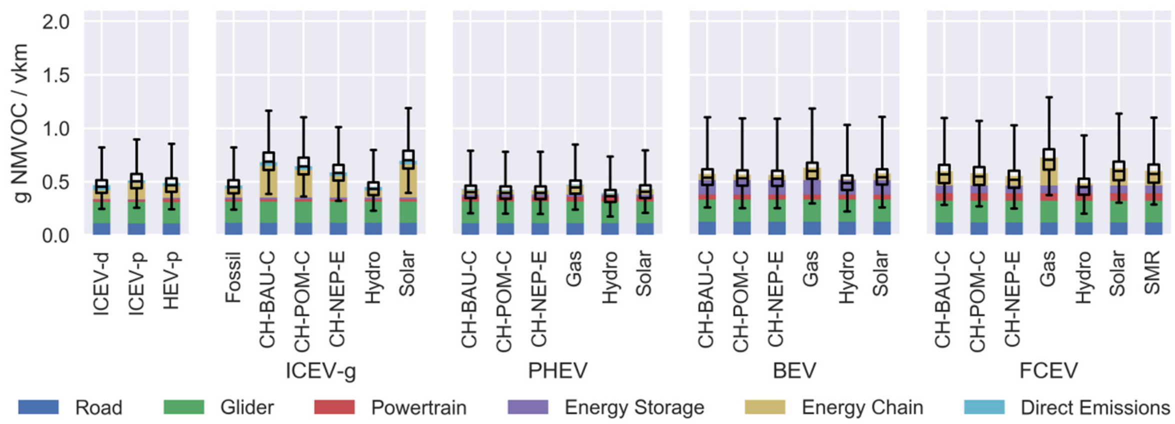

Figure 18 Vehicle photochemical oxidant formation results for future vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

3.3. Sensitivity analysis

As discussed in the previous section, results are extremely sensitive to the lifetime distance of the vehicle travelled, the vehicle size, the battery size, and the carbon intensity of the electricity grid. We examine these sensitivities in this section. For simplicity, we show results with Swiss average electricity in the current case, and the POM-C scenario for the future power supply. We include global sensitivity analysis results in the appendix.

In Figure 19 we show the total life cycle climate change emissions (in kg CO_2 eq) for each powertrain over its lifetime (shown here up to 400 000km), with all other uncertain parameters held constant at their most likely value. The impacts do not start at zero on the y axis, due to the burdens associated with producing the vehicle as well as its end-of-life treatment which occur regardless of the distance that vehicle is driven. The slope of the line indicates the relative importance of the environmental burdens due to the operating, maintenance, and fuel production phases of the life cycle.

We find that BEV and FCEV have higher production burdens than conventional vehicles, but lower operating burdens. For PHEV production burdens are much smaller due to the smaller battery. Compared to ICEV, PHEV (in all electric mode) are able to make up for their higher production burdens in less than 50 000 km, while for BEV this takes roughly 80 000 km.

We see that after 150 000 km (200 000 km in the future case) the battery is replaced in the EV, resulting in a step change in the total life cycle emissions. Of course, this comparison is very sensitive to changes in electricity mix and battery size and lifetime, and the actual number of kilometers travelled before climate impact parity can easily vary by tens of thousands of kilometers based on changes in these input values. However, the conclusion may be drawn that as vehicles are used more intensely, such as for taxis or chare sharing programs, BEV and PHEV seem to offer even larger benefits. If vehicles are not used very intensely, than the burdens of vehicle production are unlikely to be made up for through reduced operating emissions.

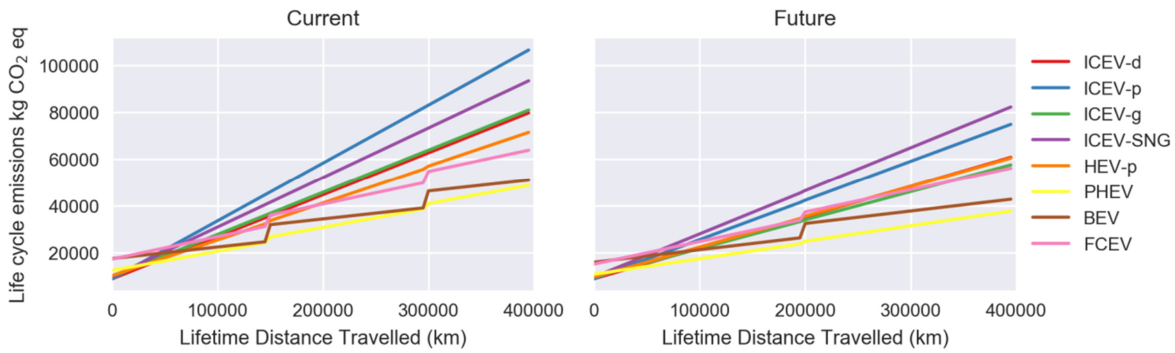

Figure 19 Sensitivity of climate change results to lifetime distance travelled

Figure 20 shows the sensitivity in results to vehicle mass in a hexbin plot for each powertrain type. Hexbin plots show the frequency with which the Monte Carlo analysis found a certain result. That is, darker regions on the plot are more likely. The y axis for each subplot shows the climate change contributions per vehicle kilometer, while the x axis shows the curb mass of the vehicle. As expected, heavier vehicles have higher energy consumption and thus higher GHG emissions. Vehicles with more efficient powertrains, such as FCEV and HEV are generally less sensitive to vehicle mass. For the BEV and FCEV results are less clearly linear than for other powertrains: vehicles that are heavier because of larger gliders do not result in significantly higher GHG emissions. However, vehicles that are heavier because of larger batteries or fuel cells have much higher GHG emissions, which explains the more spread out results for heavier BEV and FCEV.

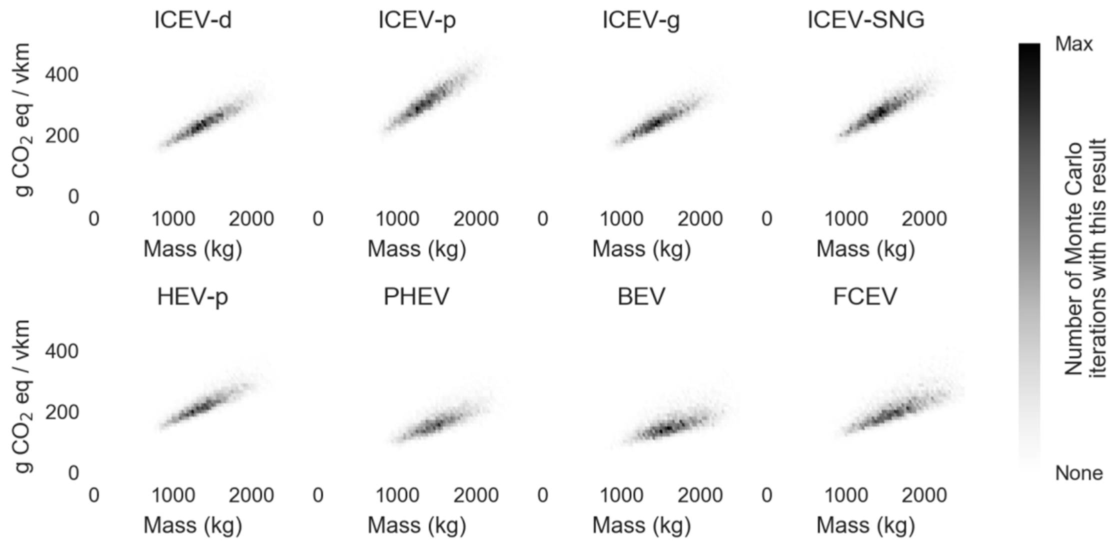

Figure 20 Sensitivity of climate change results to vehicle mass

Figure 21 shows another hexbin plot, this time for current and future BEV and PHEV versus battery size. It can be seen that climate change impacts due to current BEV are quite sensitive to the size of the battery in the vehicle with larger batteries increasing the climate change impacts of the vehicle. This sensitivity is expected to decrease in the future as the impacts of battery production are expected to decrease. For PHEV the trend is reversed. For both current and future PHEV, an increase in battery size leads to an increase in the share of kilometers driven in all electric mode, thus decreasing the overall climate change impacts. This trend of course has a limit, as increasing the battery size after a certain point no longer offsets combustion powered kilometers and only increases production impacts and energy consumption due to the larger battery.

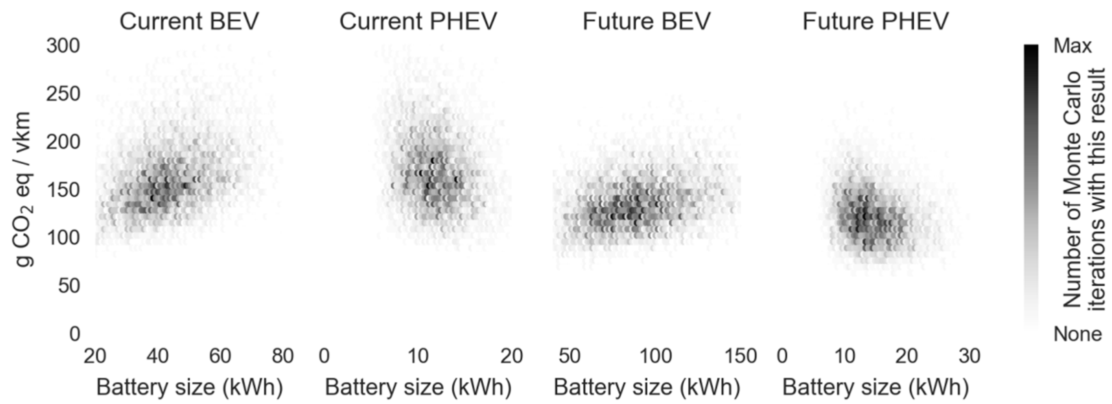

Figure 21 Sensitivity of climate change results to battery size for BEV and PHEV

In Figure 22 we show the sensitivity of results to the carbon intensity of the electricity source used to charge the battery or produce the fuel. Of course, powertrain types such as ICEV and HEV do not depend on electricity, and thus are not influenced by electricity grid carbon intensity (i.e., the line is horizontal). However, BEV, PHEV, FCEV, and ICEV-SNG depend strongly on low carbon electricity for their climate benefits. We see that the most likely result for BEV and PHEV vehicles show climate benefits compared to HEV even if the electricity mix has a carbon intensity of up to roughly 350 and 500 g CO_2 / kWh respectively.

For reference, the life cycle carbon intensity of electricity from hydroelectricity, wind, and nuclear are in the range of 5-40 g CO_2 / kWh, electricity from a modern natural gas combined cycle power plant causes roughly 400-500 g CO_2 / kWh, while the current Swiss electricity mix corresponds to slightly more than 100 g CO_2 / kWh, and the future Swiss electricity mix is expected to be between 150 and 200 g CO_2 / kWh (see Figure 3).

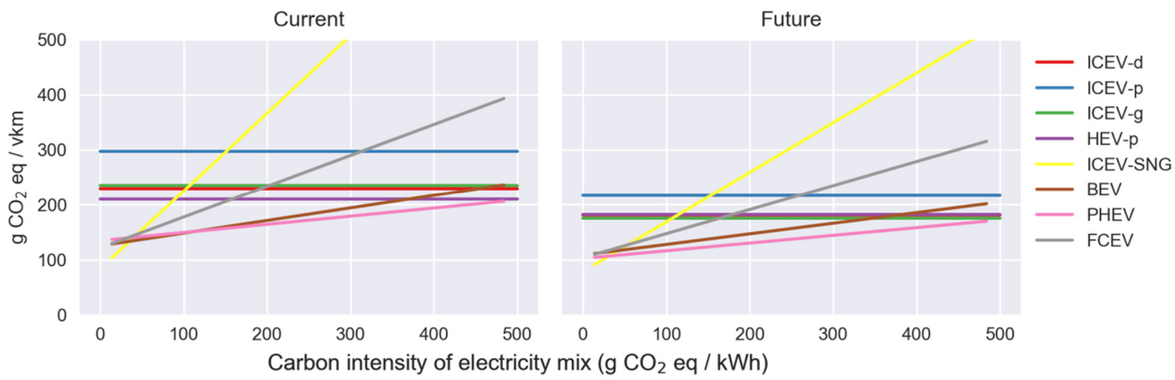

Figure 22 Sensitivity of climate change results to carbon intensity of electricity mix

4. Uncertainties and limitations

There are several limitations in this study that require discussion. There is inherent difficulty in predicting the future performance and operating conditions of different vehicle powertrains, which could have substantial impact on results. We mitigate this uncertainty through our methodological approach of determining ranges for all parameter values, and performing sensitivity analysis to determine the parameters that are driving variability in our results. However our treatment of uncertainty is limited to assumptions regarding the performance of passenger vehicles and key aspects of lithium ion battery production; we do not include uncertainty in the background database, the environmental impact characterization factors or the additional energy chain datasets that we used for synthetic methane production. Furthermore, we model the impacts of future technologies with a current background database, which is a significant limitation, though modifying the background database was out of scope for this project. A further limitation is that we generally model the production of vehicles operating in Switzerland with global production averages, with the exception of the electricity used for lithium battery production. This leads to slight inaccuracies, as the majority of vehicles that operating in Switzerland are produced in Europe. A final important limitation of this study is that the treatment of future component recycling has been very simple and we have assumed that current average material recycling rates are applicable to future passenger car components. Despite these various limitations, we are confident that changes to the modelling approach will not result in substantial influence on the most important conclusions of this study.

There are several considerations that were not treated in this study that could be very relevant in light of the goal of reducing the environmental burdens from passenger cars:

- From an environmental point of view, the development of electromobility must be paralleled with the development of electricity production from renewable sources.

- The concrete health impacts of direct emissions from combustion motors and the reduction of local air pollution via zero direct emission technologies such as BEV and FCEV in Switzerland were out of scope in this study.
- The introduction of vehicles and fuels that are viewed to be 'green' could lead to rebound effects in that drivers travel more because they feel that the vehicle has lower environmental burdens.
- A significant increase of electromobility or electricity sourced alternative fuels will greatly increase the electricity demand in Switzerland. How this additional demand should be met is not part of this analysis, but is of great importance for the long term environmental burdens of Swiss passenger mobility.

5. Conclusions

In terms of climate change, advanced powertrain concepts such as BEV, FCEV and ICEV operating with SNG only make sense when the electricity used to charge the batteries, and produce hydrogen and SNG come from low CO_2 sources. This is valid for both today and in the future. With electricity from nearly CO_2-free sources such as hydro, wind or nuclear power plants, these advanced technologies can reduce greenhouse gas emissions by roughly 50% compared to current petrol and diesel passenger vehicles. Conversely, if natural gas power plants are used to meet the additional electricity demand of electric mobility, no greenhouse gas emissions reductions will occur. The introduction of electric mobility must occur in parallel to an expansion of renewable electricity generation capacity.

In terms of the life cycle cumulative energy demand, BEV and PHEV have similar performance to fossil fueled conventional vehicles and hybrids. FCEV and ICEV powered by synthetic methane perform clearly worse in this category due to their lower overall energy chain efficiency. This is an important conclusion when considering the finite expansion potential of renewable electricity generation capacity in Switzerland.

Life cycle assessment results in categories for particulate matter formation and photochemical oxidant formation are similar for all powertrain types. However, due to their lack of direct exhaust emissions, BEV and FCEV have the potential to reduce air pollution in areas of high transport demand. These air emissions are essentially exported to regions where vehicles and vehicle components are manufactured. Life cycle based, quantitative, and reliable conclusions regarding the concrete impacts of these emissions, which have large regional variation and depend strongly on the population density of the affected area, cannot be made with the current level of knowledge. It can, however, likely be assumed that the majority of these production related emissions will be exported to areas of lower population density, where the resulting human health impacts will be lower.

The environmental impacts of passenger cars are extremely sensitive to vehicle size, with the smallest vehicles having roughly half the environmental burdens as the largest vehicles and impacts increasing roughly linearly with vehicle curb weight. Furthermore, the impacts of BEV are strongly influenced by the size of the onboard battery; a larger electric range results in higher environmental burdens per kilometer. However, it is expected that this factor will decrease in importance in the future due to improved battery production processes.

The environmental performance of alternative powertrain vehicles and fuels essentially depends on the environmental burdens of the electricity generation technology and the efficiency of the energy chain from electricity generation to the wheel.

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Appendix A. **Model input parameters**

Here we list all input parameters that are read into the calculation model

Table A-1 Vehicle input parameters

			current			future			
	powertrain	**parameter**	**Most likely**	**low**	**high**	**Most likely**	**low**	**high**	**unit**
Glider	all	lifetime kilometers	180000	80000	300000	180000	120000	400000	km
Glider	all	glider base mass	1200	600	2000	1175	550	1900	kg
Glider	all	lightweighting (weight savings compared to glider base mass by replacing steel with high strength steel)	0.1	0	0.2	0.1	0	0.25	
Glider	all	power to mass ratio	60	40	100	60	40	100	W/kg
Glider	all	frontal area slope	0.0008	0.0006	0.0009	0.0008	0.0006	0.0009	m^2 / glider base mass kg
Glider	all	frontal area intercept	1.1	1.09	1.3	1.1	1.09	1.3	m^2
Glider	all	aerodynamic drag coefficient	0.310	0.300	0.350	0.295	0.264	0.350	
Glider	all	rolling resistance coefficient	0.010	0.007	0.012	0.009	0.006	0.012	
Glider	all	average passengers	1.8	1	4	1.8	1	4	persons
Glider	all	average passenger mass	75	60	90	75	60	90	kg
Glider	all	cargo mass	20	0	250	20	0	250	kg
Powertrain	BEV, FCEV, PHEV-e, HEV-p	drivetrain efficiency	0.85	0.8	0.9	0.87	0.82	0.92	
Powertrain	ICEV-p, ICEV-d, ICEV-g	drivetrain efficiency	0.8	0.75	0.9	0.85	0.8	0.9	
Powertrain	PHEV-c	drivetrain efficiency	0.723	0.64	0.81	0.757	0.672	0.846	
Powertrain	BEV, FCEV, PHEV-e	engine efficiency	0.85	0.8	0.9	0.87	0.82	0.92	
Powertrain	ICEV-p	engine efficiency	0.26	0.24	0.28	0.32	0.28	0.34	
Powertrain	ICEV-g	engine efficiency	0.24	0.22	0.26	0.3	0.26	0.32	
Powertrain	ICEV-d	engine efficiency	0.29	0.27	0.31	0.33	0.31	0.37	
Powertrain	HEV-p, PHEV-c	engine efficiency	0.33	0.31	0.35	0.35	0.33	0.4	
Powertrain	FCEV	fuel cell stack efficiency	0.535	0.5	0.57	0.57	0.52	0.63	
Powertrain	FCEV	fuel cell power area density	900	700	1100	1000	800	1200	mW/cm^2
Powertrain	FCEV	fuel cell ancillary BoP mass per power	0.33	0.3	0.37	0.3	0.28	0.34	kg/kW
Powertrain	FCEV	fuel cell essential BoP mass per power	0.4	0.35	0.5	0.35	0.3	0.4	kg/kW
Powertrain	FCEV	fuel cell own consumption	1.15	1.1	1.2	1.125	1.08	1.15	
Powertrain	BEV, PHEV-c, PHEV-e	converter mass	4.5	4	6	4.275	3.6	6	kg
Powertrain	BEV, FCEV, HEV-p, PHEV-c, PHEV-e	inverter mass	9	8	10	8.55	7.2	10	kg
Powertrain	BEV, PHEV-c, PHEV-e	charger mass	6	4	7	5.7	3.6	7	kg

			current			future			
	powertrain	parameter	Most likely	low	high	Most likely	low	high	unit
	BEV, PHEV-c, PHEV-e, FCEV, HEV-p	power distribution unit mass	4	3	5	3.8	2.7	5	kg
	BEV, PHEV-e, PHEV-c, HEV-p, FCEV	electric motor mass per power	0.5	0.3	0.75	0.5	0.3	0.75	kg/kW
	ICEV-p, ICEV-d, ICEV-g,	electric motor mass per power				0.5	0.3	0.75	kg/kW
	BEV, PHEV-c, PHEV-e, FCEV, HEV-p	electric motor fixed mass	20	15	25	15	10	20	kg
	ICEV-p, ICEV-d, ICEV-g	electric motor fixed mass				15	10	20	kg
	ICEV-p, ICEV-g, HEV-p, PHEV-c, PHEV-e	engine mass per power	0.7	0.6	0.8	0.65	0.55	0.75	kg/kW
	ICEV-d	engine mass per power	0.8	0.7	0.9	0.75	0.65	0.85	kg/kW
	ICEV-p, ICEV-g, HEV-p, PHEV-c, PHEV-e	engine fixed mass	60	50	70	50	45	55	kg
	ICEV-d	engine fixed mass	69	59	79	59	54	64	kg
	BEV, PHEV-c, PHEV-e, FCEV, HEV-p	powertrain mass per power	0.4	0.35	0.45	0.35	0.3	0.4	kg/kW
	ICEV-p, ICEV-d, ICEV-g	powertrain mass per power	0.6	0.55	0.65	0.5	0.45	0.55	kg/kW
	BEV, PHEV-c, PHEV-e, FCEV, HEV-p	powertrain fixed mass	35	30	40	30	25	35	kg
	ICEV-p, ICEV-d, ICEV-g	powertrain fixed mass	55	45	65	50	40	60	kg
	HEV-p	combustion power share	0.75	0.6	0.9	0.75	0.6	0.9	
	ICEV-p, ICEV-d, ICEV-g	combustion power share	1			0.9			
	PHEV-c, PHEV-e	combustion power share	0.4	0.35	0.5	0.4	0.35	0.5	
	FCEV	fuel cell power share	0.75	0.6	0.9	0.75	0.6	0.9	
Auxiliaries	ICEV-p, ICEV-d, ICEV-g	auxiliary power base demand	93.75	62.5	125	71.25	45	100	W
	BEV, PHEV-c, PHEV-e, FCEV, HEV-p	auxiliary power base demand	75	50	100	71.25	45	100	W
	all	heating thermal demand	300	200	400	285	180	400	W
	all	cooling thermal demand	300	200	400	285	180	400	W
	ICEV-p, ICEV-d, ICEV-g, FCEV, HEV-p, PHEV-c	heating energy consumption	0			0			W/W
	BEV, PHEV-e	heating energy consumption	1			0.8	0.3	1	W/W
	ICEV-p, ICEV-d, ICEV-g, FCEV, HEV-p, PHEV-c	cooling energy consumption	1	0.8	1.2	0.8	0.5	1	W/W
	BEV, PHEV-e	cooling energy consumption	1	0.8	1.2	0.8	0.5	1	W/W
Energy Storage	BEV	energy battery mass	350	150	600	350	150	600	kg
	PHEV-c, PHEV-e	energy battery mass	100	50	150	50	30	100	kg
	BEV, PHEV-e, PHEV-c, HEV-p, FCEV	battery charge efficiency	0.85	0.8	0.9	0.86	0.8	0.93	
	ICEV-p, ICEV-d, ICEV-g,	battery charge efficiency				0.5	0.4	0.6	
	BEV, PHEV-e	battery discharge efficiency	0.88	0.85	0.92	0.89	0.85	0.95	
	BEV, PHEV-e	battery DoD	0.8	0.75	0.85	0.8	0.75	0.85	
	BEV, PHEV-c, PHEV-e	battery cell energy density	0.2	0.15	0.25	0.4	0.25	0.5	kWh/kg
	ICEV-p, ICEV-d, ICEV-g, HEV-p, FCEV	battery cell power density	1	0.9	1.5	1.2	1	1.7	kW/kg
	BEV, PHEV-c, PHEV-e,	battery cell mass share	0.6	0.55	0.65	0.65	0.6	0.7	
	HEV-p, FCEV	battery cell mass share	0.5	0.4	0.6	0.55	0.45	0.65	

			current			future			
	powertrain	**parameter**	**Most likely**	**low**	**high**	**Most likely**	**low**	**high**	**unit**
	ICEV-p, ICEV-d, ICEV-g,	battery cell mass share				0.55	0.45	0.65	
	BEV, PHEV-e, PHEV-c, HEV-p, FCEV	battery cell production electricity	24	6	30	15	6	24	kWh / kg battery cell
	ICEV-p, ICEV-d, ICEV-g,	battery cell production electricity				15	6	24	kWh / kg battery cell
	BEV, PHEV-e, PHEV-c, HEV-p, FCEV	battery lifetime kilometers	150000	100000	300000	200000	150000	350000	kg/kWh
	ICEV-p, ICEV-d, ICEV-g,	battery lifetime kilometers				200000	150000	350000	kg/kWh
	FCEV	fuel cell lifetime kilometers	150000	100000	300000	200000	150000	350000	kg/kWh
	FCEV	H2 tank mass per energy	0.57	0.55	0.6	0.5	0.45	0.55	kg/kWh
	ICEV-p, ICEV-d, HEV-p, PHEV-c, PHEV-e	fuel tank mass per energy	0.075	0.07	0.08	0.075	0.07	0.08	kg/kWh
	ICEV-g	CNG tank mass slope	0.2	0.18	0.22	0.2	0.18	0.22	kg/kWh
	ICEV-g	CNG tank mass intercept	25	20	30	25	20	30	kg
	ICEV-p,	petrol mass	30	20	40	25	20	35	kg
	ICEV-d	diesel mass	30	20	40	25	20	35	kg
	ICEV-g	CNG mass	25	20	30	20	15	30	kg
	HEV-p, PHEV-c, PHEV-e	petrol mass	25	20	30	20	15	30	kg
	FCEV	H2 mass	5	3	7	5	3	7	kg
Emissions	ICEV-g	CO_2 per kg fuel	2.650			2.65			kg / kg fuel
	ICEV-d	CO_2 per kg fuel	3.138			3.138			kg / kg fuel
	ICEV-p, HEV-p, PHEV-c	CO_2 per kg fuel	3.183			3.183			kg / kg fuel
	ICEV-d	SO_2 per kg fuel	0.000885			0.000885			kg / kg fuel
	ICEV-p, HEV-p, PHEV-c	SO_2 per kg fuel	0.000016			0.000016			kg / kg fuel
	ICEV-p, HEV-p, PHEV-c	Benzene	9.99E-07	5.00E-07	2.00E-06	5.00E-07	2.50E-07	9.99E-07	kg/km
	ICEV-p, HEV-p, PHEV-c	CH_4	6.49E-07	3.25E-07	1.30E-06	3.25E-07	1.62E-07	6.49E-07	kg/km
	ICEV-p, HEV-p, PHEV-c	CO	4.71E-04	2.36E-04	9.43E-04	2.36E-04	1.18E-04	4.71E-04	kg/km
	ICEV-p, HEV-p, PHEV-c	HC	7.73E-06	3.86E-06	1.55E-05	3.86E-06	1.93E-06	7.73E-06	kg/km
	ICEV-p, HEV-p, PHEV-c	N_2O	5.73E-07	2.87E-07	1.15E-06	2.87E-07	1.43E-07	5.73E-07	kg/km
	ICEV-p, HEV-p, PHEV-c	NH_3	3.70E-05	1.85E-05	7.41E-05	1.85E-05	9.26E-06	3.70E-05	kg/km
	ICEV-p, HEV-p, PHEV-c	NMVOC	7.08E-06	3.54E-06	1.42E-05	3.54E-06	1.77E-06	7.08E-06	kg/km
	ICEV-p, HEV-p, PHEV-c	NO_2	1.10E-06	5.48E-07	2.19E-06	5.48E-07	2.74E-07	1.10E-06	kg/km
	ICEV-p, HEV-p, PHEV-c	NO_x	2.19E-05	1.10E-05	4.39E-05	1.10E-05	5.48E-06	2.19E-05	kg/km
	ICEV-p, HEV-p, PHEV-c	PM	1.66E-06	8.30E-07	3.32E-06	8.30E-07	4.15E-07	1.66E-06	kg/km
	ICEV-d	Benzene	1.28E-07	6.40E-08	2.56E-07	6.40E-08	3.20E-08	1.28E-07	kg/km
	ICEV-d	CH_4	1.83E-07	9.15E-08	3.66E-07	9.15E-08	4.58E-08	1.83E-07	kg/km
	ICEV-d	CO	3.11E-05	1.56E-05	6.23E-05	1.56E-05	7.78E-06	3.11E-05	kg/km
	ICEV-d	HC	7.64E-06	3.82E-06	1.53E-05	3.82E-06	1.91E-06	7.64E-06	kg/km
	ICEV-d	N_2O	5.09E-06	2.55E-06	1.02E-05	2.55E-06	1.27E-06	5.09E-06	kg/km
	ICEV-d	NH_3	1.00E-06	5.00E-07	2.00E-06	5.00E-07	2.50E-07	1.00E-06	kg/km
	ICEV-d	NMVOC	7.46E-06	3.73E-06	1.49E-05	3.73E-06	1.87E-06	7.46E-06	kg/km

Cox, B. & Bauer, C. (2018) The environmental burdens of passenger cars: today and tomorrow. Paul Scherrer Institut, Villigen.

			current			future			
	powertrain	**parameter**	**Most likely**	**low**	**high**	**Most likely**	**low**	**high**	**unit**
	ICEV-d	NO_2	2.55E-05	1.27E-05	5.10E-05	1.27E-05	6.37E-06	2.55E-05	kg/km
	ICEV-d	NO_x	8.50E-05	4.25E-05	1.00E-03	4.25E-05	2.12E-05	8.50E-05	kg/km
	ICEV-d	PM	2.10E-06	1.05E-06	4.21E-06	1.05E-06	5.26E-07	2.10E-06	kg/km
	ICEV-g	CH_4	1.41E-05	7.06E-06	2.82E-05	7.06E-06	3.53E-06	1.41E-05	kg/km
	ICEV-g	CO	4.60E-04	2.30E-04	9.19E-04	2.30E-04	1.15E-04	4.60E-04	kg/km
	ICEV-g	HC	1.53E-05	7.67E-06	3.07E-05	7.67E-06	3.84E-06	1.53E-05	kg/km
	ICEV-g	NMVOC	1.23E-06	6.14E-07	2.46E-06	6.14E-07	3.07E-07	1.23E-06	kg/km
	ICEV-g	NO_x	4.39E-05	2.19E-05	8.77E-05	2.19E-05	1.10E-05	4.39E-05	kg/km
	ICEV-g	PM	1.66E-06	8.30E-07	3.32E-06	8.30E-07	4.15E-07	1.66E-06	kg/km

Appendix B. **Global sensitivity analysis results**

Here we provide global sensitivity analysis results according to the method of Borgonovo (2007); Plischke, Borgonovo, and Smith (2013). We present results for each powertrain separately with current and future results shown together, with the x axis representing the normalized contribution to uncertainty (which sums to one when all input variables are considered). The y axis shows the 20 variables with the largest contribution to overall uncertainty. The larger the bar, the larger the contribution of that parameter to overall variability in the results in that impact category for that powertrain. We find that the glider base mass, which represents the size of the vehicle, is the most important parameter for every powertrain and nearly every LCA impact category. Other important parameters are found to be: the NO_x emissions of current ICEV-d, the lifetime distance of all powertrains, the battery mass, lifetime and production electricity of BEV and the fuel cell size for FCEV. Also all parameters determining vehicle tank to wheel efficiency are generally important.

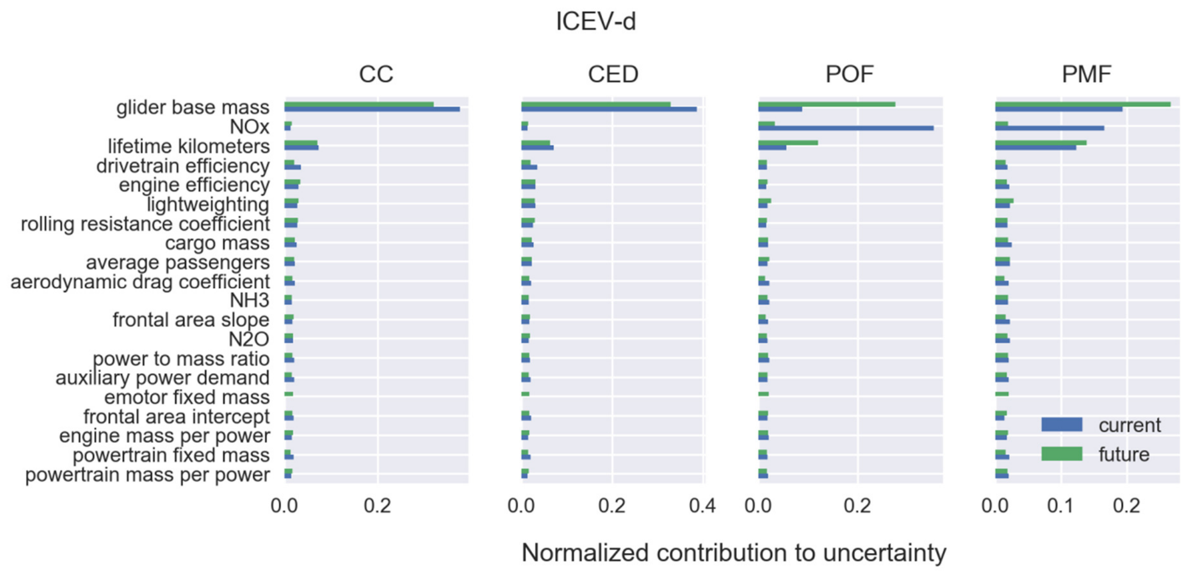

Figure B-1 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Internal combustion engine vehicle with diesel. CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

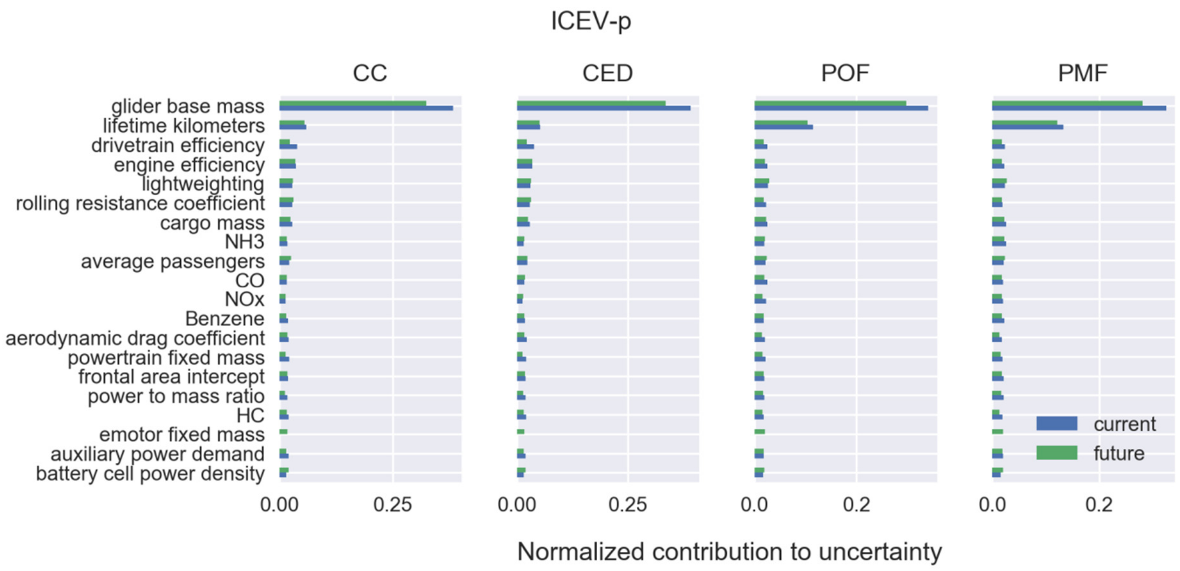

Figure B-2 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Internal combustion engine vehicle with petrol. CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

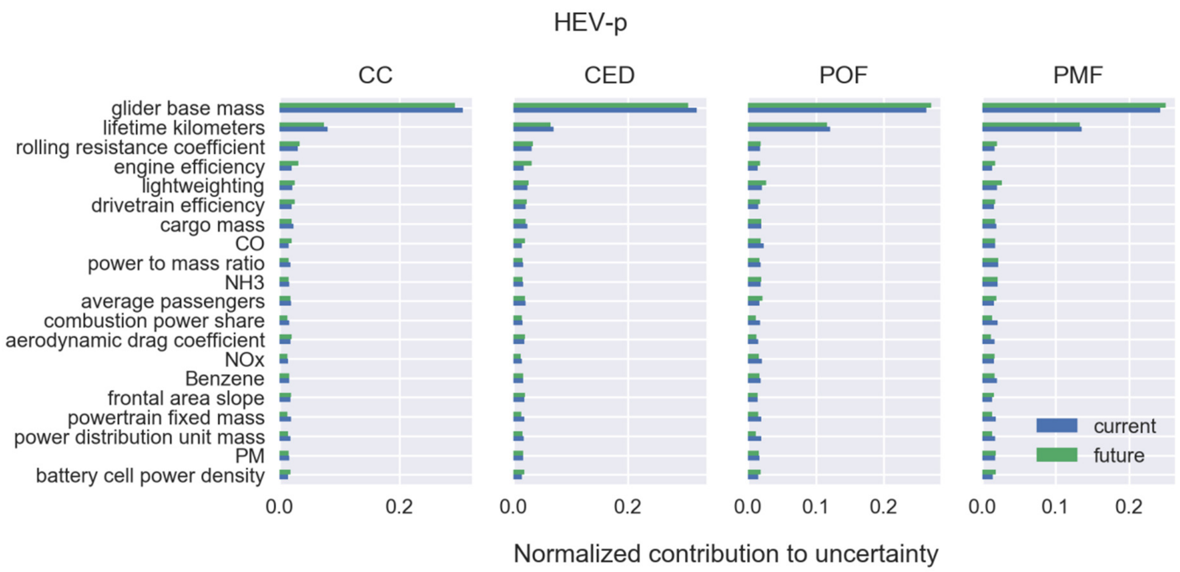

Figure B-3 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Hybrid vehicle with petrol. CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

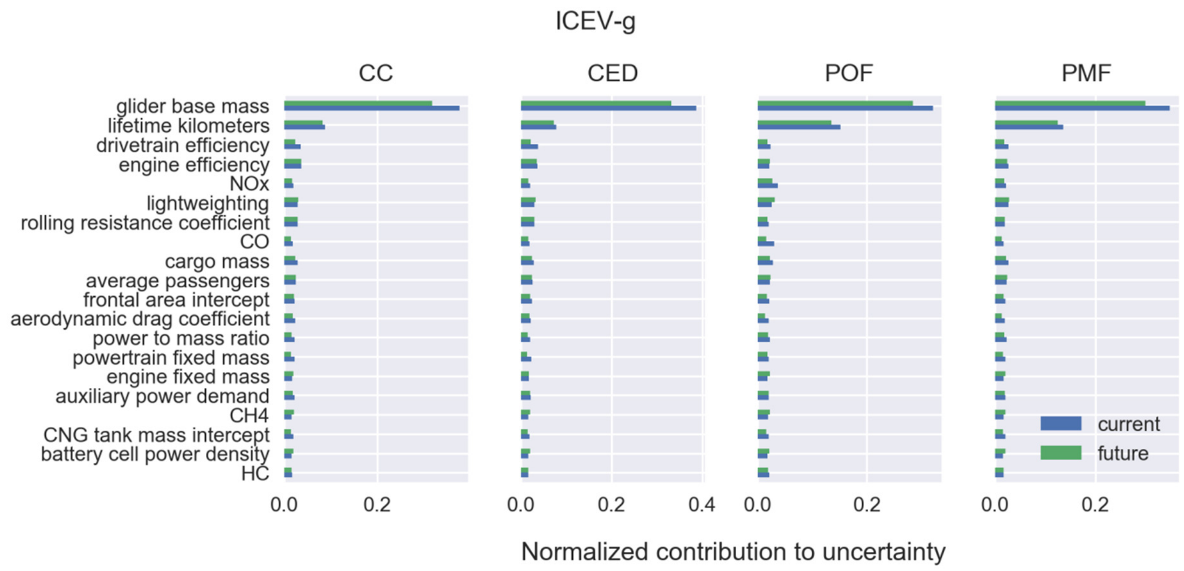

Figure B-4 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Internal combustion engine vehicle with compressed natural gas. CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

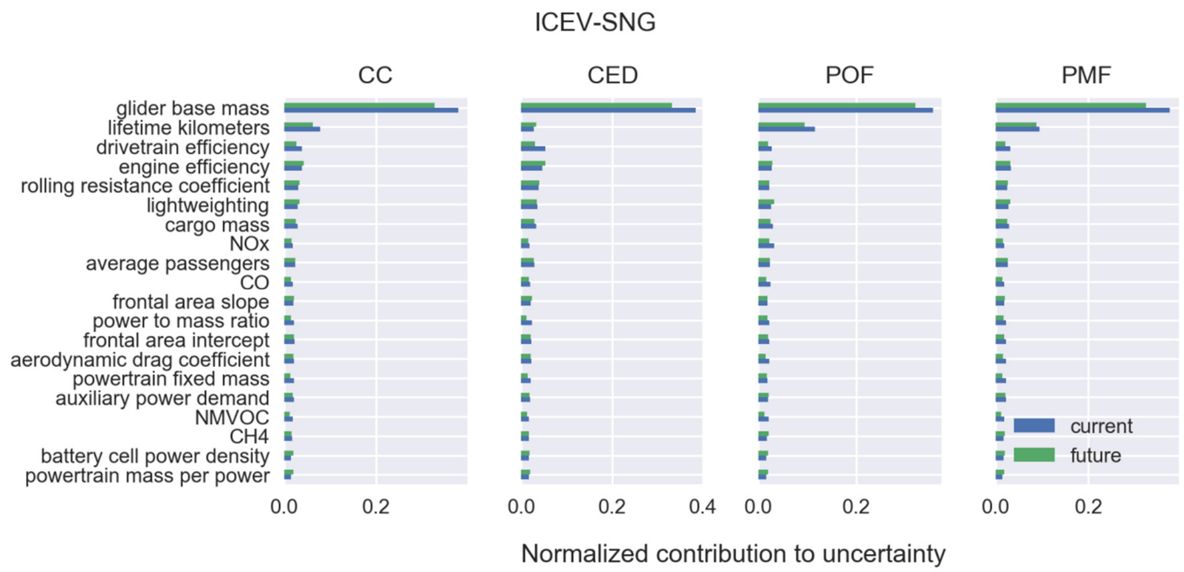

Figure B-5 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Internal combustion engine vehicle with compressed natural gas, synthetically produced with Swiss electricity. (Future electricity mix CH-POM-C). CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

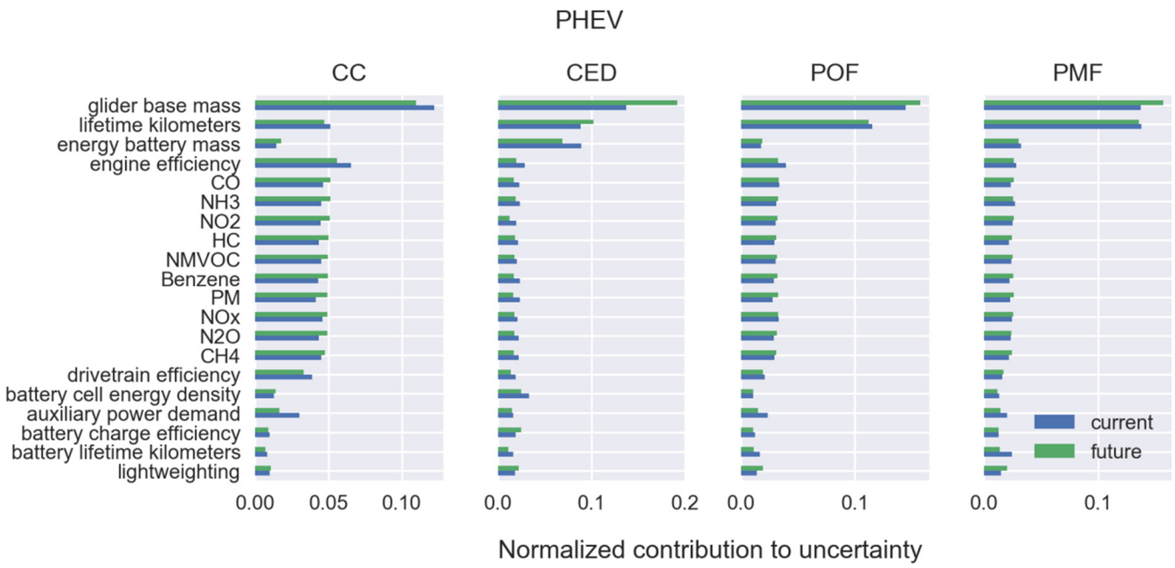

Figure B-6 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, plug in hybrid electric vehicle average operating recharged with Swiss electricity. (Future electricity mix CH-POM-C). CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

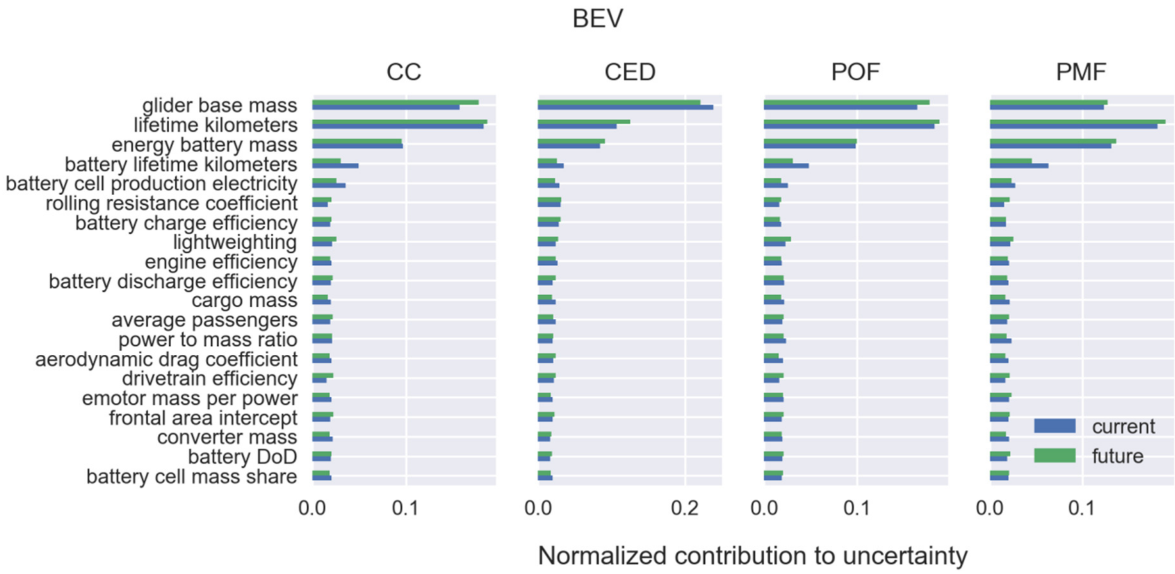

Figure B-7 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, battery electric vehicle operating with Swiss electricity. (Future electricity mix CH-POM-C). CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

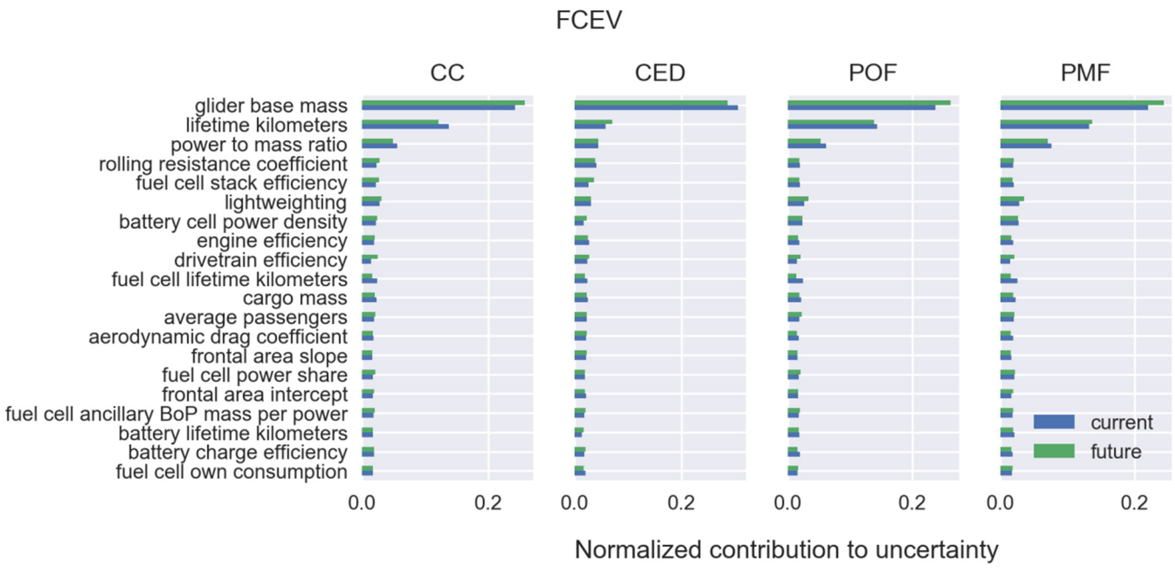

Figure B-8 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, fuel cell electric vehicle operating with hydrogen produced with Swiss electricity. (Future electricity mix CH-POM-C). CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

Appendix C. **Glossary**

BAU	Business as usual
BEV	Battery Electric Vehicle
-C	Electricity from natural gas power plants
CC	Climate Change
CNG	Compressed natural gas (90% natural, 10% biogas)
CED	Cumulative Energy Demand
CH	Switzerland
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_{2eq}	CO_2 equivalent
-d	Diesel as fuel
DAC	Direct air capture (of CO_2)
-E	Electricity from renewables
FCEV	Fuel Cell Electric Vehicle
-g	Gas as fuel
GHG	Greenhouse Gas
GWP	Global Warming Potential
H_2	Hydrogen
HC	Hydrocarbons
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NEDC	New European driving cycle
NEP	New energy policy
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen Oxides
O_3	Ozone
-p	Petrol as fuel
P2G	Power-to-Gas
PHEV	Plug-in Hybrid Electric Vehicle
PHEV-c	PHEV in petrol combustion mode
PHEV-e	PHEV in all electric mode
PM	Particulate matter
PM_{10}	PM smaller than 10µm
PMF	Particulate matter formation
POM	political measures
POF	Photochemical Oxidant Formation
SO_2	Sulphur dioxide
SMR	(H_2 from) Steam Methane Reforming
SNG	Synthetic Natural Gas
TtW	Tank-to-wheel
vkm	Vehicle-kilometer
WLTC	Worldwide harmonized Light vehicles Test Cycle
WtT	Well-to-tank
WWB	Business as usual