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MOBILITY AND THE ENERGY TRANSITION: A LIFE CYCLE ASSESSMENT OF SWISS PASSENGER TRANSPORT TECHNOLOGIES INCLUDING DEVELOPMENTS UNTIL 2050

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Abstract

The transport and electricity sectors are in the midst of major changes in an attempt to limit climate change and air pollution problems. In the coming decades conventional fossil fuelled vehicles are expected to be replaced with electric powertrain vehicles, resulting in increased electricity demand by the transport sector. At the same time, the electricity sector is also in upheaval due to policy decisions to move away from fossil and, in many locations, nuclear energy sources towards renewables such as hydro, wind, and solar. Rightfully so, many questions have been raised in the scientific literature and media regarding the environmental benefits of these new vehicle technologies and how the different energy chain and vehicle options compare. The goal of this thesis is to analyse the environmental burdens of current and future (2050) passenger transport technologies in Switzerland while taking into account future developments of the Swiss and global electricity sectors.

I use the methodology of Life Cycle Assessment (LCA) to quantify the environmental burdens from current and future passenger transportation by motorcycle (Chapter 3), aircraft (Chapter 4), urban bus (Chapter 5), and passenger car (Chapters 6 and 7) for different refuelling/ recharging energy chains. Vehicle performance is modelled using a consistent framework across powertrain types to ensure fair comparison. Road vehicle energy consumption is calculated using a physics-based model that simulates operation using internationally harmonised driving cycles. This model is calibrated with real energy consumption data for each vehicle and powertrain type. This allows prediction of future vehicle performance by estimating the potential future changes for each input parameter, such as internal combustion engine efficiency or lithium ion battery cell energy density.

In Chapter 6 I extend this model to enable Monte Carlo analysis and global sensitivity analysis to show that the electricity used for charging electric vehicles is the largest source of global variability of the environmental burdens of electric cars, though vehicle size, lifetime, driving patterns and battery size also strongly contribute to variability. I also further adapt the model using exponential smoothing of driving cycles and wind tunnel measurement results to show that future autonomous and connected vehicles could consume roughly 10% less energy per kilometer than comparable human driven vehicles.

I also incorporate future developments of the electricity sector into the calculations by integrating scenario results from the IMAGE integrated assessment model into the ecoinvent LCA database using the open source software package Wurst that I helped to create. Two scenarios from the IMAGE model are used for the development of the future electricity sector for 26 global regions: *Baseline* may be considered a business as usual type scenario, while *ClimPol* represents the aggressive decarbonisation that would be consistent with a likely probability of achieving the 2°C target. This is a significant development in the field of prospective LCA and I am able to show that without these changes to the background database, future climate burdens could be overestimated by up to 75% in the ClimPol scenario.

In Chapter 8 I compare different passenger transport modes for the Baseline and ClimPol electricity scenarios in the year 2050. Results are generally quite consistent across vehicle types. The introduction of battery electric vehicles is found to provide clear climate benefits compared to conventional combustion vehicles for all vehicle types as long as the electricity used for charging has carbon content similar to or less than that of a modern natural gas power plant. Switzerland's current and future electricity mix for all likely scenarios easily meets this requirement, so a robust conclusion may be drawn that battery electric vehicles of all types should be supported in Switzerland from a greenhouse gas (GHG) emission point of view. When other environmental impact categories are considered the superiority of battery electric vehicles is less clear, though hard conclusions cannot yet be drawn due to methodological limitations.

I also develop a simple fleet model to estimate the total life cycle emissions caused by the Swiss passenger transport sector. Fleet model results for 2050 show that if all road vehicles are powered by battery electric powertrains the total Swiss domestic passenger transport related life cycle GHG emissions are 47% lower in the Baseline scenario and 72% lower in the ClimPol scenario compared to 2017 emissions. Similar model results for fleets of fuel cell vehicles show 34% and 66% improvement respectively, while a fleet of hybridized combustion vehicles would enable reductions of 31% and 41% respectively.

When international air transport is also included in the future fleet assessment it is found to dominate the results in some categories, especially climate change and cumulative energy demand. Future growth in air transportation demand is expected to negate all climate change reductions made in ground transportation, leaving total sector emissions in 2050 roughly similar to current emission levels. If air transport demand continues to grow according to historic rates and future projections, it will become one of the most important sources of greenhouse gases in the future, as technical improvements are expected to be outpaced by growth in demand. The only remaining solutions appear to be shifting continental transport demand to electric train, which has comparatively low impacts, or curbing demand growth.

There are three main outcomes of the thesis. The first is the wealth of data published as extensive supporting information in each of my publications. These models and results should be used as inputs by energy and transport modellers as well as fed into life cycle assessment databases. The second is the open source software package Wurst that can be used to create modified versions of the ecoinvent database. This methodology has the potential to greatly improve the quality of prospective LCA. The third outcome of this thesis is the report (Chapter 7) that I helped to prepare for the Swiss Federal Office for Energy. The summary of this report is expected to reach the highest level of decision makers in the country and help inform Swiss policy regarding the energy transition.

Zusammenfassung

Um den Klimawandel und Luftverschmutzung einzudämmen, sind im Transport- und Stromsektor zurzeit grosse Umwälzungen im Gange. In den kommenden Jahrzehnten werden Fahrzeuge mit Elektroantrieb voraussichtlich die konventionellen mit fossilen Brennstoffen betriebenen Fahrzeuge ersetzen, was zu einer erhöhten Nachfrage nach Strom vonseiten des Transportsektors führt. Gleichzeitig befindet sich der Elektrizitätssektor auch im Umbruch, da die politischen Entscheidungsträger sich für den Schritt weg von fossilen Brennstoffen und mancherorts auch weg von der Kernkraft entschieden haben – dafür soll auf erneuerbare Energien wie Wasser-, Wind- und Solarenergie gesetzt werden. Zu Recht stellen Wissenschaft und Medien die Umweltfreundlichkeit einer Umstellung auf Elektrofahrzeuge in Frage und fordern Vergleiche zwischen den verschiedenen möglichen Energieketten und Fahrzeugoptionen. Das Ziel der vorliegenden Arbeit ist es, die Umweltbelastungen heutiger und zukünftiger (2050) Personentransporttechnologien in der Schweiz zu untersuchen – dies natürlich unter Berücksichtigung der zukünftigen Entwicklungen im Elektrizitätswesen in der Schweiz und weltweit.

Ich führe Lebenszyklusanalysen (LCA) durch, um die Umweltbelastungen des heutigen und zukünftigen Personentransports mit Motorrädern (Kapitel 3), Flugzeugen (Kapitel 4), Stadtbussen (Kapitel 5) und Personenwagen (Kapitel 6 und 7) mit verschiedenen Energieketten zu bestimmen. Die Leistung der verschiedenen Fahrzeuge wird für alle Antriebstypen auf einheitliche Art und Weise modelliert, damit angemessene Vergleiche angestellt werden können. Der Energieverbrauch von Strassenfahrzeugen wird mithilfe eines physikbasierten Modells berechnet, das den Betrieb aufgrund von international harmonisierten Fahrzyklen simuliert und mit den effektiven Energieverbrauchsdaten der verschiedenen Fahrzeug- und Antriebstypen kalibriert ist. Mithilfe von Schätzungen zu potentiellen Veränderungen aller Eingabeparameter (wie beispielsweise die Effizienz eines Verbrennungsmotors oder die Energiedichte eines Lithium-Ionen-Akkus) ermöglicht diese Art der Modellierung es, Aussagen über die zukünftige Leistung von Fahrzeugen zu machen.

In Kapitel 6 erweitere ich das Modell und zeige mithilfe von Monte Carlo- und globaler Sensitivitätsanalyse, dass der Strom zum Laden von Elektrofahrzeugen die grösste Schwankungsbreite in der Berechnung der Umwelteinwirkungen von Elektroautos verursacht, gefolgt von den Faktoren Fahrzeuggrösse, Lebensdauer, Fahrmuster und Akkugrösse. Zusätzlich passe ich das Modell durch die exponentielle Glättung der Fahrzyklen sowie mit Windkanalmessergebnissen an und kann aufzeigen, dass in Zukunft autonome und vernetzte Fahrzeuge pro Kilometer ca. 10% weniger Energie als ähnliche von Menschen gesteuerte Fahrzeuge verbrauchen könnten. Zukünftige Entwicklungen im Stromsektor habe ich bei meinen Berechnungen ebenfalls berücksichtigt, indem ich die Szenarioergebnisse aus dem Integrated Assessment Model IMAGE in die ecoinvent-Datenbank eingebunden habe. Dabei kommt das Open-Source Software-Package Wurst zum Einsatz, an dessen Entwicklung ich beteiligt war. In Bezug auf die zukünftige Entwicklung des Stromsektors in 26 Regionen weltweit kommen zwei Szenarien aus dem IMAGE-Modell zur Anwendung: *Baseline* entspricht einem "Weiter wie bisher"-Szenario, während *ClimPol* die aggressive Kohlenstoffreduktion abbildet, die für die Erreichung des 2°C-Ziels erforderlich wäre. Dies stellt eine bedeutende Entwicklung im Bereich der prospektiven Lebenszyklusanalyse dar, denn ich kann aufzeigen, dass ohne diese Anpassungen der Hintegrunddatenbank die Klimaauswirkungen im ClimPol-Szenario bis zu 75% zu hoch eingeschätzt werden könnten.

In Kapitel 8 vergleiche ich verschiedene Passagiertransportmodi für die Baseline- und ClimPol-Stromszenarien im Jahr 2050. Die Ergebnisse für die verschiedenen Fahrzeugtypen sind sich relativ ähnlich. Ich kann darlegen, dass die Einführung von batteriebetriebenen Elektrofahrzeugen (BEV) im Vergleich zu konventionellen Fahrzeugen mit Verbrennungsmotoren für alle Fahrzeugtypen klare Klimavorteile mit sich bringt, solange der Strom zum Laden der Fahrzeuge nicht mehr CO_2-Emissionen verursacht als Strom, der in modernen Gaskraftwerken generiert wird. Der heutige und zukünftige Strommix der Schweiz für alle wahrscheinlichen Szenarien erfüllt diese Bedingung ohne Weiteres, woraus geschlossen werden kann, dass in der Schweiz alle Typen von batteriebetriebenen Elektrofahrzeugen gefördert werden sollten, um zur Senkung von Treibhausgasemissionen beizutragen. Berücksichtigt man andere Wirkungskategorien, sind BEVs nicht mehr klar überlegen – allerdings können aufgrund von methodologischen Einschränkungen noch keine definitiven Schlussfolgerungen dazu gezogen werden.

Des Weiteren entwickle ich ein einfaches Flottenmodell, um die über den gesamten Lebenszyklus durch den schweizerischen Personentransportsektor verursachten Emissionen zu berechnen. Ergebnisse des Flottenmodells für 2050 zeigen, dass bei einer Umstellung aller Strassenfahrzeuge auf BEV die durch den schweizerischen Inland-Personenverkehr über den Lebenszyklus verursachten Treibhausgasemissionen im Baseline-Szenario 47% und im ClimPol-Szenario 72% tiefer als die Emissionswerte von 2017 wären. Ähnliche Modellierungen von Flotten von Brennstoffzellenfahrzeugen zeigen eine Verbesserung von 34% bzw. 66%, während eine Flotte von Hybridfahrzeugen Reduktionen von 31% bzw. 41% verzeichnen könnte.

Wenn man den internationalen Flugverkehr in den prospektiven Flottenbewertungen berücksichtigt, dominiert er die Ergebnisse in einigen Kategorien, insbesondere Treibhausgasemissionen und Primärenergiebedarf. Die steigende Nachfrage nach Lufttransport wird voraussichtlich sämtliche Reduktionen von Treibhausgasemissionen aus dem Landverkehr aufheben – dies führt zu ungefähr gleichbleibenden Emissionswerten im Jahr 2050 für den gesamten Transportsektor. Sollte die Nachfrage im Luftverkehr die bisherige bzw. vorhergesagte Wachstumsrate beibehalten, wird dieser wohl in Zukunft einer der Hauptverursacher von Treibhausgasemissionen sein, denn technische Verbesserungen können mit der steigenden Nachfrage höchstwahrscheinlich nicht Schritt halten. Als scheinbar einzige Lösungen bleiben einerseits das Ausweichen auf andere Transportmodi, vor allem elektrische Züge, deren Klimaauswirkungen eher tief sind, und andererseits das Bremsen der Nachfrage übrig.

Diese Doktorarbeit zeichnet sich durch drei Hauptergebnisse aus: Erstens habe ich eine grosse Datensammlung erarbeitet, die all meinen Publikationen als Anhang beigefügt ist. Diese Modelle und Ergebnisse sollten als Grundlage für weitere Energie- und Transportmodelle dienen und Eingang in Lebenszyklus-Datenbanken finden. Das zweite Ergebnis meiner Arbeit ist das Open-Source Software-Package Wurst, mithilfe dessen auf die Beantwortung spezifischer Forschungsfragen zugeschnittene Versionen der ecoinvent-Datenbank erstellt werden können. Die dabei entwickelte Methodologie hat das Potential dazu, die Qualität von prospektiven Lebenszyklusanalyen massgeblich zu verbessern. Das dritte Ergebnis dieser Arbeit ist der Bericht für das Bundesamt für Energie (Kapitel 7), den ich mitverfasst habe. Die Zusammenfassung dieses Berichts soll den Entscheidungsträgern auf höchster politischer Ebene vorgelegt werden und so die Schweizer Politik zur Energiewende mitprägen.

Glossary

Abbreviation	Definition
Baseline	Business as usual scenario from IMAGE model
BAU	Business as usual
BAU-C	Swiss electricity scenario: business as usual with natural gas power plants
BEV	battery electric vehicle
BEV-LR	Long range battery electric urban bus
BEV-SR	Short range opportunity charging battery electric urban bus
BoP	Balance of plant
CADC	Common artemis driving cycle
CC	Climate change
CCS	Carbon capture and storage
CED	Cumulative energy demand
CH-BAU-C	Swiss electricity scenario: business as usual with natural gas power plants
CH-NEP-E	Swiss electricity scenario: new energy policy with renewables
CH-POM-C	Swiss electricity scenario: political measures scenario with natural gas power plants
ClimPol	Climate policy scenario from IMAGE model
CTI	Commission for technology and innovation
EV	Electric vehicle
FCEV	fuel cell electric vehicle
GHG	Greenhouse gas
Glider	Represents all parts of a vehicle that are not powertrain specific, such as chassis, panels, wheels etc.
GWP	Global warming potential
HBEFA	Handbook of emission factors for road transport
HEV-d	Hybrid electric vehicle with diesel engine
HEV-p	Hybrid electric vehicle with gasoline engine
HT	Human toxicity
HTP	Human toxicity potential
ICAO	International civil aviation organisation
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
ICEV-CNG	Internal combustion engine vehicle with compressed natural gas engine
ICEV-d	Internal combustion engine vehicle with diesel engine
ICEV-g	Internal combustion engine vehicle with compressed natural gas engine
ICEV-p	Internal combustion engine vehicle with gasoline engine
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHV	Lower heating value of combustion
LNB	Large narrow body
LTO	Landing and take-off
LWB	Large wide body
MD	Mineral depletion
NEDC	New European driving cycle
NEP-E	Swiss electricity scenario: new energy policy with renewables
NMVOC	non methane volatile organic compounds
OEW	Operational empty weight
OPT	Optimistic
P2G	Power to gas
PEM	Proton exchange membrane
PHEV	Plug-in hybrid electric vehicle
PHEV-c	Plug-in hybrid electric vehicle operating in combustion mode
PHEV-e	Plug-in hybrid electric vehicle operating in pure electric mode
pkm	Passenger kilometer
pkm eq	Passenger kilometer equivalent (includes ton kilometers)
PM	Particulate matter
PMF	Particulate matter formation
PMFP	Particulate matter formation potential
POF	Photochemical oxidant formation
POFP	Photochemical oxidant formation potential

Abbreviation	Definition
PV	Photovoltaic
REG	Regional
RPT	Regular public transport
SCCER	Swiss competence center for energy research
SMR	Steam reforming of methane
SNB	Small narrow body
SNG	Synthetic natural gas
SWB	Small wide body
TA	Terrestrial acidification
tkm	Ton kilometer
TtW	Tank to wheel
vkm	Vehicle kilometer
WHVC	World harmonized vehicle cycle for heavy duty vehicles
WLTC	Worldwide harmonized light vehicles test cycle
WMTC	World harmonized motorcycle test cycle

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Chapter 1. **Introduction**

1.1. Background information

Continued emission of greenhouse gases will cause long lasting changes in the climate system and increase the likelihood of severe and irreversible impacts for people and ecosystems. Substantial and sustained reductions in greenhouse gas emissions are required to limit climate change [1]. In order to combat climate change, Switzerland has committed to reduce its domestic greenhouse gas emissions by at least 20% compared to 1990 by 2020 [2] and intends to progress to 50% reductions in 2030 and between 70% and 85% reductions by 2050 [3]. Passenger and goods transport in Switzerland are the largest contributors to greenhouse gas emissions and are responsible 39% of domestic CO_2 emissions[1] and 36% of final energy consumption [4]. While most sectors have managed to decrease greenhouse gas emissions in recent decades, transport sector emissions have increased due to growth in transport demand [2]. According to the baseline scenario of the Swiss Federal Office for Spatial Development, domestic passenger transport demand is expected to further increase by roughly 25% in 2040 compared to 2010 [5] and international passenger air transport demand in Western Europe is expected to increase by 3.4% per year in the same time frame, representing an increase in air transport demand of 173% [6]. Thus, in order to meet Swiss climate goals without influencing transport demand, the greenhouse gas emissions per passenger kilometer of Swiss transport will have to reduce drastically in the coming decades.

Road transport is the largest source of the pollutant nitrogen oxide (NO_x) in Switzerland, and is also responsible for substantial emissions of fine particulate matter (PM10) into the atmosphere, both of which have significant health burdens [4]. These problems have been recognised, and action is being taken. Since vehicle exhaust emission regulations have been introduced in the 1990s, tailpipe emissions of new vehicles in Switzerland have decreased drastically, in some cases by over an order of magnitude [7], though there are exceptions where the exhaust emission regulations have been unsuccessful, particularly regarding NOx emissions from diesel engines [8, 9].

Improvements have also been made in terms of CO_2 emissions from passenger cars. Until 2006 the average CO_2 emissions per car decreased by roughly 1.5% per year, and by 3.6% per year between 2007 and 2015 [10]. Starting in 2015, regulations have been in place to limit the fleet average CO_2 emissions of new vehicles to 130 g/km [3, 10]. This limit is planned to decrease to 95 gCO_2/km in 2020, with further reductions likely in the future [3, 10].

While advanced combustion vehicles are able to meet current, and likely next generation regulatory emission limits, the consensus between governments and car manufacturers seems to be that electric drivetrain vehicles will ultimately be the technology of choice as emissions limits tend toward zero [11]. In fact, many governments provide financial or other benefits to owners of electric powertrain vehicles and some have even announced plans to ban the sale or operation of combustion vehicles altogether in the coming decades [12]. Currently about 1.8% of new cars sold in Europe have a hybrid drivetrain, while roughly 1% are battery electric or plug-in hybrids [11].

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[1] When international air transportation is included this figure increases to 46% Source: 4. Swiss Federal Statistical Office, *Mobility and Transport Pocket Statistics 2017*. 2017: Neuchâtel.

A parallel path to reducing the environmental burdens of passenger transport is through support of public transit, such as trains and urban buses. Significant improvements have been made in the development of urban buses, both conventional and electric powered, and many transport authorities have stated goals to move to a zero emission bus fleet in the very near future [13].

While electric drivetrains are often regarded as a “silver bullet” solution to issues of climate change and urban pollution, this can be quite far from the truth. The environmental burdens of producing battery and fuel cell electric vehicles are substantial and the benefits of their lower operating emissions do not always outweigh these upfront costs [14-16]. Furthermore, advanced powertrain vehicles often face other disadvantages, such as higher costs or decreased range [17].

Electric and fuel cell vehicles have been shown to provide environmental benefits only when powered by clean electricity sources [14, 18, 19]. While the current Swiss electricity mix fits this criterion, there is uncertainty regarding the source of electricity that will be used to charge a large fleet of future electric vehicles in Switzerland, as the additional electricity demand of replacing all passenger vehicles in Switzerland with electric drivetrains would increase electricity demand by over 20% [17, 20]. Furthermore, as a consequence of the Fukushima nuclear disaster, Switzerland has decided to move away from nuclear power. The official Swiss energy strategy is to reduce electricity demand through efficiency while significantly expanding the capacity of new renewables [21]. However, there is a strong chance that the expansion of renewable electricity generating capacity will not be sufficient and that new electricity demand may be met by the construction of new natural gas fired power plants [20-23].

Large changes are expected in the Swiss transport and energy sectors in the coming decades; decisions will have to be made regarding which technologies to support and which infrastructure to develop. In order to make informed decisions, all potential technologies and scenarios should be understood to the best degree possible. This thesis should provide information to support such decisions, and improve the methodology used to answer such questions.

1.2. Objectives of this thesis

The goal of this thesis is to assess the environmental performance of different current and future passenger transportation options in Switzerland. In order to meet this goal, I define two research questions to be answered in this thesis:

1. What are the environmental burdens of different passenger transportation modes and technologies operating in Switzerland both today and in the future (2050)?
2. How might these conclusions change under different national and global energy scenarios?

Furthermore, in answering these main questions, I ask two sub-questions:

1. How robust are these conclusions? What are the uncertainties of these models and how sensitive are they changes in input parameters?
2. How might we improve our models to provide more robust conclusions?

Finally, an additional objective of this thesis is to communicate findings with decision makers and the general public so that future decisions may be made with the best possible knowledge.

1.3. Thesis outline

In Chapter 1 I set the scene for this thesis and describe the current challenge of reducing the greenhouse gas and pollutant emissions of passenger transport, and how the transport sector is likely on the cusp of a revolution towards electrified drivetrains. I explain that the **goal of this thesis** is to analyse all technologies that may contribute to this revolution, while improving the quality of such analysis.

Chapter 2 contains a summary of the most important **methodology** used to answer the research questions defined in Chapter 1. Further descriptions of the methodology used are included in each of the following chapters as required.

Chapter 3 presents a paper that was published in the journal Applied Energy [24] that examines the life cycle costs and environmental burdens of different sized conventional, battery and fuel cell **motorcycles** with a European focus.

Chapter 4 presents a life cycle assessment of the Swiss **air transport sector** from 1990 until 2050 that was published in the journal Transportation Research Part D: Transport and the Environment [25].

Chapter 5 is a conference paper that was presented at the 30th Electric Vehicle Symposium in Stuttgart, 2017 [26]. In this paper we present findings regarding the environmental performance of current and future **urban buses** with different energy sources and a European focus.

Chapter 6, likely the methodological highlight of this thesis, is a manuscript currently under peer review for the journal Environmental Science and Technology. The paper presents an assessment of the current and future environmental burdens of **battery electric passenger cars with focus on uncertainty** quantification using a global focus.

Chapter 7 is a result of efforts to share the knowledge generated during this PhD with decision makers. The text from this chapter is a scientific background report written for the Swiss Federal Office for Energy regarding the environmental burdens of current and future **passenger cars with all relevant powertrain types** and energy chains operating in Switzerland. The project also included synthesis of the results into a four page fact sheet that contains the most important results presented in a simple way for decision makers. This fact sheet is included in Appendix B (in German).

In Chapter 8 I redo the calculations from the previous chapters for all transportation modes to harmonise input assumptions and use Swiss electricity mixes. I also include passenger transport by train from the ecoinvent database. All results are calculated using the future background databases for presented in Chapter 6. This allows **comparison of all current and future transport modes operating in Switzerland** in a fair and consistent way as the same calculation methodology is used for their assessment. I also develop a simple fleet model and quantify the total environmental burdens due to the Swiss passenger transport sector in 2017 and 2050 for several scenarios.

Finally, in Chapter 9 I critically assess the contributions made during this thesis and discuss the limitations of my work. I also draw some overall **conclusions** and discuss the potential for future research in the field.

Chapter 2. **Methodology**

In this section I present a description of the modelling approach and common methodology used in the following chapters.

2.1. Approach

The general approach used in this thesis is designed to compare the environmental burdens of all transportation modes and technologies on a level playing field, while avoiding the shifting of burdens outside of the analysis scope. Based on these requirements, I select the methodology of Life Cycle Assessment (LCA) for the quantification of environmental burdens. More information on the LCA methodology is presented in section 2.2.

The models for each transport mode are designed to keep all non-powertrain specific components such as the chassis, seats, steering mechanism etc. constant for all powertrains and to change only those components that are specific for the powertrain. Thus the comparison is designed to compare vehicles of the same size, shape and power class to ensure that the differences found in the results are truly due to differences in the powertrain.

I choose to model vehicle performance instead of using data for existing vehicles because it allows:

1. The comparison of vehicles that are exactly equivalent, with the exception of powertrain specific differences.
2. The modification of individual model parameters to represent future changes to vehicle components, so that performance and environmental burdens may be calculated endogenously, and interplay of various model parameters can be captured.
3. The modification of individual model parameters to examine the sensitivity of results.

More information on vehicle modelling is available in section 2.4 and in the individual chapters of the thesis.

Despite the fact that vehicles used in the analysis are modelled, I ensure model validation with external data sources, such as manufacturer descriptions, online vehicle databases, third party energy consumption measurements, and scientific literature. Description of model validation is discussed in each chapter separately.

A final point to mention regarding the approach used in this thesis is that I have used the python programming language in the format of jupyter notebooks (http://jupyter.org/), and used Brightway2 [27] for all LCA calculations. Jupyter notebooks are ideal for this form of scientific work as they can be published as supporting information for each publication so that readers have access to all calculations, and input data so that the work is completely transparent and reproducible.

2.2. Life cycle assessment

LCA is a methodology that compiles inventories of all environmentally relevant flows (such as emissions, natural resource consumption, energy and material demand as well as waste) of a products’ or services’ entire life cycle, from resource extraction to end-of-life. It further calculates the contribution of these environmental flows 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.

LCA can be used to better understand the environmental performance of a product and determine potential areas of improvement within the product's lifecycle. Furthermore, LCA can compare the environmental performance of different products that serve the same purpose.

According to ISO 14040 [28], LCA must be performed in a framework consisting of four stages: goal and scope definition, inventory analysis, impact assessment and interpretation. Although these separate stages are performed sequentially, there is also a strong iterative component to LCA. That is, after completing the first inventory analysis and impact assessment, interpretation of the results may lead to refinement of the goal and scope definition and inventory analysis resulting in a new impact assessment. Figure 2.1 shows the stages of an LCA, which will be further discussed in the following subsections.

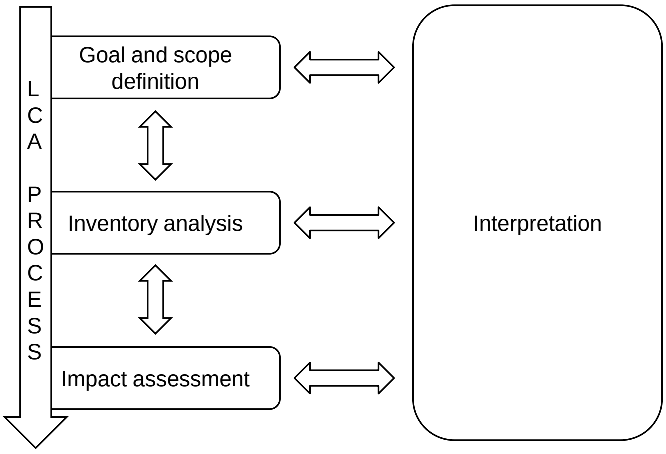

Figure 2.1 Stages of life cycle assessment. Adapted from ISO 14040 [28]

2.2.1. Goal and scope

In this thesis, LCA is used to compare the driving of passenger vehicles for one kilometer, averaged over the entire vehicle lifetime. This functional unit is referred to as the vehicle kilometer (vkm). When different sized vehicles or vehicles with different numbers of passengers are compared, the functional unit of the passenger kilometer (pkm) is used. Vehicle kilometers and passenger kilometers may be converted by simply multiplying or dividing by the lifetime average number of passengers in the vehicle.

The system boundary is always defined as cradle-to-grave and includes both the equipment life cycle as well as the entire fuel chain in this thesis. The intended audience for the study is other scientists and decision makers, with some results also presented to the general public, for example the fact sheets generated in Chapter 7. The geographical scope varies between Switzerland, Europe and Global, and is defined in each chapter.

2.2.2. Life cycle inventory

The Life Cycle Inventory (LCI) is the list of all material and energy flows to and from the environment over the product or service's life cycle, which are quantified with the use of a life cycle database. The ecoinvent database (versions 3.2 to 3.4, defined in each chapter) [29] is used as the LCA database in this thesis. The recycled content approach is used with the “allocation, cut-off by classification” system model for attributional LCA. Where possible, the life cycle inventories for transport technologies are built using datasets directly from the ecoinvent database in this thesis. Where the environmental burdens of a life cycle phase are significant and the ecoinvent datasets are known to be lacking in some way, datasets are created based on literature review using the ecoinvent database for the modelling of upstream processes.

One major difficulty in performing LCA of future technologies (known as prospective LCA) is the lack of a consistent LCA database that matches the time frame of the technology to be assessed. The status quo in the LCA literature is to use the current background database to model the background processes for the future technology. I show that this can lead to significant errors and propose an improvement to the status quo in Chapter 6, which is also used in the transport technology comparison of Chapter 8. I describe a novel method to modify LCA databases to reflect future conditions in section 2.3.

2.2.3. Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) quantifies and groups the environmental burdens due to the LCI into categories associated with known environmental issues. In this thesis I use the ReCiPe 2008 LCIA method with the hierarchist perspective [30]. The environmental impact categories most relevant[2] to passenger transport are discussed below.

Climate Change (CC) represents the contribution to climate change due to the emission of greenhouse gases such as CO_2 and CH_4. For this indicator I select the most recent global warming potential characterization factors from the IPCC 2013 as implemented by the ecoinvent Centre [29, 31]. CC is quantified in kg CO_2 equivalent.

Human Toxicity (HT) represents human exposure to toxic chemicals such as heavy metals and hydrocarbons. HT is quantified in kg 1,4 DB equivalent.

Photochemical Oxidant Formation (POF) considers the formation of ground level ozone due to the reaction of NO_x with Non Methane Volatile Organic Compounds (NMVOCs). POF is quantified in kg NMVOC equivalent.

Particulate Matter Formation (PMF) considers the human health impacts of fine particles in the air that can enter the lungs. The method takes into account not only the direct emission of particulates, but also the formation of secondary particulates due to emissions such SO_x, $NO_{x,}$ and ammonia (NH_3). PMF is quantified in kg PM_{10} equivalent.

Mineral Depletion (MD) represents the impact on society due to depletion of mineral resources. MD is quantified in units of kg Fe equivalent.

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[2] I note that the terrestrial acidification impact category is also relevant for passenger transport. However, in the context of passenger transportation, conclusions for this impact category are nearly always the same as for the impact category particulate matter formation so I do not explicitly include this category in the thesis.

Cumulative Non-Renewable Energy Demand (CED) includes all primary energy demand from fossil and nuclear sources. In chapters 7 and 8 this method is extended to include also renewable energy sources such as solar irradiation, biomass, wind and hydro energy. CED is quantified in units of MJ.

There are two further impact categories relevant for passenger transport that are not included in this thesis. Land use is very relevant when comparing different transport modes or considering biofuels as an energy source. However, as the main chapters of this thesis focus on the performance of different powertrains for the same transport mode and do not consider biofuels, this indicator is less relevant and thus excluded. Land use should be included in future research where the performance of different transport modes are explicitly compared. The second relevant impact category that could not be not included is health impact due to noise. Significant differences in noise performance per kilometer travelled would be expected for different vehicle powertrain types and transport modes. However, the methodology for inclusion of noise as an impact category is not yet sufficiently developed and thus I am forced to exclude this impact category.

2.3. Linking life cycle databases with integrated assessment models

The methodology developed as part of this thesis to link integrated assessment model results with LCA databases is described in detail in Mendoza Beltran, Cox [32]. In this section I provide a brief overview for the reader to better understand the results presented in Chapters 6 and 8.

One major weakness in prospective LCA is that no background databases are available that represent the future global economy used to produce the future foreground system. While prospective LCA studies usually take pains to modify the most important foreground processes, for example in the LCA of a future electric car the car efficiency and the electricity grid technology mix used to charge the batteries would be modified for the future, the rest of the system is usually modelled using the current standard of technology [14, 15, 17, 33, 34]. That is, the future car is produced using the current electricity system, with current steel production and so on. Some studies however, have attempted to correct this simplification and include changes to key processes in the background, such as electricity, certain metals, and concrete production [35, 36]. However, the limitation of the NEEDS [35] and THEMIS [36] approaches is that they require significant manual work to create the future database, which makes model updates difficult and changes opaque. For this reason, the background databases developed in the NEEDS project have not been used in future work, and results from the THEMIS model are still published with the outdated ecoinvent version 2.2 [37, 38].

The goal of the methodology established here is to create a framework that allows easy, reproducible, and transparent changes to LCA databases based on external data sources. The software should be written to enable updating the work for new versions of input data or background databases with minimal effort. Ideally a single well accepted source of future technology performance would be used to ensure data consistency. For the scope of this thesis, it was determined to limit the scope to only changes to the global electricity sector. Changes to the future electricity sector are relevant as electricity contributes significantly to LCA results for most products, and the electricity sector is expected to change dramatically in the coming decades.

Scenario results from the IMAGE integrated assessment model [39] are selected as input data; the model contains both technology and market developments for multiple sectors, geographic regions, and scenarios. Furthermore, IMAGE is held in high regard in the integrated assessment modelling community [40]. IMAGE provides a detailed description of the possible development of the future energy system within a wider context of drivers of environmental change. The IMAGE implementation of the Shared Socio-economic Pathways are a set of community scenarios used by many modelling teams [41]. We use the 'Middle of the Road' scenario, SSP2 (Baseline), and a variant of this scenario (ClimPol) in which an aggressive climate policy is introduced that limits the greenhouse gas concentration to 450 ppm CO_2 eq in 2100 – consistent with a likely probability of achieving the 2^{o}C target.

In this first attempt to link integrated assessment model results with LCA databases we decided to avoid value judgements as much as possible and only use data that are included in the single input data source to modify the LCA database. This means that even if better or more detailed data were available from other sources, the IMAGE data were used. This helped to limit the scope of this potentially very large task. Future work should involve a detailed search for the best data with which to model each process.

The methodology used to create a future version of the ecoinvent database using IMAGE model outputs is described in Figure 2.2. Input variables from the user are the year for which the updated database should be valid, and the IMAGE scenario to be used for input data. The creation of the future version of ecoinvent takes place in five steps as described below.

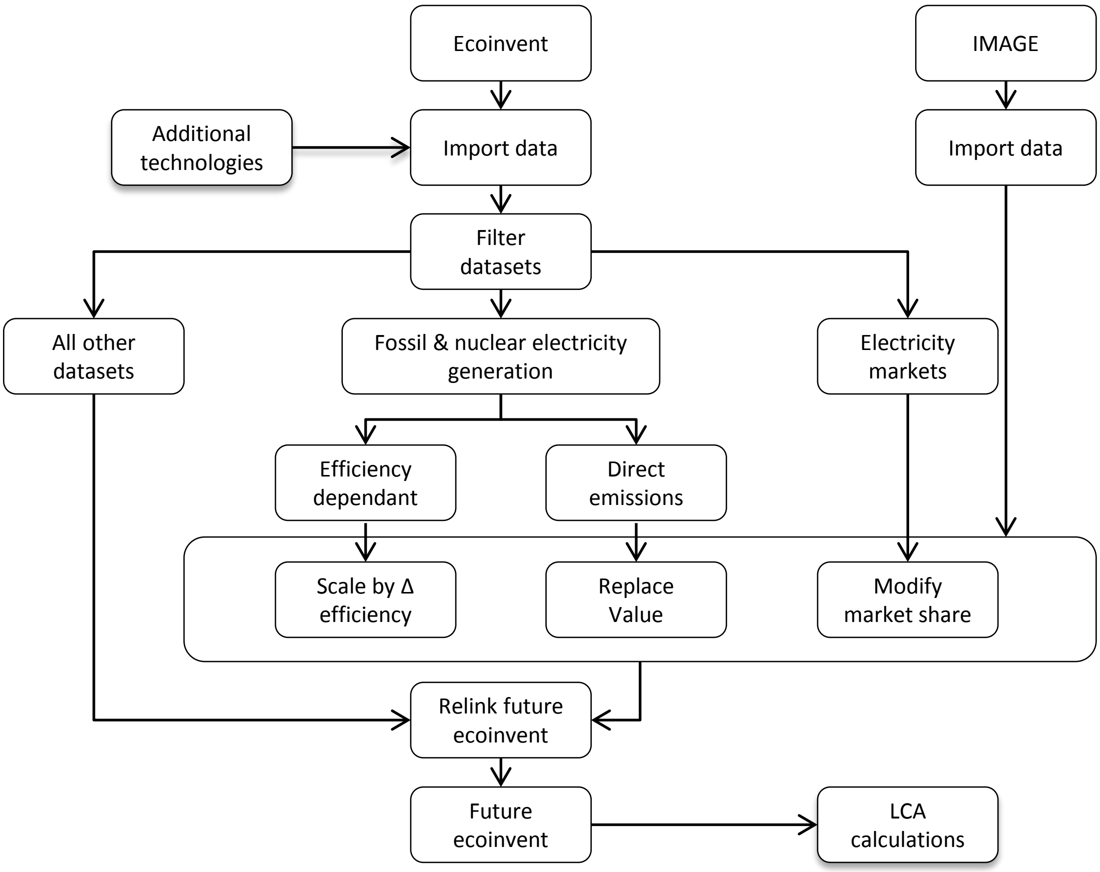

Figure 2.2 Schematic of procedure to modify ecoinvent using integrated assessment model results

Data preparation

In the first step, the allocated ecoinvent database (versions 3.3 and 3.4 have both been successfully used) is imported into a list of single output unit processes that can be modified. Additionally, LCI data for electricity generation with carbon capture and storage from fossil fuels and biomass are imported from Volkart, Bauer [42] as these technologies are important in the future, but aren't available in ecoinvent. Concentrated solar power datasets are also included using datasets that have been generated at PSI for a future ecoinvent release.

In a parallel step, the IMAGE output files are imported into the python data analysis library pandas (https://pandas.pydata.org/), with the year and IMAGE scenario selected by the user.

Modifying electricity production datasets

In the next step, electricity generation datasets for all fossil fuels, nuclear and biomass are modified in two ways:

1. Direct emissions of substances tracked by the IMAGE model, such as NOx, SOx, methane, and carbon monoxide are modified directly in ecoinvent. This means that the IMAGE emission amount is directly copied into the ecoinvent unit process. Analysis of results shows that the emissions tracked by the IMAGE model include nearly all important emissions in terms of common environmental impact categories. The one exception is particulate matter (PM), which is quantified in the IMAGE model as black carbon. As no clear relationship between black carbon and PM emissions could be included, PM emission reductions are included using method two described below.
2. All other processes, such as the power plant infrastructure and fuel consumption are assumed to scale with the changing efficiency of the process, which is taken from the IMAGE model. That is, we take the ecoinvent values as the base, and if the IMAGE model results show a 10% efficiency improvement compared to the ecoinvent value (relative), the value in the ecoinvent unit process is decreased by 10%.

Advanced technologies such as ultra-supercritical coal power plants are not modelled explicitly, but as the IMAGE model does assume the development of these technologies in terms of future plant efficiencies and emissions, their improvements relative to current coal power plants are implicitly included in the model.

As the IMAGE model results do not contain explicit assumptions regarding the improved efficiencies of renewable electricity generation technologies[3], such as wind or solar, these technologies are left unchanged. Capacity factors of all electricity generating technologies are also left unchanged.

Modifying electricity market datasets

Following this, the average market electricity for each region in ecoinvent is adapted using IMAGE results. First, a list of ecoinvent unit processes is created for each IMAGE electricity generation

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[3] The IMAGE model does consider future improvements to renewable technologies, but they are defined as reductions in terms of cost per installed capacity. As there is no obvious way to separate cost improvements from efficiency improvements, we omit these improvements in order to avoid a value judgement.

technology. For example, the IMAGE technology „Coal steam turbine“ is matched to two ecoinvent processes:

- i. electricity production, hard coal
- ii. electricity production, lignite

When matching ecoinvent datasets to IMAGE technologies, all ecoinvent datasets have been used that match the IMAGE technology description without judgement of whether that specific technology will be important in the future. For fossil and nuclear technologies this is of lesser importance as efficiencies and emissions are updated with IMAGE data anyway. However, for renewable technologies, the future electricity market is being filled with “outdated” datasets for solar PV and wind turbines. This is an area for future improvement in the methodology.

Next all ecoinvent high voltage electricity market datasets are modified in turn in the following four steps:

1. All electricity supply exchanges are deleted from the dataset. Exchanges for the transmission grid, transmission losses, supervision and emissions are not modified.
2. The ecoinvent location is matched to a region in the IMAGE model. If the ecoinvent location is contained in multiple IMAGE regions, the IMAGE technology shares are averaged.
3. For each IMAGE electricity technology to be included in the market, a list of ecoinvent processes is created. The first choice is to select ecoinvent processes that match the IMAGE technology and have the same ecoinvent location as the market dataset. If this is not possible, the second choice is to select all matching technologies in the same IMAGE region as the market dataset. If more than one technology is matched, the electricity contribution is shared equally between them[4].
4. The total electricity produced is confirmed to sum to one kilowatt hour.

In the last step for electricity market modification, all additional electricity suppliers and electricity imports to medium and low voltage electricity markets are removed, as we make the simplifying assumption that all technologies feed into the high voltage network.

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[4] This is best explained by a series of short examples of how the IMAGE technology electricity from coal steam turbines would be added to the ecoinvent electricity markets:

1. The ecoinvent region Belgium has only hard coal power plants and no lignite powert plants, thus 100% of the IMAGE electricity generation share for coal would be allocated to the the ecoinvent hard coal electricity generation dataset for Belgium
2. The ecoinvent region Germany has both hard coal and lignite power plants. Thus, the modified German electricity market would have an equal share of hard coal and lignite power, that sum to the share defined by the IMAGE results. The current share of hard coal and lignite in ecoinvent has no influence on the results.
3. The ecoinvent region Switzerland has no coal fired power plants. Thus, all hard coal and lignite power plants with ecoinvent regions that correspond to the IMAGE region „Western Europe“ would be shared equally to make up a proxy for Swiss coal fired power plant electricity generation. The sum of these contributions would be equal to the share of electricity by coal steam turbines defined by the IMAGE results.

Relink database and perform LCA calculations

Finally, the unlinked list of unit processes to which the changes were made is relinked based on name, reference product, unit, and location and the data is re-written into a database so that LCA calculations may be performed with Brightway2 [27]. “Linking” is a term that refers to actually creating digital links between individual LCI datasets. For example, a technology requiring an input of electricity from a certain location at a certain voltage level is linked to the electricity market dataset that supplies that voltage level in that region.

Analysis of changes to the database

Figure 2.3 shows a comparison between the original ecoinvent v3.4 and modified versions of the database representing the year 2040 for both IMAGE scenarios as presented in Chapter 6. Results look very similar when ReCiPe endpoint totals are used for comparison. Climate change scores are calculated for every process in each database, and the ratio is taken between the score for each process in the modified database to the original process score. A score of less than one indicates that the future process will have lower climate change contributions than in the present. As can be seen in the figure, the majority of processes have a score of less than one. However, certain processes are found to have a score much higher than one. These are typically processes that consume significant amounts of electricity and are located in countries with electricity mixes that are much cleaner than their neighbours. Examples include Switzerland, France, and Norway. Because the geographical regions are much larger in the IMAGE model than in ecoinvent, these countries are all given the Western European average electricity mix in the updated version of the database, significantly increasing the climate change scores for their electricity markets. In order to avoid this error and enable realistic comparisons between results calculated with the original version of ecoinvent with modified versions, global or European average datasets were used where possible, as the geographic regions of IMAGE and ecoinvent coincide quite well at this level. This is quite reasonable for Swiss transport technologies, as all vehicles are imported and very few products are actually produced in Switzerland. In Chapter 8, where Swiss specific ecoinvent processes are required, I simply use the above described methodology to modify Swiss electricity markets in ecoinvent using electricity scenarios from the Swiss energy strategy [21].

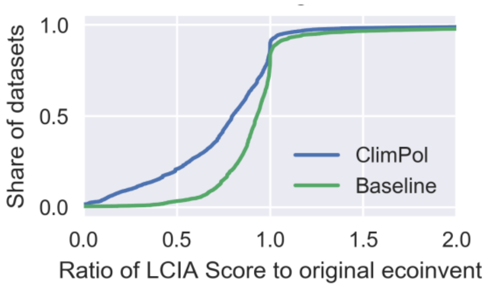


Figure 2.3 Ratio of climate change scores for future LCA database to current ecoinvent 3.4. The figure shows the ratio of the climate change score from the updated database for each future electricity scenario to the original ecoinvent 3.4 score for each dataset in the database.

2.4. Road vehicle energy consumption modelling

For the reasons discussed in section 2.1, I choose to model and validate vehicle energy consumption based on vehicle parameters rather than use measured values.

I use a modified version of the backward facing methodology of Guzzela and Sciarretta [43], which is also used in project THELMA [14, 17] for the energy consumption calculation of all road passenger transport modes. This method simulates the operation of a vehicle following a fixed velocity versus time curve. These speed curves are defined by world harmonized test cycles defined by the UN ECE Working Party on Pollution and Energy group and are considered to represent average driving in Europe, Japan and the United States [44]. They are considered to be more realistic than the New European Driving Cycle (NEDC) [45].

This methodology calculates wheel traction power demand given a velocity (v) versus time profile and assumptions about mass, vehicle frontal area, coefficient of aerodynamic drag (C_d), air density (ρ), and rolling resistance (C_r) according to the equation

$$Power_{wheel} = \left(\frac{v^2 Area\, C_d\, \rho}{2} + 9.81\, mass\, C_r + mass\, \dot{v}\right) v.$$

Figure 2.4 shows a sample velocity versus time curve for a 2017 long range electric urban bus (in black on the right y-axis) and the corresponding power demands as defined in the above equation. The Tank to Wheel (TtW) energy consumption of the vehicle can then be calculated using input values for powertrain and battery efficiencies, as well as auxiliary power demands, such as lighting, navigation, and heating and air conditioning, and recuperative braking efficiency. The summation of the power curves is integrated over time and divided by the total distance driven during the test cycle to calculate the energy consumed by the vehicle per kilometer driven. The model is validated by comparing the calculated energy consumption results with literature values for measured vehicle energy demand.

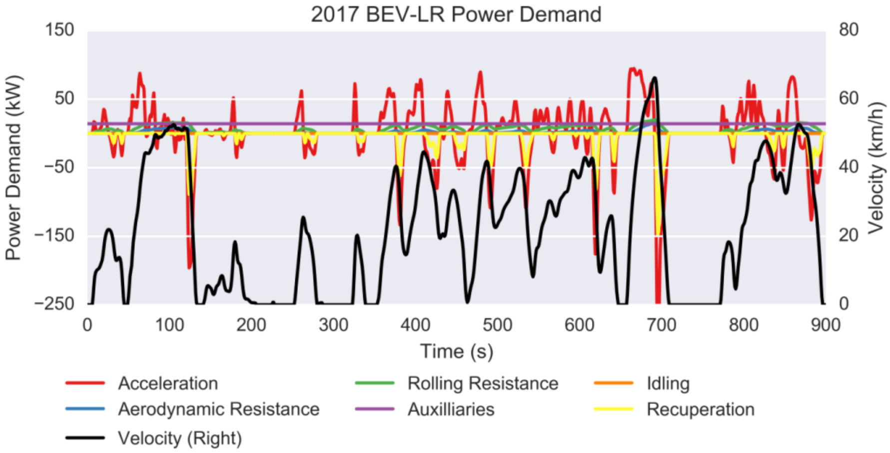
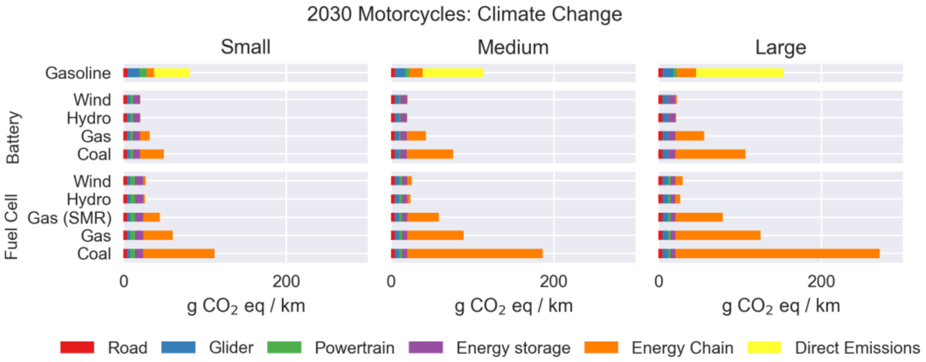


Figure 2.4 Sample vehicle energy demand calculation result for a 2017 urban bus with a long range battery electric powertrain.

Chapter 3. **The environmental and cost performance of current and future motorcycles**

Abstract

This work presents an integrative approach to environmental and cost assessment of current and future motorcycle technologies for four motorcycle size categories, three powertrain types, and a variety of fuel supply chains. We consider conventional gasoline (ICEV), battery electric (BEV) and fuel cell electric (FCEV) motorcycles with production years from 1990-2030. Motorcycle energy consumption is modelled based on the world harmonized motorcycle test cycle and calibrated with data measured from existing motorcycles. We model the potential future performance of motorcycles by adapting the model input parameters according to historic trends and future component performance predictions. We find that smaller motorcycles have much better environmental performance than larger motorcycles, though this is mostly due to the fact that larger motorcycles have different driving patterns: urban driving is found to have much lower environmental impact per kilometer than highway driving. Current BEV are found to have similar ownership costs to ICEV. They also have reduced climate change potential by roughly 60% when they are powered by electricity from natural gas, 80% when powered by renewables, and they still offer advantages over conventional motorcycles when charged with electricity from hard coal. Next generation BEV are found to have similar environmental performance advantages, though with a definite cost advantage. FCEV climate change reduction potential is found to depend strongly on the source of the hydrogen fuel, with climate benefits being substantial with hydrogen originating from renewable energy sources. Future cost competitiveness of FCEVs is linked closely to the development of fuel cell costs.



Publication Details

Due to copyright reasons this chapter has been removed from the public version of the thesis. Interested readers are directed to: Cox, B.L. and C.L. Mutel, *The environmental and cost performance of current and future motorcycles.* Applied Energy, 2018. **212**: p. 1013-1024. https://doi.org/10.1016/j.apenergy.2017.12.100. Copyright 2018 Elsevier.

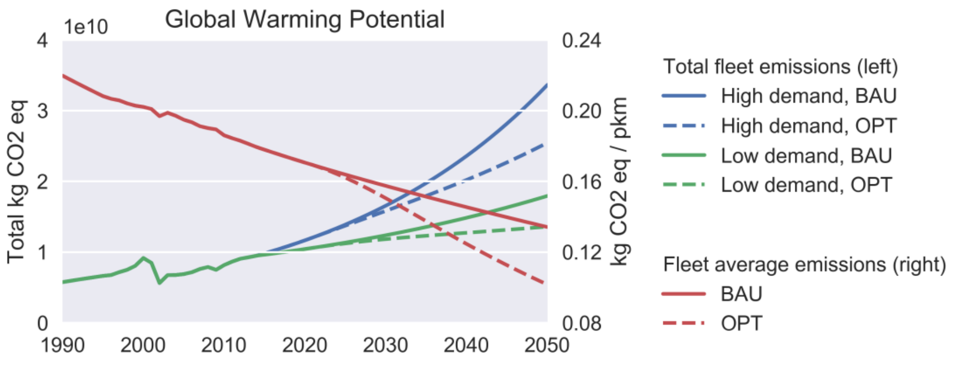
Author contribution

I am the first author of this publication and led all aspects of the work completed. Chris Mutel assisted with the development of the calculation framework, data collection, and editing the manuscript.

Chapter 4. **Life cycle assessment of air transportation and the Swiss commercial air transport fleet**

Abstract

In this work we present a life cycle assessment of air transportation, the Swiss commercial aircraft fleet, and its potential development from 1990 to 2050. We first perform a life cycle assessment of air transport with 72 common aircraft types for different flight distances. These results are globally valid. Based on these results, a parameterized model of 5 aircraft size categories is developed that includes variation in aircraft production year, flight distance and maximum seating capacity. Future aircraft improvement is modelled with two scenarios that consider conservative and optimistic assumptions regarding future improvements to aircraft weight, fuel efficiency, aerodynamics, and exhaust emissions. In a third step, this model is calibrated to Swiss and European conditions and used to calculate the environmental burdens from Swiss passenger and freight civilian air transport. The model is found to accurately predict national aircraft fuel consumption to within 7% accuracy over a 25 year period, with the exception of the aftermath of the terrorist attacks of 2001. Results show that, despite significant improvements in per passenger kilometer emissions, overall environmental burdens due to air transportation are likely to continue increasing in the future due to rapidly increasing demand. Results further show that as exhaust emissions from aircraft are further reduced, the main cause of many environmental impacts caused by air transport will be due to upstream impacts of kerosene production, and not the direct operating of aircraft.



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Author contribution

I am the first author of this publication and led all aspects of the work completed. Wojciech Jemioło provided the basis for this work with his master thesis and Chris Mutel assisted with the development of the calculation framework and editing the manuscript.

Chapter 5. **Environmental assessment of current and future urban buses with different energy sources**

Abstract

We perform a comparative life cycle assessment of urban buses powered by diesel, diesel-hybrid, natural gas, fuel cells, and batteries. The novelty of this work lies in the use of a consistent framework across multiple powertrain types considering both current and 'next generation' technology levels. This, combined with the variety of energy chains included makes this, to the best of our knowledge, the most comprehensive life cycle assessment of urban buses available to date.

Publication details

This chapter is reproduced with permission from Cox, B., A. Castillo, and C. Mutel, Environmental assessment of current and future urban buses with different energy sources, in The 30th International Electric Vehicle Symposium & Exhibition. 2017, Stuttgart. http://papers.evs30.org/proceedings/.

Author contribution

I am the first author of this publication and led all aspects of the work completed. Analy Castillo contributed to data collection, results analysis and manuscript editing. Chris Mutel assisted with the development of the calculation framework and editing the manuscript.

5.1. Introduction

Although public transport by urban bus is generally more environmentally efficient than with individual passenger cars, conventional buses are still associated with significant local air pollution and emissions of greenhouse gases. Many transport authorities have stated commitments to reduce these impacts or even transition to a zero emissions fleet within the next 15 years [13]. Transport authorities looking to renew their fleets are faced with a decision between multiple bus technologies, each with different strengths and weaknesses as well as infrastructure requirements. This decision is made more difficult by the rapid rate of improvement of advanced technologies such as battery and fuel cell electric buses. Furthermore, because the performance of urban buses depends strongly on operating conditions, the results from different studies and manufacturer information are not always directly comparable.

In order to support these decision makers, we develop a framework that allows consistent comparison of different bus powertrains and energy chain configurations using life cycle assessment. We consider six different powertrain variants: diesel (ICEV-D), diesel hybrid (HEV-D), compressed natural gas (ICEV-CNG), fuel cell electric (FCEV), short range opportunity charging battery electric (BEV-SR), and long range plug-in battery electric (BEV-LR). Though this paper focusses on 2017 and 2030 bus construction years, the model includes all construction years from 1990 to 2030.

The novelty of this work lies in the use of a consistent framework across multiple powertrain types with the same operating conditions to assess energy consumption and operating emissions. A further novelty of the work is that we include the expected performance of the next generation of buses, as it is this technology level that is expected to replace conventional buses. This combined with the variety of energy chains considered makes this, to the best of our knowledge, the most comprehensive life cycle assessment of urban buses available to date.

5.2. Life cycle assessment

We perform cradle-to-grave life cycle assessment using the ecoinvent 3.2 database with the cut-off system model [29] and the Brightway2 software [27]. We include the entire bus material cycle, from production to regular maintenance and end-of-life, as well as the entire fuel cycle and operating emissions. The functional unit of our study is one vehicle kilometer (vkm).

Due to time and space constraints, we limit presentation of life cycle impact assessment results to the two categories that we feel are most relevant for urban public transportation:

- Global Warming Potential (GWP) represents the contribution to climate change due to the emission of greenhouse gases such as CO_2 and CH_4. For this indicator we have selected the most recent global warming potential characterization factors from the IPCC [31], as implemented by the ecoinvent center. GWP is quantified in kg CO_2 equivalents using a 100 year reference time period.
- Particulate Matter Formation Potential (PMFP) considers the human health impacts of fine particles in the air. We consider not only the direct emission of particulates, but also the formation of secondary particulates due to emissions such SO_x, NO_x and ammonia (NH_3). PMFP is quantified in kg PM 10 equivalents. This indicator is calculated using the ReCiPe 2008 method with the hierarchist perspective [30]. We use PMFP to represent the urban air quality aspects of bus operation, as NO_x and particulate emissions are among the most important emissions from buses.

5.3. Bus modelling

In this presentation we focus on standard 12 m buses. All buses are assumed to have a lifetime of 12 years and travel a total of 750 000 km during their lifetime. We model 6 different bus powertrain types, which are briefly described below:

ICEV-D: Internal Combustion Engine Vehicle – Diesel. This is a standard diesel powered bus that meets European emission level EURO VI. It has a 230 kW engine.

ICEV-CNG: Internal Combustion Engine Vehicle – Compressed Natural Gas. This is a standard compressed natural gas powered bus that meets European emission level EURO VI. It has a 230 kW engine.

HEV-D: Hybrid Electric Vehicle – Diesel. This is a hybrid bus configuration with a 185 kW diesel engine that operates a generator. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking and 150 kW of lithium ion power batteries (15 kWh storage capacity). The bus meets European emission level EURO VI. The bus does not have the ability to recharge batteries from the electricity grid.

FCEV: Fuel Cell Electric Vehicle. This is a Polymer Electrolyte Membrane (PEM) fuel cell powered bus that operates on hydrogen. The fuel cell has net power output of 150 kW and 80 kW of lithium ion power batteries (8 kWh) are used to balance the load. Two 75 kW electric motors that are capable of recuperative braking are used to power the wheels.

BEV-SR: Battery Electric Vehicle – Short Range. This is a battery electric bus powered by lithium ion batteries. This bus is assumed to have a range of only 12 km, but is assumed to regularly recharge its batteries along the route with inductive charging. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking.

BEV-LR: Battery Electric Vehicle – Long Range. This is a battery electric bus powered by lithium ion batteries. This bus is assumed to have a range of 200 km, and is assumed to charge its batteries once per day. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking.

In general, while modelling bus performance, we keep the basic parameters of all buses the same and include differences between buses only where they are due to differences in powertrains. A summary of the most important bus parameters for each powertrain type is shown in Table 5.1. Furthermore, the following sections discuss some of the most important aspects of the life cycle inventories for buses. Section 3.1 examines the modelling assumptions for batteries, wireless charging, fuel cells and hydrogen storage in more detail. Section 3.2 describes how we modelled bus energy consumption. Section 3.3 looks at the operating emissions from buses, while section 3.4 describes the energy chains used to refuel and recharge the buses.

Table 5.1 Summary of most important bus parameters

			ICEV-D	HEV-D	ICEV-CNG	FCEV	BEV-SR	BEV-LR
Bus mass	kg	2017	10890	10960	11110	11050	10720	12680
		2030	10730	10760	10890	10570	10330	11410
Maximum Range	km	2017	500	500	500	500	12	200
		2030	500	500	500	500	12	200
Traction energy demand	MJ/km	2017	5.3	3.9	5.3	4.4	4.4	4.7
		2030	4.8	3.5	4.8	3.9	3.9	4.0
Onboard energy storage	kWh	2017	2420	1800	2580	1480	86	380
		2030	2100	1570	2230	1230	75	325
Auxiliary Power	kW	2017	7.0	5.3	7.0	5.3	5.3	5.3
		2030	5.4	4.9	5.4	4.9	4.9	4.9
HVAC Power	kW	2017	5.3	5.3	5.3	8.5	8.5	8.5
		2030	4.1	4.1	4.1	6.6	6.6	6.6
Tank to Wheel Efficiency	%	2017	29.0	30.0	27.5	41.6	85.0	85.0
		2030	30.2	31.2	28.6	43.9	85.6	85.6
Charging efficiency	%	2017	-	-	-	-	85	90
		2030	-	-	-	-	85	90
Recuperation efficiency	%	2017	-	50	-	50	50	50
		2030	-	53	-	53	53	53
Total energy consumption	MJ/km	2017	17.5	12.9	18.6	10.6	5.1	5.5
		2030	15.1	11.3	16.0	8.9	4.5	4.7

5.3.1. Batteries, induction chargers, fuel cells and hydrogen tanks

Energy batteries are modelled to be lithium ion batteries with a current energy density of 150 Wh/kg, assumed to improve to 250 Wh/km in 2030 [117]. LCI data for lithium ion batteries is taken from ecoinvent on a per kilogram basis. Batteries are assumed to be liquid cooled for BEV in order to extend their lifetime. Batteries are assumed to be replaced once during the bus lifetime for current buses and not at all for 2030 buses [167]. Power batteries are modelled to be the same lithium ion batteries as used for energy storage. We assume a maximum discharge rate of 10 C to define the power capabilities of batteries.

Short range battery buses are charged by induction charging. Life cycle inventories for the inductive charging units are taken from Bi, De Kleine [168]. We reduce the efficiency of charging for short range electric buses from 90% to 85% to account for the speed of charging and losses in the inductive charging system.

Hydrogen tanks are made of an aluminium cylinder wrapped with carbon fiber with stainless steel connections. Hydrogen tanks are assumed to have a mass storage efficiency of 5%, increasing to 7% in 2030 [103].

Fuel cells are assumed to be Polymer Electrolyte Membrane (PEM) type. We take the basic fuel cell model from Simons and Bauer [33], using the 2020 fuel cell as the 2017 base case for performance and manufacturing. However, as heavy duty fuel cells are typically operated to optimize lifetime, we decrease the power density from 800 mW/cm^2 to 600 mW/cm^2 for 2017 models. For 2030 the power density is set to 800 mW/cm^2 which represents expected improvements in power density and catalyst loading, the two parameters that have the most influence on the environmental impacts of fuel cell production. Furthermore, average fuel cell system efficiency (LHV) is increased from 49% in 2017 to 54% in 2030. The fuel cell stack is assumed to be replaced twice for 2017 buses, and only once for 2030 buses [169].

5.3.2. Bus energy consumption

Operating energy consumption is determined by modelling each bus driving the urban section of the World Harmonized Vehicle Cycle (WHVC) for heavy duty vehicles [44]. We calculate the instantaneous power at each second of the WHVC required for the bus to follow the pre-determined velocity versus time profile. This includes the power requirements to overcome rolling and aerodynamic resistance, acceleration/ deceleration, auxiliary power and heating and cooling demands, which are all calculated using typical values for urban buses. Bus mass is determined by the model by summing the mass of the bus glider and powertrain with the mass of the energy storage system, which is calculated iteratively with energy consumption considering the required range of the bus. For average operation we consider that the air conditioner is running 25% of the time and the heater 15% of the time. Auxiliaries are assumed to be slightly more efficient for electric powertrains compared to combustion powertrains, which often use less efficient pneumatic systems. Input values for auxiliary consumption are from Andersson [170]. Figure 5.1 shows a sample result of the power demand for a 2017 long range battery electric bus.

Integrating the power demand over the driving cycle and dividing by the total distance travelled yields energy consumption per kilometre travelled. We use average efficiencies for all powertrain components, such as engines, motors, transmissions etc. to calculate tank to wheel efficiency for each powertrain (see Figure 5.2).

We choose to model the energy consumption of buses instead of directly taking real world data. The reason for this is that the modelling approach allows us to consider individual improvements to buses over time, such as improved fuel cell stack efficiency, or use of heat pumps to reduce heating energy demand, while this is not possible when directly using real world measured data. Furthermore, the method allows consistent comparison for different bus powertrain types as all other variables, such as driving cycle and auxiliary power demand may be held constant. We calibrate model results with real world data found in the literature and manufacturer claims and find that the current model results fit very well with current bus performance for all powertrain types.

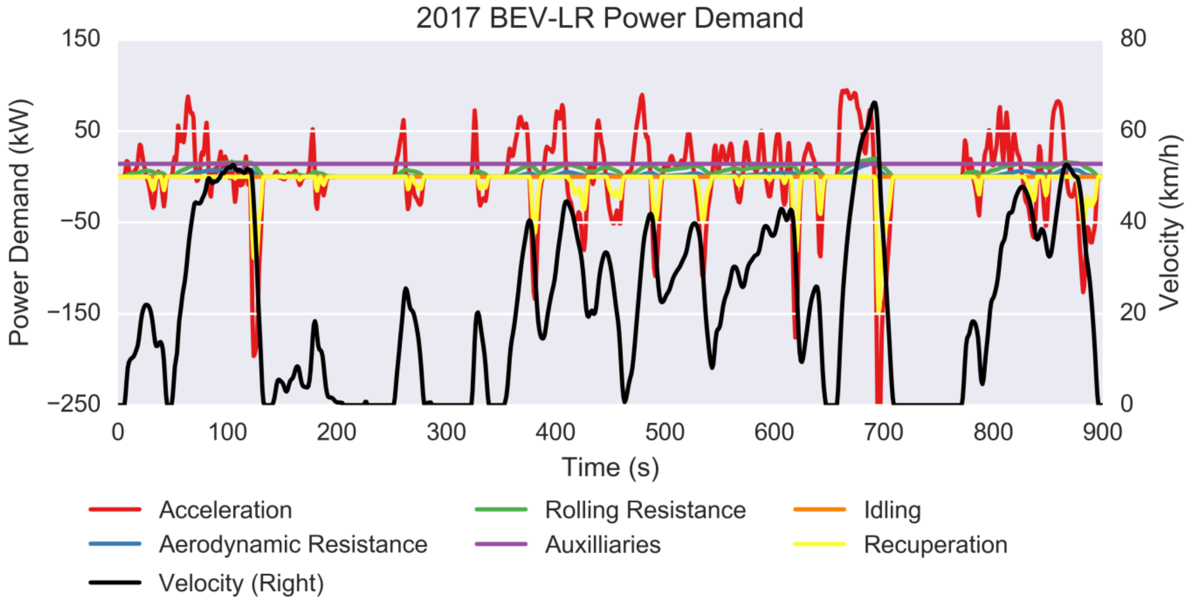

Figure 5.1: 2017 Sample bus power demand while driving the WHVC Urban driving cycle.

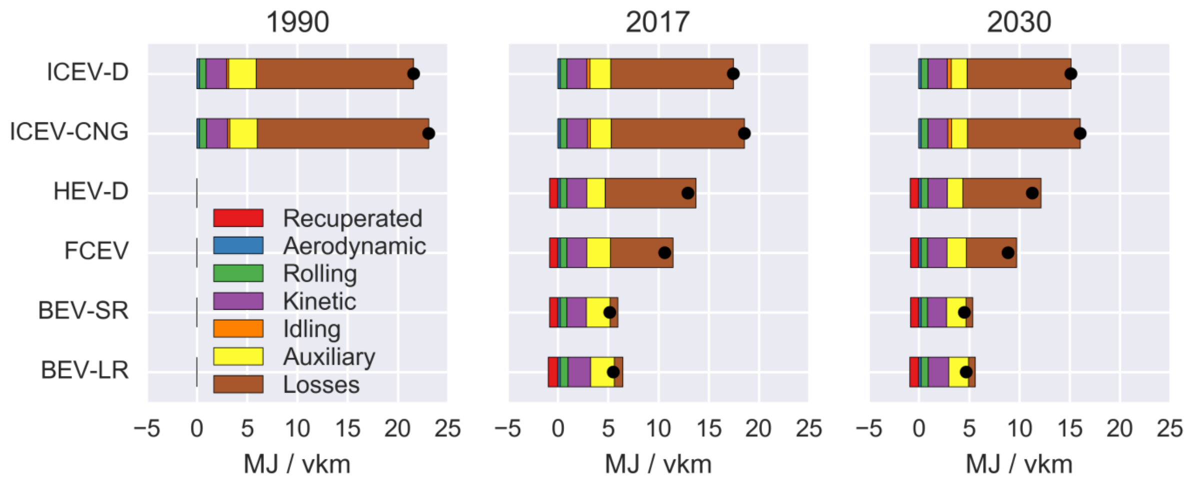

Figure 5.2: Tank to wheel energy consumption per vehicle kilometer for 12 m urban buses produced in 1990, 2017, and 2030.

5.3.3. Bus operating emissions

We calculate exhaust emissions for diesel and natural gas buses on the basis of emissions per kWh of energy consumed, which is also how the European heavy duty vehicle emissions regulations are defined. The reason that we make this distinction is because it allows us to better consider the emissions of vehicles that aren’t yet included in the emissions databases such as hybrid buses or buses of different sizes, or to include the impacts of different air conditioning load scenarios.

Emissions values are taken from the EMEP 2013 [112] and the HBEFA version 3.2 [7], and converted to emissions per kWh of consumed energy. We make the simple assumption that emissions per unit energy in 2030 are the same as in 2017. However, because future buses are modelled to have lower energy consumption, the emissions per kilometre travelled will also decrease in the future.

We further consider particle emissions due to tire, brake and the road wear from the EMEP 2013 [112]. Buses with regenerative braking are assumed to have reduced brake wear particle emissions.

5.3.4. Energy Chains

Although the model includes a wide variety of energy chains, for the purpose of brevity we limit results to the most relevant energy chains for this paper.

Electricity production is considered to be from natural gas combined cycle plants and onshore wind turbines operating in Germany. Hydrogen is produced by either electrolysis with the above electricity sources or steam reforming of methane (SMR). Electricity datasets are taken directly from ecoinvent. Hydrogen production datasets are taken from Simons and Bauer [121], but efficiency values are updated based on the most recent and future values listed by the US Department of Energy [122].

5.4. Results and discussion

Results are presented for global warming potential (Figure 5.3) and particulate matter formation potential (Figure 5.4) for 12 m buses. We compare 2017 and 2030 buses, but also include results for

ICEV buses produced in 1990 to give a better understanding of how the environmental impacts of buses have changed over time.

When renewable energy is available, in this case wind electricity, battery electric vehicles have excellent potential to reduce the global warming impacts of urban buses. We find that short range opportunity charge buses have the best environmental performance due to reduced battery manufacturing impacts as well as efficiency gains due to weight reductions. If opportunity charging is not feasible, long range electric buses also show excellent performance. Fuel cell buses charged with renewable energy still have excellent performance in terms of global warming, and are essentially free from the range concerns that faced by battery electric buses.

If the source of primary energy is natural gas, battery electric buses still offer climate benefits compared to combustion engine buses, though fuel cells do not. When diesel is the fuel source, hybrids are found to always outperform conventional diesel buses. Significant improvement is expected in the environmental performance of all bus powertrain types by 2030, though the ranking of technology performance remains the same.

In terms of particulate matter formation potential, the most obvious result is that direct emissions from combustion buses have been drastically reduced since 1990. Current conventional buses actually perform very well in this category compared to battery and fuel cell buses. The reason that fuel cell buses perform comparatively poorly in this category is due to the upstream emissions in the energy chain. For hydrogen from SMR, this is due to the emissions in the methane production chain. For hydrogen from electrolysis this is due to the large amount of nickel used in the electrolyzer, as SO_x emissions from nickel smelting are quite high. It is important to note that LCA does not account for the location of emissions and that upstream emissions, which may take place far from humans, are counted equally as direct tailpipe emissions that are emitted in city centers. Thus, the only conclusions we can reasonably draw from these results are that current combustion buses have greatly reduced their urban air pollution contributions compared to older buses, though the emissions are still not zero. Conversely, battery and fuel cell buses do have nearly zero direct emissions, though their upstream emissions are similar or even higher than those of combustion buses.

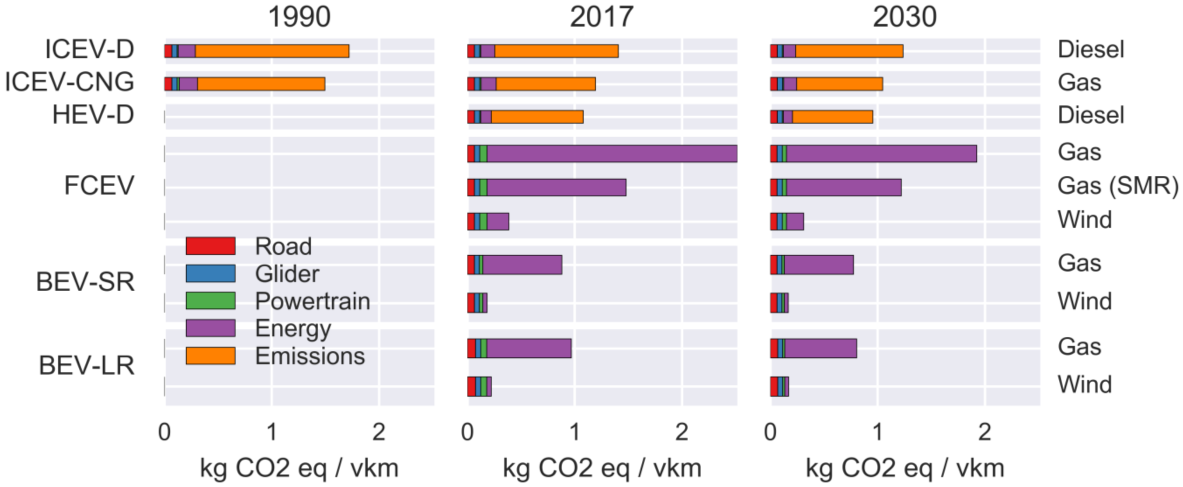

Figure 5.3: Global warming potential results for 12 m urban buses produced in 1990, 2017, and 2030.

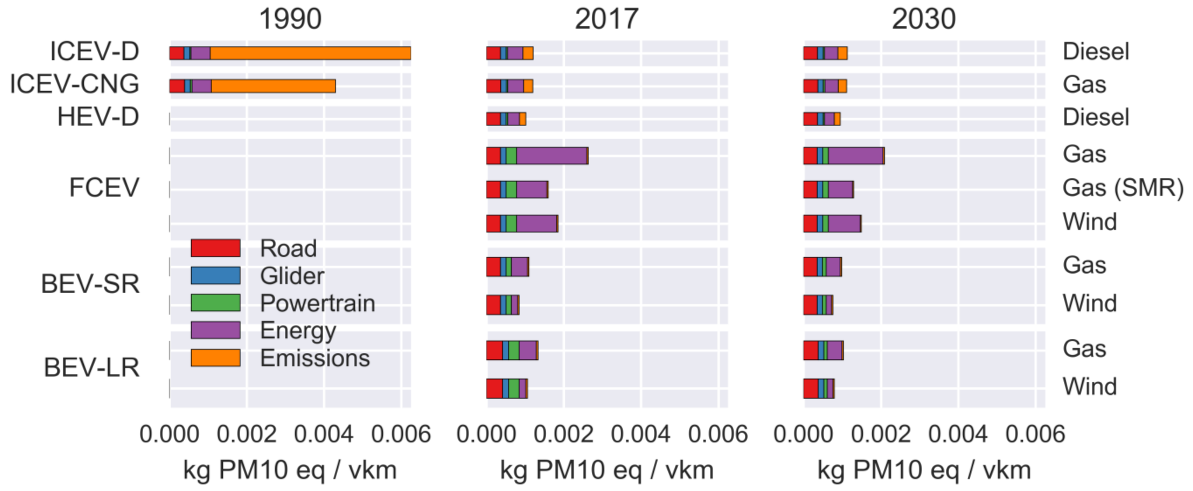

Figure 5.4 Particulate matter formation potential results for 12 m urban buses produced in 1990, 2017, and 2030.

5.5. Conclusions

In this work we compare the life cycle environmental impacts of past, current and next generation urban buses. We considered all likely powertrain combinations including combustion, hybrid, fuel cell and battery electric buses as well as a variety of different primary energy sources. Based on this detailed analysis of urban buses, we conclude that battery electric buses have the best environmental performance in nearly all environmental impact categories, for nearly all primary energy carriers. However, battery electric buses are not suitable for some bus routes due to range restrictions or the inability to install fast charging stations on route. In these cases, fuel cell buses are also a good choice as they have good performance in nearly all environmental impact categories – so long as a renewable source of hydrogen is available. When this is not the case, hybrid electric buses are preferable, especially if they have sufficient energy storage capacity to operate in all electric mode in city centers.

5.6. Acknowledgments

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5.7. Authors

Brian Cox is working towards his PhD from the Swiss Federal Institute of Technology in Zurich (ETHZ) in the Technology Assessment group at the Paul Scherrer Institut (PSI). Brian received his M.Sc. degree from the ETHZ in Energy Science and Technology in 2014, and his B.Sc. in Mechanical Engineering from the Schulich School of Engineering at the University of Calgary, Canada in 2008. He is currently involved in the Swiss Competence Center for Energy Research in Mobility, and is studying the environmental and cost implications of the Swiss Energy Transition.

Analy Castillo is a fourth year PhD Student from the University of California Irvine (UCI) in the Advanced Power and Energy laboratory and she is a visiting scientist at the Paul Scherrer Institut (PSI). As a part of the collaboration between UCI and PSI, Analy is working with the Technology Assessment group with a main focus on environmental and cost assessments of alternative transportation systems for the fleet optimization of transit agencies. Her current areas of interest are Life Cycle and Multi Criteria Assessments.

Chris Mutel received his doctoral degree from ETH Zürich, and wrote his dissertation on the computational methodology of regionalized LCA. He has published on sensitivity and uncertainty analysis, regionalization, neural networks, agricultural production and inventory data, and land and water use in LCA. He has also written numerous open-source software programs, including the Brightway2 LCA framework. Chris joined the Paul Scherrer Institute as a staff scientist in 2014. In the Technology Assessment group, he works to advance the science of life cycle assessment (LCA) through new methodologies, better understanding of uncertainty and sensitivity, and meta-analysis.

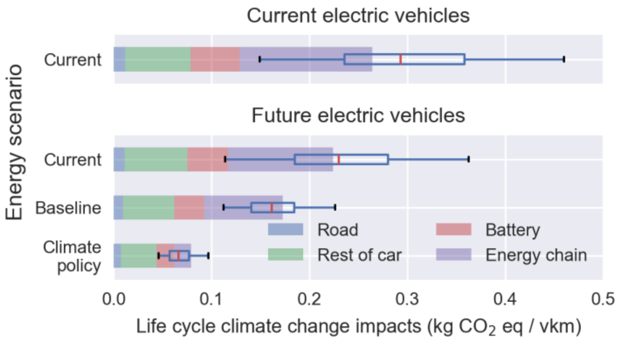
Chapter 6. **Uncertain environmental impacts of future electric vehicles**

Abstract

The future environmental impacts of battery electric vehicles (EVs) are very important given their expected dominance in future transport systems. Previous studies have shown these impacts to be highly uncertain though a detailed treatment of this uncertainty is still lacking. We help to fill this gap by using Monte Carlo and global sensitivity analysis to quantify parametric uncertainty and also consider two additional factors that have not yet been addressed in the field. First, we include changes to driving patterns due to the introduction of autonomous and connected vehicles. Second, we deeply integrate scenario results from the IMAGE integrated assessment model into our life cycle database to include the impacts of changes to the electricity sector on the environmental burdens of producing and recharging future EVs.

Future EVs are expected to have 45-78% lower climate change impacts than current EVs. Electricity used for charging is the largest source of variability in results, though vehicle size, lifetime, driving patterns and battery size also strongly contribute to variability. We also show that it is imperative to consider changes to the electricity sector when calculating upstream impacts of EVs, as without this, results could be overestimated by up to 75%.

Graphical abstract



Publication details

Due to copyright reasons this chapter has been removed from the public version of the thesis. Interested readers are directed to: Cox, B.L., Mutel, C.L. , Bauer, B., Mendoza Beltran, A., and van Vuuren, D.P., *Uncertain environmental footprint of current and future battery electric vehicles*. Environmental Science and Technology, 2018. 52 (8), p. 4989–4995. DOI: 10.1021/acs.est.8b00261. Copyright 2018 American Chemical Society.

Author contribution

I am the first author of this publication and performed all calculations and prepared the manuscript. Chris Mutel greatly contributed to the calculation framework and edited the manuscript. Christian Bauer provided guidance regarding the modelling of EV and edited the manuscript. Angelica Mendoza Beltran greatly contributed to the generation of the future versions of the LCA database and edited the manuscript. Detlef van Vuuren provided detailed knowledge of the IMAGE model and edited the manuscript.

Chapter 7. **Environmental assessment of current and future passenger cars in Switzerland**

Publication details

This report was delivered to the Swiss Federal Office for Energy as part of a small consulting project to examine the environmental burdens of passenger current and future passenger cars by Brian Cox and Christian Bauer. The project also delivered a 'Fact Sheet' that summarizes the findings which can be found in Appendix B along with input values for the calculation.

Author contribution

I am the first author of this report and performed all calculations and wrote the report. Christian Bauer created the fact sheets, assisted with editing the report, and translated the final version into German.

7.1. Introduction

The environmental performance of electric and conventional vehicles has been prevalent in the recent literature [14, 16, 79, 80, 182], and also the press [9, 45, 183-186]. 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 [21] 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[7] 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[8].

7.2. 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 B.

7.2.1. 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.

We perform attributional LCA according to the ISO standards ISO 14040 and 14044 [28, 147] and use the ecoinvent v3.4 database with the system model “allocation, cut-off by classification” [29]. The LCA calculations are performed using the Brightway2 software package [27]. The goal of our study is to compare the life cycle environmental impacts of passenger cars with production years 2017

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

(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 characterisation factors from the most recent IPCC report with the 100 year time horizon [31], as implemented in ecoinvent.

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.

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 [30].

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 [30].

7.2.2. 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 [187]. 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 dependant 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 7.1. 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 [188].

The most likely values correspond to a medium sized car, which is roughly the equivalent of a VW Golf. Table 7.1 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 7.1 Most Important common vehicle parameters Sources: a: Authors own calculation or estimate, b: [17], c: [188], d: [189].

Parameter	unit	Current Most Likely	Lowest	Highest	Future 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 [14, 17, 123]. 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) [45]. 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 [45]. We compare these results to energy consumption and CO_2 emission monitoring data for all new cars sold in Europe [190] 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 [45, 69, 174, 187, 191-202] 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 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 [14, 16-19, 33]. We also discuss the share of electric versus combustion powered driving for PHEV. We include the complete list of input values in Appendix B, and a summary of the most relevant assumptions and calculation results in Table 7.2.

Table 7.2 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 [17]. 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 [203]. 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 [96]. 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 analysed in Ellingsen, Majeau-Bettez [96] was not operating at full capacity [79, 80, 95, 171, 204, 205]. 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 [206] 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 [207], 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 7.1 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 median. 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.

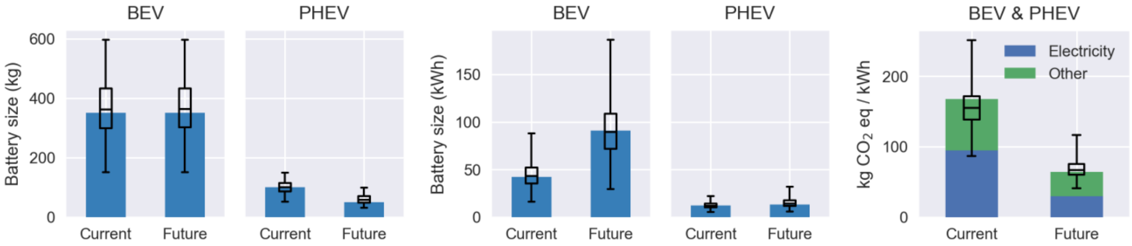

Figure 7.1 Energy storage battery size in kg (left) and in kWh (center), and climate change impacts of battery production (right).

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 optimised lithium ion batteries in HEV, FCEV, and future ICEV with the same LCI that we use for energy optimised 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 [203].

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 [15, 17, 33]. 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 [33], 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 [14, 15, 33, 98, 99].

Very little data exists regarding actual fuel cell lifetimes in passenger cars. We lean on the assumptions from previous LCA studies [14, 15, 33], targets from the US Department of Energy [98, 99], and reports from fuel cell bus projects [169, 208, 209] 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 fibre with stainless steel fittings. The composition of the tank is assumed to be: 20% aluminum, 25% stainless steel, and 55% carbon fibre (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 [103-107].

Vehicle exhaust emissions

Tailpipe operating emissions from combustion engines are included using data from HBEFA 3.3 [7]. 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 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 [9, 210]. 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 localised 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 [187, 211]. We fit a logarithmic curve to the vehicle ranges and utility factors reported by Plötz, Funke [187] 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 7.2 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.

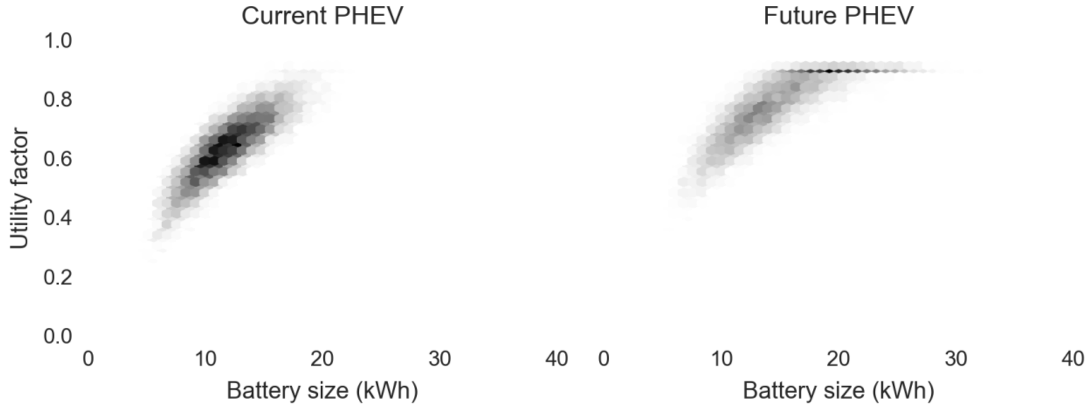

Figure 7.2 Plug in hybrid electric vehicle utility factor versus battery size.

7.2.3. Vehicle energy supply

Electricity supply used to charge current BEV is assumed to be the current low voltage Swiss consumption electricity mix. For the future electricity supply, we use three scenarios from the Swiss Energy Perspectives defined by Prognos [21]. 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 [39, 41, 212]. 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 using the above electricity sources (medium voltage), or with Steam Reforming of Methane (SMR). LCI data for electrolysis is taken from Zhang, Bauer [213], while LCI data for SMR is taken from Simons and Bauer [121]. Electrolysis and compression are assumed to require 58 kWh electricity per kilogram of hydrogen produced [213].

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 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, Bauer [213]. 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, Bauer [213]). In Zhang, Bauer [213], 0.5 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 *7.3* to Figure 7.6 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.

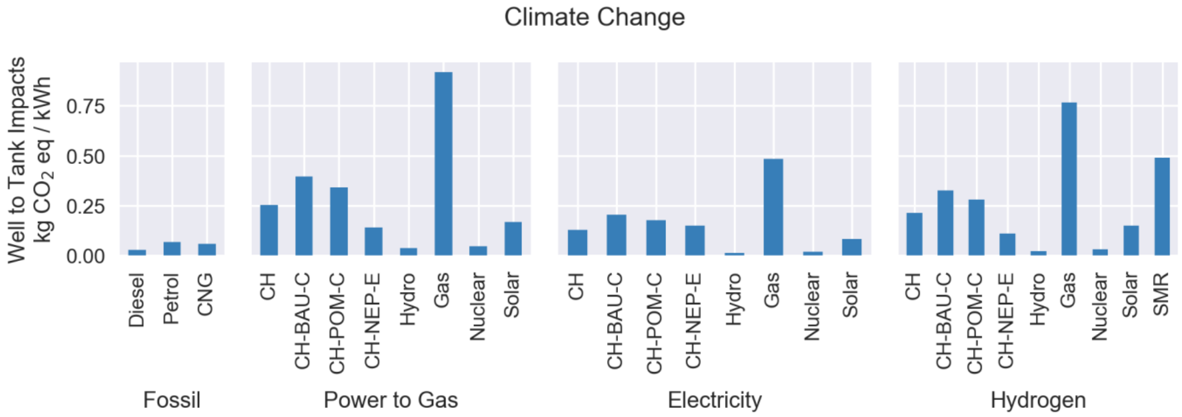

Figure *7.3* Well-to-tank climate change results for all energy chains

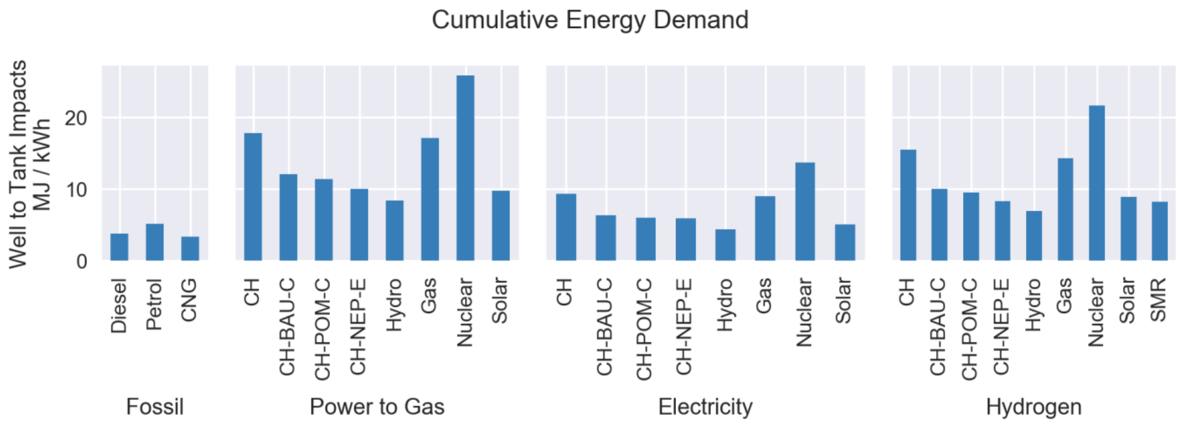

Figure 7.4 Well-to-tank cumulative energy demand results for all energy chains

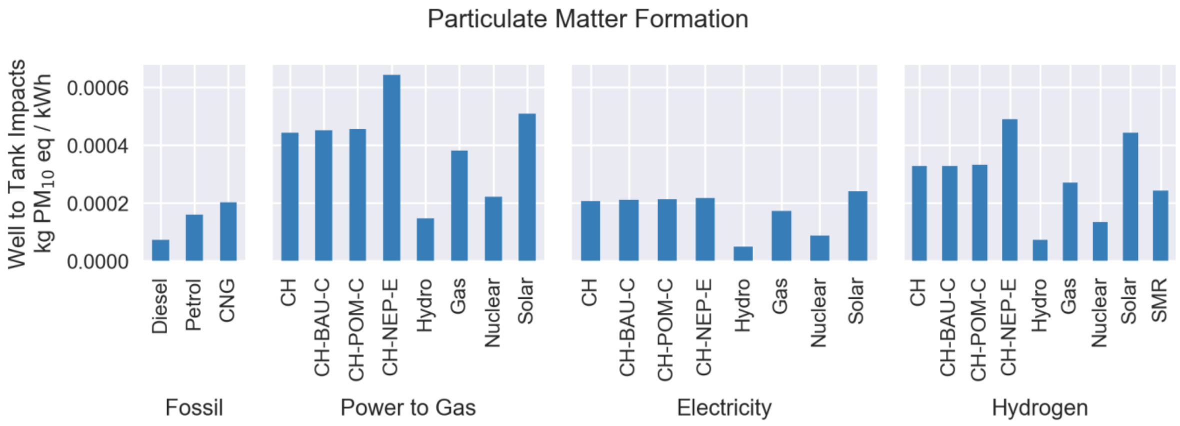

Figure 7.5 Well-to-tank particulate matter formation results for all energy chains

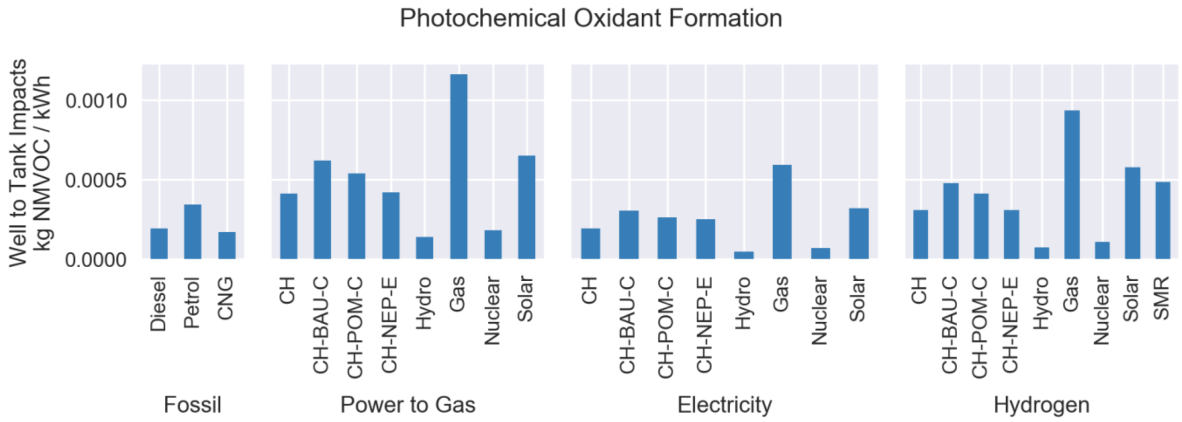

Figure 7.6 Well-to-tank photochemical oxidant formation results for all energy chains

7.3. Results and Discussion

In this section we present results for all powertrains. We first examine the vehicle mass and energy consumption in section 7.3.1, followed by LCA results in section 7.3.2, and sensitivity results to key parameters in section 7.3.3. 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.

7.3.1. Vehicle mass and energy consumption

Figure 7.7 shows 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.

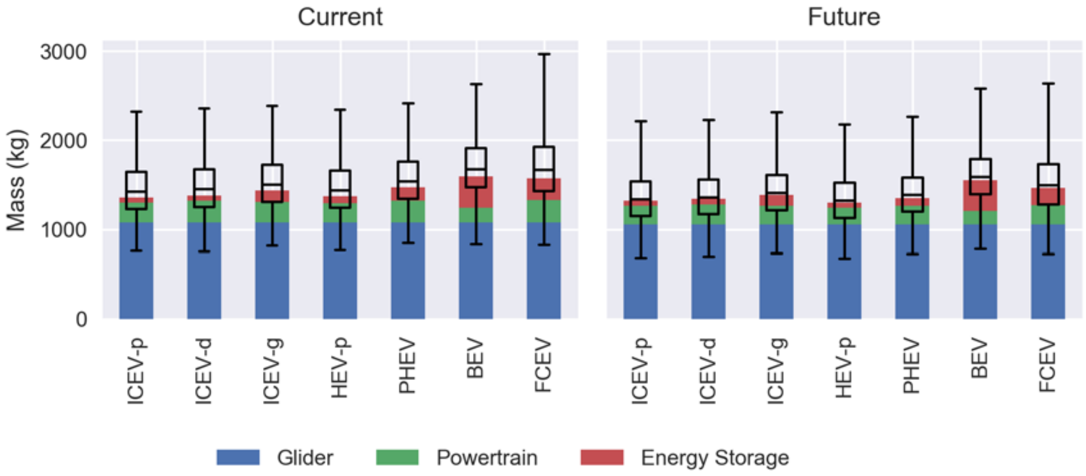

Figure 7.7 Vehicle mass for different powertrain technologies. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

Figure 7.8 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 7.20. The bar chart results in Figure 7.8 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 7.2. 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 7.2.2, 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 7.3.2.

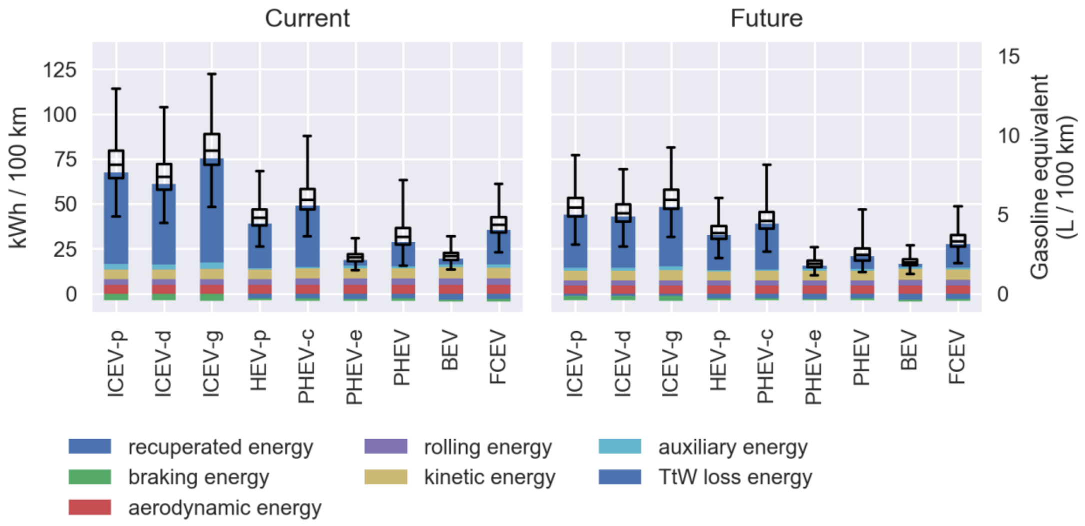

Figure 7.8 Vehicle tank-to-wheel energy consumption results. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

7.3.2. 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 fuelled 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 7.2.2. Results for climate change are presented for separately for electric and combustion operating modes in Figure 7.11 and Figure 7.12. 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 7.2.3. Results are split into contributions from different parts of the vehicle and its life cycle (shown in different colours) 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 7.9 and Figure 7.10 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 7.19. 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.

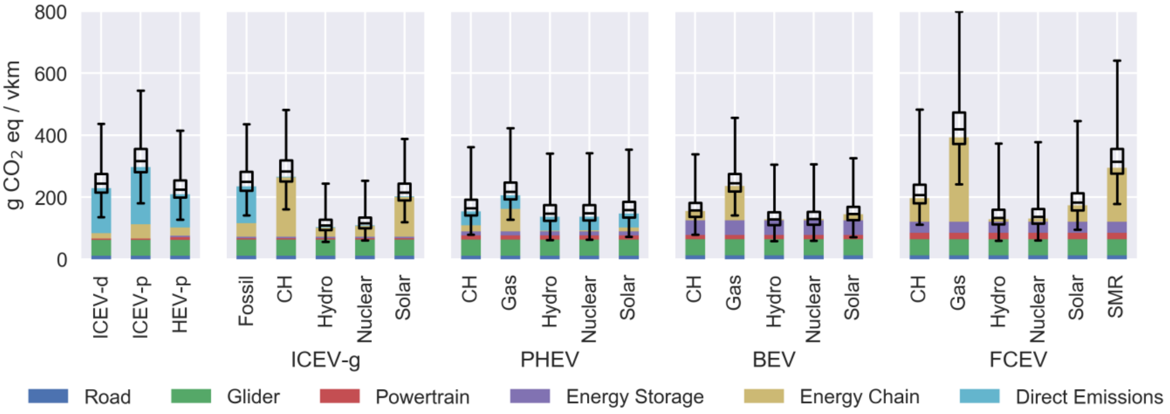

Figure 7.9 Vehicle climate change results for current vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

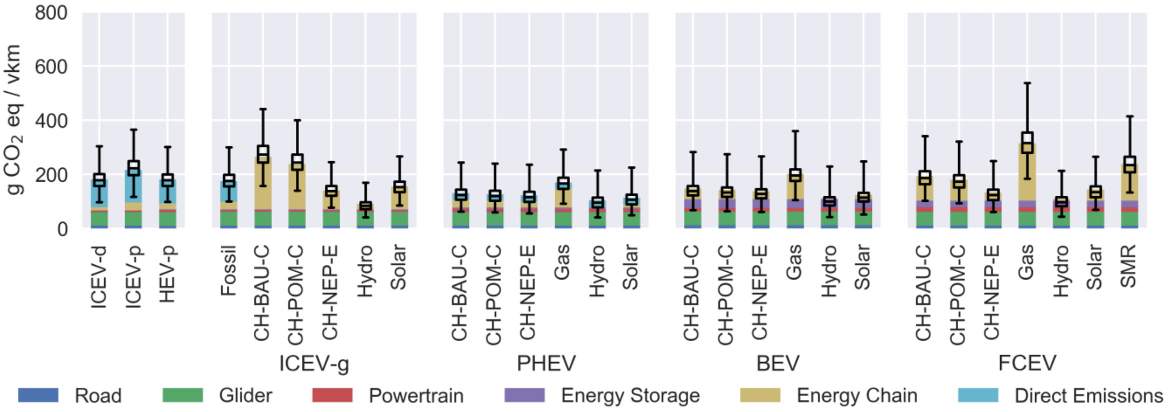

Figure 7.10 Vehicle climate change results for future vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

Figure 7.11 and Figure 7.12 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.

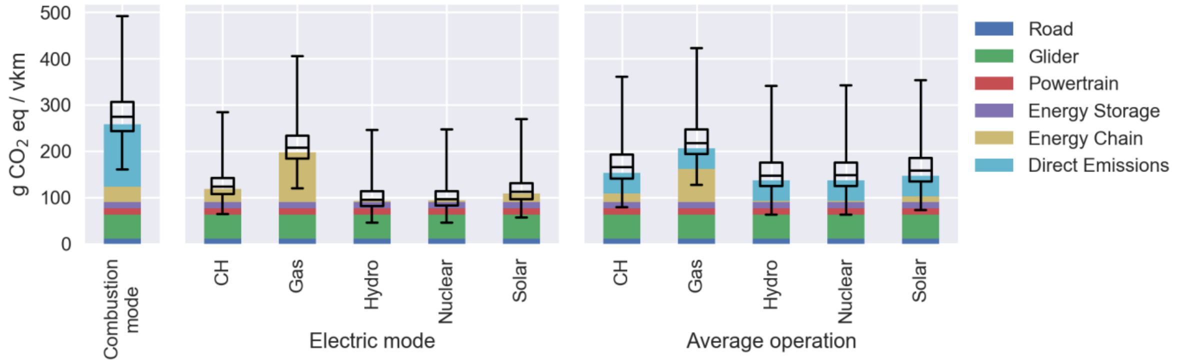

Figure 7.11 Vehicle climate change results for current PHEV vehicles with for different operating modes. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

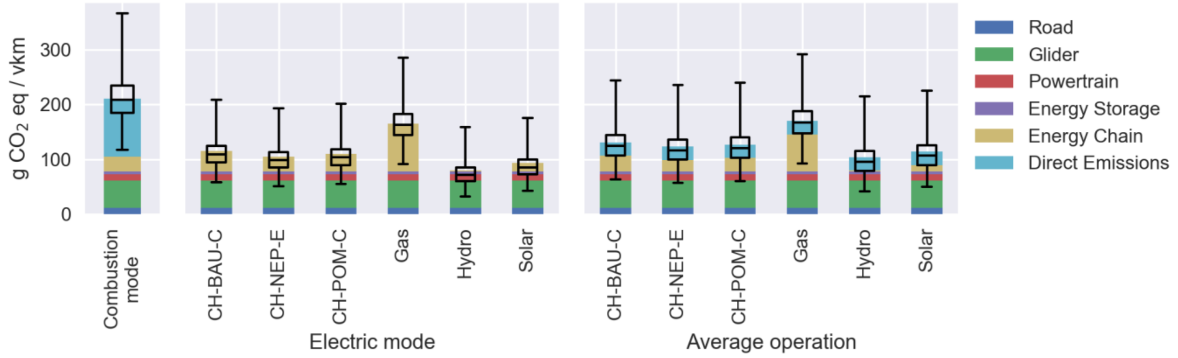

Figure 7.12 Vehicle climate change results for future PHEV vehicles with for different operating modes. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

In Figure 7.13 and Figure 7.14 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.

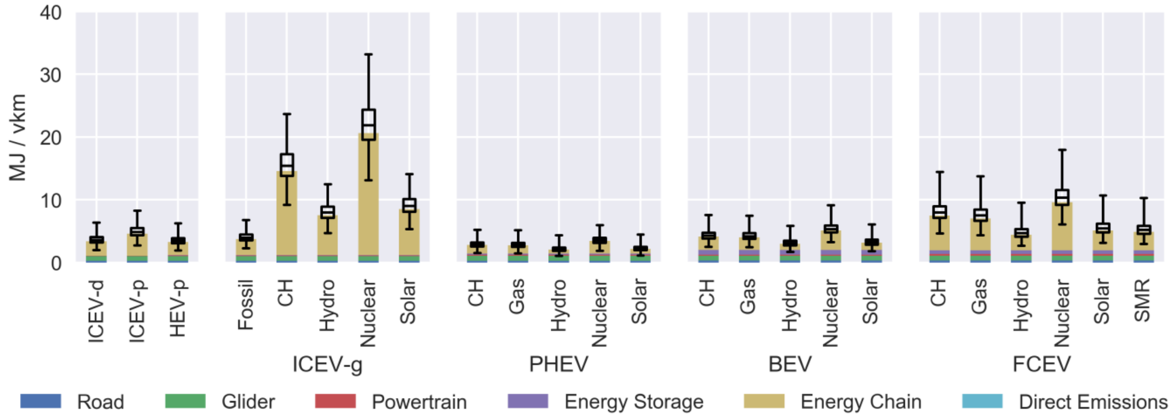

Figure 7.13 Vehicle cumulative energy demand results for current vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

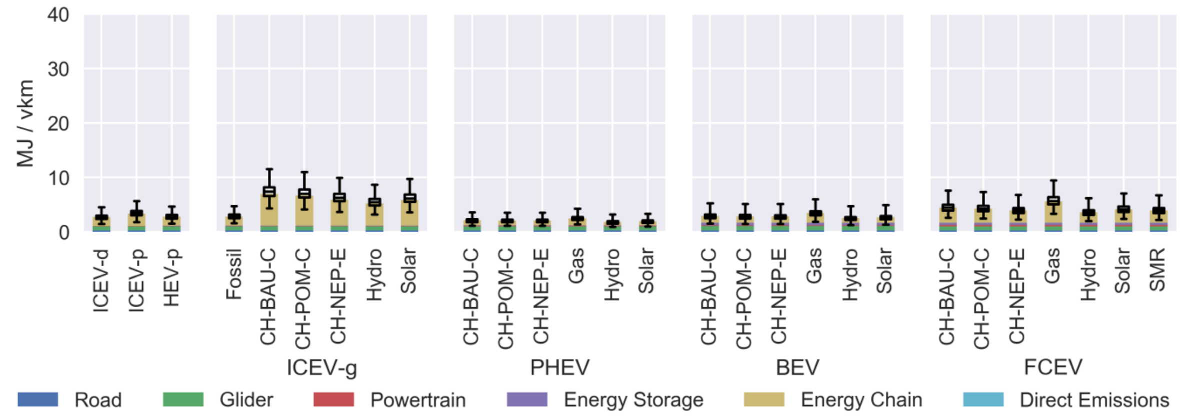

Figure 7.14 Vehicle cumulative energy demand results for future vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

In Figure 7.15 and Figure 7.16 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 characterisation 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.

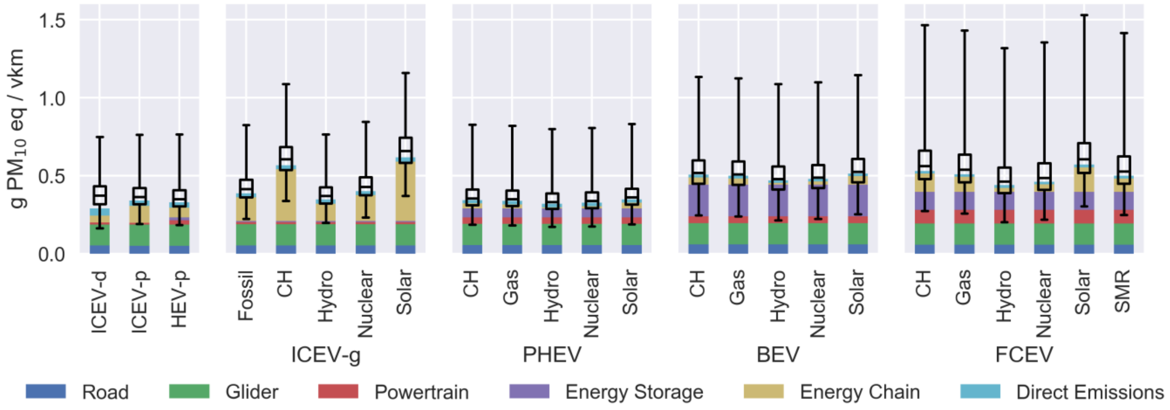

Figure 7.15 Vehicle particulate matter formation results for current vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

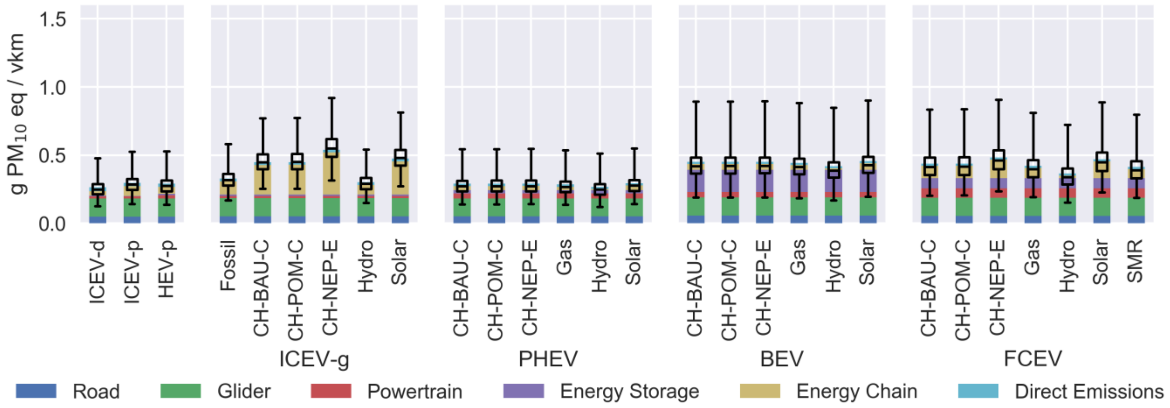

Figure 7.16 Vehicle particulate matter formation results for future vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

Figure 7.17 and Figure 7.18 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 median 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.

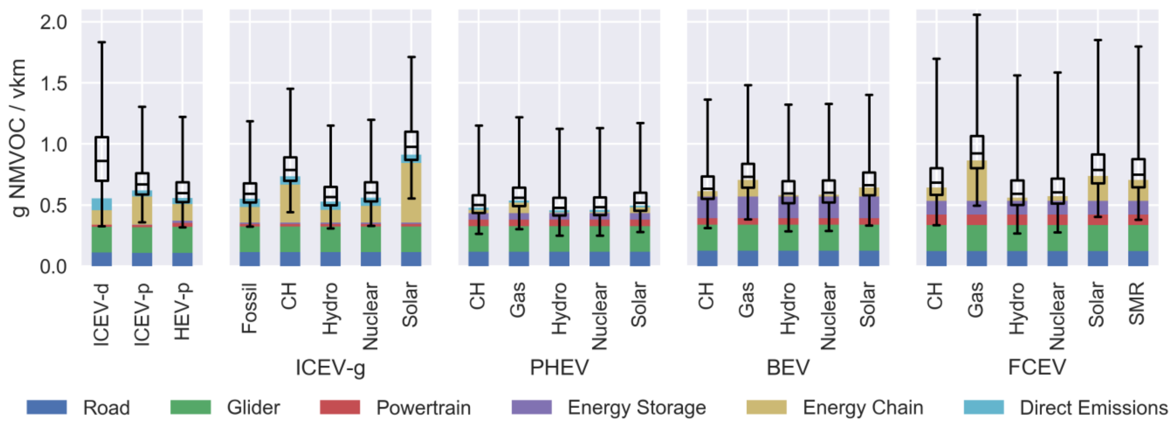

Figure 7.17 Vehicle photochemical oxidant formation results for current vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and performance.

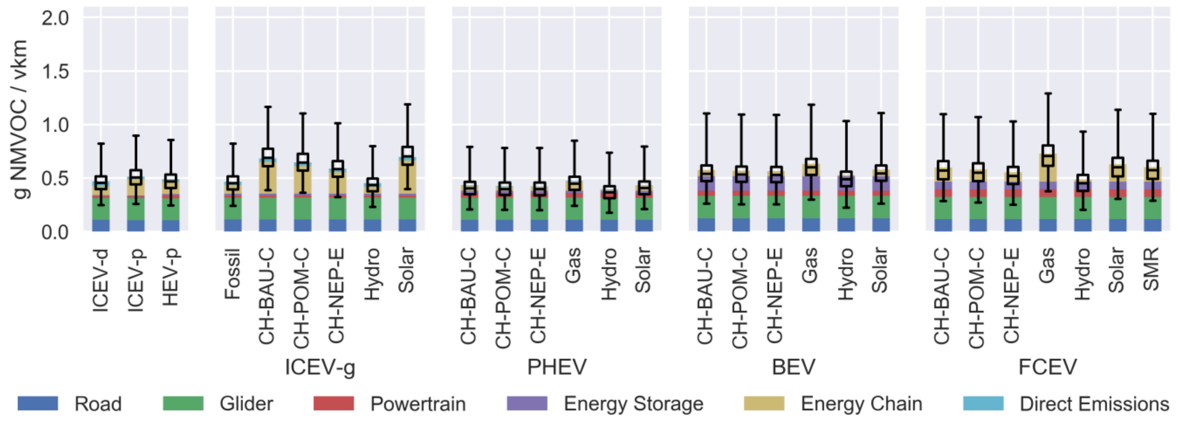

Figure 7.18 Vehicle photochemical oxidant formation results for future vehicles. Bar chart shows most likely result; whisker plot shows variability due to different vehicle design and uncertainty of future performance.

7.3.3. 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 7.19 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.

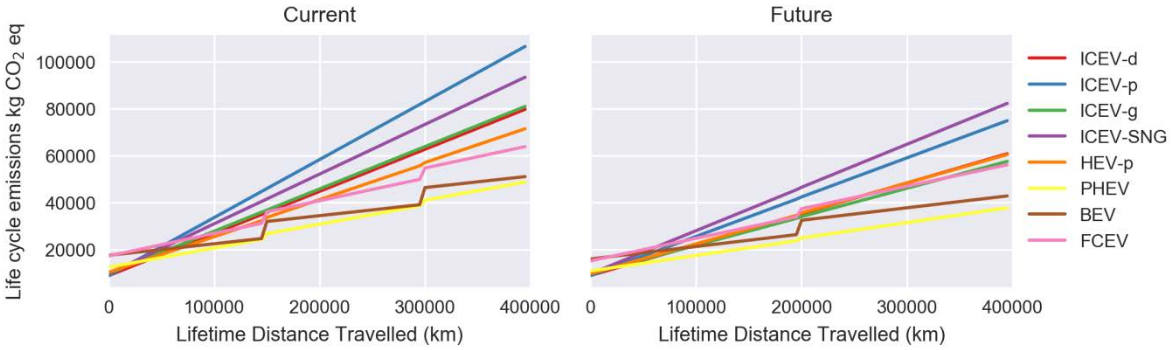

Figure 7.19 Sensitivity of climate change results to lifetime distance travelled

Figure 7.20 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.

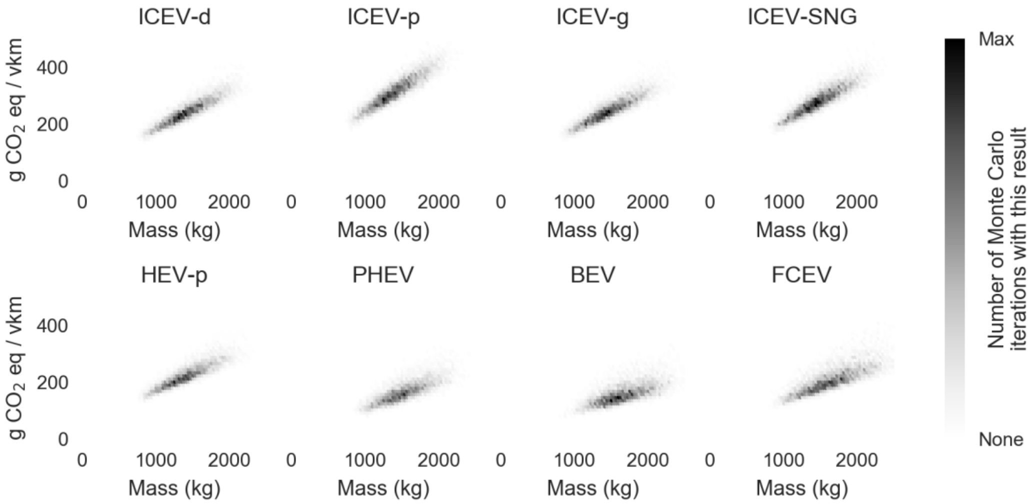

Figure 7.20 Sensitivity of climate change results to vehicle mass

Figure 7.21 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.

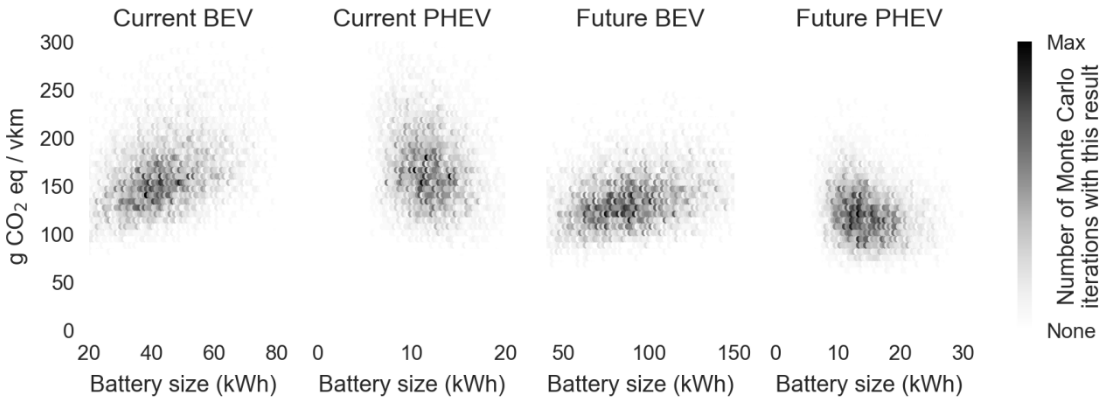

Figure 7.21 Sensitivity of climate change results to battery size for BEV and PHEV

In Figure 7.22 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 and nuclear are below 20 g CO_2 / kWh, electricity from a modern natural gas combined cycle power plant causes roughly 500 g CO_2 / kWh, while the current Swiss electricity mix corresponds to roughly 130 g CO_2 / kWh, and the future Swiss electricity mix is expected to be between 150 and 200 g CO_2 / kWh (see Figure *7.3*).

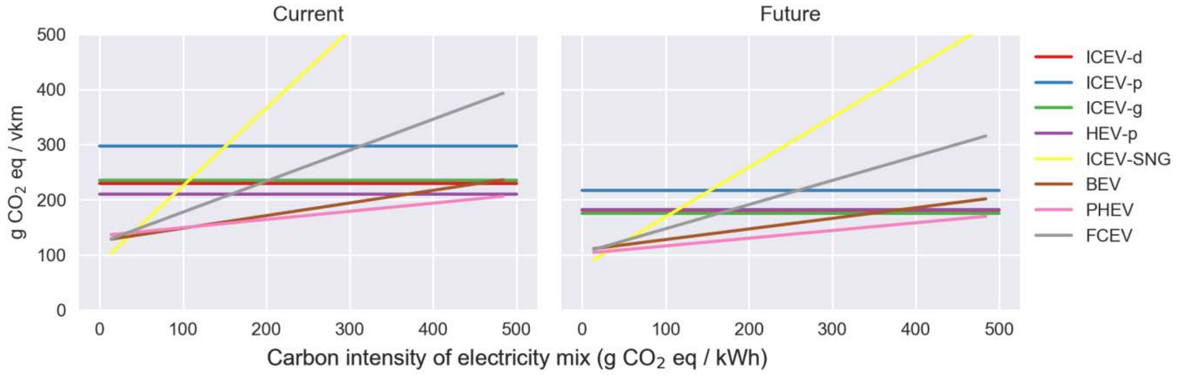

Figure 7.22 Sensitivity of climate change results to carbon intensity of electricity mix

7.4. 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 characterisation 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, and is explored in Cox, Mutel [214]. 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 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.

7.5. 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.

7.6. Acknowledgments

This background document and the corresponding fact sheet were created for the Swiss Federal Office for Energy. Much of the input data and calculation methodology used in this report was developed within the dissertation of Brian Cox which was completed within the Swiss Competence Center for Energy Research (SCCER) Efficient Technologies and Systems for Mobility, funded by the Commission for Technology and Innovation (CTI).

The authors would like to thank several PSI employees for their contributions: Xiaojin Zhang for access to data for synthetic methane LCI data as well as Simon Schneider and Tom Terlouw for their help in data collection. We would further like to thank Chris Mutel for his help developing the methodology used in the calculations for this report.

Finally, we would like to thank Hans-Jörg Althaus (Infras) and Christoph Schreyer (BFE), for their helpful comments during the development of the fact sheet and background report.

Chapter 8. **The environmental burdens of current and future passenger transport in Switzerland**

8.1. Introduction

In this chapter I build on the results and methodologies presented in the previous chapters to provide a comparison of current (2017) and future (2050) passenger transport modes in Switzerland. I re-run all models to use Swiss electricity as an input for battery charging and hydrogen production and also use the background databases developed in Chapter 6 for the assessment of future technologies. Furthermore, I provide a simple calculation of the total passenger transport sector impacts for three different powertrain scenarios used to meet 2050 transport demand according to official Swiss transport demand forecasts [5].

Section 8.2 describes the methods used for the comparison and fleet assessment. Section 8.3 presents and discusses the results, section 8.4 describes some of the most important uncertainties and limitations in the assessment and, finally, section 8.5 contains conclusions regarding current and future passenger transport in Switzerland.

8.2. Methods

8.2.1. Transport modes considered

All transportation modes from previous chapters as well as urban, regional and long distance trains are included. The vehicle sizes and powertrains considered for each mode and transportation distance are summarized in Table 8.1, where I also provide a reference to the chapter in this thesis where the transport mode model is described in detail. Table 8.2 shows the number of passengers per vehicle or the passenger load factor for each transport mode, distance, and year. The load factors for trains were not available in the ecoinvent documentation so they have been omitted. Future passenger load factors for all modes except aircraft are assumed to be the same as current ones. In the following sections I describe each transport mode separately.

Table 8.1 Transportation modes considered

Transport mode	Vehicle type/ distance	Powertrains	Chapter
Cars	small, mid-sized, large	ICEV-d, ICEV-g, ICEV-p, HEV-p, PHEV-c, PHEV-e, BEV, FCEV	Chapter 7
Motorcycles	4, 11, 25, 50 kW	ICEV-BEV, FCEV	Chapter 3
Urban buses	12 m bus (Maxi)	ICEV-d, ICEV-g, HEV-d, BEV-SR, BEV-LR, FCEV	Chapter 5
Trains	urban, regional, long distance	Electric	
Aircraft	500 km, 4000 km		Chapter 4

Table 8.2 Average passengers per vehicle or passenger load factor for different transport modes. *[215]

Transport Mode	2017	2050	
Cars	1.56*	1.56	passengers
Motorcycles	1	1	passengers
Urban buses	13.4	13.4	passengers
Aircraft – 500 km	71.4	76.1	% of capacity
Aircraft – 4000 km	84.3	89.4	% of capacity

Motorcycles

The calculation model for motorcycles is the same as the one described in Chapter 3, although in this chapter I extrapolate results up to 2050. I assume the annual rate of change for all input parameters to remain constant after 2030 until 2050. The hydrogen production datasets are also updated using values from Zhang, Bauer [213] as in Chapter 7. All other input values and calculation steps are the same as discussed in Chapter 3.

Aircraft

The models described in Chapter 4 are used to calculate the environmental burdens of Swiss aircraft. I show results for 500 km and 4000 km flights with the Swiss average aircraft size and the business as usual (BAU) scenario to model future performance without any changes to the model presented in Chapter 4.

Urban Buses

The calculation model for urban buses is the same as the one used in Chapter 5, though battery and hydrogen production datasets are updated to match those from Chapter 7. Although the model is capable of calculating results for 4 bus sizes, results focus on the most common 12 m bus size in this chapter as results per passenger kilometer are similar.

Cars

The evaluation of passenger cars uses the model described in Chapter 7 of this thesis. As the results presented in Chapter 7 are for 2040, I make the simple assumption that the improvement rate from 2017 until 2040 continues linearly for another 10 years, though the 2050 value is not allowed to be outside of the defined minimum and maximum values for 2040. For simplicity, I leave out the uncertainty in the input parameters and include only results for the most likely value of each parameter. I also exclude the synthetic gas pathway for compressed natural gas powered combustion vehicles.

Results are differentiated for small, mid-sized, and large cars as shown in Table 8.3. Mid-sized vehicles correspond to the most likely values used in Chapter 7. The glider base mass for small and large cars is taken from the car sizes used in Chapter 6. I also scale energy battery size and fuel tank capacity for small and large cars based on the ratio of their glider base mass to that of mid-sized cars. Note that the glider base mass value does not consider explicit lightweighting attempts which are considered separately as discussed in Chapter 7.

Table 8.3 Glider base mass for current and future cars with three size classes

Glider base mass (kg)	Small	Mid-sized	Large
Current	900	1100	1400
Future	880	1075	1370

Trains

The environmental burdens of passenger trains are not included in any of the previous chapters. I directly use ecoinvent datasets for Swiss urban, regional and long distance passenger transport by train in this comparison, with two changes. The first change is that Swiss average electricity is used instead of the electricity mix of the Swiss federal railways. The reason for this is to allow fair comparison with other transport modes, and also that no future data were available for this electricity mix. The second change is that I make the assumption that future Swiss passenger trains will consume 20% less electricity per passenger kilometer than current trains, which is a goal of the Swiss federal railways [216]. All other aspects of the datasets are assumed to remain constant in the future.

The climate change impacts for Swiss passenger trains are shown in Figure 8.1 below for the current situation (left) and for three different scenarios for 2050 on the right. The production and maintenance of the tracks and trains is found to make up roughly 30-60% of the total climate change contribution, which is higher than for other transport modes. However, variation between the different transport distances and database versions is still mostly due to differences in energy consumption.

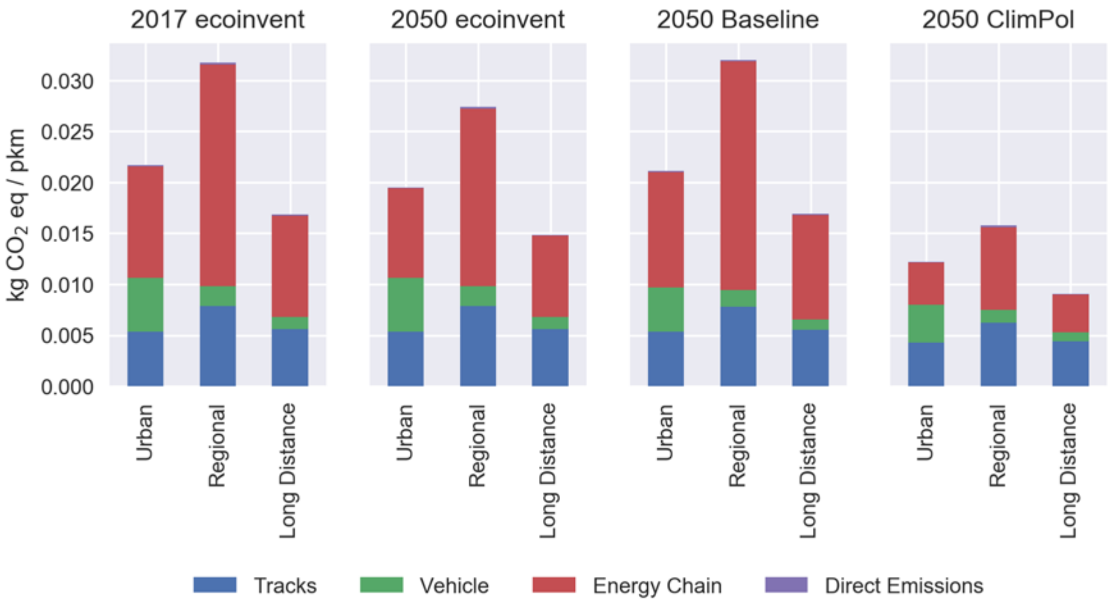

Figure 8.1 Climate change results for current and future Swiss passenger trains.

8.2.2. Energy chains

Two potential development pathways for the Swiss electricity sector are used based on future electricity mixes defined in the Swiss Energy Perspectives [21]. As in Chapter 7, the two scenarios are selected that may be considered to be the worst and best cases respectively: Business as Usual, with new electricity demand being met by additional natural gas power plants (BAU-C) and New Energy Policy with new demand being met by expansion of renewables where possible and the balance of electricity coming from imports (NEP-E). Figure 8.2 shows the climate change impacts of Swiss electricity for both scenarios. It should be noted that these results are calculated using different background database scenarios as described below.

Hydrogen production is considered only for PEM electrolysis of water with grid average low voltage electricity using LCI data from Zhang, Bauer [213] as in Chapter 7.

For sensitivity analysis, I also calculate results with what might be considered the marginal electricity and hydrogen mixes in Switzerland: electricity from a natural gas combined cycle power plant and hydrogen from steam reforming of methane. These results are shown for medium sized passenger cars in Figure 8.5.

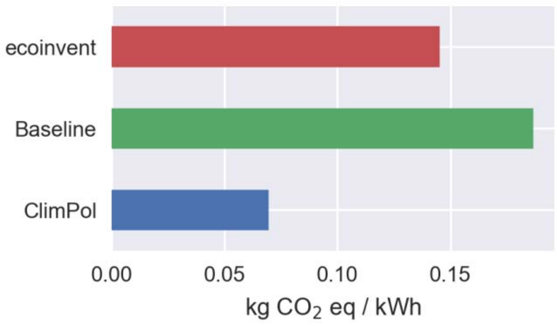

Figure 8.2 Climate change impacts for Swiss low voltage electricity for three background databases

8.2.3. Life cycle assessment background databases

The three different versions of the ecoinvent database described in Chapter 6 are used for the calculation of the life cycle impacts of future transport technologies. However, as the focus of this chapter is on Swiss transportation, I make one important change in this chapter. While in Chapter 6 the Swiss electricity mix was taken from the IMAGE integrated assessment model (which means that it was taken as the Western European average), in this chapter I define the Swiss electricity mix also in the background database explicitly using two scenarios from the Swiss Energy Perspectives as described above. Thus, the 'Baseline' background database is defined using the BAU-C Swiss electricity mix and the 'ClimPol' background database is defined using the NEP-E Swiss electricity mix. All results for future passenger transport modes are calculated using these three databases. Results for current passenger transport modes are calculated using ecoinvent version 3.4

8.2.4. Transport sector model

This section is an extension to the thesis that is meant to give an indication of the total sector level environmental burdens due to 2050 passenger transport in Switzerland for different energy and powertrain scenarios. The total domestic passenger transport demand for Switzerland in 2050 is taken from the Swiss Transport Outlook 2040 [5], which also makes a demand projection for 2050 for a single scenario [217]. Figure 8.3 shows the Swiss passenger transport demand. While four scenarios are presented for 2040, they vary by less than 5%, so it is deemed acceptable for our purposes to use the single scenario for 2050 for comparison with 2017. As the base year for the Swiss Transport Outlook is 2010, I use 2017 transport demand data from the Swiss Federal Statistical Office [4]. Furthermore, I also use this data source to disaggregate the Swiss Transport Outlook demand values from public transport into buses and trains, as well as private motorised transport into cars and motorcycles. The demand for international air transportation is taken from the low growth demand scenario in Chapter 4, considering passenger transportation only. This growth rate of 3% per year is in the range of historical growth of air transport demand in Switzerland, and also matches estimates for Switzerland and Western Europe [6, 125, 126, 132].

Table 8.4 shows the breakdown of Swiss passenger demand for different transport modes (with and without domestic and international air transport) and the breakdown of powertrains assumed to supply the demand. For 2017, the mix of vehicle powertrains is taken from Swiss statistical data for new vehicle registrations in 2016 [159]. For 2050, three powertrain scenarios are presented: the BEV and FCEV scenarios are made up of only these powertrains; the Fossil scenario is made up of hybrid cars and buses, and ICEV motorcycles. All three powertrain scenarios include electric trains and conventional aircraft. The breakdown of passenger transport by train is calculated based on data from the SBB and Swiss statistical data [4, 159, 218].

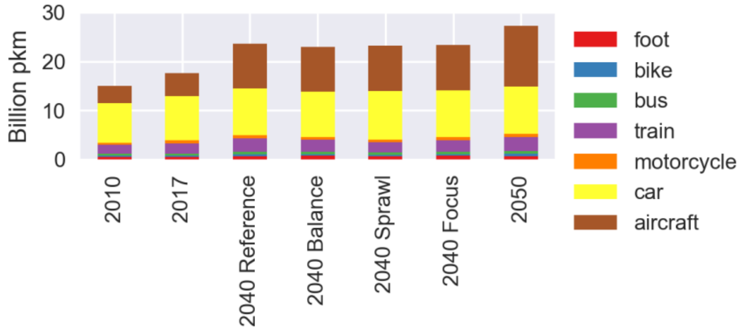

Figure 8.3 Total Swiss passenger transport demand. Source: [4, 5, 217]

Table 8.4 Swiss passenger demand breakdown by mode and powertrain. Source: [4, 159, 217, 218]

Transport mode	Passenger transport mode share				Powertrain share per mode				
	Excluding air transport		Including air transport				2050 Powertrain Scenario		
	2017	2050	2017	2050	Powertrain	2017	BEV	FCEV	Fossil
Aircraft			26.4%	45.4%	Swiss average	100%	100%	100%	100%
Car	70.2%	65.1%	51.6%	35.6%	ICEV-p	58.3%			
					ICEV-d	36.2%			
					ICEV-g	0.2%			
					HEV-p	3.8%			100%
					BEV	1.5%	100%		
					FCEV	0.0%		100%	
Motorcycle	4.2%	3.9%	3.1%	2.1%	ICEV	98.8%			100%
					BEV	1.2%	100%		
					FCEV	0.0%		100%	
Bus	3.4%	4.1%	2.5%	2.2%	Diesel	94.1%			
					CNG	0.0%			
					Hybrid	4.7%			100%
					Battery-LR	0.6%	50.0%		
					Battery-SR	0.6%	50.0%		
					Fuel Cell	0.0%		100%	
Train	16.0%	19.2%	11.8%	10.5%	Long distance	65.0%	65.0%	65.0%	65.0%
					Regional	24.1%	24.1%	24.1%	24.1%
					Urban	10.9%	10.9%	10.9%	10.9%
Bike	1.7%	2.6%	1.3%	1.4%	Bike	100%	100%	100%	100%
Foot	4.4%	5.0%	3.3%	2.7%	Foot	100%	100%	100%	100%

With the exception of aircraft travel, for which I use the fleet model developed in Chapter 4, passenger transport demand in 2017 and 2050 is assumed to be met with only vehicles that enter the fleet in that year. That is, the age structure of vehicle fleet is not considered and only the current new vehicle shares are considered for the powertrain mix. This is a simplification made to avoid having to build a fleet model which is considered out of scope for this simple assessment. I estimate that this leads to underestimation of the total fleet level impacts by roughly 15% as the average vehicle age in the fleet roughly 5 years old and vehicles improve by roughly 3% per year [10]. This is also seen in the model validation results in the following section. Furthermore, travel by foot and bike is assumed to have zero life cycle emissions, which is not true, but they are negligible compared to the other transport modes considered. Electric bicycles that travel over 25 km/h are included as motorcycles.

8.3. Results and discussion

8.3.1. Transportation mode comparison

Figure 8.4 shows climate change results for all transport modes per passenger kilometer (pkm). The left-most column shows results for 2017 technologies, while the other three columns show results for 2050 technologies calculated with (from left to right) the current ecoinvent background database, the Baseline background database and the ClimPol background database. The different rows show different transport modes and vehicle sizes. Battery electric powertrains are found to provide substantial climate benefits in Switzerland for all transport modes both today and for all future average electricity scenarios considered. While this is especially true in the ClimPol scenario, where the impacts of producing electricity and batteries are lowest, the conclusion also holds for the Baseline scenario. When battery electric vehicles are assumed to be charged by the likely “worst-case electricity mix”, from a natural gas combined cycle power plant, BEV are still found to provide climate benefits when calculated with the ClimPol background database, and to be comparable to combustion powertrains when calculated with the Baseline background database (see Figure 8.5). Fuel cell powertrains for all vehicle types are found to provide climate benefits in the ClimPol scenario, and also for urban buses and motorcycles in the Baseline scenario. If the marginal hydrogen production mix of steam methane reforming is considered, fuel cell passenger cars do not provide climate benefits compared to conventional powertrains in any scenario.

Results for other LCIA categories are included in Appendix C and show that battery and fuel cell electric vehicles for all transport modes do show some disadvantages in environmental impact categories that are strongly influenced by the production of the vehicle, especially mineral depletion and human toxicity. It is questionable, however, how accurate these results are as they stem almost exclusively from the mining of several metals, namely, copper, nickel, manganese, and platinum. As future datasets do not consider changes to recycling rates, changing metal scarcity, and emissions from mining, no certain conclusions can be made about the inferiority of BEV and FCEV in these categories. In terms of cumulative energy consumption, fuel cell powertrains are disadvantaged due to the efficiency of the hydrogen production chain.

When comparing the different transport modes, it is important to keep in mind that these results are shown per passenger kilometer and that, especially for cars, the number of passengers in the car has a large influence on the result. The results are shown for the 2015 Swiss average of 1.56 passengers per car; if the vehicle is driven with only a single passenger than the results increase by over 50%, but if the vehicle has four passengers, results are reduced by over a factor of two. The number of passengers could change dramatically in the future due to ICT developments that could improve the potential for car sharing. Conversely, the rise of autonomous vehicles could potentially also decrease the average number of passenger cars. Regardless of passenger load factors, electric trains are found to be the most environmentally efficient of all transport modes, and have the best performance in nearly every impact category. This is especially true in long distance travel, where the feasibility of electric cars is still uncertain, and air travel impacts are worse yet than conventional combustion powered passenger cars.

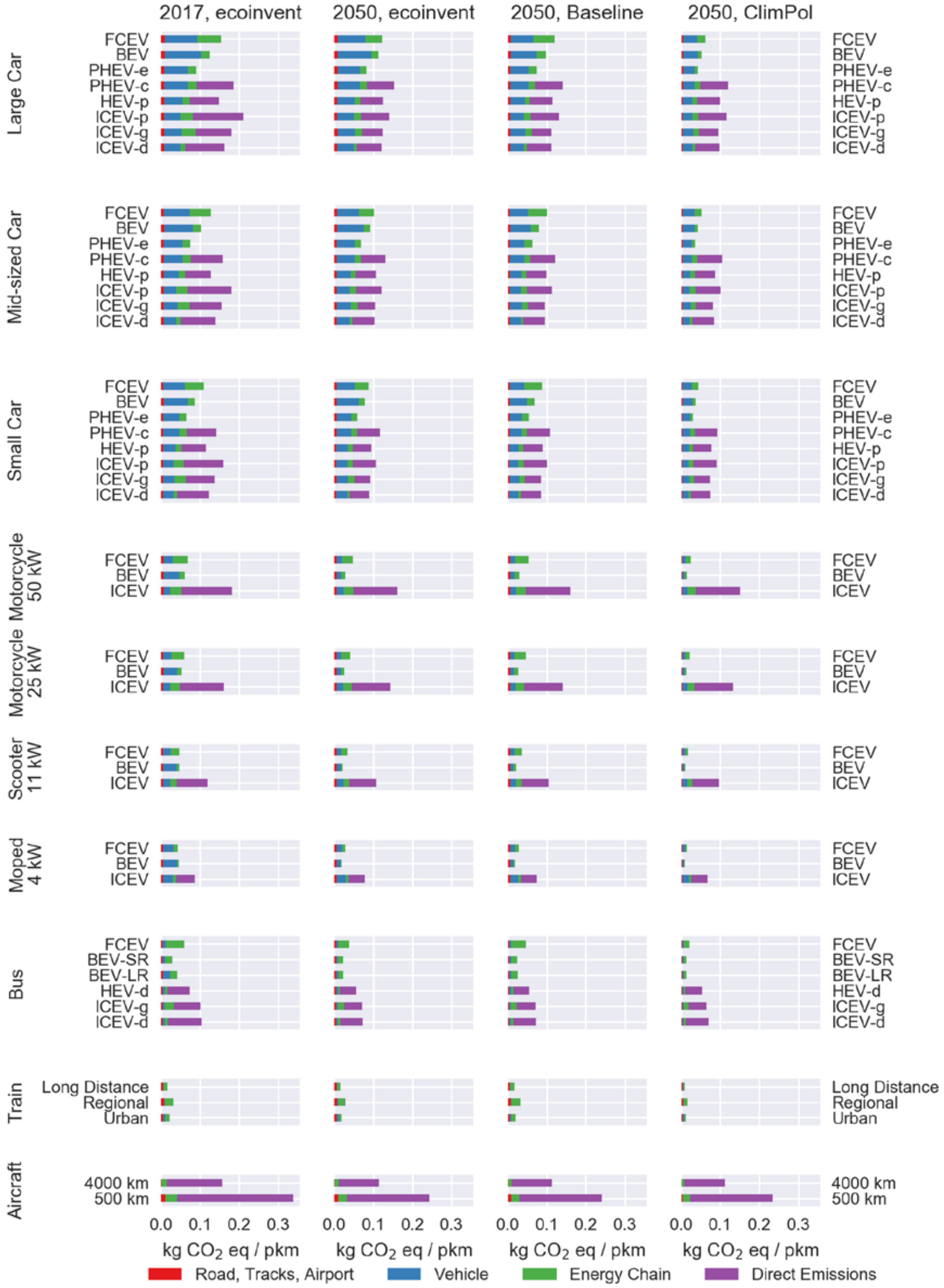

Figure 8.4 Transportation mode comparison – climate change

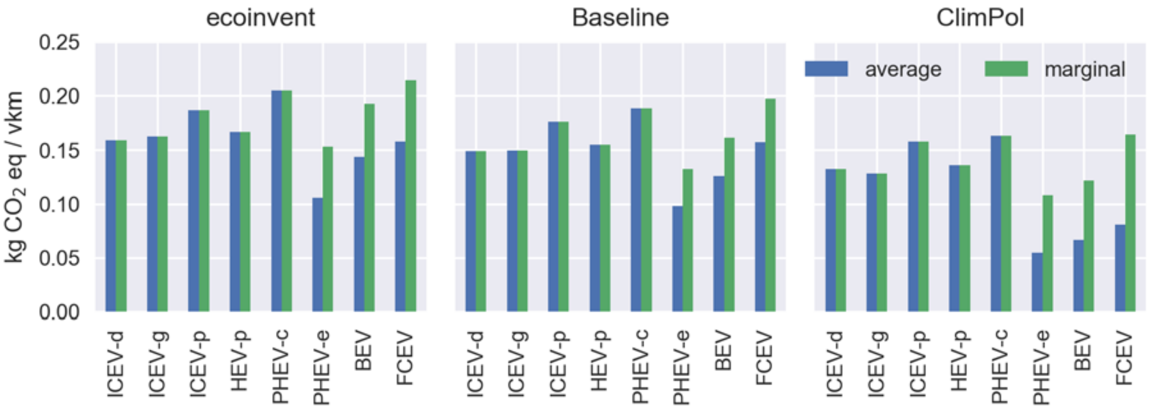

Figure 8.5 Climate change results per vehicle kilometer for future medium size passenger cars with average and marginal mixes for electricity and hydrogen production. Marginal electricity mix is assumed to be electricity from a natural gas combined cycle power plant. Marginal hydrogen mix is assumed to be from steam reforming of methane.

Quantitatively, the results for individual technologies may be summarized as follows: the life cycle climate change contribution of a 2017 mid-sized petrol powered passenger car is around 180 g CO_2 eq / pkm. Future technology developments, including mild hybridisation will likely reduce this impact to around 100-125 g CO_2 eq / pkm, while still maintaining petrol as the motive fuel. If future fuel cell vehicles are used, the life cycle greenhouse gas emissions could be reduced to 50-100 g CO_2 eq / pkm, depending on the future electricity system. With battery electric passenger cars, climate change impacts could be reduced to 43-82 g CO_2 eq / pkm, again depending on the future development of the electricity system. Through the downsizing of passenger cars to lighter models and increasing the number of passengers per car it would be possible to reduce the life cycle climate change impacts of passenger car transport to below 40 g CO_2 eq / pkm. If future urban transport relied instead on a combination of trains, motorcycles and buses, it is expected that the average climate change impact would even be below 25 g CO_2 eq / pkm in the baseline scenario and on the order of 10-20 g CO_2 eq / pkm in the ClimPol scenario.

8.3.2. Sector level results

Figure 8.6 shows the total Swiss domestic transport sector (excluding air transport) related climate change impacts for 2017 and 2050. Results for other impact categories are included in Appendix C. The panel on the left shows results for 2017, with the current powertrain and electricity mixes. The three panels on the right side refer to the three background energy scenarios similar to Figure 8.4. The x-axis shows the powertrain scenario for cars, motorcycles and buses. In the Fossil scenario, hybrid vehicles are taken for cars and buses and ICEV are taken for motorcycles. Trains are electric in all powertrain scenarios.

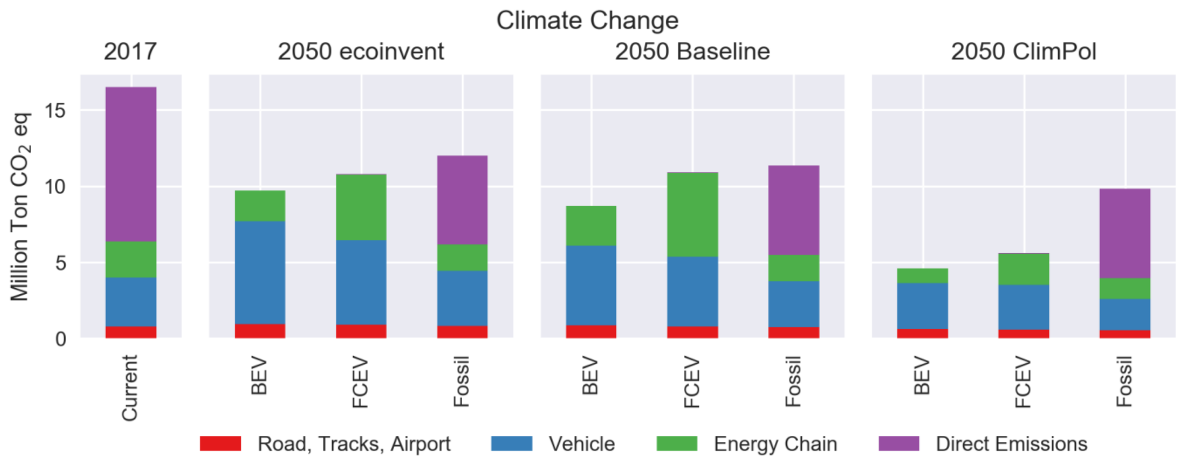

Figure 8.6 Swiss transportation sector level impacts, excluding air transportation- climate change per year

It is possible to validate the fleet model results by comparing the total direct CO_2 emissions with Swiss national statistics. 2017 model results show a total direct emission of 10.1 million tons of CO_2 eq from all modes of Swiss passenger transportation excluding all air transport. This compares quite well with the official value of 11.1 million tons CO_2 in 2015 [4]. The reasons for this 10% underestimation are also apparent. The first and main reason for the underestimation is that the fleet model assumes that all transport is provided by vehicles with a 2017 level of technology and powertrain mix. In reality, transport is provided by vehicles with a variety of ages, and older vehicles have higher CO_2 emissions. The second reason for the underestimate is that I have excluded all air transport in the model estimate, though the Swiss statistics include domestic air travel, which constitutes roughly 1% of total emissions [4]. A third simplification of the model is that passenger cars, motorcycles and buses are modelled as only one size class, which likely does not exactly match the average vehicle size in Switzerland as this was not calibrated exactly.

Direct emissions in 2050 are decreased by roughly 40% compared to the current situation in the fossil scenario. The BEV and FCEV scenarios show, as expected, direct GHG emissions from passenger transportation are essentially zero in the future.

Energy chain related emissions for the BEV and FCEV scenarios are dependent on the development of the Swiss electricity sector. The FCEV scenario results are more sensitive to this parameter due to the overall higher electricity consumption of the hydrogen production chain.

The climate change impacts from the vehicle life cycle are found to vary strongly with the background database used for the calculation, i.e., with the development of the global electricity sector. This is especially important for the BEV powertrain scenarios which have comparatively small impacts due to other life cycle phases. This result confirms the importance of the methodological improvement of considering developments of the electricity sector in the background database. A prospective LCA performed according to the status quo, where the future electricity mix is considered in the foreground for BEV charging, but not vehicle production would have overestimated the total BEV fleet climate change impacts by 1.5 and 3.7 million tons CO_2 eq if the international electricity sector developed according to the Baseline or ClimPol scenarios respectively. This would have constituted overestimation of the total impacts by approximately 15 and 37% respectively.

Taken as a whole, the results shown Figure 8.6 inspire cautious optimism regarding the potential for Switzerland to reduce its climate change impacts from domestic passenger transport in the future. Despite future growth in domestic transport demand, all scenarios show significant improvement. The baseline scenario in 2050 with fossil powertrains shows a reduction of 31% compared to 2017. This scenario requires a minimum of change in usage patterns for drivers, as the fuel infrastructure system will stay the same. In the Baseline energy scenario there is no climate benefit to switching to fuel cell powertrains. Switching to battery electric powertrains on the other hand would result in a 47% improvement compared to the current system. In the ClimPol scenario the reduction compared to 2017 is 41% for the fossil scenario, 66% for the fuel cell scenario and 72% for the battery electric vehicle scenario.

Figure 8.7 shows Swiss passenger transport related climate change contributions including domestic and international passenger transport by aircraft. These results appear far less promising than results for domestic transport only. This is especially alarming when taking into account that these results are calculated with the low air transport growth scenario. Even if the optimistic technology development scenario from Chapter 4 were to be included, results would only decrease by several million tons CO_2 eq per year. If global climate change emissions growth from passenger transportation is to be curbed, massive changes will have to be made in the air transport sector. It seems as though improvements on aircraft design and jet engines will not be sufficient. Alternative fuels may present some climate benefits, but producing them at the volumes required will be a massive challenge in the coming decades. The only remaining option appears to be the reduction of long distance transportation demand and shifting to high speed electric trains where possible.

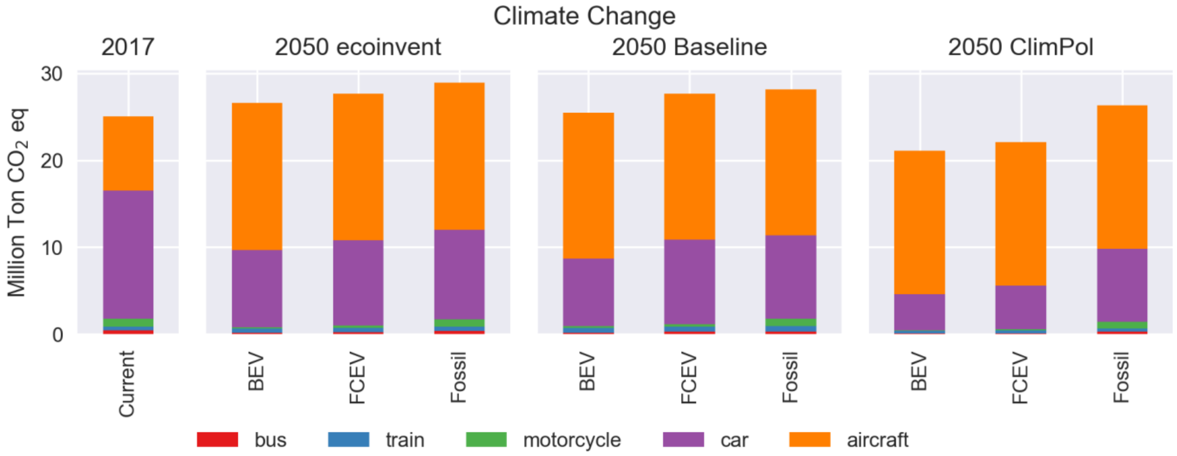

Figure 8.7 Swiss transportation sector level impacts, including air transportation- climate change per year

When other environmental impact categories (see Appendix C) are considered, the conclusions are similar for the fleet as they are for individual technologies. Cumulative energy demand for domestic transport will likely decrease slightly, except if fuel cells are widely used, which will increase total energy demand. Impacts from human toxicity and mineral depletion will increase for all powertrain types, though most substantially for BEV and FCEV scenarios. These conclusions are quite independent of the background database version, as the environmental burdens are not caused by electricity production. Environmental burdens due to particulate matter formation and photochemical oxidant formation increase in all scenarios, mostly due to the large growth in landing and take-off emissions from international air travel. While photochemical oxidant formation results

=are rather independent of the powertrain scenario, particulate matter formation scores are higher for BEV and FCEV scenarios. These are upstream PM emissions resulting from electricity production. It should be noted here that PM emissions from electricity production were not directly modified using IMAGE scenario results during the database modification, so the PM emissions from future electricity production are likely overestimated here.

8.4. Uncertainties and limitations

The uncertainties and sensitivities for each transport mode and powertrain are described in detail in the previous chapters. Here I focus on some of the uncertainties and limitations that pertain to the comparison of different transport modes and estimation of sector wide impacts.

The first and main difficulty encountered when comparing different transport modes is that the results are highly dependent on the average number of passengers per vehicle assumed. I have taken the Swiss average vehicle load factors from 2015 [215] and assumed that they will be also valid in 2050. Changing these load factors would have a nearly one-to-one impact on the results. Substantial reductions in environmental burdens per kilometer could be achieved if these values were to increase, which may be possible given the potential of ICT to link car sharing partners. Conversely, the average number of passengers per car may also decrease with the introduction of autonomous cars which could spend a significant share of their driving time without a passenger. This is a highly uncertain parameter with a strong impact on the results that should be the focus of future research.

A second limitation along these lines has to do with the potential wide scale adoption of autonomous vehicles. This technological breakthrough will have wide scale impacts on transport demand, vehicle load factors and the shares of private versus public transportation. These factors were not considered here, though they certainly warrant further investigation. Furthermore, the introduction of autonomous and connected vehicles will likely allow passenger car energy consumption reductions on the order of 10% (see Chapter 6) which were also not considered here.

A third important limitation of the comparison is the electricity mix assumed for charging batteries and producing hydrogen. I have considered three different average electricity mixes: current, BAU-C and NEP-E and examined results for individual transport modes and the whole sector assuming that these electricity mixes were constants. In reality, the total electricity demand in Switzerland (and therefore the electricity mix) would look quite different if all vehicles on the road were powered by fossil fuels, hydrogen produced by electrolysis, or direct battery charging. In fact, the total difference in annual electricity demand would be on the order of Terawatt hours, which would certainly change the average electricity mix in Switzerland. The impacts of the most extreme case can be understood by looking at the sensitivity of results to differences in marginal versus average electricity mix in Figure 8.5. Here we see that if BEV are charged only with electricity from natural gas combined cycle power plants they still provide climate benefits in the ClimPol scenario where the global impacts of battery production are small. In the Baseline scenario, BEV charged with the marginal mix have comparable climate impacts to combustion powertrain vehicles. Another example of the limitation of the current missing link between electricity and transport sectors in the model is that the opportunities for hydrogen production and battery charging to be used as a variable load to help with grid stabilisation have also not been considered. Future work should focus on increasing coupling of LCA models with transport and energy models to better explore these uncertainties.

Finally, as discussed in the methodology section, the fleet model used here was extremely simplistic and was meant to give an indication of the fleet wide impacts of different powertrain and energy scenarios. Future work should include building a fleet model that accounts for vehicle age and retirement rates, well as adoption rates of new technologies, and a variety of different vehicle sizes and powertrain options.

8.5. Conclusions

In this chapter I quantify and compare the environmental burdens of different current and future passenger transportation technologies in Switzerland, taking into account different future scenarios for the development of national and global electricity sectors. I further present a simple fleet model to estimate the total environmental burdens of passenger transport in Switzerland both in 2017 and in 2050.

Results clearly show that electrification of mobility will reduce per kilometer passenger transportation related environmental burdens, especially in terms of climate change, in Switzerland. This conclusion can be made with reasonable independence to future developments of the Swiss electricity sector, though a cleaner electricity sector will further reduce mobility related climate change contributions. Electric vehicles are also the most efficient in terms of the overall energy chain which is very important in a country such as Switzerland where the overall potential for expansion of renewable electricity generation is limited. Fuel cell vehicles could also provide nearly the same climate benefits if the future Swiss electricity mix has low carbon content, though this scenario has much higher electricity demand. Conversely, production of hydrogen for mobility may allow better integration of intermittent renewables into the grid, which could also provide system benefits that are not quantified here. An ideal system could be that the majority of vehicles are pure BEV, and vehicles that require additional range are equipped with a fuel cell range extender. The production of this smaller amount of hydrogen has lower energy chain efficiency, but has the benefit of adding some flexibility into the system in terms of energy storage. Future work should focus on linking energy and transport models with LCA to better understand such trade-offs.

Electric trains are found to be the most efficient means of transporting passengers, though when filled to capacity, all road passenger transport modes with electric drives have comparable environmental performance. An optimised transport system will likely consist of a mix of different transport modes so that convenience and availability are balanced with high passenger load factors and system efficiency.

In terms of meeting long distance international transportation demand, electrified trains are clearly the best available solution in the long run, even with fossil based electricity mixes. While aircraft have improved substantially in the past decades and are expected to continue improving, they are not compatible with climate change targets as long as they are powered by fossil fuels.

Results from the simple fleet model show that climate change impacts from Swiss domestic passenger transport demand will generally decrease in the future, though the reductions depend on the types of vehicles put on the road as well as the development of the national and global electricity sectors. If all road vehicles in 2050 are powered by fossil fuels, GHG emission reductions on the order of 31-41% compared to 2017 are expected. If all road vehicles are powered by fuel cells with hydrogen produced by electrolysis, GHG emissions reductions would be 34-66%, with emissions strongly dependent on the development of the Swiss electricity mix. If all 2050 road vehicles are battery electric emissions reductions of 47-72% are expected.

There are some environmental impact categories that are expected to get worse in the future. Mineral depletion and human toxicity impacts are calculated to roughly double in the future for the BEV and FCEV scenarios, with the impacts coming from the increased number of vehicles on the road, but mostly due to the materials required for producing batteries and fuel cells. It should be noted here that future recycling programs and cleaner mining practices could greatly reduce these impacts, though they are not included here. Conversely, increasing mineral scarcity might have the opposite effect. Cumulative energy demand, particulate matter formation and photochemical oxidant formation potential from domestic passenger transport are expected to remain roughly constant in the future, with efficiency improvements broadly cancelling out increased transport demand.

Converting to BEV or FCEV based domestic transportation will reduce direct vehicle emissions in Switzerland to nearly zero in the future. In the Baseline scenario, this national reduction is accompanied by an increase in foreign emissions due to the production of the vehicle. In the ClimPol scenario there is also a reduction in most foreign emissions due to improvements in the electricity sector.

When international air transport is included in the fleet model, this transport mode dominates results in some categories. Future air transport is found to make up nearly two-thirds of 2050 passenger transport related climate change impacts and nearly half of cumulative energy demand.

Chapter 9. **Discussion and conclusions**

In this concluding chapter, I first summarize the work done and mention several highlights from each chapter in section 9.1. I then summarize the main conclusions of the thesis in section 9.2 and go on to describe the limitations and recommended future work in section 9.3. I provide some final concluding remarks in section 9.4.

9.1. Summary of work and highlights

In this thesis, I present models that quantify the life cycle environmental burdens of current and future passenger transport for different transportation modes.

Chapter 3 presents a paper that Chris Mutel and I published in the journal Applied Energy where we examine the life cycle costs and environmental burdens of motorcycles with a European focus [24]. In this paper, we show that battery electric motorcycles are already cost competitive with conventional motorcycles and offer large environmental benefits, even with electricity generated from fossil fuels. We further show that the variability in motorcycle environmental performance is mostly due to driving speed, and that the energy consumption for urban motorcycle operation is far lower than for highway driving. Methodological highlights of the paper include model validation using real motorcycle data scraped from online motorcycle databases and published motorcycle energy consumption data, and the use of jupyter notebooks and extensive supporting information files to make the calculations completely transparent – a trend that is continued in my other publications. A further highlight of this paper is the one-at-a-time sensitivity analysis to examine the impacts of all important input parameters.

Chapter 4 presents a paper published in the journal Transportation Research Part D: Transport and the Environment [25]. In this paper, my co-authors and I perform life cycle assessment of the Swiss air transport sector from 1990 until 2050. Based on literature data, we first perform LCA for 72 common aircraft types for different flight distances. We then perform linear regression on these life cycle inventories and use other data sources to develop LCI for representative aircraft that can be used to model the entire Swiss aircraft fleet, including future performance until the year 2050. We combine these models with Swiss statistical data to calculate the environmental burdens of the entire Swiss air transport sector annually from 1990 to 2015 and for two future demand scenarios until 2050. Models are validated using national kerosene consumption data and are found to be within a 7% error margin for each year. We also address uncertainties using two scenarios for future technology development and two scenarios for future air transport demand. The main conclusion of this paper is that despite rapid improvements being made in aircraft efficiency, these improvements are far outpaced by growth in air transport demand, and that overall environmental burdens of the sector are likely to increase in the future. The main methodological highlight of this paper is the separate quantification of aircraft operating emissions based on the phase of flight. This allows the use of different characterisation factors for cruise phase emissions, which has significant impacts on results, but has never been done before in LCA. Until now, the use of different characterisation factors for different emission altitudes has either been completely neglected or merely approximated with a simplified uplift factor for average flight distances [136, 142, 219, 220]. The use of flight phase characterisation factors for impact categories other than climate change has never been published before to the best of my knowledge. As is the case with my other publications, all underlying calculation files are made available in the supporting information so that the results are completely reproducible.

Chapter 5 is based on work that I presented at the 30th Electric Vehicle Symposium in Stuttgart, 2017 [26]. In this conference paper, my co-authors and I examine the environmental performance of current and future urban buses with different energy sources. While the conference paper is written using a methodology that is very similar to that found in Chapter 3, the presentation slides showed a first application of Monte Carlo analysis and use of modified versions of the ecoinvent database that are further developed and published in Chapter 6.

Chapter 6 is based on a manuscript published in the journal Environmental Science and Technology. In this paper, my co-authors and I assess the environmental burdens of current and future battery electric passenger cars with a focus on uncertainties in foreground processes. We make use of uncertainty assessment techniques such as Monte Carlo analysis and global sensitivity analysis, which lead to a better understanding of the parameters that drive variability in the results. Furthermore, we include a methodology that I developed to endogenously capture the potential energy consumption impacts of autonomous and connected vehicles in LCA using exponential smoothing of harmonised driving cycles. This method allows for a simple estimation of autonomous vehicle energy consumption with varying vehicle parameters such as weight, aerodynamics, driving profile, rolling resistance, and recuperative braking capabilities. Until now, the potential for autonomous and connected vehicles has not been included in any published LCA of future vehicles. Furthermore, other published studies that assess the energy consumption impacts of autonomous cars have yet to propose a methodology that can endogenously calculate energy savings considering the interrelated effects of traffic smoothing, recuperative braking, mass reduction, platooning, and increased auxiliary energy demand [172, 175, 176, 178].

Perhaps the main methodological development included in Chapter 6 is the use of integrated assessment model results to systematically modify all electricity production datasets and create future versions of the ecoinvent database. This is an important improvement upon the prospective LCA status quo of assuming that the current LCA database can be used for the assessment of future technologies by changing only selected foreground processes. We demonstrate in Chapter 6 that neglecting to make these changes to the background database when assessing the impacts of producing and operating future battery electric cars could lead to inaccuracies in results by up to 75% in scenarios for radical electricity sector decarbonisation. What is perhaps even more significant is that Chris Mutel and I wrote the Wurst software package (https://github.com/IndEcol/wurst) to perform these changes in an open source software format that is free for anyone to use. This software enables systematic changes to be made to the ecoinvent database in an efficient and transparent manner with minimum effort. This software has the potential to greatly improve the quality of prospective LCA for all who choose to embrace it. We are able to conclude in Chapter 6 that globally operated future electric vehicles are expected to have 45-78% lower climate change impacts than current electric vehicles. The electricity mix used for charging is found to be the largest source of variability in results, though vehicle size, lifetime, driving patterns and battery size also strongly contribute to variability.

Chapter 7 is a scientific background report that I wrote with Christian Bauer for the Swiss Federal Office for Energy comparing the environmental performance of current and future passenger cars with different powertrain types. We use the uncertainty assessment methods developed in Chapter 6 and expand the model to consider all relevant passenger car powertrain types. Furthermore, we synthesize the results into a four page fact sheet for decision makers that presents the most important results of the assessment in a simple way. Thus, the results from this thesis should directly contribute to decision making regarding passenger transportation and the energy transition in Switzerland.

Finally, in Chapter 8 I update the previously shown calculations for all transportation modes using harmonized input assumptions with a Swiss focus. I include two scenarios for the future development of the Swiss electricity sector from Chapter 7 as well as future LCA databases that represent scenarios for the global electricity sector as presented in Chapter 6. I use a simple fleet model to estimate the total environmental burdens due to Swiss passenger travel for each electricity scenario and for three powertrain scenarios. Due to the depth of the analysis performed in the individual chapters as well as the breadth of the analysis covering all relevant passenger transport modes and different future national and global electricity scenarios, I am able to draw meaningful conclusions about the environmental burdens of the future Swiss passenger transport sector. The most important of these conclusions are summarised in the following section.

9.2. Summary of conclusions

The goal of this thesis is to gain a better understanding of the environmental burdens associated with the different transportation technologies that may be used to meet future passenger transportation demand in Switzerland and how these conclusions may change under different future electricity scenarios. In this section, I summarize some of the most important findings. More detailed conclusions can be found at the end of each individual chapter.

The relative performance of conventional combustion engine vehicles compared to hybrids and battery and fuel cell electric vehicles is quite similar for cars, motorcycles and urban buses. The introduction of battery electric vehicles provides clear climate change benefits for all vehicle types as long as the electricity used for charging has a carbon content similar to or less than that generated by a modern natural gas power plant. Switzerland’s current and future electricity mix for all likely scenarios easily meets this requirement, so a robust conclusion may be drawn that from a greenhouse gas emission point of view, battery electric vehicles of all types should be promoted in Switzerland.

There are concerns among drivers regarding the range and recharging times of battery electric vehicles that lead to some vehicle manufacturers installing very large batteries in their vehicles, which increases vehicle cost and energy consumption and also significantly increases the environmental burdens of vehicle production. This is unlikely to pose a long term concern, however, as battery cell energy density is expected to substantially increase in the medium term and the impacts of battery production, namely due to electricity demand, are expected to decrease. Furthermore, the introduction of high power rapid battery charging without implications on battery lifetime will likely further reduce the need for vehicles with very large batteries. Urban buses are an excellent example of this technological breakthrough, and several manufacturers are already making use of on-route charging to provide very short, high power charging sessions to reduce battery size requirements. A short-term solution for vehicles with less predictable operating schedules is to design vehicles with a plug-in hybrid configuration, as this allows greater utilisation of the onboard batteries and circumvents range anxiety. Fuel cells are an excellent candidate to be used as range extenders in plug-in hybrid electric vehicles.

While pure fuel cell vehicles are found to have comparable climate change impacts to battery electric vehicles for very low carbon content electricity mixes, it is likely their overall energy chain efficiency that will be their downfall for widespread adoption in Switzerland for passenger vehicles. The losses caused by multiple energy conversion steps result in higher greenhouse gas emissions and an increase in electricity demand that is likely not tolerable in a country such as Switzerland where there is limited potential for the expansion of renewable electricity generation capacity. Similar conclusions may be drawn concerning power-to-gas fuelled vehicles. There are, however, likely certain applications that these vehicles may thrive in – a notable one being their combination with energy storage or electricity grid stabilisation, another being in markets where pure battery electric vehicles are not possible due to range, recharging or other constraints.

When other environmental impact categories are considered, the superiority of battery electric vehicles is less clear. In the categories for mineral depletion and human toxicity, battery electric vehicles perform worse than all other powertrain types, and have even double the environmental impacts compared to future hybrid vehicles. It should be noted, however, that these impacts are almost entirely due to the production of copper and manganese sulfate used in batteries. A large-scale battery recycling program would likely greatly reduce these impacts, but was not considered in this thesis. Furthermore, the future emissions caused by mining these materials are also uncertain and not treated in this work.

I use a simple fleet model to quantify the life cycle environmental burdens caused by the 2050 domestic Swiss passenger transport sector in a scenario where all road vehicles are powered by battery electric powertrains. Results are quantified for two electricity scenarios considering both domestic and global developments. In the Baseline scenario, which can be considered a business as usual scenario, the total passenger transport related life cycle GHG emissions are 47% lower than in 2017. In the ClimPol scenario, which represents aggressive decarbonisation of the national and global electricity sectors, life cycle GHG reductions are 72% compared to 2017[9]. In both scenarios, the direct GHG emissions from domestic transport in Switzerland tend towards zero, indicating that Switzerland's passenger transport sector will likely be able to meet its share of the 70-85% CO_2 emission reduction targets compared to 1990 in 2050 [3] if the majority of the fleet is converted to electric powertrains. In the Baseline scenario, the upstream GHG emissions due to Swiss passenger transport will increase by 37%, while in the ClimPol scenario they will decrease by 28%. In fact, the most significant differences between these two scenarios are due to emissions that occur upstream in the vehicle life cycle, mostly outside of Switzerland, and decisions made in Switzerland regarding the construction of new electricity generating capacity have only a limited impact on the overall GHG emissions in these scenarios as in all cases, the average Swiss electricity mix is expected to have relatively low carbon footprint. Of course, if one considers that all new electric vehicles would be charged by marginal electricity producer, which will most likely be natural gas combined cycle power

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[9] For comparison, if the 2050 fleet were to be made up of solely fossil fuelled hybrid vehicles, the Baseline reduction would amount to 31% and the ClimPol reduction to 40% with the direct tailpipe GHG emissions being reduced by 40%.

plants, this conclusion does not hold and climate reductions in this scenario are on the order of 30-40% compared to 2017.

Fleet simulations with BEV powertrains also show local air pollution due to vehicle exhaust tending towards zero, which will likely have substantial health benefits for the Swiss population as transportation is currently the largest emitter of NO_x in Switzerland [4]. However, already today a significant share of environmental burdens caused by Swiss passenger transport occurs outside of Switzerland for nearly all impact categories. This will further increase in the future if conventional vehicles are replaced with battery electric vehicles.

When international air transport is also included in the future fleet assessment, it is found to dominate the results in some categories, making up nearly two thirds of the life cycle climate change contribution and half of cumulative energy demand. If air transport demand continues to grow according to projections, it will become one of the most important sources of greenhouse gas emissions in the future, and no obvious technical solution is available to mitigate these air transport emissions without curbing or shifting demand. Efforts should be made to shift this transport demand to high speed electric rail networks to the greatest extent possible.

9.3. Limitations and future work

9.3.1. Life cycle assessment methodology

In this thesis, I use the methodology of life cycle assessment to quantify and compare the environmental burdens of current and future transport technologies. LCA is well suited to such assessments as its goal is to include all environmental burdens associated with the transportation technology and to avoid the shifting of environmental burdens to outside of the analysis scope. However, there are some limitations to the LCA method that should be discussed.

While the goal of LCA is to include the entire product life cycle, it is still incomplete in this thesis with notably the services sector being underrepresented in LCA. The impacts of these missing sectors could be estimated through the use of environmentally extended input-output analysis or hybrid LCA, but this was not done here. Furthermore, the work at hand focusses on environmental burdens; costs, social impacts, and accident risks are excluded. Even within the realm of environmental burdens, the methodology used is not complete. The excluded environmental burdens most relevant for an assessment of transport technologies are human health impacts due to noise pollution and land use. Furthermore, even for categories considered in this thesis, knowledge of all environmental exchanges and their burdens is still not complete, as highlighted by new findings from PSI's Atmospheric Chemistry Lab regarding particulate matter [221].

Another limitation of the LCA methodology used in this thesis is the fact that environmental burdens are not assessed with consideration of where the emissions occur. Of particular relevance to transport technologies are the human health impacts due to tailpipe emissions from vehicles in highly populated urban centers. In this study, as is standard practice in LCA, these emissions were assigned equal characterisation factors to emissions that occur in areas of low population density. My results show that LCA scores in impact categories such as particulate matter formation and photochemical oxidant formation are quite similar for BEV, FCEV, and ICEV as the total life cycle emissions are fairly similar. If the location and population density of the emission location were to be considered in the calculation, there would likely be more differentiation between the results, with ICEV expected to have higher environmental burdens. Increasing the regional resolution of LCI generation and LCIA methods is one way to approach future work in this regard; another approach could be to build on the Impact Pathway Approach used in project THELMA [17].

9.3.2. Prospective life cycle assessment methodology

In addition to the general limitations of the life cycle assessment methodology used here, there are some limitations related specifically to the use of LCA to model the environmental burdens of future technologies. Aside from the difficulty in modelling future technology performance, there is also the difficulty in finding a suitable background database to use for the assessment. Within the scope of this thesis, I helped develop software to ease the creation of “future LCA databases” and include future changes to the electricity sector in the ecoinvent database when calculating results for chapters 6 and 8. I have also shown the importance of including these changes to the electricity sector for the accuracy of results.

The discovery of how much this can affect results highlights the urgency of extending these future changes to other aspects of the database, such as, but not limited to, goods transportation, heat production and consumption, material recycling rates, component production locations, production of key materials, material efficiencies, and fossil fuel production. Furthermore, in this proof-of-concept work, I took only results from the IMAGE model; a complete approach would include data from many sources. Methods should be developed to include the uncertainty of future developments into the dataset structure, for example including variability among future technology predictions from different independent sources. I hope that a community can be built around the Wurst software for sharing future technology datasets and software used to create future versions of LCA databases.

A further and related limitation is the fact that all LCA calculations are performed with an attributional system model – that is, average processes are assumed to produce and operate future transport technologies. However, especially in the case of system wide transitions from conventional to electric vehicles, a consequential view might be more appropriate. Future work should include the improvement of consequential LCA databases so that sensitivity of results to this modelling choice can be easily included in results.

Another difficulty lies in finding harmonised future scenarios to link with the background database. For example, in the future fleet scenarios for BEV and FCEV, the same Swiss electricity mix was assumed, despite the fact that the two scenarios would result in substantially different total Swiss electricity demands, and thus different electricity mixes used for battery charging and hydrogen production. Future work should include linking LCA with transport and energy models for harmonized scenario production. Furthermore, the use of battery and fuel cell electric vehicles to act as storage mediums for electricity to help with integration of intermittent renewables into the grid should also be considered. Such systems level models will be required to answer future questions about the energy system as the transportation and electricity sectors become further interlinked.

A complete methodology for prospective LCA would also include updated life cycle impact assessment methods, which are considered out of scope for this thesis.

9.3.3. Modelling of transportation technologies

This set of limitations relates to the modelling of the transportation technologies themselves. One limitation is that there is significant variation in performance within vehicle classes and even for the same vehicle with different driving patterns. Results are shown for average vehicles in each class and for average driving patterns. In Chapters 6 and 7, I present methods to quantify these uncertainties, though I make the simplification of removing these uncertainties in the technology comparison in Chapter 8.

A second limitation is that there is significant uncertainty in defining the future performance characteristics of technologies. I try to mitigate this uncertainty by using one-at-a-time sensitivity analysis in Chapter 3, scenarios in Chapter 4, and Monte Carlo analysis in Chapters 5 to 7. Nevertheless, there is some concern that the selected parameters may not accurately reflect the future technology performance. Moreover, the performance improvements assumed here generally consider consistent annual improvement of a technology rather than technological breakthroughs, which are very hard to predict. I do, however, attempt to include one breakthrough regarding the introduction of autonomous and connected vehicles in Chapter 6. In order to show the importance of this breakthrough, I clearly compare results with and without the breakthrough and how the uncertainty related to this parameter compares to other uncertainties in the model. This could be used as a template for the incorporation of certain other potential breakthroughs, such as extremely fast battery charging, or significantly increased car-pooling rates, though other potential breakthroughs remain nearly impossible to include in the model.

A third limitation in modelling transportation technologies is that I generally use life cycle inventories for current technologies as proxies for future technology LCIs with changes only to key parameters. An example of this is lithium ion batteries, where the same basic LCI currently valid for the production of one kilogram of battery is assumed to be valid for the future production of one kilogram of battery, with only the cell energy density, the ratio of cell to battery structure and cell production electricity consumption changed. In fact, the majority of datasets used to model future technologies are defined for current production. This simplification may be justified, as care was taken to update the most important aspects of the models that are found to contribute to the results. However, more work could be done to adapt additional datasets.

The fourth limitation that warrants discussion is the fact that vehicle component production has been assumed to occur as global average processes. This means that regional variation of vehicle production has been totally omitted. Future work could be done to create regional datasets for the most important vehicle components that are known to be produced in different locations, such as vehicle gliders, lithium ion batteries and fuel.

9.3.4. Transport mode comparison and fleet model

The first and most obvious limitation in the transport mode comparison and fleet model presented in Chapter 8 that should be corrected in future work is that not all transport modes are covered in sufficient detail. Passenger trains are only superficially treated, though they will definitely be relevant in future sustainable transport systems. Moreover, I chose to exclude freight transportation from the assessment in order to allow more time to develop the methodology for linking integrated assessment models to LCA databases. While I believe this was the correct decision as it significantly improves the quality of the results, datasets for future freight transportation should be generated so that a complete model of the transport sector may be developed.

A second difficulty encountered when comparing different transport modes is that the results are highly dependent on the average number of passengers per vehicle assumed. I have taken the Swiss average vehicle load factors from 2015 [215] and assumed that they will be also valid in 2050. Substantial reductions in environmental burdens per kilometer could be achieved if these values were to increase, which may be possible given for instance the potential of ICT to link car sharing partners. Conversely, the average number of passengers per vehicle may also decrease with the introduction of autonomous cars, which could spend a significant share of their driving time without a passenger. This is a highly uncertain parameter with a strong impact on the results that should be the focus of future research.

Finally, the fleet model used in Chapter 8 was extremely simplistic and was meant only to give an indication of the fleet wide impacts of different powertrain and energy scenarios. Future work should include building a fleet model that accounts for vehicle age and retirement rates, well as adoption rates of new technologies, and a variety of different vehicle sizes, powertrain options, and usage profiles. Once all individual transport technologies have been modelled, the next logical step would be to move towards modelling the entire transport sector. Such a model could be used to determine, for example, the optimum mix of short and long range electric vehicles or the impacts of moving from privately owned vehicles to car sharing schemes, or even to fleets of autonomous vehicles and how they might best interact with public transportation. Rebound effects and increased distances travelled due to autonomous driving are further areas of potential study along these lines.

9.4. Conclusions

In this thesis, I examine the environmental burdens of different passenger transportation modes and technologies both today and in the future. I develop models for motorcycles, aircraft, urban buses and passenger cars with both current and future performance. In order to include future changes to the electricity sector in my models, I develop methods to systematically modify the electricity sector datasets in life cycle assessment databases using external data sources. I have made the software we developed open access and publically available in the hope that others will build on my methods to improve the accuracy and representativeness of the LCA databases used for their studies and increase the overall accuracy of LCA models. I further develop models to include Monte Carlo analysis and global sensitivity analysis in the assessment of future transport technologies to test the sensitivity of results to uncertain input parameters, and conclude that these uncertainties are significant compared to uncertainties in the background database in the case of electric passenger cars.

The results from this thesis are expected to directly contribute to decision making regarding the Swiss energy transition. I am the first author of a PSI report solicited by the Swiss Federal Office for Energy that summarizes my findings regarding the environmental burdens of passenger cars and includes a four page fact sheet that is expected to reach the highest level of decision makers in Switzerland.

Finally I develop a simple fleet model including all relevant passenger transport modes in Switzerland and quantify the total life cycle environmental impacts due to Swiss passenger transport for several powertrain and electricity scenarios in 2050. With this simple fleet model, I am able to show that the electrification of road vehicles will substantially contribute to meeting Switzerland’s domestic climate goals and that the real climate concern in the long term appears to be greenhouse gas emissions caused by international air transport, which are not included in Switzerland’s climate targets, though they are likely to surpass domestic passenger transport related greenhouse gas emissions before 2050.

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Appendix B. **Supporting information for Chapter 7**

B.1. **Fact sheet**

Fact sheet: The environmental burdens of passenger cars: today and tomorrow

This fact sheet and the corresponding background report describe the environmental burdens of current and future passenger cars on the basis of life cycle assessment. The assessment includes the entire life cycle of vehicles: manufacturing, operation and end-of-life. It also includes the production chain of the fuel, whether petrol, diesel, gas, electricity or hydrogen (H_2) and the entire fuel chain infrastructure. This life cycle perspective is important because, although battery and fuel cell vehicles do not emit any pollutants through their exhaust, the environmental burdens of producing these vehicles and the electricity and hydrogen that they consume can be substantial.

Vehicle technologies and fuels

Conventional vehicles with combustion motors (ICEV) can be operated using petrol, diesel or gas. Alternatively, vehicles can be powered by electric motors, such as battery or fuel cell electric vehicles (BEV and FCEV, respectively). The „fuel" for these vehicles is electricity that is either stored directly in batteries, or in the form of hydrogen that is converted into electricity using fuel cells as it is needed. Plug-in hybrids have an onboard battery that be charged from the electricity grid and also a combustion motor. They can operate either in electric or combustion mode. In the future, electricity vehicles may operate using synthetic natural gas (SNG). In this case, electricity is used indirectly to produce hydrogen via electrolysis. This hydrogen is then reacted with CO_2 to produce SNG which can be combusted in standard combustion motors to power vehicles (ICEV-SNG).

Summary of findings:

- When BEV and FCEV are powered by electricity or hydrogen from sources with low CO_2 emissions they cause substantially lower greenhouse gas emissions than petrol, diesel and gas powered ICEV (Figure B-1 „Greenhouse gas emissions" and Figure B-4).
- This means that the introduction of electric mobility should be accompanied by an increase in renewable electricity generation capacity. Electricity should also be used more efficiently in other sectors.
- Electric vehicles cause essentially zero direct exhaust emissions, and can thus help improve air quality in regions with high transport demand.
- The production of BEV and FCEV causes greater environmental burdens than the production of ICEV. Increased greenhouse gas emissions from vehicle production can be compensated for by lower operating emissions after roughly 50 000 kilometers of vehicle life, as long as electricity and hydrogen are from low CO_2 sources (Figure B-3).
- The CO_2 balance of BEV depends strongly on the CO_2 intensity of the electricity used to charge the battery (Figure B-4). This is also true for FCEV and ICEV that operate using synthetic natural gas produced using the „power-to-gas" process.
- BEV have the highest overall energy efficiency. FCEV and ICEV operated with synthetic natural gas are less efficient, especially due to large energy losses in the fuel production chain.
- With this in mind, BEV are the best option among the low emission vehicles to use renewable electricity most efficiently.

The life cycle assessment results in Figures B-1 to B-4 represent average mid-sized vehicles. The most important assumptions for the vehicles are summarized in Table B-1.

Table B-1 Base vehicle parameter values in the life cycle assessment

			Lifetime	**Vehicle mass**	**Fuel consumption (Real operation)**		**Range**	**Efficiency "tank-to-wheel"**	**Emissions-standard for exhaust emissions**
			km	kg	L gasoline eq. per 100 km	per 100 km	km	%	
2017	**ICEV**	**Petrol**	180 000	1357	7.6	7.6 Liter	524	21	EURO 6
		Diesel		1380	6.9	6.3 Liter	656	23	EURO 6
		Gas		1434	8.5	5.8 kg	512	19	EURO 6
	Battery electric			1595	2.2	19.5 kWh	173	64	
	Fuel cell electric			1570	4.0	1.1 kg	468	34	
2040	**ICEV**	**Petrol**	180 000	1319	5.0	5.0 Liter	669	27	EURO 6 -50%
		Diesel		1340	4.9	4.5 Liter	775	28	EURO 6 -50%
		Gas		1383	5.4	3.7 kg	641	26	EURO 6 -50%
	Battery electric			1554	1.9	16.6 kWh	439	78	
	Fuel cell electric			1462	3.1	0.8 kg	601	46	

The improvements in 2040 vehicle emissions and energy consumption visible in the below figures B-1 to B-4 are mostly due to expected technological improvements: motor efficiency increases, vehicle weight reductions and exhaust emissions reductions.

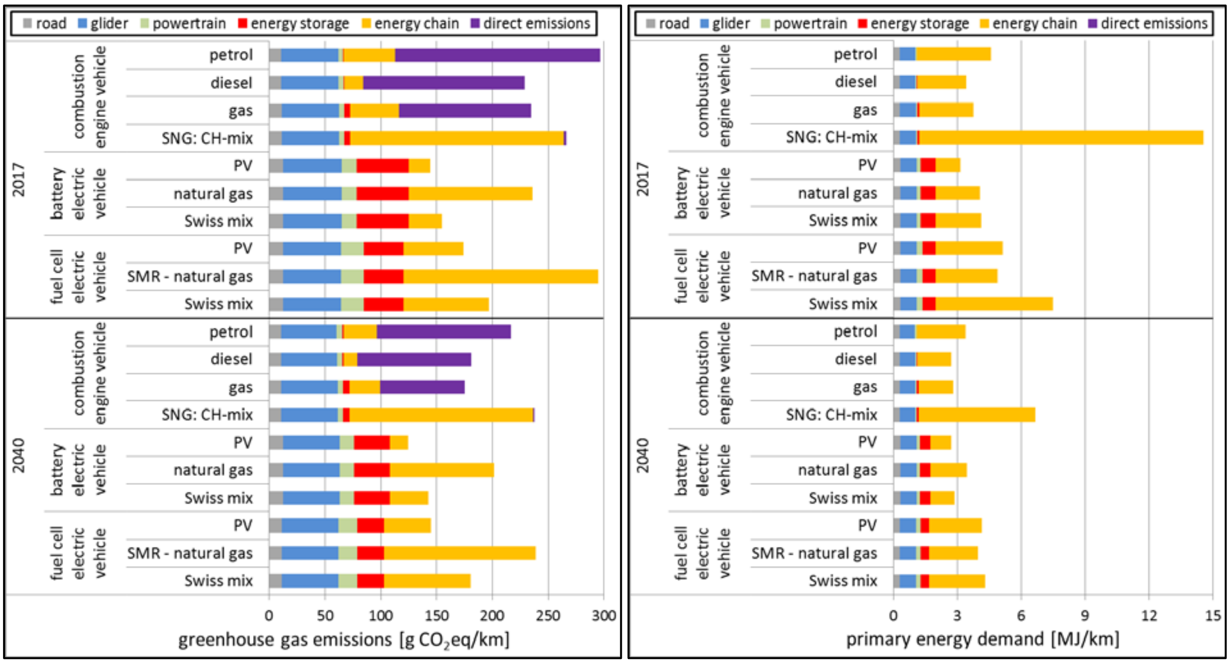

Figure B-1 Greenhouse gas emissions (left) and primary energy demand (right) from passenger vehicles in 2017 and 2040 per vehicle kilometer. „PV“: photovoltaic; „SNG“: Synthetic natural gas, here produced via electrolysis using the Swiss electricity mix and CO_2 captured from ambient air; Hydrogen for fuel cell vehicles is produced either via steam methane reforming („SMR“) or electrolysis (Swiss electricity mix or PV electricity); „Gas“ is a mix of 90% fossil natural gas and 10% biogas. The different colored bars show the source of the emissions: production, operation, maintenance, and end-of-life of vehicle components and the road, the fuel production chain and the direct emissions of the vehicles.

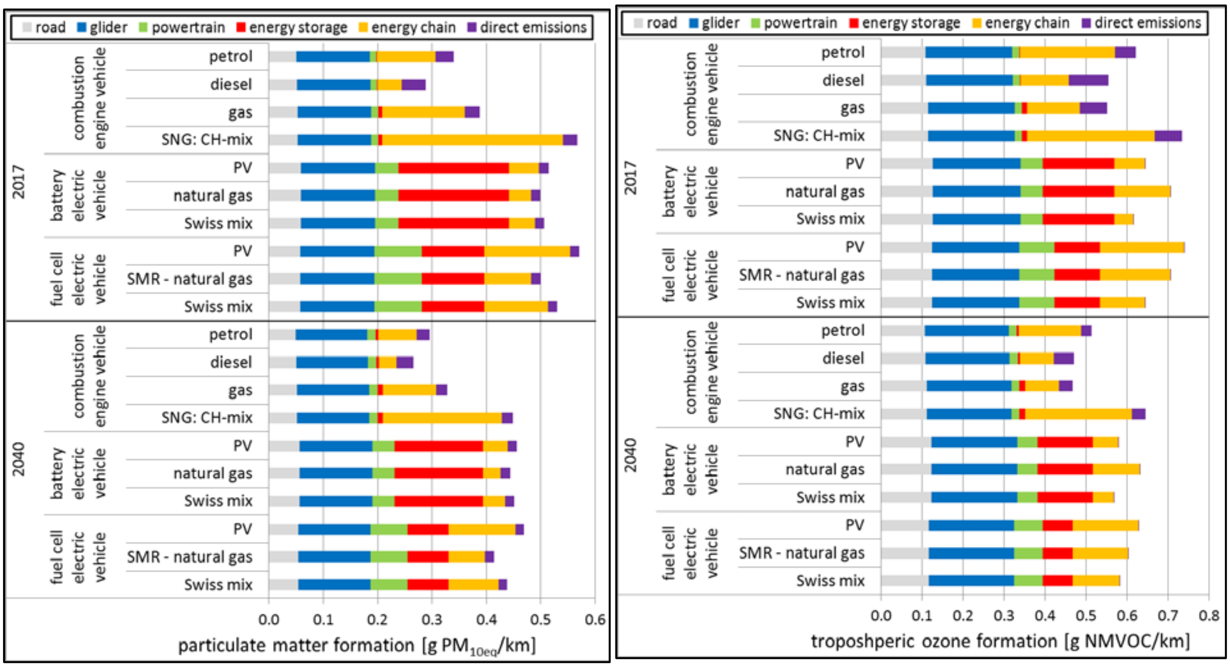

Figure B-2 Fine particulate emissions (left) and emission of pollutants that contribute to summer smog (right) from passenger vehicles in 2017 and 2040 per vehicle kilometer. „PV“: photovoltaic; „SNG“: Synthetic natural gas, here produced via electrolysis using the Swiss electricity mix and CO_2 captured from ambient air; Hydrogen for fuel cell vehicles is produced either via steam methane reforming („SMR“) or electrolysis (Swiss electricity mix or PV electricity); „Gas“ is a mix of 90% fossil natural gas and 10% biogas. The different colored bars show the source of the emissions: production, operation, maintenance and end-of-life of vehicle components and the road, the fuel production chain and the direct emissions of the vehicles.

Figure B-2 shows that a substantial portion of the air pollution due to electric vehicles is caused by the production of the battery. These emissions are, however, generally released in sparsely populated areas where few people can be affected, for example, in mines where raw metals are produced. The resulting health impacts are estimated to be much lower compared to emissions that occur in densely populated areas with high transport demand. Conversely, some of these emissions are shifted to densely populated industrial centers in Asia where batteries are produced and many people can be affected.

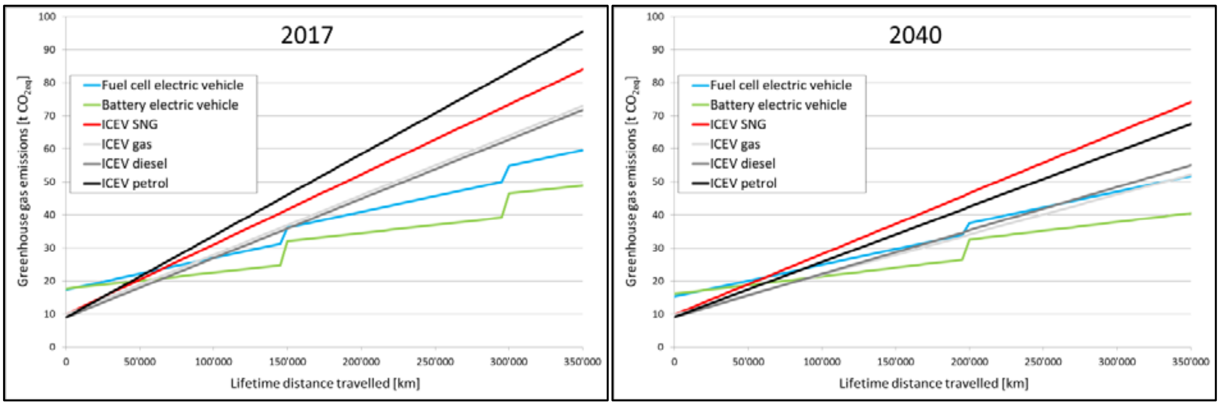

Figure B-3 Greenhouse gas emissions during the entire life cycle of different vehicle powertrain types in 2017 (left) and 2040 (right). „ICEV“: vehicle with combustion motor; „SNG“: Synthetic natural gas, here produced via electrolysis using the Swiss electricity mix and CO_2 captured from ambient air. The Swiss electricity mix is assumed here for both the charging of batteries for battery electric vehicles and for the production of hydrogen for use in fuel cell vehicles. „Gas“ is a mix of 90% fossil natural gas and 10% biogas. Batteries and fuel cells are assumed to be replaced after 150 000 km (2017) and 200 000 km (2040).

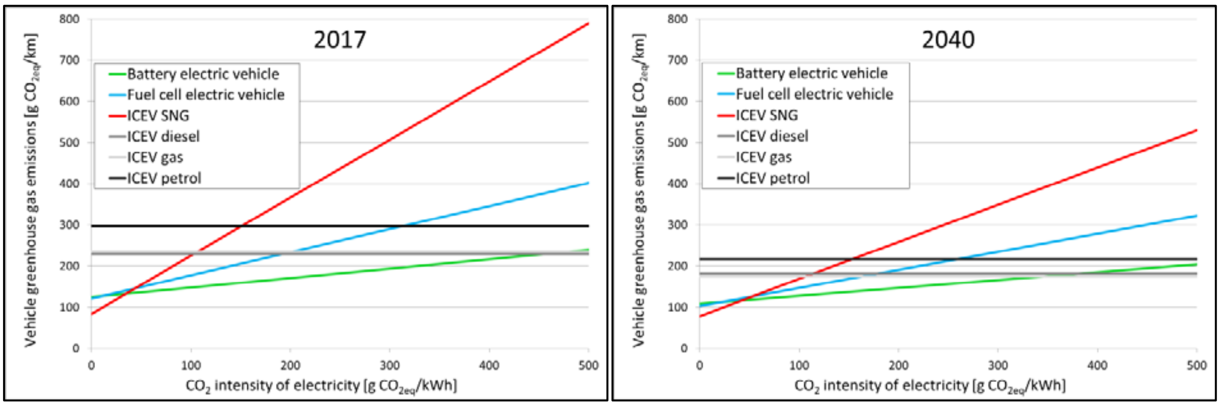

Figure B-4 Greenhouse gas emission dependency on CO_2 intensity of the electricity used to charge batteries for battery electric vehicles, produce hydrogen for fuel cell vehicles, and to produce synthetic natural gas. „ICEV“: vehicle with combustion motor; „SNG“: Synthetic natural gas, here produced via electrolysis and CO_2 captured from ambient air. „Gas“ is a mix of 90% fossil natural gas and 10% biogas. As the CO_2 intensity of the electricity increases, battery electric vehicles show the best advantages compared to fossil fueled vehicles because of their efficient use of electricity. For electricity with extremely low CO_2 intensity, SNG vehicles have the best performance because the production of batteries and fuel cells can be avoided. The lines for BEV, FCEV, and ICEV-SNG are less steep for 2040 than for 2017 because vehicle efficiency is expected to increase and vehicles will require less energy per kilometer driven in the future. For reference: hydro and wind electricity in Switzerland have CO_2 intensities of roughly 10-30 g CO_{2eq}/kWh; photovoltaic systems produce roughly 70-100 g CO_{2eq}/kWh; natural gas power plants would reach levels around 400-500 g CO_{2eq}/kWh and the current Swiss electricity mix has a CO_2 intensity of slightly over 100 g CO_{2eq}/kWh.

The environmental impacts of battery production

Lithium-ion batteries are the current standard for battery electric vehicles, the production of which results in substantial environmental burdens. Thus, vehicles with larger batteries, and correspondingly larger ranges, tend to have larger environmental burdens. A current battery system weighing 350 kg has a storage capacity of roughly 40 kWh, though thanks to improving energy density of batteries, a battery system of the same weight may store roughly 90 kWh in the year 2040. The lifetimes for current and 2040 batteries are assumed to be 150 000 km and 200 000 km, respectively. The most important factor for the environmental burdens of battery production is the energy consumed during the production of the battery cells. The two main determinates are how much electricity this process consumes and how that electricity is generated. Better life cycle assessment results are found for vehicles with „cleaner“ battery production, efficient recycling processes, and „second-lives“ for the batteries, for example as storage capacity for photovoltaic systems in buildings. However, such „second-lives“ are not considered here.

Validity of Life cycle assessment

Several assumptions and input parameters have significant impact on the life cycle assessment results of passenger cars. These include energy consumption, exhaust emissions from combustion motors, and lifetimes of vehicles and key components such as batteries. The results in this fact sheet are valid for the input assumptions listed in Table B-1. The background report contains realistic ranges for all input values and shows their impact on results. For example: What changes if diesel vehicles fail to meet emission requirements and produce significantly more nitrogen oxides than allowed? Or, how would results change if batteries were produced with an entirely renewables-based electricity system? The background report documents all input parameters and data sources. Furthermore, additional results, for example for plug-in hybrid vehicles are included.

B.2. **Calculation input parameters**

Here we list all input parameters that are read into the calculation model in chapter 7.

Table B-2 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
	all	glider base mass	1200	600	2000	1175	550	1900	kg
	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	
	all	power to mass ratio	60	40	100	60	40	100	W/kg
	all	frontal area slope	0.0008	0.0006	0.0009	0.0008	0.0006	0.0009	m^2 / glider base mass kg
	all	frontal area intercept	1.1	1.09	1.3	1.1	1.09	1.3	m^2
	all	aerodynamic drag coefficient	0.310	0.300	0.350	0.295	0.264	0.350	
	all	rolling resistance coefficient	0.010	0.007	0.012	0.009	0.006	0.012	
	all	average passengers	1.8	1	4	1.8	1	4	persons
	all	average passenger mass	75	60	90	75	60	90	kg
	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	
	ICEV-p, ICEV-d, ICEV-g	drivetrain efficiency	0.8	0.75	0.9	0.85	0.8	0.9	
	PHEV-c	drivetrain efficiency	0.723	0.64	0.81	0.757	0.672	0.846	
	BEV, FCEV, PHEV-e	engine efficiency	0.85	0.8	0.9	0.87	0.82	0.92	
	ICEV-p	engine efficiency	0.26	0.24	0.28	0.32	0.28	0.34	
	ICEV-g	engine efficiency	0.24	0.22	0.26	0.3	0.26	0.32	
	ICEV-d	engine efficiency	0.29	0.27	0.31	0.33	0.31	0.37	
	HEV-p, PHEV-c	engine efficiency	0.33	0.31	0.35	0.35	0.33	0.4	
	FCEV	fuel cell stack efficiency	0.535	0.5	0.57	0.57	0.52	0.63	
	FCEV	fuel cell power area density	900	700	1100	1000	800	1200	mW/cm^2
	FCEV	fuel cell ancillary BoP mass per power	0.33	0.3	0.37	0.3	0.28	0.34	kg/kW
	FCEV	fuel cell essential BoP mass per power	0.4	0.35	0.5	0.35	0.3	0.4	kg/kW
	FCEV	fuel cell own consumption	1.15	1.1	1.2	1.125	1.08	1.15	
	BEV, PHEV-c, PHEV-e	converter mass	4.5	4	6	4.275	3.6	6	kg
	BEV, FCEV, HEV-p, PHEV-c, PHEV-e	inverter mass	9	8	10	8.55	7.2	10	kg
	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 (not corrected for SNG or biogas content)	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

			current			**future**			
	powertrain	**parameter**	**Most likely**	**low**	**high**	**Most likely**	**low**	**high**	**unit**
	ICEV-d	NMVOC	7.46E-06	3.73E-06	1.49E-05	3.73E-06	1.87E-06	7.46E-06	kg/km
	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

B.3. Global sensitivity analysis results

Here we provide global sensitivity analysis results according to the method of Plischke, Borgonovo [231], Borgonovo [232]. 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.

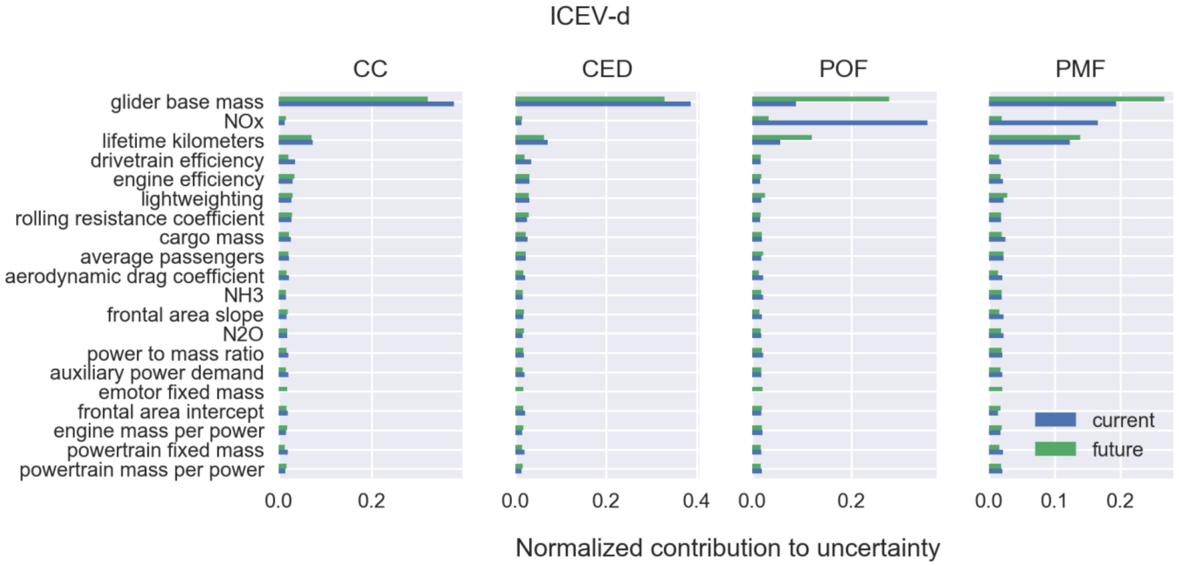

Figure B-5 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Internal combustion engine vehicle with diesel. CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

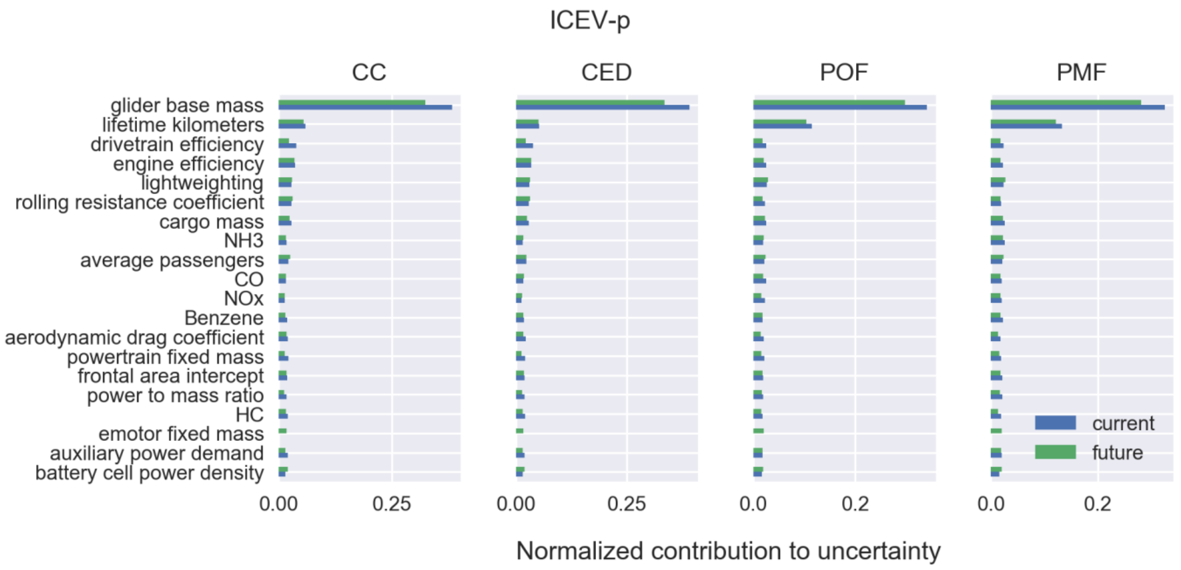

Figure B-6 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Internal combustion engine vehicle with petrol. CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

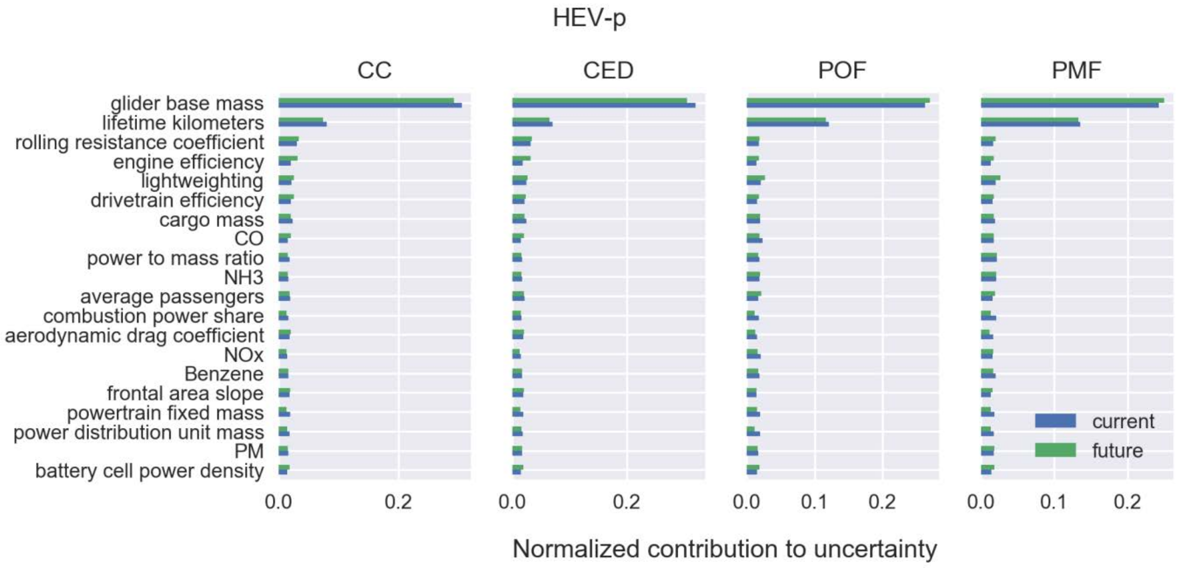

Figure B-7 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Hybrid vehicle with petrol. CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

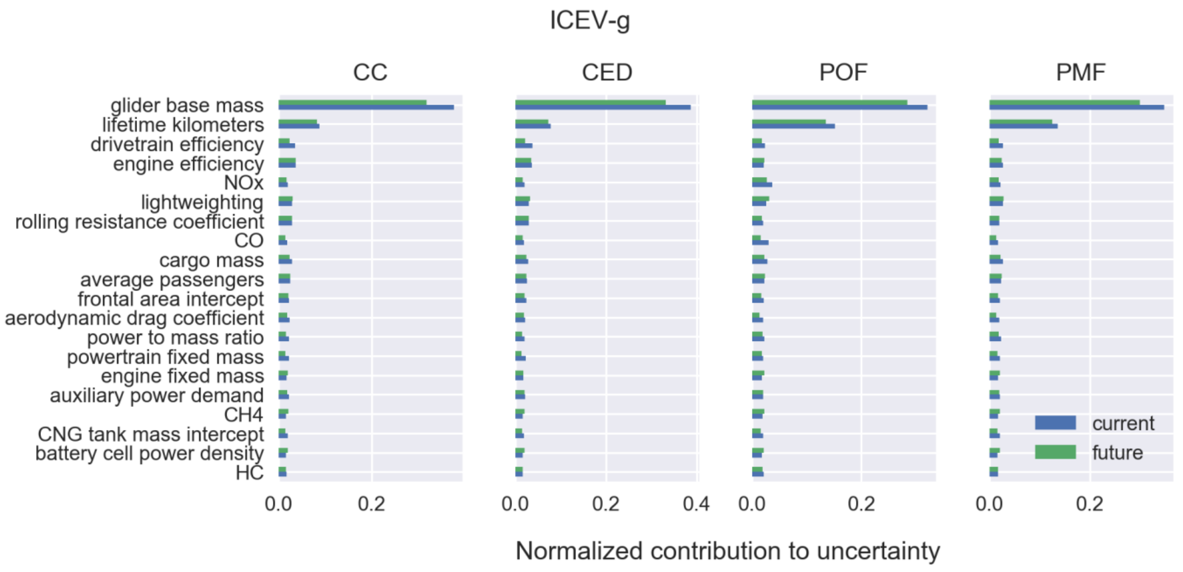

Figure B-8 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Internal combustion engine vehicle with compressed natural gas. CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

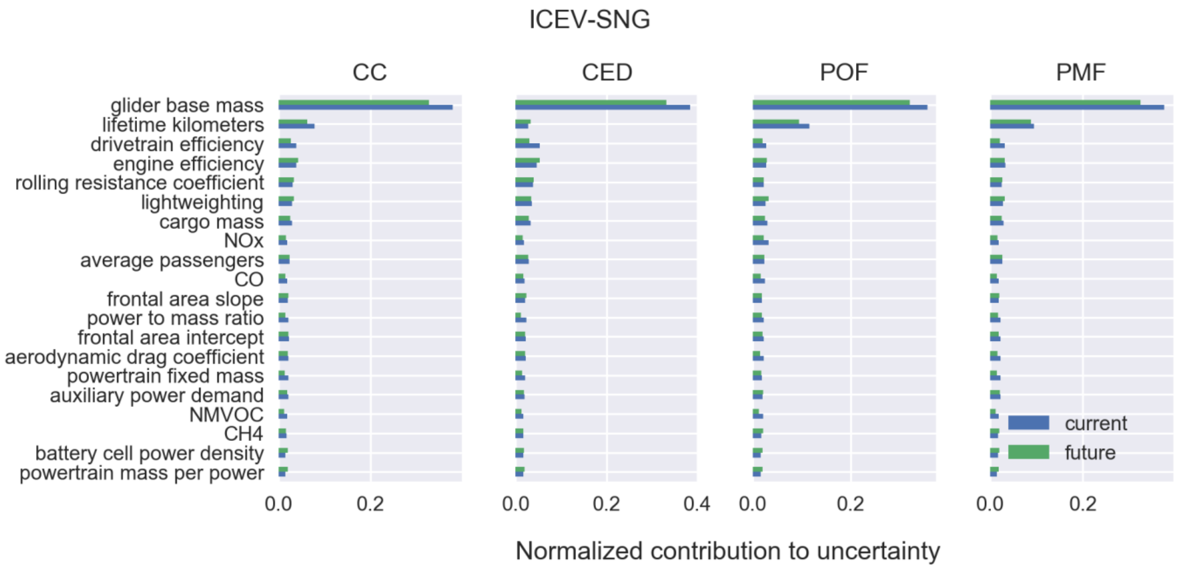

Figure B-9 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, Internal combustion engine vehicle with compressed natural gas, synthetically produced with Swiss electricity. (Future electricity mix CH-POM-C). CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

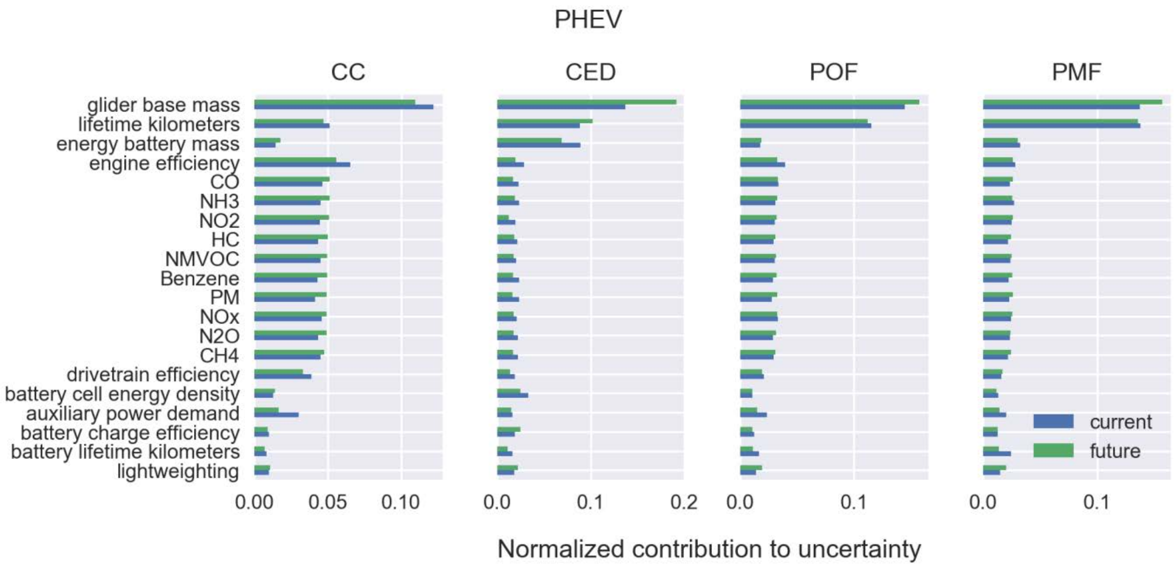

Figure B-10 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, plug in hybrid electric vehicle average operating recharged with Swiss electricity. (Future electricity mix CH-POM-C). CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

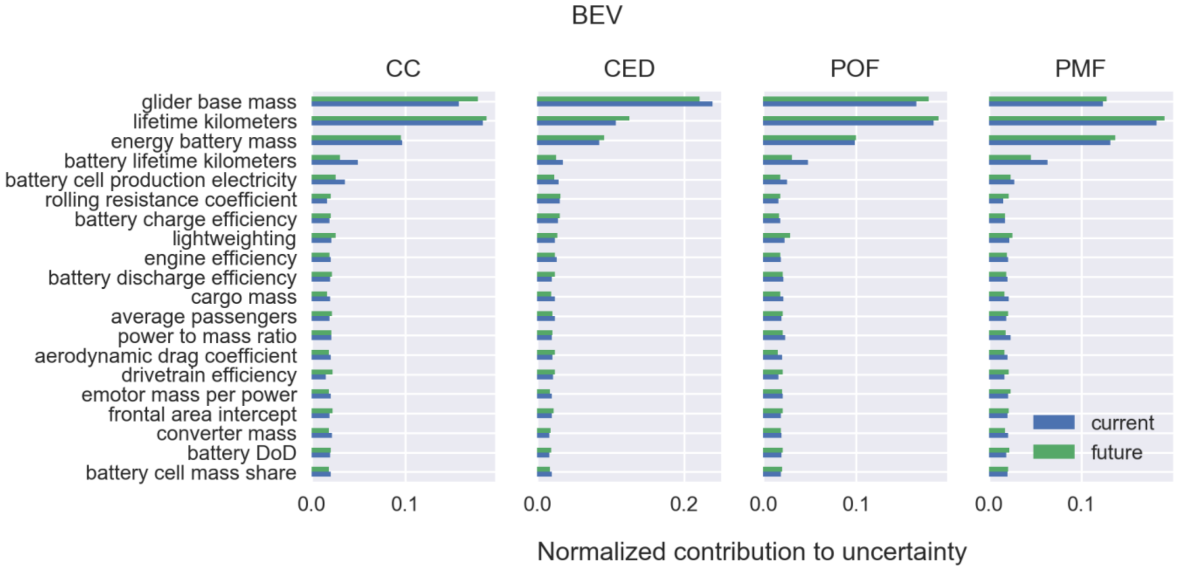

Figure B-11 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, battery electric vehicle operating with Swiss electricity. (Future electricity mix CH-POM-C). CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

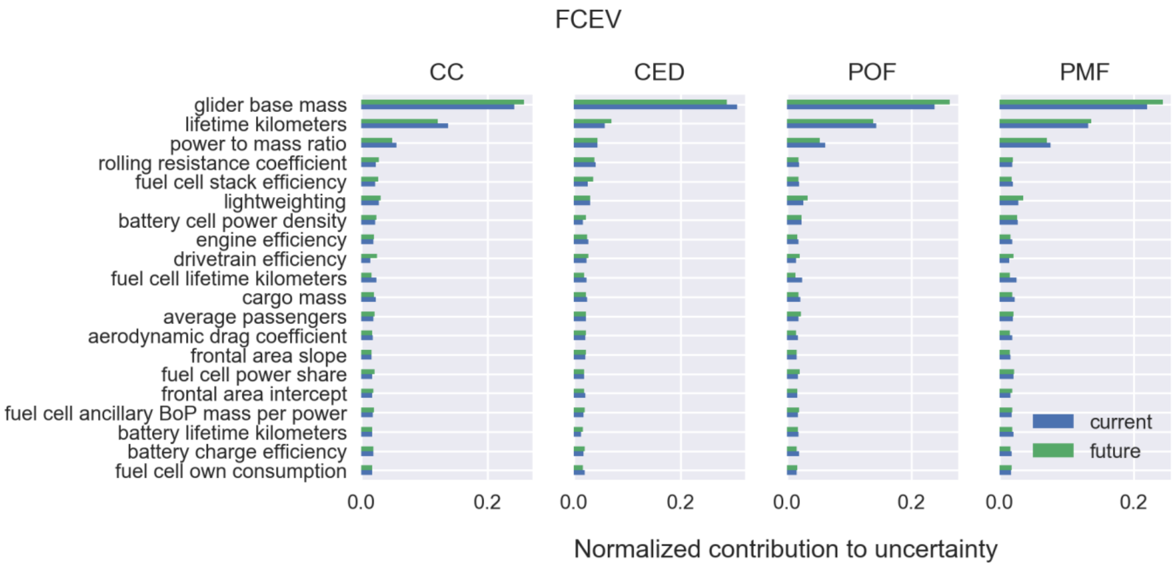

Figure B-12 Global sensitivity analysis results. Top 20 contributors to overall uncertainty, fuel cell electric vehicle operating with hydrogen produced with Swiss electricity. (Future electricity mix CH-POM-C). CC: Climate Change, CED: Cumulative Energy Demand, POF: Photochemical Oxidant Formation, PMF: Particulate Matter Formation.

Appendix C. **Supporting information for Chapter 8**

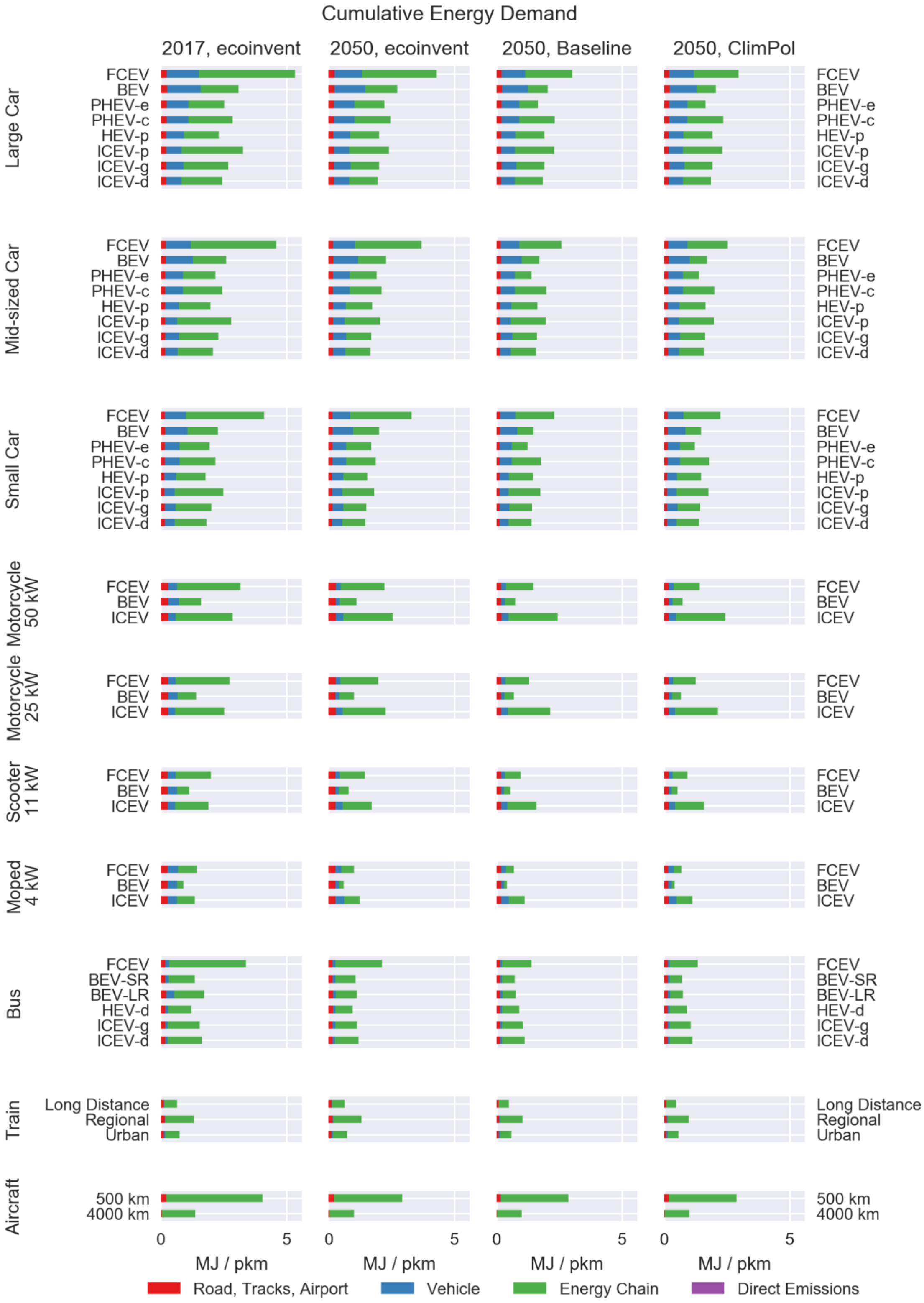

Figure C-1 Transportation mode comparison- cumulative energy demand

Figure C-2 Transportation mode comparison- human toxicity

Figure C-3 Transportation mode comparison- mineral depletion

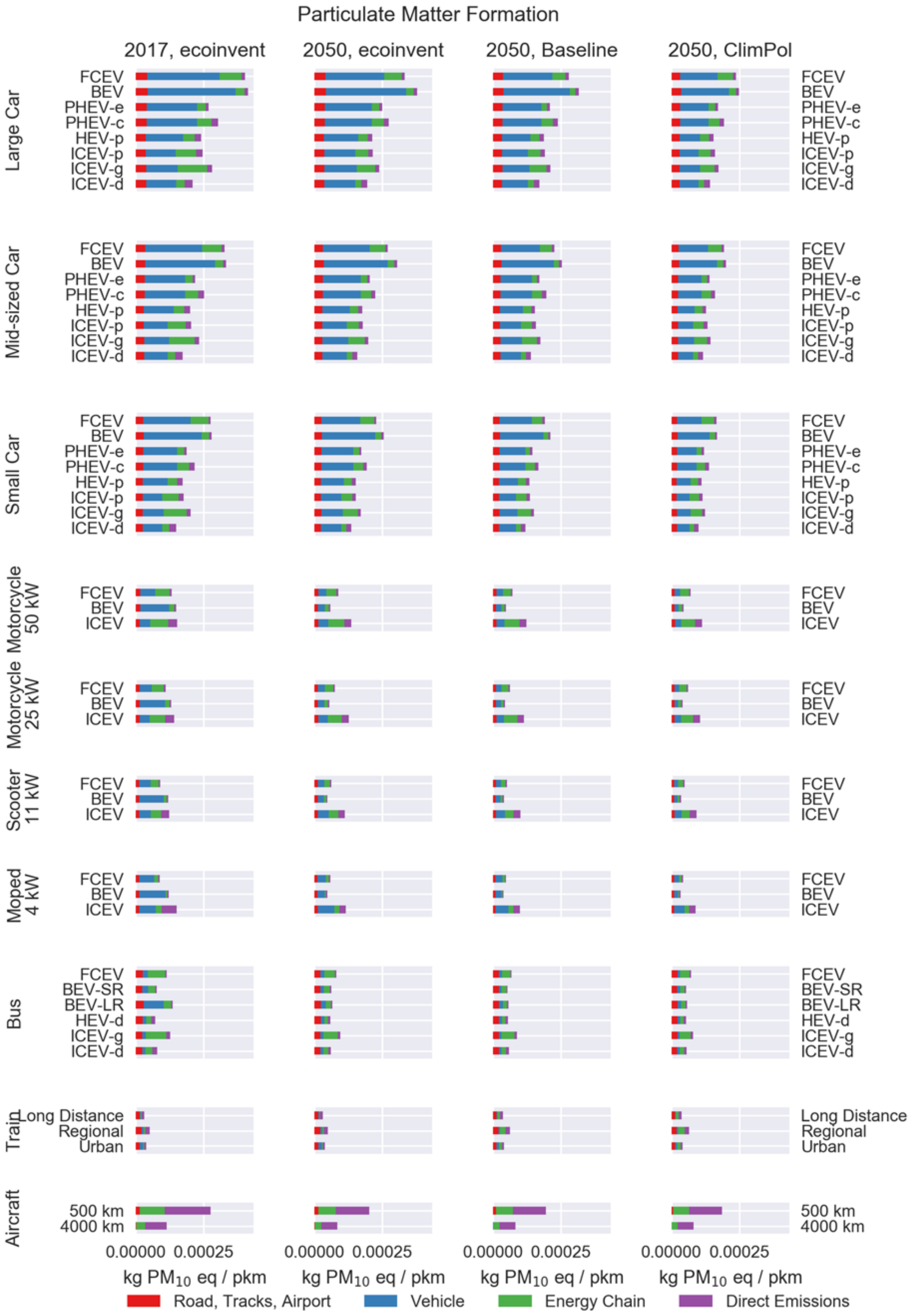

Figure C-4 Transportation mode comparison- particulate matter formation

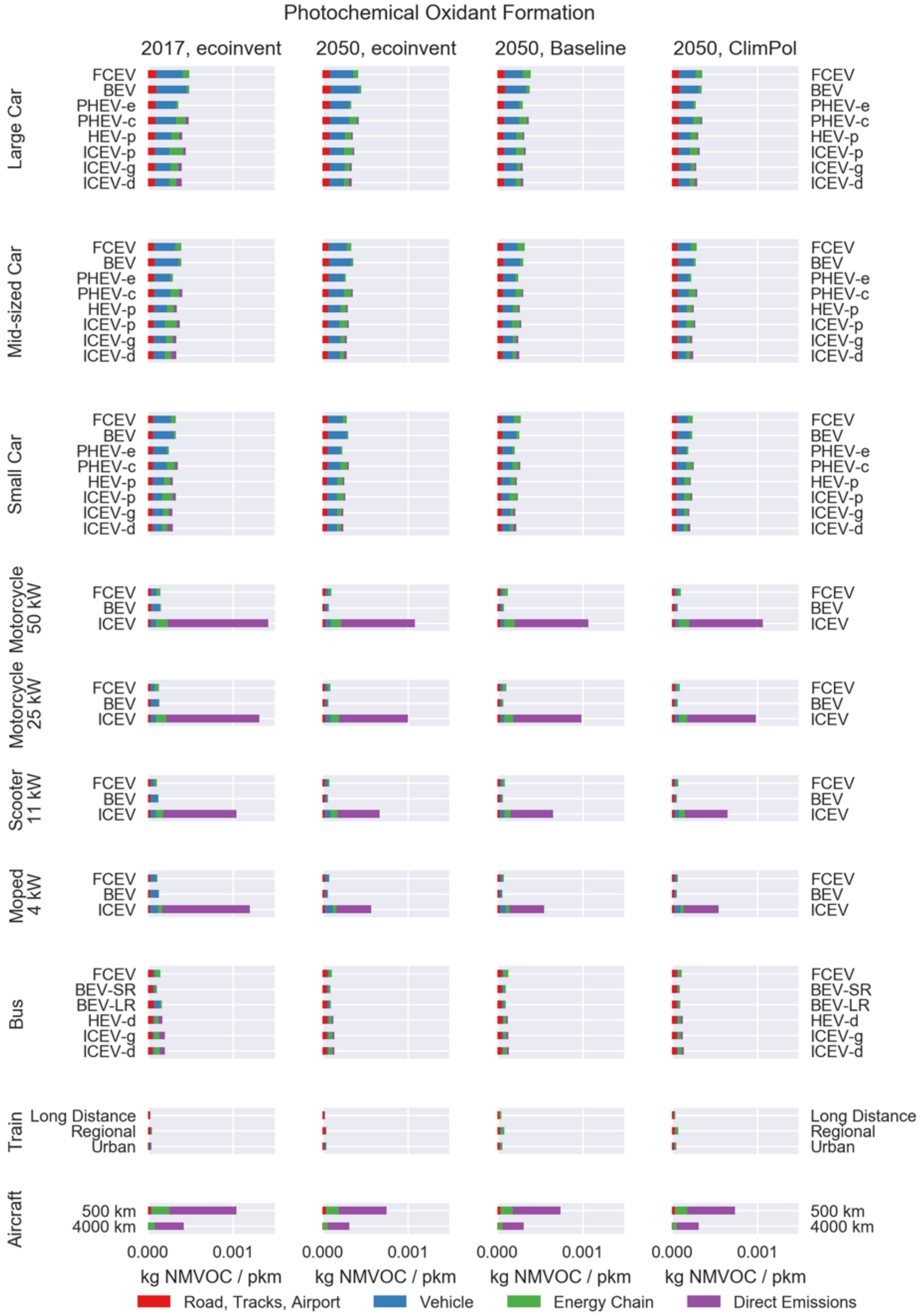

Figure C-5 Transportation mode comparison- photochemical oxidant formation

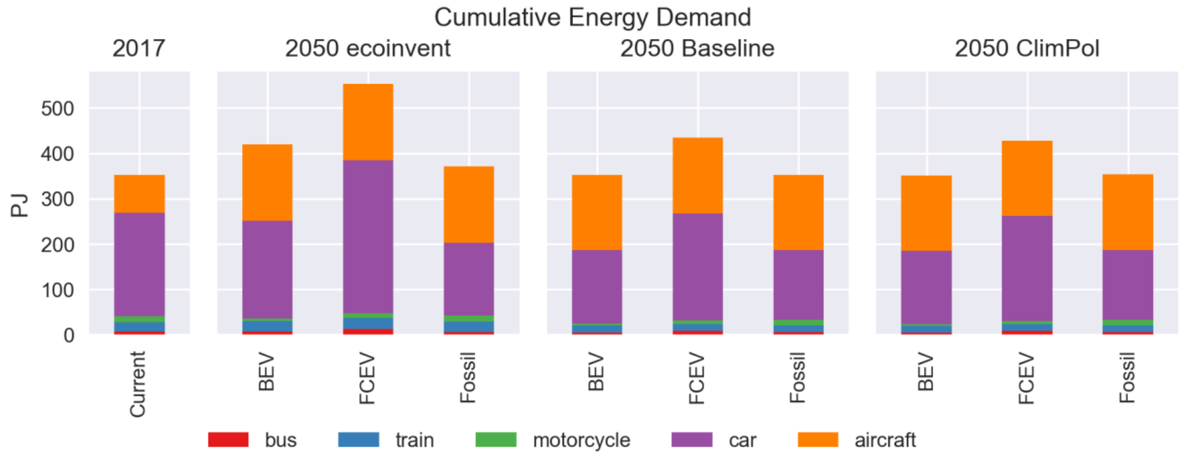

Figure C-6 Swiss transportation sector level impacts- cumulative energy demand

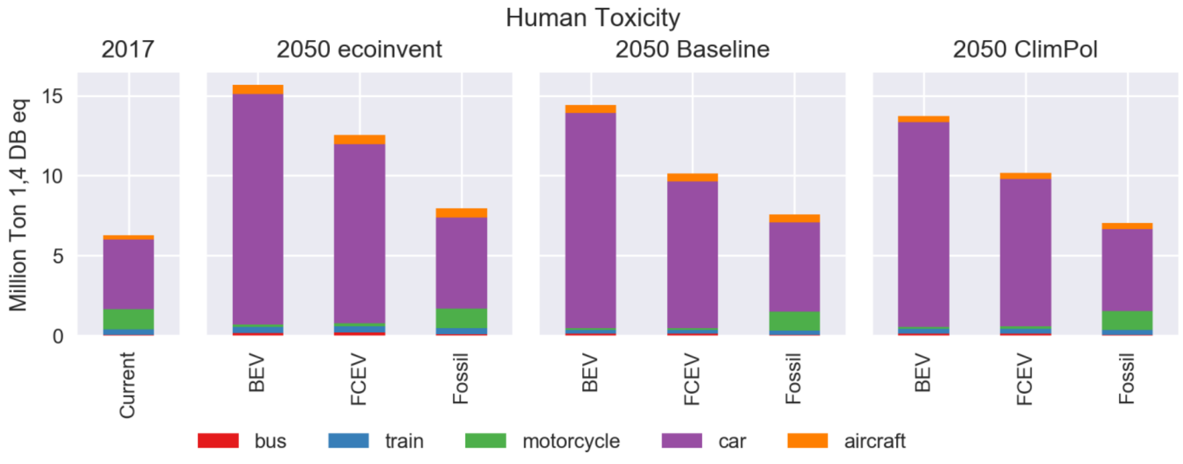

Figure C-7 Swiss transportation sector level impacts- human toxicity

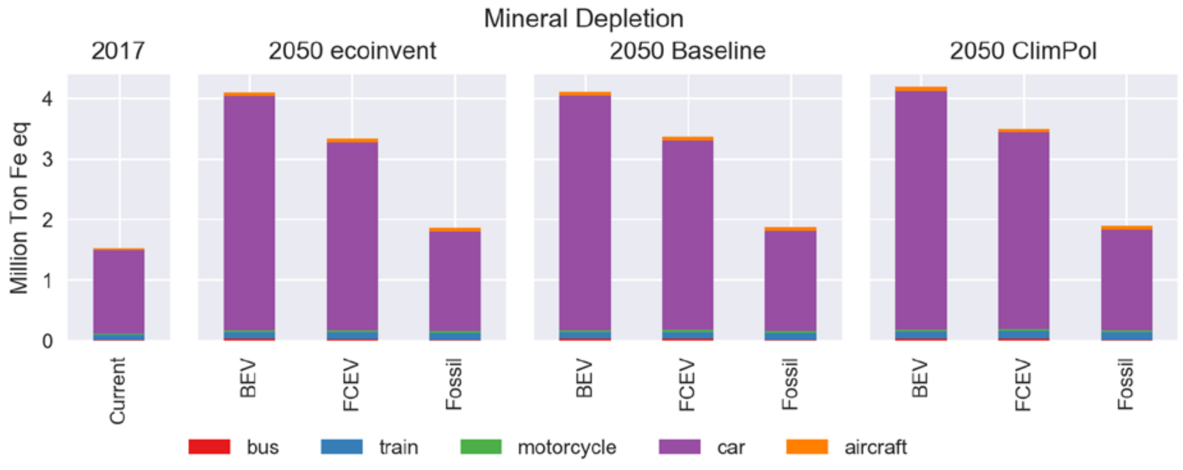

Figure C-8 Swiss transportation sector level impacts- mineral depletion

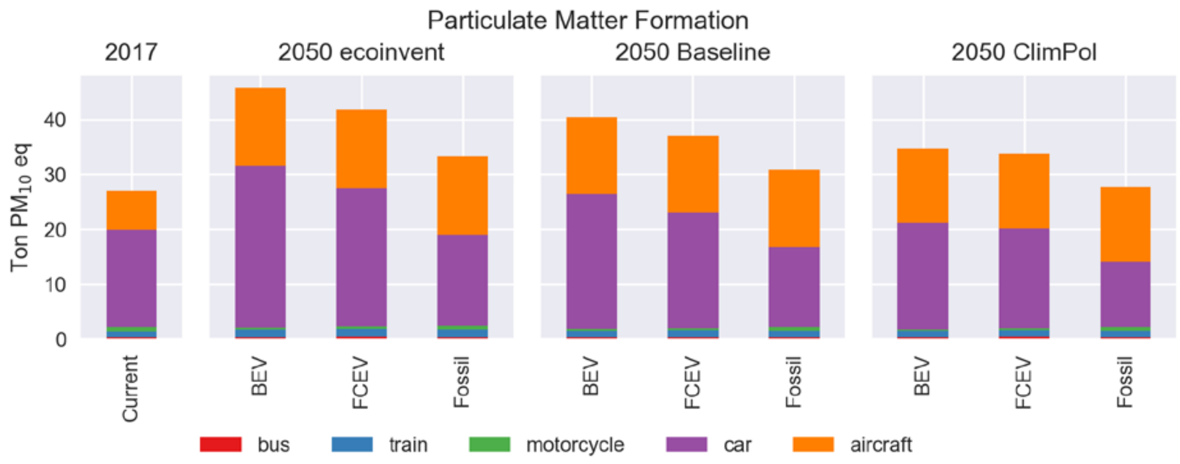

Figure C-9 Swiss transportation sector level impacts- particulate matter formation

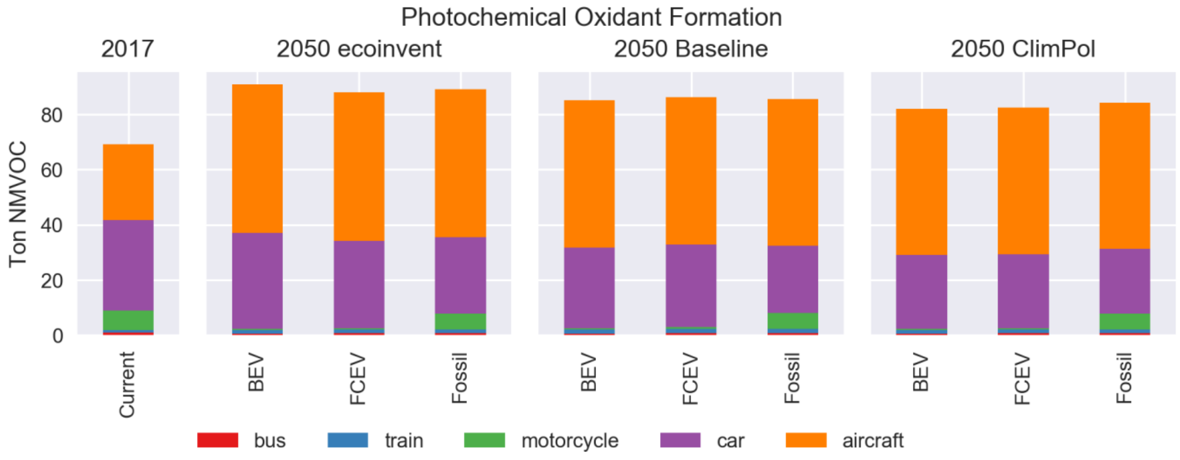

Figure C-10 Swiss transportation sector level impacts- photochemical oxidant formation

Curriculum Vitae

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Education

PhD in Mechanical and Process Engineering (2018)
Swiss Federal Institute of Technology in Zurich, Switzerland
Mobility and the energy transition: a life cycle assessment of Swiss passenger transport technologies including developments until 2050

MSc in Energy Science and Technology (2014)
Swiss Federal Institute of Technology in Zurich, Switzerland
Life cycle assessment and life cycle cost analysis of a cracked ammonia fueled alkaline fuel cell for powering remote base transceiver stations
With Distinction (GPA: 5.79/6.0)

BSc in Mechanical Engineering (2008)
Schulich School of Engineering, University of Calgary, Canada
Design of a spray contactor system to capture atmospheric CO_2
With Distinction (GPA: 3.75/4.0)

Professional Experience

PhD student, Paul Scherrer Institut, Villigen, 2014-2018

- Life cycle assessment of transportation and energy systems
- Python programming

Piping and Arrangement Planning Engineer, Alstom Power, Baden, 2008-2013

- Design of steam turbine piping and auxiliary equipment
- Support of tendering, engineering, fabrication, and erection works

Undergraduate Research Assistant, University of Calgary, 2007-2008

- Study of atomization and sprays with focus on maximum energy efficiency
- Modeling in Mathematica

Intern Gas Turbine Combustor Development, Alstom Power, Baden, 2006-2007

- Combustion stability research (Thermoacoustics) and experiments
- Modeling in Matlab/Simulink

Undergraduate Research Assistant, University of Calgary, 2005-2006

- Mechanical design and fabrication of robotic forceps for neurosurgery research
- Modeling in Solidworks

Research Interests

- Energy and Transport Systems Analysis
- Life Cycle Assessment

Languages

- English native speaker
- Fluent German (C1-C2)

Soft Skills

- Quick thinking and grasps difficult concepts easily
- Able to present complex ideas concisely
- Self-motivated, independent and well organized
- Self-confident speaker and presenter

Selected Awards

Willi Studer Prize
Swiss Federal Institute of Technology in Zurich, 2015
Highest standing in graduating class Energy Science and Technology, D-ITET

Talisman Energy Inc. Undergraduate Scholarship in Energy and Related Studies in Engineering
University of Calgary, 2007
Largest one-time award given at University of Calgary during this year

Canadian Society of Mechanical Engineers Medal
University of Calgary, 2006
Highest standing in 3rd year of Schulich School of Engineering - Mechanical

List of publications

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Bauer, C., et al., *Potentials, costs and environmental assessment of electricity generation technologies*. 2017. PSI, WSL, ETHZ, EPFL.

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Frischknecht, R., et al., *LCA of mobility solutions: approaches and findings—66th LCA forum, Swiss Federal Institute of Technology, Zurich, 30 August, 2017*. The International Journal of Life Cycle Assessment, 2018. 23: p. 381–386.