Opportunities and challenges for electric mobility: an interdisciplinary assessment of passenger vehicles

Final report of the THELMA project in co-operation with the Swiss Competence Center for Energy Research “Efficient technologies and systems for mobility”

Report

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Acronyms

A-ECMS	Adaptive Equivalent Consumption Minimization Strategy
AER	All-Electric Autonomy Range
AGC	Automatic Generation Control
BAU	Business As Usual
BE	Battery Electric
BEV	Battery Electric Vehicle
CA	Cluster Analysis
CC	Combined Cycle
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
DALY	Disability Adjusted Life Years
DETEC	Department of the Environment, Transport, Energy and Communications
DOE	Degree of Electrification
E85	Mix of 85% bioethanol, 15% gasoline
EC	European Commission
EG	Electric Generator
EIA	Environmental Impact Assessment
EM	Electric Motor
EMPA	Swiss Federal Laboratory for Materials Testing and Research
EMPA-LCAM	EMPA Life Cycle Assessment and Modeling Unit
EoL	End-of-life
ETHZ	Swiss Federal Institute of Technology in Zurich
ETHZ-ESD	ETHZ Chair of Ecological Systems Design
ETHZ-IVT	ETHZ Institute for Transport Planning and Systems
ETHZ-LAV	ETHZ Aerothermochemistry and Combustion Systems Laboratory
ETHZ-PSL	ETHZ Power Systems Laboratory
EuroNCAP	European New Car Assessment Programme
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FCS	Fuel Cell System
Fleet 2050 MCDA – CO2, Primary Energy 50/50 Weights	CO2 Emissions and Non-renewable Primary Energy Use 50% each
Fleet 2050 MCDA – ECO80 Weights	Economy 80%, Environment, Society, Security of Energy Supply and Driver Utility 5% each
Fleet 2050 MCDA – ENV80 Weights	Environment 80%, Economy, Society, Security of Energy Supply and Driver Utility 5% each
Fleet 2050 MCDA – EQUAL Weights	Environment, Economy, Society, Security of Energy Supply and Driver Utility equally weighted
Fleet 2050 MCDA – SEC80 Weights	Security of Energy Supply 80%, Environment, Economy, Society, and Driver Utility 5% each
Fleet 2050 MCDA – SOC80 Weights	Society 80%, Environment, Economy, Security of Energy Supply and Driver Utility 5% each
Fleet 2050 MCDA – UTI80 Weights	Driver Utility 80%, Environment, Economy, Society, and Security of Energy Supply 5% each
FRDB	Federal Register of Buildings and Dwellings
FSO	Swiss Federal Statistical Office
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle

IPCC	Intergovernmental Panel on Climate Change
KERS	Kinetic Energy Recuperation Systems
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFC	Load Frequency Control
MATSim	Multi-Agent Transport Simulation Model
MCDA	Multi-criteria Decision Analysis
MCDA	Multi-Criteria Decision Analysis
MDCEV	Multiple Discrete-Continuous Extreme Value Decision Model
NEDC	New European Driving Cycle
NEP	New Energy Policy
NGCC	Natural Gas Combined Cycle
NiMeH	Nickel-Metal-Hydride
OPF	Optimal Power Flow
PEM	Proton Exchange Membrane
PGS	Planetary Gear Set
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PMT	Passenger Miles Travelled
POM	Political Measures
PSI	Paul Scherrer Institute
PSI-LEA	PSI Laboratory for Energy Systems Analysis
PV	Photovoltaic
RES	Renewable Energy Sources
SFOE	Swiss Federal Office for Energy
SMR	Steam Methane Reforming
SOC	State of Charge
SUV	Sport Utility Vehicle
Swiss mix	Swiss electricity supply mix (incl. electricity imports)
THELMA	TecHnology-centered ELectric Mobility Assessment
TOU	time-of-use
TSO	Transmission System Operator
UCTE	Union for the Coordination of the Transmission of Electricity (continental Europe)
V2G	Vehicle to Grid
Vehicle MCDA – ECO85 Vehicle Weights	Economy 85%, Environment, Society and Driver Utility 5% each
Vehicle MCDA – ENV85 Weights	Environment 85%, Economy, Society and Driver Utility 5% each
Vehicle MCDA – EQUAL Weights	Environment, Economy, Society and Driver Utility equally weighted
Vehicle MCDA – SOC85 Weights	Society 85%, Environment, Economy, and Driver Utility 5% each
Vehicle MCDA – UTI85 Weights	Driver Utility 85%, Environment, Economy, and Society 5% each
vkm	Vehicle-kilometer
VMT	Vehicle Miles Travelled
WLTP	World-Harmonized Light-Duty Vehicles Test Procedure
WLTP	Worldwide harmonized Light vehicles Test Procedure
WP	Work Package
WS	Weighted Sum
YLD	Years Lived with Disability
YOLL	Years Of Life Lost
ZEBRA	Zeolite Battery Research Africa

Executive summary

Electric mobility technologies could potentially contribute to the goals of the Swiss energy policy, which include assuring a more sustainable supply of energy. The goal of sustainability implies a wide range of concerns, including protecting the climate, minimizing pollution, protecting ecosystems and human health, and assuring security of supply, affordability and social acceptance.

The recent advances in technologies relevant for electric mobility and the inherent advantages of the electric grid in supplying and delivering energy combine to move electric powertrain technology into a good position to meet the present conflicting economic, environmental and social criteria for sustainability. If future growth of the Swiss electricity system can maintain its present low carbon content generation mix, with relative price stability and security from interruption, then vehicles with electrified drivetrains can potentially make real contributions to a more sustainable Swiss transportation system.

A detailed, technology-centered system analysis is a prerequisite for understanding the strengths and weaknesses of the options developed, evaluating trade-offs compared to both conventional and other advanced alternatives, and assessing the potential contributions of the technology options to a more sustainable future.

The specific goals of the THELMA project are defined as follows:

- To assess environmental performance of electric vehicle technologies (in particular, batteries and fuel cells) in comparison with combustion options driven by fossil fuels. Future technology advancements should be taken into account along with the impacts of energy supply infrastructure and its evolution.
- To account for the role of, and requirements on, the electric grid depending on the various options for electric mobility. Furthermore, in applicable cases, synergetic effects are to be addressed.
- To carry out case studies on a regional or local level assessing the environmental implications of the expansion of electric mobility and its integration with the energy supply system. In particular, the performance of centralized vs. decentralized energy supply options should be evaluated.
- To assess aggregated environmental and economic vehicle technology attributes, thus enabling a cost-benefit analysis of electric mobility options both on the technology level as well as for alternative scenarios on the national level.
- To evaluate the relative sustainability of the options by combining their performance on environmental, economic and social criteria with stakeholder preference profiles.

The scope of the THELMA project includes:

- **Vehicle classes:** automobiles of various classes.
- **Drivetrains and energy carriers:** electric (battery and fuel cell) vehicles, fuel cell and internal combustion engine (ICE) hybrids, plug-in hybrids, and ICE vehicles using gasoline, diesel and methane gas from fossil resources.
- **Electricity/energy supply:** alternative electricity supply mixes, hydrogen production from renewable, nuclear or fossil fuels.

- **Time horizon:** detailed technology evolution until year 2030; outlook until year 2050.
- **Applications:** Swiss-specific case; environmental case studies on local level; impact pathways approach and external cost analysis on technological and national level; life cycle, cost benefit and sustainability assessment on technological and national levels.
- **Geographic boundaries for LCA and impact assessment:** beyond Swiss national borders.
- **Evaluation criteria:** environmental, economic and social (limited), security of supply and driver utility.

The overall approach of the THELMA project is based on a comprehensive combination of interdisciplinary technology assessment, vehicle and powertrain simulation, traffic simulation, power systems analysis, and integration of results. This begins with characterization of a wide range of drivetrains and energy carriers. The drivetrains (electrified and baseline internal combustion engines) and energy carriers (batteries and fuels) are combined with various vehicle options (e.g. different vehicle classes, down-weighting, etc.) to define a wide range of vehicles (a "virtual fleet" of designs).

Life Cycle Assessment (LCA) is used to provide a vector of average burdens for different energy carriers and for vehicle materials or components. The LCA burdens for vehicles components or materials are then combined with vehicle descriptions to obtain burdens per vehicle kilometer travelled.

Local and/or regional scenarios are defined to study the impacts of electric mobility and decentralized versus centralized energy supply. Both vehicle technology and scenario descriptions are then used to find the distribution of charging load patterns by location and time of day, so that transmission network modeling can be used to determine system dispatch (generator operation) and cost, including grid constraints, if any exist. Modeling of future technology developments must therefore be consistent with assumptions for future traffic patterns, charging load patterns, and future generation and grid expansion. Power network modeling shall include comparison of central versus customer controlled charging patterns (including battery costs) and include analysis of vehicle to grid (V2G) network services.

The integration analysis task combined criteria indicators partially originating from other tasks to characterize local and climate-related emissions, resource burdens and social concerns. Where possible, these indicators were monetized to obtain external costs that were added to direct technology costs to obtain total costs. The various indicators were aggregated using alternative stakeholder preference profiles and multi-criteria decision analysis (MCDA) tools, so that total cost and MCDA rankings for selected technologies and for the overall national mobility options could be compared.

The following conclusions can be drawn from the present study:

- **Electric mobility can strongly reduce consumption of non-renewable energy and GHG-emissions of future individual car mobility in Switzerland.** The largest reductions result if non-fossil energy resources are used for electricity and hydrogen production. Thus, compared to the base year 2012 and based on the analyzed fleet scenarios for Swiss passenger cars in 2050, the consumption of non-renewable energy could be reduced by 10%-65% and the total life cycle Greenhouse Gas (GHG) emissions are estimated to be reduced by

25%-65%, depending on the penetration rate of advanced powertrain vehicles and the development of the energy system. This conclusion is essential since efficiency improvements and climate protection are the core goals of the new Swiss energy policy.

- **Electric mobility is found to increase national electricity demand by 12.1 TWh and 27.5 TWh per year for 90% fleet penetration of BEV and FCEV respectively.**
- **Environmental external costs of individual technologies with high standards have limited influence on their ranking but cumulative external costs are very substantial.** Current external costs of the car fleet in Switzerland are in the range of about 0.7 – 1.9 billion EURO per year; the broad range of this estimate is associated with large uncertainties of external costs caused by greenhouse gases. The evaluated scenario without electric vehicles but taking into account the advancements of fossil fuel vehicles leads to a reduction of the annual external costs by about 25 % in year 2050; the corresponding reduction in a scenario with 80 % penetration of electric vehicles is close to 50 %. It should be noted that external costs of accidents and noise are not included in these estimates.
- **Future BEVs and FCEVs exhibit strongly improved performance over a range of criteria and stakeholder profiles.** The evaluations of fleet options by and large reflect the behavior of technologies in accordance with the shares of the various types of vehicles. The estimated indicators exhibit a clear tendency towards improving performance parameters with time. This applies in particular to electric cars. Apart from the above mentioned reductions in consumption of non-renewable energy consumption and GHG emissions there are, for example, remarkable cost reductions within the time horizon considered, with costs of battery vehicles being reduced by a factor of two and fuel cell cars by a factor of three. But also other indicators such as average mortality or ranges and charging times for Battery Electric Vehicles (BEV) are expected to improve decisively. In the balanced multi-criteria perspective (i.e. with equal preference given to the high level criteria), with the exception of scenarios with Steam Methane Reforming (SMR), fleets with various shares of electric vehicles rank at the same level as the hypothetical future fleet fully dominated by (much improved) Internal Combustion Engine Vehicles (ICEV). Also, excluding scenarios with SMR, the sustainability performance of fleet scenarios is clearly better than that of the current fleet.
- **Electric mobility faces challenges with regard to a number of factors.** These include costs, range and charging performance for BEV, environmental performance for example with regard to metal depletion, dependence of future availability of nearly carbon-free electricity for charging BEV and production of hydrogen, deployment of the necessary infrastructure, and last but not least the continued trend towards remarkable improvements of conventional technologies.

For detailed results and conclusions we refer to chapters covering the various Work Packages and to the chapter summarizing the conclusions.

Recommendations for further work include, among others, improvements with regard to data, methods used, tool developments and substantial scope extensions.

A subset of the recommendations is listed here:

- Collection and analysis of primary industry data from manufacturers of batteries and fuel cells, establishment of Life Cycle Inventory (LCI) data for specific future battery technologies

not considered in this work, such as Li-air or Li-sulfur, and for future fuel cells explicitly taking into account new materials and manufacturing technologies.

- Extension of grid analysis to address a substantially higher penetration of BEV and PHEV with time horizon of year 2050, i.e. beyond year 2030 as implemented in the present study.
- Modeling of imports and exports as endogenous parameters within the power system model.
- Analysis of additional municipalities, aiming at identification of low-impacting communities to help to identify structural factors (like short commuting distances), that are favorable for keeping the mobility demand at moderate level.
- Consolidation of the improvements of the traffic simulation mode MATSim that the THELMA project brings to the software. This may involve applications of the simulation to similar problems (i.e. involving energy consumption calculation, use of electric vehicles, etc.) as well as differentiating weekday and weekend scenarios.
- Refinements of integration analysis for example by consequently implementing the analysis for year 2050 rather than extrapolating from 2030 results as is done in some tasks of this project.
- Updates and extensions of technology assessment are necessary, particularly having in mind that the reference year for current technologies as defined in the THELMA project is 2012.
- Interdisciplinary assessment of biofuels and their implementation in the fleet model is considered to be a high priority.
- Autonomous vehicles are not addressed in this work. Given the potentially revolutionary impact they could have on the future mobility they need to be included and subjected to detailed analysis.
- Since the infrastructure necessary for the expansion of electric mobility is addressed to a very limited extent in this work, the development of the infrastructure and the associated impacts on economy, environment, risks etc. as well as social acceptance issues should be investigated in order to achieve a more realistic assessment of future mobility.
- Work on mobility demand and associated social aspects are included to very a limited extent and call for much extended attention. This includes consideration of rebound effects.
- The fleet analysis builds on rather arbitrary assumptions about future composition of the future fleet. Furthermore, though electricity supply scenarios and energy supply chains constituted part of the analysis, no energy-economic model with mobility as one of the end use sectors is used in the present work. Such a model allows representation of the complex and dynamic interplay of the mobility sector with the overall energy system and is able to endogenously generate cost-optimal solutions also under climate protection constraints.
- The current analysis needs to be extended to cover the whole mobility sector, i.e. other modes of passenger mobility such as motorcycles, buses, railway and airplanes as well as transport of goods.

During the last two years the THELMA Project was coordinated with the Swiss Coordination Centre for Energy Research (SCCER) “Efficient technologies and systems for mobility” http://www.sccer-mobility.ch/ to mutual benefit. Some of the developments mentioned above are already pursued within this SCCER.

Finally, one of the achievements of the THELMA Project is the fact that five students defended their Ph. D. thesis fully or partially based on their work within the THELMA Project.

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1. Project content

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1.1. Project background

Project **THELMA** (**T**ec**H**nology-centered **EL**ectric **M**obility **A**ssessment) was established to carry out an integrated, technology-based study of light electric vehicles' potential in Switzerland, assessing tradeoffs and sustainability compared to other drivetrains and fuels.

The project was established in April 2010 based as an activity of the Competence Center for Energy and Mobility in co-operation with swisselectric research and Swiss Petroleum Association (German: Erdöl-Vereinigung). The co-operation and co-ordination with the Swiss Competence Center for Energy Research "Efficient Technologies and Systems for Mobility" made it possible to extend the scope and depth, particularly with regards to the overall integration of the assessment carried out in the various Work Packages (WPs) of THELMA.

The THELMA consortium brings together a highly qualified research team from ETH Zürich, the Swiss Federal Laboratory for Materials Testing and Research (EMPA) and the Paul Scherrer Institute (PSI). The THELMA project was structured to build on the strengths and experience of these research groups.

1.2. The national and international context: strategies and perspectives

Today, the transport sector is responsible for 27% of global total final energy consumption and nearly 25% of global CO_2 emissions (International Energy Agency, 2009, International Energy Agency, 2013). Over 95% of transport energy is supplied by oil, amounting to over 2250 MToe per year and exceeding 60% of global annual oil consumption (International Energy Agency, 2009, International Energy Agency, 2013). In the last 40 years, global transport energy use has steadily increased by 2-2.5% per year, more than doubling between 1971 and 2006 (International Energy Agency, 2009). In the coming decades mobility demand is expected to continue to increase, leading to further increases in fossil fuel consumption. For example, the IEA predicts that the global passenger car fleet, which was 870 million strong in 2011, will increase to 1.7 billion cars by 2035 (International Energy Agency, 2012).

This large demand for mobility and the related consumption of fossil fuels results in serious environmental, economic and social burdens. Aside from their contribution to global warming, emissions from the combustion of fossil fuels also contain pollutants such as particulate matter, SO_2, NO_x, and CO which can cause serious health problems, especially in cities where pollutant concentrations are highest (Takeshita, 2011). Furthermore, such reliance on fossil fuels raises issues of energy security for many countries that rely on imports to satisfy their fossil energy demand. The geological distribution of oil and the political stability of producing regions make price stability and

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security of supply problematic. Declining production from present reserves and the uncertain costs of discovering and recovering lower quality reserves only serve to further emphasize the risks of future cost escalation and decreasing supply.

In addition to the primary concerns of fossil dependence and CO_2 emissions, there are also a range of additional problems associated with sustainability, including health concerns associated with emissions (NO_x, CO, and particulates), noise, and social concerns.

In order to reduce the impacts of mobility, many governments are setting limits on fuel consumption or CO_2 and other pollutant emissions of new cars, such as the European Union, United States, China, and Japan (An et al., 2011). For example, the European Union has regulated the fleet average CO_2 emissions of new cars to 130 g CO_2 per kilometer by 2015, reducing to 95 g CO_2 per kilometer by 2020. This fits into the European Union's larger goal of reducing domestic greenhouse gas emissions to 20% below 1990 levels by 2020 and further to 80% below 1990 levels by 2050 (European Commission, 2014). In order to reach the 80% reduction by 2050 goal, the European Union is planning to reduce transport section greenhouse gas emissions by 60% compared to 1990 levels by 2050 (European Commission, 2011).

In 2011 the Swiss Federal Council and Parliament decided to move away from nuclear based electricity production and restructure the energy system to meet ambitious sustainability goals. The goal of sustainability implies a wide range of concerns, including protecting the climate, minimizing pollution, protecting ecosystems and human health, and assuring security of supply, affordability and social acceptance. Resulting from this decision, the Federal Council has developed the Energy Strategy 2050, which is a long-term national energy policy based on forecasts of energy supply and demand as well as climate goals under three different scenarios as reported in the document "Energy Perspectives 2050" (Prognos, 2012). These three scenarios define three potential futures for the Swiss energy system. The Business As Usual (BAU) scenario considers only energy policy instruments that are currently in place and that energy demand and efficiency improvements will continue to develop as they have in recent history. The Political Measures (POM) scenario considers the implementation of all political measures currently being considered by the federal council and that energy demand and efficiency improvements will continue to develop as they have in recent history. The New Energy Policy (NEP) scenario is the target scenario for the federal council and considers a possible development until 2050 that includes a reduction of CO_2 emissions down to 1-1.5 t per person. By 2050, the demand for personal and goods transport in Switzerland is expected to increase by 23-32% and 48-57% respectively (Swiss Federal Office for Spatial Development, 2012, Prognos, 2012). Despite this large growth in transport demand, depending on scenario, final energy consumption of transport in Switzerland is projected to reduce by 29-54% and CO_2 emissions by 37.7-85.7% by 2050 compared to 2010 (Prognos, 2012). See Figure 1.1 below.

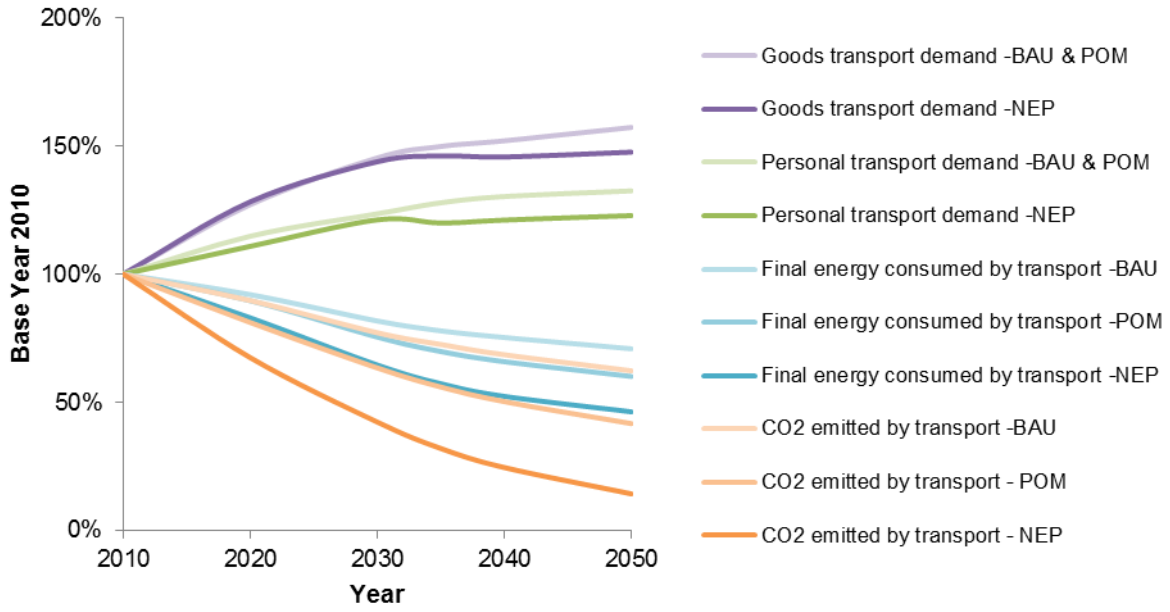

Figure 1.1 Transport demand, final energy consumption and CO_2 emission forecasts until 2050 under the three scenarios defined in the Energy Perspectives 2050.Business As Usual (BAU), Political Measures (POM), and The New Energy Policy (NEP).

1.3. E-mobility as a potential solution

Technological advances in oil extraction may extend the life and reduce the political risk of the fossil oil supply while improved internal combustion engine (ICE) technology may increase efficiency and reduce emissions. However, these improvements will only provide a bridge or extend the transition to real, long-term sustainability. The only real solution is a non-fossil, zero (net) carbon energy carrier that can be produced and delivered, and then carried and used in a vehicle with acceptable characteristics (e.g. range) and cost. This energy carrier may be electricity, gas (hydrogen or syngas) or a range of synthetic liquid fuels. Performance along the full energy carrier pathway or chain is important, and different alternatives have different present disadvantages. Electricity can be nearly carbon-free, and is relatively easy to deliver, but it is still difficult to carry enough onboard the vehicle at a low enough size and cost. Hydrogen is still more expensive from “zero-carbon” sources, relatively hard to handle (transportation and on-board storage), and fuel cells are still expensive. Synthetic fuels have relatively high energy densities and are easy to burn, the carbon to cost balance is often poor, or production may have environmental and social side effects. At present a combined system of a drivetrain using a non-fossil, “zero-carbon” energy carrier is still either unavailable or the total cost per kilometer is too expensive.

Recent, continuing advances on a range of relevant technologies and the inherent advantages of the electric system in supplying and delivering energy combine to mean that electric mobility is among the best options to meet the conflicting economic, environmental and social criteria for sustainability. If future growth of the Swiss electricity system can maintain the low carbon content of the generation mix, and the relative price stability and security from interruption, then lightweight vehicles with electrified drivetrains can potentially make real contributions to a more sustainable Swiss transportation system. Advances in battery and supercapacitor technologies, hydrogen storage (to a lesser degree), and better fuel cells and IC engines as prime movers make such potential contributions ever more likely. Increased electrification offers advantages in power distribution and management (e.g. braking regeneration, and more efficient operating of ICEs), and allows varying

degrees of hybridization to optimize combining the relative advantages of power generation and storage.

E-mobility technologies also present a range of challenges and opportunities to the electric system. Obviously electric and plug-in hybrid vehicles must be charged, and the location and time of the additional load affects the existing electric system. This can present a need for new generation capacity and energy, as well as possible new transmission capacity. On the other hand, if charging times can be shifted to off-peak hours, new capacity can be minimized. If vehicles can supply electricity back to the grid from battery storage or distributed generation (vehicle to grid, or V2G), then there is a potential for providing grid services like load leveling, spinning reserve, or support for stochastic renewables (sun and wind). Charging loads or V2G power supply may be either centrally controlled or coordinated by price signals, including battery-life related costs. All of these considerations require modeling the power system's operation and stability. Figure 1.2 below shows the overlap between vehicle traffic density and the electric power transmission grid.

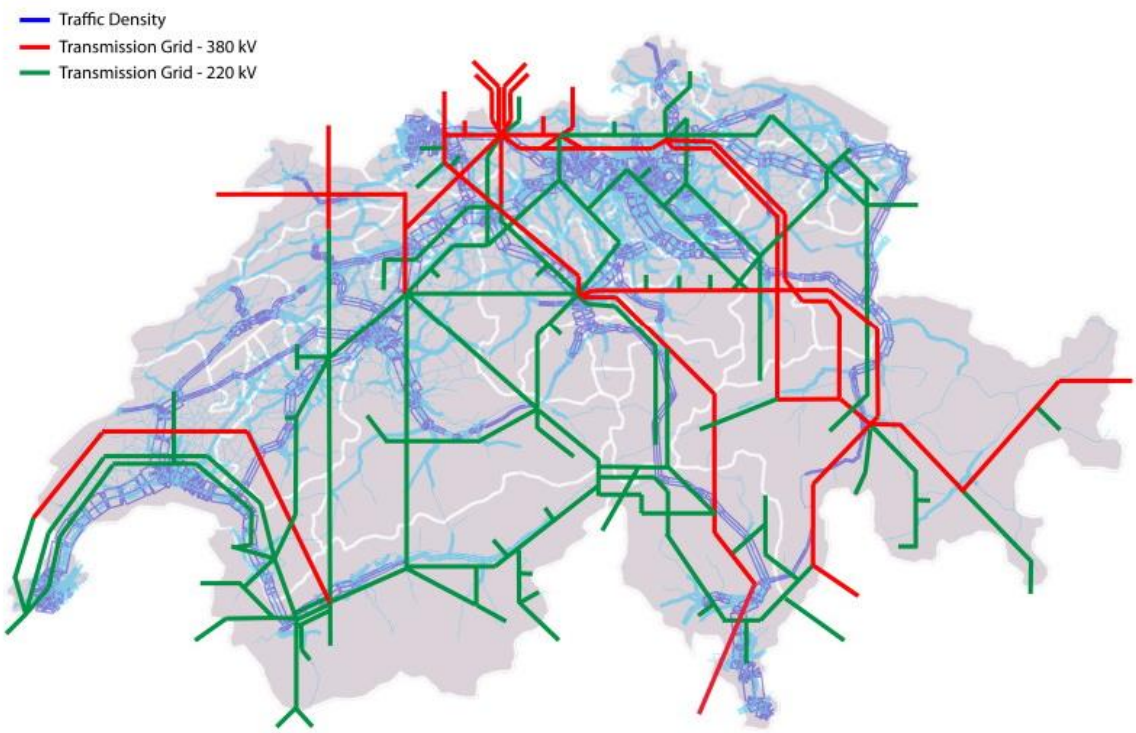

Figure 1.2 Swiss traffic density and electric transmission grid

In addition to technical advances related primarily to E-mobility, there are also ongoing advances in combustion engines, reducing loads and losses due to accessories, rolling resistance, aerodynamic drag, and down-sizing/down-weighting that all contribute to lower vehicle energy use. Advances in some technologies may provide a competitive advantage to one or several drivetrains (e.g. better batteries advance Electric Vehicles (EVs) more than hybrids, but better power electronics advance EVs and hybrids v. ICE drivetrains), while light-weighting is an advantage to all drivetrains. This means advancing technologies creates a complex environment of competition and co-evolution between different drivetrains.

1.4. Sustainable mobility as a multi-criteria problem

The analysis of the transportation sector is a classic example of a large, complex problem suited to multi-criteria analysis, including the effects of Life Cycle Assessment and environmental impact assessment. The system has large investments in vehicles and infrastructure, large costs and impacts and changes slowly due to long turnover times. The problem has many participants or stakeholders (manufacturers, fuel suppliers, customers, safety and environmental regulators, etc.), all of whom care about a broad range of criteria in different ways. And there are no easy, optimal solutions. Instead, there are only complex trade-offs between a range of Pareto-optimal solutions (individual vehicles or case study scenarios).

From a societal level we have already seen that the criteria include total costs, the environment (including climate), and security of supply. But because people buy cars individually, this implies that other characteristics of individual vehicles also matter, i.e. purchase and lifetime costs, drivability or performance, range, utility (passengers and payload), safety, etc. For this reason, it is important that a technology-centric analysis characterizes a broad range of criteria so that individual customers, stakeholders, or fleet analysts can all compare costs, total costs and Multi-Criteria Decision Analysis (MCDA) rankings.

Cost and environmental burdens need to be considered from a life cycle perspective in order to avoid leakages – i.e. burdens occurring outside the system under consideration. Thus, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) form a logical basis for taking into account environmental and cost aspects within MCDA.

1.5. Project goals and scope

THELMA's purpose was to make a comprehensive assessment of the tradeoffs and sustainability implications of the increased use of light electric vehicles, as compared to other drivetrains and fuels. The goal was thus to compare a full range of vehicle technologies, based on those criteria considered important by major stakeholders. These measure both direct and indirect effects, i.e. not just exhaust emissions and downwind health and environmental impacts, but also upstream fuel chain effects. This technology based analysis was then used as a basis for national level scenarios that include electric grid related impacts. These national scenarios were supplemented by local community case studies. Ultimately, the analytical results were integrated using both the total cost approach and multi-criteria decision support to form a transparent and trustworthy basis for evaluating sustainability and inform decision-makers and stakeholders.

The specific goals of the project were defined as follows:

- To assess LCA-based environmental performance of electric vehicle technologies (in particular, batteries and fuel cells) in comparison with combustion options driven by fossil fuels or hydrogen. Future technology advancements need to be considered along with the impacts of energy supply infrastructure and its evolution.
- To account for the role of, and requirements on, the electric grid depending on the various options for electric mobility. Furthermore, in applicable cases, synergetic effects were to be addressed.

- To carry out case studies on a regional or local level assessing the environmental implications of the expansion of electric mobility and its integration with the energy supply system. In particular, the performance of centralized vs. decentralized energy supply options should be evaluated.
- To assess aggregated environmental and economic vehicle technology attributes, thus enabling a cost-benefit analysis of electric mobility options both on the technology level as well as for alternative scenarios on the national level.
- To evaluate the relative sustainability of the options by combining their performance on environmental, economic and social criteria with stakeholder preference profiles.

The scope of the THELMA project was defined as follows:

- **Vehicle classes:** automobiles of various classes.
- **Drivetrains and energy carriers:** electric (battery and fuel cell) vehicles, fuel cell and ICE hybrids, plug-in hybrids, and ICE vehicles using gasoline, diesel and methane gas from fossil resources.
- **Electricity/energy supply:** alternative electricity supply mixes, hydrogen production from renewable, nuclear or fossil fuels.
- **Time horizon:** detailed technology evolution until year 2030; outlook until year 2050.
- **Applications:** Swiss-specific case; environmental case studies on local level; impact pathways approach and external cost analysis on technological and national level; life cycle, cost benefit and sustainability assessment on technological and national levels.
- **Geographic boundaries for LCA and impact assessment:** beyond Swiss national borders.
- **Evaluation criteria:** environmental, economic and social (limited), security of supply, driver utility.

1.6. THELMA approach

A detailed, technology-centered system analysis is a prerequisite for understanding the strengths and weaknesses of the options developed, examining their costs and benefits compared to both conventional and other advanced alternatives, and assessing their potential contributions to a more sustainable future.

The overall approach employed by the THELMA project is to perform a detailed, comprehensive combination of technology assessment, life cycle assessment, power systems analysis, and integration of results. This begins with characterization of a wide range of drivetrains and energy carriers. The drivetrains (electric and competing ICE) and energy carriers (batteries and fuels) are to be combined with other vehicle options (e.g. different vehicle classes, down-weighting, etc.) to define a wide range of vehicles (a “virtual fleet” of designs). Life cycle analysis is used to provide a vector of average burdens for different energy carriers and for vehicle materials or components. The LCA burdens for vehicles components or materials are then combined with vehicle descriptions to obtain burdens per vehicle. Local and/or regional scenarios are defined to study the overall impacts of vehicles penetrating into the Swiss fleet. Both vehicle technology and scenario descriptions are then used to find the distribution of charging load patterns by location and time of day, so that transmission network modeling can be used to determine system dispatch (generator operation) and cost, including grid constraints, if any exist. These various tasks must be coordinated so that technology, LCA, scenario, and transmission modeling assumptions are consistent. Modeling of future technology developments must therefore be consistent with assumptions for future traffic

patterns, charging load patterns, and future generation and grid expansion. Power network modeling includes comparison of central versus customer controlled charging patterns (including battery costs) and analysis of V2G grid services. The integration analysis task combines criteria indicators partially originating from other tasks to characterize local and climate related emissions, resource burdens and some social concerns. Where possible, these indicators are monetized to obtain external costs that are added to direct technology costs to obtain total costs. All indicators are aggregated using selected stakeholder preference profiles and multi-criteria decision analysis tools, so that total cost and MCDA rankings can be compared.

1.7. Project structure and framework

The following analytic tasks (called work packages) have been defined. These work packages are also used throughout the rest of the proposal to organize the sections on related research, research targets, research plans and specific timetables and milestones.

WP1: Life Cycle Assessment (LCA) – LCA-based environmental performance of vehicles and energy supply chains (electricity and fuels). Focus to be on technologies and materials related to E-mobility vehicles, with competing vehicle technologies included for comparison. Includes predicted future advances in vehicle technologies and the energy supply infrastructure up to 2030, with results that can be extrapolated for use in other packages in analysis for up to the year 2050. (EMPA-LCAM, PSI-LEA).

WP2: Vehicle simulation and powertrain assessment – Technology characterization of future drivetrains for E-mobility designs, plus competing drivetrain technologies. Includes the direct analysis of technology criteria, and supplying technology descriptions to WP1, WP4 and WP5. (ETHZ-LAV, PSI-LEA).

WP3: Power system modeling – Analysis of the impacts on electric system dispatch, transmission constraints and costs due to the presence of new charging loads from electric vehicles. Includes analysis of vehicle-to-grid storage or generation. (ETHZ-PSL).

WP4: Case studies – Perform studies on the regional and/or local level assessing the sustainability implications of electric mobility options penetrating the transportation market, compared to competing vehicle technologies. Includes integration with the energy supply system, and in particular analysis of centralized vs. decentralized energy supply systems. (ETHZ-ESD, ETHZ-IVT).

WP5: Analysis integration – Integration of sustainability measures based on technology-specific assessment of vehicles, including local/regional pollution, carbon emissions, resource use and social concerns (e.g. energy security, etc.). Includes aggregation of these measures, based on inclusion of external costs to produce total costs, and the use of stakeholder preferences for sustainability criteria to produce rankings of both individual vehicle and scenario alternatives. (PSI-LEA).

WP6: Project management & coordination – Management and co-ordination of the other five work packages, including dissemination of final results (PSI-LEA).

Figure 1.3 provides an overview of the structure and partners involved in THELMA as well as the relationships among the various work packages.

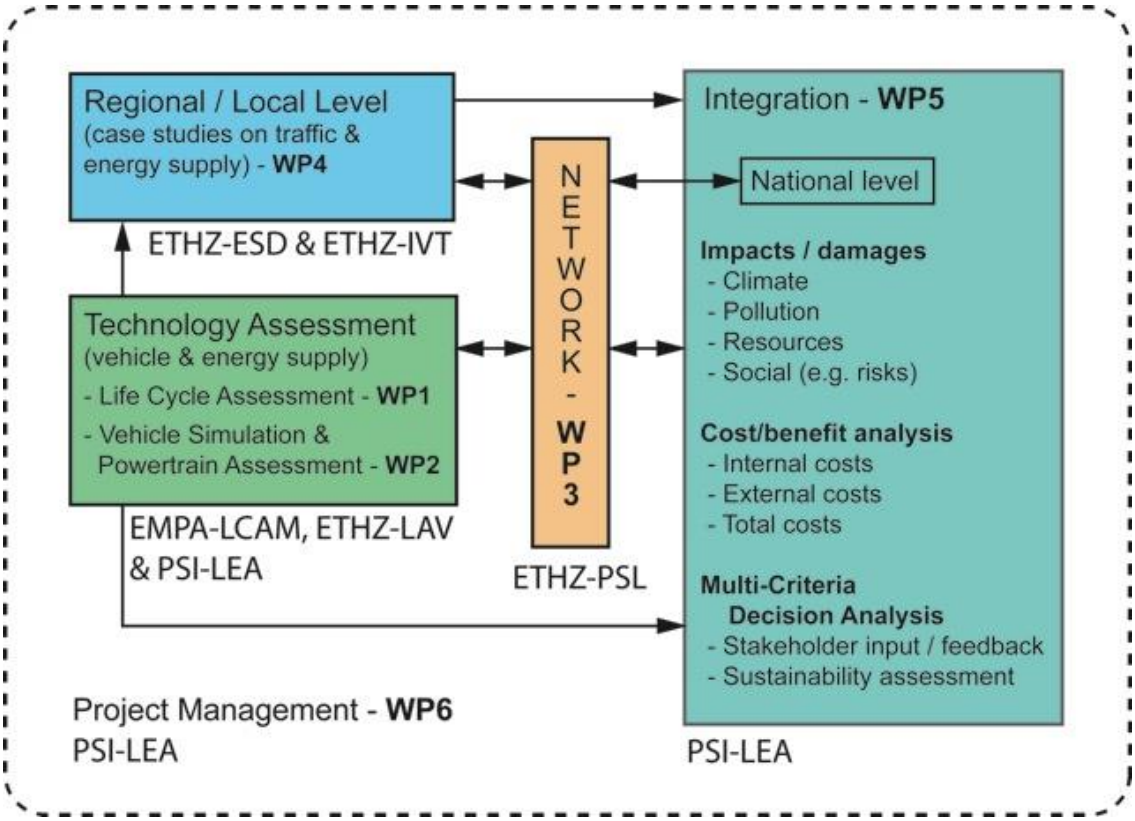

Figure 1.3 THELMA framework diagram with work package tasks and partners.

Each work package addresses the following key issues and questions.

Work Package 1: Life Cycle Assessment (LCA)

The key question for LCA is to characterize the full transportation chains for different combinations of vehicles and energy carriers. In some cases, energy carrier data may already exist (e.g. current electricity mixes and some of today's fuels), but need to be modified and extrapolated. In other cases, original LCA of energy carriers (e.g. advanced chemistry batteries) and prime movers (e.g. fuel cells) needs to be performed. Likewise, LCA for the set of alternate fuels for ICE drivetrains that compete with electric mobility options needs to be completed. For the LCA analysis of drivetrains and vehicles, a key question is disaggregation of the results on the basis of material content, components or processes, so that the LCA burdens per vehicle can be calculated for a large combination of different drivetrain and vehicle options (class, size, light-weighting, etc.).

Work Package 2: Vehicle simulation and powertrain assessment

The primary task of Work Package 2 includes the characterization and modeling of current and future powertrain technologies. In particular conventional, hybrid electric (including plug-in hybrids), battery electric and fuel cell vehicles are simulated for assorted driving cycles, representative of real-world driving conditions. These drivetrain models are combined to generate large sets of consistent vehicle designs combining different drivetrains, vehicle classes and energy carriers. Each vehicle design is characterized by multiple criteria, including energy use, performance, and cost. In addition, environmental indicators are calculated based on life cycle results of Work Package 1.

Work Package 3: Power system modeling

The chief issue in power system modeling is to model the addition of electric drivetrain vehicles to the power grid. The first step is to take technology and scenario descriptions from Work Packages 2 and 4 to generate charging load distributions by time of day and location. This charging load is combined with normal load patterns and system operation is simulated, including transmission system constraints on generation dispatch, to obtain least-cost operation of the power system. Future scenarios of energy supply and demand are modeled. A key question involves whether charging is controlled or uncontrolled.

Different charging strategies may be compared, ranging from purely convenience-based to including load shifting incentives induced by time-of-use tariffs. These charging strategies may also be compared to centralized control based on minimizing utility cost. Questions also include the provision of grid ancillary services, where not only load-shifting is considered but also the use of vehicle to grid.

Work Package 4: Case studies

In this work package, electric mobility in the context of household consumption on the level of Swiss municipalities is assessed. Energy supply and demand for important energy-related activities are modeled and strategies to effectively reduce environmental impacts are proposed. For this purpose, the multi-agent transport simulation is enhanced and a predictive building stock energy demand model is developed and coupled with life-cycle assessment models to account for the environmental dimension. The prospective energy systems are optimized using ecological criteria. This task has the main responsibility for constructing case study scenarios, including forecasts of future traffic patterns. These traffic patterns are then combined in Work Package 5 with customer charging rules (in coordination with the WP3 on power system modeling). The integrated scenario modeling must also combine results from Work Packages 1, 2 and 3 to produce scenario results. Scenario formulation also includes regulatory and political boundary conditions for Swiss conditions.

Work Package 5: Analysis integration

The chief task of Work Package 5 is the aggregation of results from tasks 1 through 4. It also includes estimation of additional criteria. These will include, for example, social indicators like energy carrier risk, autonomy, cost sensitivity, etc. This task also includes monetization of external costs associated with local & regional impacts (e.g. due to PM, NO_x emissions) and global effects (e.g. due to CO_2 emissions), using appropriate models for transport, damages and valuation. Appropriate models for distributed, tailpipe emissions are combined with more detailed models for emissions from centralized power plant emissions. Externalized costs are added to direct costs to find average total vehicle costs per kilometer.

Multi-criteria indicators related to vehicle sustainability are combined with stakeholder preferences based on generic stakeholder profiles. Indicator data will be normalized and combined with stakeholder indicator weights using a Multi-criteria Decision Analysis (MCDA) algorithm for ranking of discrete alternatives. MCDA ranking of national vehicle fleet and grid operation scenarios is also performed. Total cost and MCDA ranks are compared.

Work Package 6: Project management & coordination

This work package has the task of coordinating efforts within all the other work packages, managing

the overall THELMA project in a productive and effective manner, and disseminating the analytic and scenario results to stakeholders and decision-makers concerned in the mobility area.

1.8. Project deliverables

Based on the above-stated project goals, the following key deliverables were generated:

- Life Cycle Inventories and Life Cycle Impact Assessment results for current and future electric (battery and fuel cell) vehicles, fuel cell and internal combustion engine (ICE) hybrids, plug-in hybrids, and ICE vehicles using gasoline, diesel, and methane gas from fossil resources.
- A self-consistent set of electrified and conventional vehicle designs, representative of Swiss and International fleets; validated vehicle simulation results for key criteria such as cost, fuel use, performance, utility; trade-off assessment for vehicle technology from the present to 2050.
- Tools for the investigation of Plug-in Hybrid Electric Vehicle (PHEV) impacts on distribution and transmission assets and their lifetime; method and tool to model and assess asset lifetime with and without V2G operation schemes; methods controlling V2G scheduling operations in order to achieve network friendly vehicle operation.
- Case studies for selected Swiss municipalities addressing mobility and energy supply scenarios based on an integrated model of energy supply and demand, and transport simulation model; identification of strategies to cost-efficiently reduce the overall environmental impact of mobility and energy use of municipalities.
- A set of sustainability indicators characterizing current and future mobility options for Switzerland; assessment of externalities associated with these options; MCDA-based ranking of mobility options on the technological and scenario levels with consideration of stakeholder preferences.

1.9. Report organization

Chapters 2 – 6 summarize the approaches and results of Work Packages 1 – 5, respectively. Chapter 7 contains the main conclusions and outlook. Appendices A – G provide complementary information on inputs and models used as well as complete sets of technology and fleet performance indicators, and MCDA results.

Acronyms

BAU	Business As Usual
EMPA	Swiss Federal Laboratory for Materials Testing and Research
EMPA-LCAM	EMPA Life Cycle Assessment and Modeling Unit
ETHZ	Swiss Federal Institute of Technology in Zurich
ETHZ-ESD	ETHZ Chair of Ecological Systems Design
ETHZ-IVT	ETHZ Institute for Transport Planning and Systems
ETHZ-LAV	ETHZ Aerothermochemistry and Combustion Systems Laboratory
ETHZ-PSL	ETHZ Power Systems Laboratory
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCDA	Multi-criteria Decision Analysis
NEP	New Energy Policy
PHEV	Plug-in Hybrid Electric Vehicle
POM	Political Measures
PSI	Paul Scherrer Institute
PSI-LEA	PSI Laboratory for Energy Systems Analysis
V2G	Vehicle to Grid
WP	Work Package

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2. Work Package 1 "Life Cycle Assessment"

Authors: Christian Bauer[10], Andrew Simons[11] (PSI); Andrea Del Duce[12], Hans-Jörg Althaus[13] (Empa)

2.1. Introduction

Evaluation of the environmental performance of current and new passenger vehicle technologies is one of the key aspects contributing to one of the overarching goals of the THELMA project, a more comprehensive vehicle assessment addressing trade-offs between environmental, economic and social aspects.

Such an environmental evaluation must be based on Life Cycle Assessment (LCA), since not only the environmental burdens due to operation of vehicles, but also due to their production and end-of-life as well as those of the associated fuel chains need to be included in such assessments. For this purpose, Work Package 1 (WP1) developed new Life Cycle Inventory (LCI) data for a broad range of current and future passenger vehicle technologies (and the associated fuel chains), which were used as a basis for the LCA.

2.2. Specific objectives

Developing new LCI data and quantifying the associated Life Cycle Impact Assessment (LCIA) results for a broad range of current and future passenger cars in a modular way – i.e. for the individual components of the vehicles – was defined as specific objective of WP1. LCI data for fuel chains are mainly based on previously established data and to a limited extent on external data sources. These LCI data and LCIA results serve as inputs for other THELMA work packages, namely WP2 and WP5, in which they can be used for evaluation of the environmental performance of cars using vehicle simulation, as well as for quantification of environmental performance criteria in multi-criteria assessment of individual vehicles and potential future car fleets.

Another objective was the development of a user-friendly tool allowing for comparative LCA of vehicles with characteristics (vehicle weight, propulsion system, fuel demand, etc.) defined by stakeholders.

2.3. Scope

The scope of WP1 covers the complete set of generic[14] passenger vehicles, which are assumed to be potentially relevant on the market between today and 2030. LCI data for their components and the associated production and fuel chains are established and the associated LCIA results quantified.

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[14] „generic" in the sense that the LCI data do not represent specific car models, but are supposed to be representative for selected vehicle categories, e.g. "city car", "medium-sized car", and "large car". Cars corresponding to these categories would for example be a Renault Twingo, a VW Golf, and a Lexus 600, respectively.

The vehicle set, which can be evaluated based on the developed LCI data can be categorized according to vehicle size:

- City car
- Medium-sized car
- Large car
- Van
- Small lorry
- Bicycle
- Scooter

The vehicles can also be further differentiated according to their type of primary body materials:

- Standard (as of today)
- Light-weight aluminum
- Light-weight fibre reinforced polymers

LCI data for four different propulsion systems are available:

- Internal combustion engine (ICE) with tailpipe emission data corresponding to EURO 3, 4, 5 and 6
- Hybrid (ICE + battery)
- Battery electric (BE)
- Fuel Cell (FC + battery)

Bicycles can only be evaluated as human-powered or electric; and scooters only as BE and ICE vehicles.

The powertrain of hybrids, battery electric and fuel cell electric vehicles (BEV, FCEV[15]) contains another battery than the "normal" lead acid battery of ICEV. Three different types of such "propulsion batteries" have been analyzed:

- Nickel-metal-hydride (NiMeH)
- Li-Ion
- ZEBRA[16] (Na-$NiCl_2$)

A large set of fuels for vehicle operation is available:

- Fossil: gasoline, diesel, natural gas
- "Bio"fuels: biogas, biodiesel, E85 (85% bioethanol, 15% gasoline)
- Hydrogen (for FCEV): produced via steam methane reforming (SMR) of natural gas; coal gasification; biomass gasification; electrolysis using the Swiss consumption mix, the Swiss certified electricity mix, or the European mix; electrolysis using PV, wind, hydro, nuclear, wood, natural gas CC[17], or geothermal power

[15] Sometimes abbreviated "FCV".
[16] Zeolite Battery Research Africa.
[17] CC: „Combined Cycle"

- Electricity (for BEV and plug-in hybrids): Swiss consumption mix, Swiss certified power mix, European consumption mix, hydro, PV, wind, wood, geothermal, natural gas, coal, and a user-specified mix[18]

The LCI data of the different components and some fuel production pathways are quantified for three different time horizons (with some of them assumed to be identical for all three reference years):

- Present (2012)
- "Near future" (2020)
- "Far future" (2030 and beyond)

The LCA tool developed in WP1 allows the user to individually specify a set of vehicles for a comparative assessment of the environmental performance based on a variety of LCIA indicators. The vehicles need to be specified in terms of the following characteristics/parameters:

- Vehicle type and size
- Type of materialization
- Power train type
- Emission class (for ICEV and hybrids)
- Battery type
- Temporal scenario
- Fuel (energy source)
- Masses of the glider and the drivetrain, of potential batteries and fuel cells
- Fuel consumption for driving only and for auxiliaries
- Total driving lifetime
- Lifetimes of batteries and fuel cells

Certain unrealistic characteristics and parameter combinations are disabled, also depending on the temporal scenario chosen. E.g. "present" (as of 2012) and "EURO6" is no valid combination, while "far future" and "EURO3" will result in a warning. Parameter setting, e.g. lifetimes of batteries and vehicles, is only possible within certain ranges which are estimated to be realistic.

Based on the characteristics and parameters provided by the user, the tool calculates LCIA results for the following indicators and methods:

- ReCiPe (H/A) mid- and endpoints (Goedkoop et al., 2012)
- Impact 2002+ mid- and endpoints (Jolliet et al., 2003)
- IPCC 2007 global warming potential (GWP 20/100/500a) (Solomon et al., 2007)
- Ecological scarcity 2006 (Frischknecht et al., 2009)
- Cumulative energy demand (with subcategories) (Hischier et al., 2010)
- CML abiotic resource depletion (Oers et al., 2002)

The LCIA results as quantified in WP1 do not represent location-specific impacts on human health and ecosystems, which is in line with state-of-the-art LCA practice today, since damage factors in

[18] The user can specify a certain electricity mix providing the preferred shares of available power generation technologies for all three time horizons.

commonly used LCIA methods usually represent average European/global conditions. However, besides these LCIA results, also the cumulative environmental flows are calculated. These can be used for further processing, e.g. estimation of site-specific impacts using the impact-pathway approach as performed within WP5.

2.4. Methodology and data

2.4.1. Life Cycle Assessment (LCA)

Life Cycle Assessment is used as the method to estimate the overall environmental burdens of passenger vehicles including its production, operation and end-of-life as well as the associated fuel chains. The LCA carried out in this WP1 is based on the methodology as standardized according to ISO 14040-14044 (ISO, 2006a, ISO, 2006b). The four required steps of LCA are the following:

1. Goal and scope definition: A detailed description of the goals of the assessment, the question(s) to be answered, the target audience, the system boundaries and the impact assessment methods to be used needs to be established.
2. Data collection (Life Cycle Inventory): Data collection will cover the complete life cycle of the products in focus: production, use, and end-of-life (disposal and/or recycling). Data in LCA are classified either as "primary data/foreground data", or "secondary data/background data". The latter are e.g. the production process of generic materials such as steel or chemicals and freight transport processes; whereas the foreground data represent the systems/technologies in focus of the study, i.e. vehicles and their individual components as well as fuel supply chains.
3. Life Cycle Impact Assessment (LCIA): Cumulative life cycle inventory data – i.e. LCA results – are calculated based on the collected primary data and the background data. Application of LCIA methods allows for a quantification of potential impacts on the environment and on human health.
4. Interpretation: The LCA results including the comparative evaluation with alternative system will be described and interpreted.

2.4.1.1. Goal and scope

Primary goal of this WP1 is the establishment of a set of consistent LCI data allowing for an unbiased comparative evaluation of the environmental performance of a broad range of passenger vehicle technologies, as described in chapter 2.3. The associated LCA results are supposed to represent the environmental burdens associated with travelling 1 km with a certain vehicle technology, i.e. the functional unit used in the comparison is 1 vehicle-km (vkm or just km).

The LCA is carried out based on the attributional approach, i.e. representing the current (or future, respectively) economic system, as it is (or supposed to be in the future, respectively). Therefore, the LCA results on their own are technology specific per vehicle kilometer. This is subject to a number of limitations with regard to conclusions concerning the consequences of a large-scale future market penetration of innovative vehicle technologies such as BEV or FCEV in terms of environmental burdens and potential impacts. Complete analysis would require taking into account economic feedbacks (also in other sectors than transport and mobility), market mechanisms, rebound effects and application of consistent scenarios for future development of specific production chains and the economic system.

The system boundaries, i.e. the included processes and the division between foreground and background system, is shown in Figure 2.1.

The target audience is diverse and includes both scientific and non-scientific stakeholders. Apart from this report, the LCA results are communicated via target-oriented tools and media, i.e. scientific papers as well as reports and articles for the general public.

The impact assessment methods used are listed in chapter 2.3.

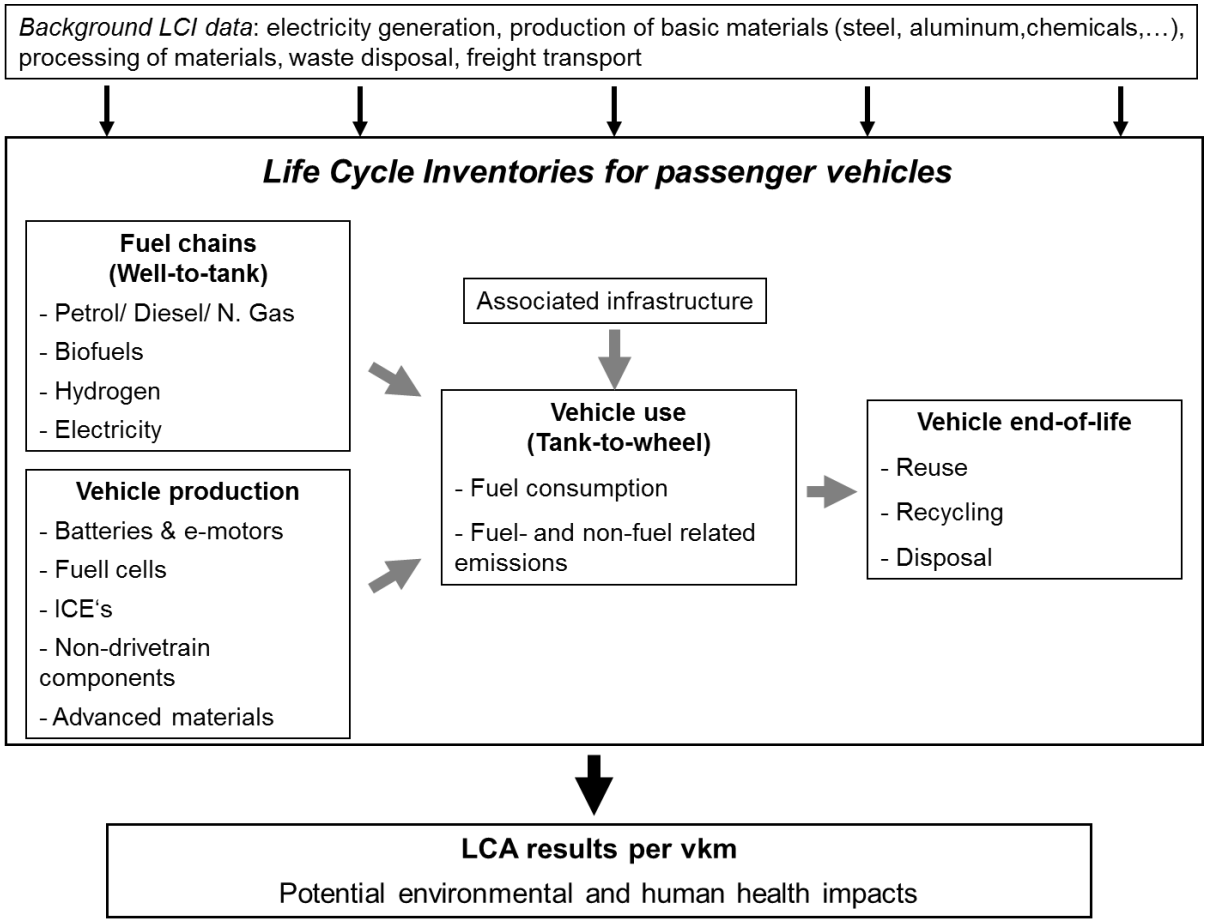


Figure 2.1 System boundaries of the WP1 LCA; vkm = vehicle-km.

2.4.1.2. Data collection

The new LCI data are largely established according to guidelines provided by ISO (ISO, 2006a, ISO, 2006b). LCI data of the processes in the ecoinvent LCI database, v2.2 (ecoinvent, 2012), serve as background LCI data and the associated quality guidelines (Frischknecht et al., 2005) as a landmark. End-of-life (EoL) treatment of the vehicle infrastructure, i.e. the glider and the powertrain (incl. batteries and fuel cells), represents an exception: instead of the cut-off approach, a substitution approach as described in (Althaus and Gauch, 2010, Habermacher, 2011) was chosen in order to represent the above-average recycling rates in the automobile industry.[19]

Data sources for the establishment of new LCI data are diverse: They include public databases such as the TREMOVE model (Ceuster et al., 2007) and the EMEP/EEA Emissions Inventory Guidebook

[19] According to The European Union's directive regarding vehicle EoL "2000/53/EC" (EC 2000) at least 85% of the weight of vehicles should be re-used, recovered or recycled.

(Ntziachristos et al., 2009) used for quantifying vehicle emission data and road infrastructure as presented in detail in (Simons, 2016) scientific literature and primary industry data from fuel cell and battery research for the LCI data of vehicle infrastructure, with details provided by (Althaus and Gauch, 2010, Habermacher, 2011) for engines, electric motors and gliders; by (Bauer and Simons, 2010, Looser, 2011, Notter et al., 2010, Simons and Bauer, 2011a) for batteries; (Miotti et al., 2015, Simons and Bauer, 2015) for fuel cells; and by (Del Duce et al., 2016) for further electric vehicle components.

LCI data for hydrogen production chains have been established as part of this project and are documented in (Simons and Bauer, 2011b). LCI data for electricity supply chains representing current technologies are based on LCI data from the ecoinvent database v2.2 and (Roth et al., 2009) . LCI data for electricity supply chains representing future technologies are based on LCI data from (Roth et al., 2009) with European electricity mixes according to the projections of the NEEDS project (ESU-services, 2008). Future Swiss electricity mixes are quantified according to the results of PSI's energy economic modeling of the Swiss electricity sector for 2020 and 2035, respectively (Ramachandran and Turton, 2012, Ramachandran and Turton, 2013), adopting the electricity demand cases of the latest Swiss Federal energy strategy (Prognos, 2012) but providing least cost supply solutions for alternative scenarios. LCI data from the ecoinvent database v2.2 (ecoinvent, 2012) are used for fossil fuel supply chains.

2.4.1.3. Life Cycle Impact Assessment (LCIA)

Calculation of cumulative LCA results and quantification of LCIA results has been performed using the LCA software SimaPro v7.3.3 with the implemented LCIA methods (PRé, 2013). These LCIA methods used for estimation of potential impacts on human health, ecosystem quality and natural resources are listed in chapter 2.3. The indicators analyzed in more detail are discussed in chapter 2.5.2. The broad range of methods and environmental indicators allows for a comprehensive comparative evaluation of individual technologies. Both midpoint and endpoint LCIA indicators are provided, which guarantees transparency without aggregation of different impact categories (midpoint level), but also potentially less complex interpretation of LCIA results (endpoint level). The use of several LCIA methods – ReCIPe, Impact 2002+, Ecological scarcity – reduces the likelihood of misinterpretation based on specific features of one single method.

2.4.1.4. Interpretation

The LCA results provided by this WP1 (see chapter 2.5) and other work packages (WP2 and WP5) based on the LCI data established in WP1 allow for a comparative technology-specific assessment of the environmental burdens and potential impacts of the broad range of vehicle technologies for different time frames as outlined in chapter 2.3. They also highlight the "environmental hot-spots" in the life cycle of vehicles, i.e. those processes in production, use, and end-of-life, which generate the highest environmental burdens. The validity of the results beyond the assessment on the technology level is limited, since interdependencies in the future development of economic and technological sectors have not been taken into account.

The associated uncertainties are highest for "far-future" technologies (2030 and beyond), since the ways in which vehicle technologies as well as fuel chains are expected to develop depend on many uncertain factors. Whether individual passenger vehicles as we know them today will still be used in highly developed countries in 2030 and beyond may be expected but is not granted. The

uncertainties in the LCIA indicators also vary: These are highest in aggregated endpoint indicators, which include normalization and subjective weighting steps, followed by non-aggregated endpoint indicators with substantial uncertainties in the quantification of the potential impacts on human health and ecosystem quality caused by different stressors. Less uncertain are in general midpoint indicators; however, there are also large variations within these.

The LCIA results generated in WP1 are generic in the sense that location-specific effects in the impact assessment are not considered. This currently represents common practice in LCIA, since location specific impact factors are hardly available. Location-specific impact assessment is carried out in WP5.

2.4.2. Life Cycle Inventory (LCI) data

Table 2-1 to Table 2-30 provide an overview of the complete foreground LCI data established and used within WP1. If not explicitly mentioned in the name of the datasets, they are assumed to be valid for current, near future as well as far-future options, respectively. These datasets are used in the LCA tool of WP1 and their cumulative LCI and LCIA results are combined based on the vehicle specification provided by the user resulting in vehicle specific LCIA results per km driven (see chapter 2.5).

Exhaust emission data of vehicles during operation are split into species proportional to the fuel demand (e.g. CO_2, heavy metals, etc.) and those regulated by the EURO emission classes, which have to be below certain limits and are therefore not directly proportional to fuel demand (e.g. NO_x, particulate matter, etc.). In addition, there are non-exhaust emissions from road, break and tire wear as well as fuel evaporation.

Table 2-1 LCI datasets for production and maintenance of roads and 2-wheelers.

Name of the dataset	Road provision	Operation and maintenance, road	Bicycle production	Bicycle, maintenance	Electric bicycle, glider production	Electric bicycle, electric drivetrain production	Electric bicycle, maintenance	Scooter, ICE, maintenance	Scooter, ICE drivetrain production	Scooter, glider production	Scooter, electric drivetrain production	Scooter, electric, maintenance
unit	my	my	kg	unit	kg	kg	unit	unit	kg	kg	kg	unit

Table 2-2 LCI datasets for passenger vehicle infrastructure.

Name of the dataset	Passenger car, ICE, maintenance	Passenger car, ICE drivetrain (1.4L 55kW) production	Passenger car, standard glider production	Passenger car, lightweight Al glider production	Passenger car, lightweight plastic glider production	Passenger car, electric drivetrain (100kW motor) production	Passenger car, electric (w/o battery), maintenance
unit	unit	kg	kg	kg	kg	kg	unit

Table 2-3 LCI datasets for battery and fuel cell systems and fuel tanks.

Name of the dataset	Battery, Lithium-ion	Battery, NaCl+Ni (ZEBRA)	Battery, NiMH, HEV, prismatic	battery, lead acid	PEM fuel cell system	Fuel tank, compressed hydrogen gas, 700bar	Fuel tank, compressed natural gas
unit	kg	kg	kg	kg	kg	kg	kg

Table 2-4 LCI datasets for exhaust emissions of scooters.

Name of the dataset	Exhaust emission scooter, petrol, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emission scooter, petrol, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emission scooter, petrol, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emission scooter, petrol, fuel independent part per average km, Euro 3	Exhaust emission scooter, E85, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emission scooter, E85, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emission scooter, E85, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emission scooter, E85, fuel independent part per average km, Euro 3
unit	kg	kg	kg	km	kg	kg	kg	km

Table 2-5 LCI datasets for exhaust emissions of petrol cars.

Name of the dataset	Exhaust emissions, car, petrol, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, car, petrol, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, car, petrol, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, car, petrol, fuel independent part per average km, Euro 3	Exhaust emissions, car, petrol, fuel independent part per average km, Euro 4	Exhaust emissions, car, petrol, fuel independent part per average km, Euro 5	Exhaust emissions, car, petrol, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-6 LCI datasets for exhaust emissions of E85 cars.

Name of the dataset	Exhaust emissions, car, E85, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, car, E85, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, car, E85, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, car, E85, fuel independent part per average km, Euro 3	Exhaust emissions, car, E85, fuel independent part per average km, Euro 4	Exhaust emissions, car, E85, fuel independent part per average km, Euro 5	Exhaust emissions, car, E85, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-7 LCI datasets for exhaust emissions of diesel cars.

Name of the dataset	Exhaust emissions, car, diesel, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, car, diesel, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, car, diesel, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, car, diesel, fuel independent part per average km, Euro 3	Exhaust emissions, car, diesel, fuel independent part per average km, Euro 4	Exhaust emissions, car, diesel, fuel independent part per average km, Euro 5	Exhaust emissions, car, diesel, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-8 LCI datasets for exhaust emissions of biodiesel cars.

Name of the dataset	Exhaust emissions, car, biodiesel, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, car, biodiesel, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, car, biodiesel, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, car, biodiesel, fuel independent part per average km, Euro 3	Exhaust emissions, car, biodiesel, fuel independent part per average km, Euro 4	Exhaust emissions, car, biodiesel, fuel independent part per average km, Euro 5	Exhaust emissions, car, biodiesel, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-9 LCI datasets for exhaust emissions of natural gas cars.

Name of the dataset	Exhaust emissions, car, natural gas, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, car, natural gas, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, car, natural gas, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, car, natural gas, fuel independent part per average km, Euro 3	Exhaust emissions, car, natural gas, fuel independent part per average km, Euro 4	Exhaust emissions, car, natural gas, fuel independent part per average km, Euro 5	Exhaust emissions, car, natural gas, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-10 LCI datasets for exhaust emissions of biogas cars.

Name of the dataset	Exhaust emissions, car, biogas, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, car, biogas, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, car, biogas, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, car, biogas, fuel independent part per average km, Euro 3	Exhaust emissions, car, biogas, fuel independent part per average km, Euro 4	Exhaust emissions, car, biogas, fuel independent part per average km, Euro 5	Exhaust emissions, car, biogas, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-11 LCI datasets for exhaust emissions of petrol vans.

Name of the dataset	Exhaust emissions, van, petrol, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, van, petrol, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, van, petrol, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, van, petrol, fuel independent part per average km, Euro 3	Exhaust emissions, van, petrol, fuel independent part per average km, Euro 4	Exhaust emissions, van, petrol, fuel independent part per average km, Euro 5	Exhaust emissions, van, petrol, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-12 LCI datasets for exhaust emissions of E85 vans.

Name of the dataset	Exhaust emissions, van, E85, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, van, E85, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, van, E85, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, van, E85, fuel independent part per average km, Euro 3	Exhaust emissions, van, E85, fuel independent part per average km, Euro 4	Exhaust emissions, van, E85, fuel independent part per average km, Euro 5	Exhaust emissions, van, E85, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-13 LCI datasets for exhaust emissions of diesel vans.

Name of the dataset	Exhaust emissions, van, diesel, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, van, diesel, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, van, diesel, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, van, diesel, fuel independent part per average km, Euro 3	Exhaust emissions, van, diesel, fuel independent part per average km, Euro 4	Exhaust emissions, van, diesel, fuel independent part per average km, Euro 5	Exhaust emissions, van, diesel, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-14 LCI datasets for exhaust emissions of biodiesel vans.

Name of the dataset	Exhaust emissions, van, biodiesel, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, van, biodiesel, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, van, biodiesel, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, van, biodiesel, fuel independent part per average km, Euro 3	Exhaust emissions, van, biodiesel, fuel independent part per average km, Euro 4	Exhaust emissions, van, biodiesel, fuel independent part per average km, Euro 5	Exhaust emissions, van, biodiesel, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-15 LCI datasets for exhaust emissions of natural gas vans.

Name of the dataset	Exhaust emissions, van, natural gas, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, van, natural gas, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, van, natural gas, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, van, natural gas, fuel independent part per average km, Euro 3	Exhaust emissions, van, natural gas, fuel independent part per average km, Euro 4	Exhaust emissions, van, natural gas, fuel independent part per average km, Euro 5	Exhaust emissions, van, natural gas, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-16 LCI datasets for exhaust emissions of biogas vans.

Name of the dataset	Exhaust emissions, van, biogas, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, van, biogas, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, van, biogas, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, van, biogas, fuel independent part per average km, Euro 3	Exhaust emissions, van, biogas, fuel independent part per average km, Euro 4	Exhaust emissions, van, biogas, fuel independent part per average km, Euro 5	Exhaust emissions, van, biogas, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-17 LCI datasets for exhaust emissions of diesel heavy duty vehicles.

Name of the dataset	Exhaust emissions, HDV, diesel, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, HDV, diesel, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, HDV, diesel, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, HDV, diesel, fuel independent part per average km, Euro 3	Exhaust emissions, HDV, diesel, fuel independent part per average km, Euro 4	Exhaust emissions, HDV, diesel, fuel independent part per average km, Euro 5	Exhaust emissions, HDV, diesel, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-18 LCI datasets for exhaust emissions of biodiesel heavy duty vehicles.

Name of the dataset	Exhaust emissions, HDV, biodiesel, fuel dependent part per kg fuel consumed, present (2012)	Exhaust emissions, HDV, biodiesel, fuel dependent part per kg fuel consumed, near future (2020)	Exhaust emissions, HDV, biodiesel, fuel dependent part per kg fuel consumed, far future (>2030)	Exhaust emissions, HDV, biodiesel, fuel independent part per average km, Euro 3	Exhaust emissions, HDV, biodiesel, fuel independent part per average km, Euro 4	Exhaust emissions, HDV, biodiesel, fuel independent part per average km, Euro 5	Exhaust emissions, HDV, biodiesel, fuel independent part per average km, Euro 6
unit	kg	kg	kg	km	km	km	km

Table 2-19 LCI datasets for non-exhaust emissions.

Name of the dataset	Fuel evaporation emissions, petrol, per average km	Fuel evaporation emissions, E85, per average km	Non-Exhaust emissions, tyre wear, per kg emitted	Non-Exhaust emissions, break wear, per kg emitted	Non-Exhaust emissions, road wear, per kg emitted
unit	km	km	kg	kg	kg

Table 2-20 LCI datasets for current power supply (I).

Name of the dataset	Electricity low voltage, Swiss consumption mix, at grid, present (2012)	Electricity low voltage, Swiss certified electricity, at grid, present (2012)	Electricity low voltage, average European consumption, at grid, present (2012)	Electricity low voltage, user-defined mix, at grid, present (2012)	Electricity low voltage, Swiss wind power production, at grid, present (2012)	Electricity low voltage, Swiss PV production, at grid, present (2012)
unit	kWh	kWh	kWh	kWh	kWh	kWh

Table 2-21 LCI datasets for current power supply (II).

Name of the dataset	Electricity low voltage, Swiss hydro production, at grid, present (2012)	Electricity low voltage, Swiss wood cogeneration, allocation exergy, at grid, present (2012)	Electricity low voltage, modern Swiss combined gas power production, at grid, present (2012)	Electricity low voltage, average European coal power production, at grid, present (2012)	Electricity low voltage, average Swiss nuclear power production, at grid, present (2012)
unit	kWh	kWh	kWh	kWh	kWh

Table 2-22 LCI datasets for near future power supply (I).

Name of the dataset	Electricity low voltage, Swiss consumption mix, at grid, near future (2020)	Electricity low voltage, Swiss certified electricity, at grid, near future (2020)	Electricity low voltage, average European consumption, at grid, near future (2020)	Electricity low voltage, user-defined mix, at grid, near future (2020)	Electricity low voltage, Swiss wind power production, at grid, near future (2020)	Electricity low voltage, Swiss PV production, at grid, near future (2020)
unit	kWh	kWh	kWh	kWh	kWh	kWh

Table 2-23 LCI datasets for near future power supply (II).

Name of the dataset	Electricity low voltage, Swiss hydro production, at grid, near future (2020)	Electricity low voltage, Swiss wood cogeneration, allocation exergy, at grid, near future (2020)	Electricity low voltage, modern Swiss combined gas power production, at grid, near future (2020)	Electricity low voltage, average European coal power production, at grid, near future (2020)	Electricity low voltage, average Swiss nuclear power production, at grid, near future (2020)
unit	kWh	kWh	kWh	kWh	kWh

Table 2-24 LCI datasets for far future power supply (I).

Name of the dataset	Electricity low voltage, Swiss consumption mix, at grid, far future (>2030)	Electricity low voltage, Swiss certified electricity, at grid, far future (>2030)	Electricity low voltage, average European consumption, at grid, far future (>2030)	Electricity low voltage, user-defined mix, at grid, far future (>2030)	Electricity low voltage, Swiss wind power production, at grid, far future (>2030)	Electricity low voltage, Swiss PV production, at grid, far future (>2030)
unit	kWh	kWh	kWh	kWh	kWh	kWh

Table 2-25 LCI datasets for far future power supply (II).

Name of the dataset	Electricity low voltage, Swiss hydro production, at grid, far future (>2030)	Electricity low voltage, Swiss wood cogeneration, allocation exergy, at grid, far future (>2030)	Electricity low voltage, Swiss geothermal production, at grid, far future (>2030)	Electricity low voltage, modern Swiss combined gas power production, at grid, far future (>2030)	Electricity low voltage, average European coal power production, at grid, far future (>2030)	Electricity low voltage, average Swiss nuclear power production, at grid, far future (>2030)
unit	kWh	kWh	kWh	kWh	kWh	kWh

Table 2-26 LCI datasets for fossil fuels and biofuels.

Name of the dataset	petrol, low-sulphur, at Swiss service station	E85, low-sulphur, at Swiss service station	diesel, low-sulphur, at Swiss service station	biodiesel, low-sulphur, at Swiss service station	natural gas, from high pressure network (1-5 bar), at Swiss service station	biogas, from high pressure network (1-5 bar), at Swiss service station
unit	kg	kg	kg	kg	kg	kg

Table 2-27 LCI datasets for hydrogen production, near future (I).

Name of the dataset	H2 from natural gas (SMR), 700 bar, at Swiss service station, near future (2020)	H2 from hard coal gasification and reforming, 700 bar, at Swiss service station, near future (2020)	H2 from biomass gasification and SMR, 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (Swiss consumption mix), 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (Swiss certified electricity), 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (European consumption mix), 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (Swiss wind power), 700 bar, at Swiss service station, near future (2020)
unit	kg	kg	kg	kg	kg	kg	kg

Table 2-28 LCI datasets for hydrogen production, near future (II).

Name of the dataset	H2 from electrolysis (Swiss PV production), 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (Swiss hydro production), 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (Swiss wood cogeneration), 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (modern Swiss combined gas power production), 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (average European coal power production), 700 bar, at Swiss service station, near future (2020)	H2 from electrolysis (average Swiss nuclear power production), 700 bar, at Swiss service station, near future (2020)
unit	kg	kg	kg	kg	kg	kg

Table 2-29 LCI datasets for hydrogen production, far future (I).

Name of the dataset	H2 from natural gas (SMR), 700 bar, at Swiss service station, far future (>2030)	H2 from hard coal gasification and reforming, 700 bar, at Swiss service station, far future (>2030)	H2 from biomass gasification and SMR, 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (Swiss consumption mix), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (Swiss certified electricity), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (European consumption mix), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (Swiss wind power), 700 bar, at Swiss service station, far future (>2030)
unit	kg	kg	kg	kg	kg	kg	kg

Table 2-30 LCI datasets for hydrogen production, far future (II).

Name of the dataset	H2 from electrolysis (Swiss PV production), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (Swiss hydro production), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (modern Swiss combined gas power production), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (average European coal power production), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (average Swiss nuclear power production), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (Swiss geothermal power production), 700 bar, at Swiss service station, far future (>2030)	H2 from electrolysis (Swiss wood cogeneration), 700 bar, at Swiss service station, far future (>2030)
unit	kg	kg	kg	kg	kg	kg	kg

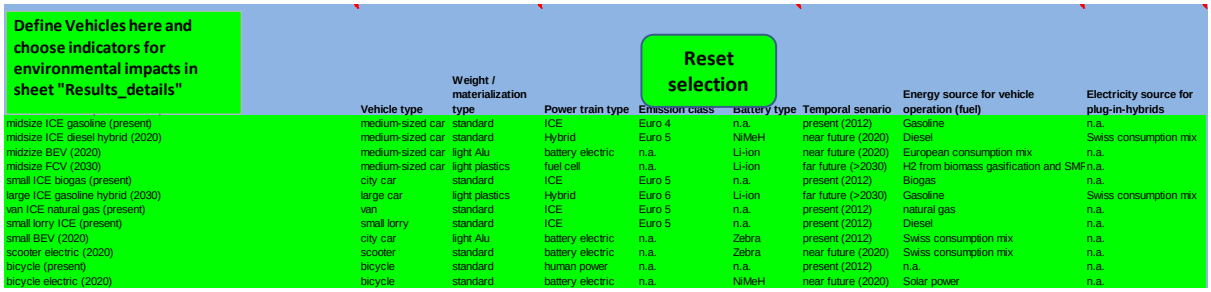
2.5. Results

2.5.1. LCA tool

Work package 1 does not only provide LCA results (see chapter 2.5.2), one of its outcomes is a user-friendly tool – an excel file with a kind of "user-interface" – which allows for configuration of specific vehicles according to parameters listed in chapter 2.3. Based on these specifications, the tool generates LCIA results, which can be used as environmental indicators for comparison of the environmental performance.

The results show the origin of burdens and potential impacts in the life cycle of vehicles, i.e. the overall result is split into contributions from road, drivetrain, propulsion battery, fuel cell system, rest of the vehicle (glider, engine), exhaust emissions, non-exhaust emissions, and fuel supply.

The following graphs show the way the user is supposed to enter the vehicle specification (Figure 2.2) and the type of LCIA results which can be generated. The vehicle specification in these graphs is not meant to be input to a consistent environmental comparison of technologies fulfilling a similar purpose, but rather serves as illustrative example for the broad range of vehicles which can be specified and LCIA results which can be generated.



	Vehicle type	Weight / materialization type	Power train type	Emission class	Battery type	Temporal senario	Energy source for vehicle operation (fuel)	Electricity source for plug-in-hybrids
midsize ICE gasoline (present)	medium-sized car	standard	ICE	Euro 4	n.a.	present (2012)	Gasoline	n.a.
midsize ICE diesel hybrid (2020)	medium-sized car	standard	Hybrid	Euro 5	NiMeH	near future (2020)	Diesel	Swiss consumption mix
midzize BEV (2020)	medium-sized car	light Alu	battery electric	n.a.	Li-ion	near future (2020)	European consumption mix	n.a.
midsize FCV (2030)	medium-sized car	light plastics	fuel cell	n.a.	Li-ion	far future (>2030)	H2 from biomass gasification and SMF	n.a.
small ICE biogas (present)	city car	standard	ICE	Euro 5	n.a.	present (2012)	Biogas	n.a.
large ICE gasoline hybrid (2030)	large car	light plastics	Hybrid	Euro 6	Li-ion	far future (>2030)	Gasoline	Swiss consumption mix
van ICE natural gas (present)	van	standard	ICE	Euro 5	n.a.	present (2012)	natural gas	n.a.
small lorry ICE (present)	small lorry	standard	ICE	Euro 5	n.a.	present (2012)	Diesel	n.a.
small BEV (2020)	city car	light Alu	battery electric	n.a.	Zebra	present (2012)	Swiss consumption mix	n.a.
scooter electric (2020)	scooter	standard	battery electric	n.a.	Zebra	near future (2020)	Swiss consumption mix	n.a.
bicycle (present)	bicycle	standard	human power	n.a.	n.a.	present (2012)	n.a.	n.a.
bicycle electric (2020)	bicycle	standard	battery electric	n.a.	NiMeH	near future (2020)	Solar power	n.a.

Figure 2.2 "User-interface" for specification of vehicles in the LCA tool. The first column contains free text, i.e. "names of the vehicles" need to be specified by the user; in the other columns, the user can select among the available options.

Figure 2.3 shows – as an example for the LCIA indicators which can be selected and displayed and as illustration of the broad range of vehicles which can be evaluated – cumulative Greenhouse Gas (GHG) emissions in terms of [kg CO_2eq/km] with the split into contributions from different parts of the vehicle and life cycle for the vehicles specified in Figure 2.2.

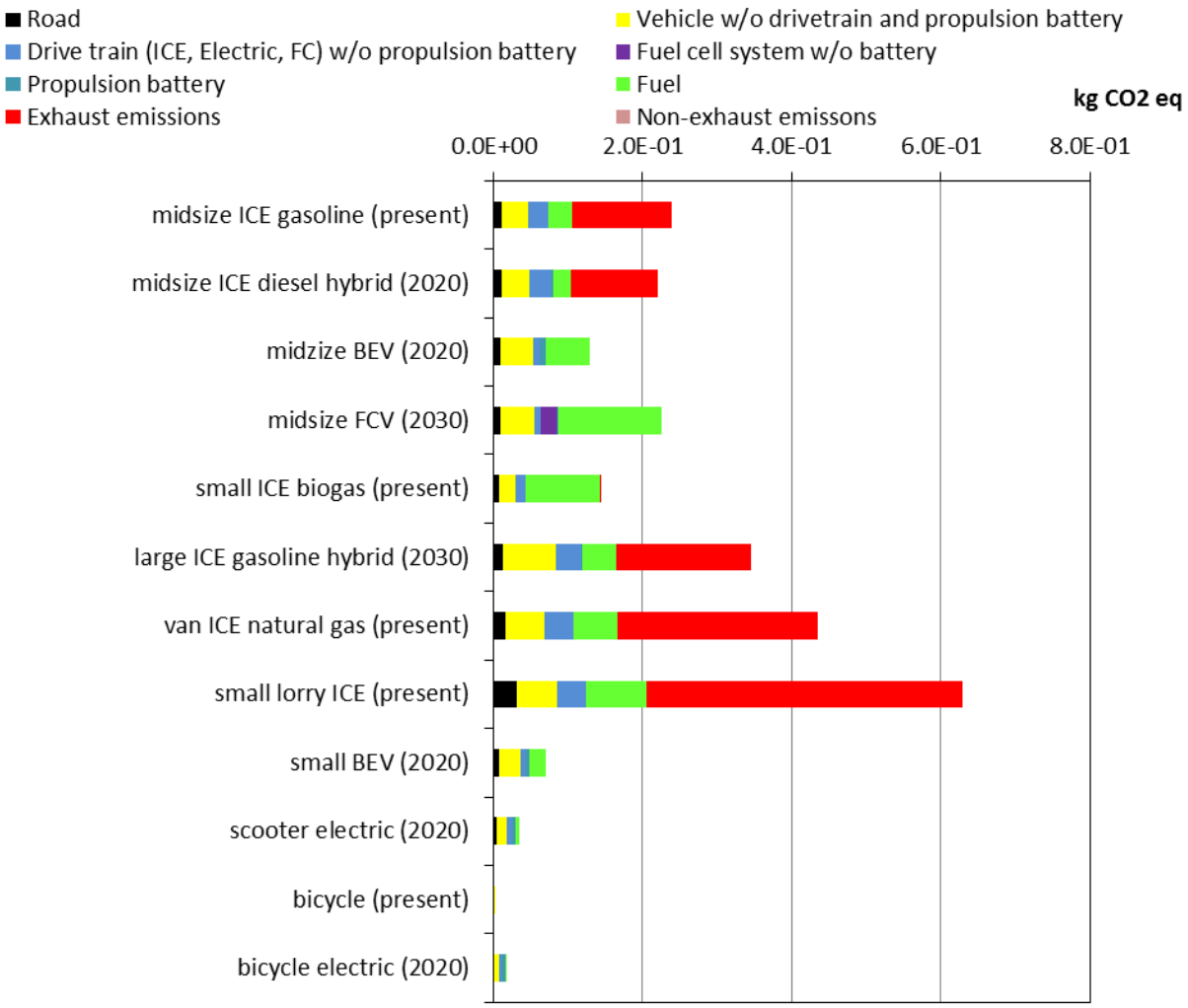


Figure 2.3 LCIA results for the vehicles specified in Figure 2.2 showing cumulative GHG emissions according to IPCC 2007 GWP 100a per vehicle-km. This selection and comparison is not meant to be representative for a set of vehicles fulfilling the same purpose.

The tool can generate life cycle results for a broad range of LCIA indicators and these can be displayed in a spider diagram for the user-specified set of vehicles as illustrated in Figure 2.4.

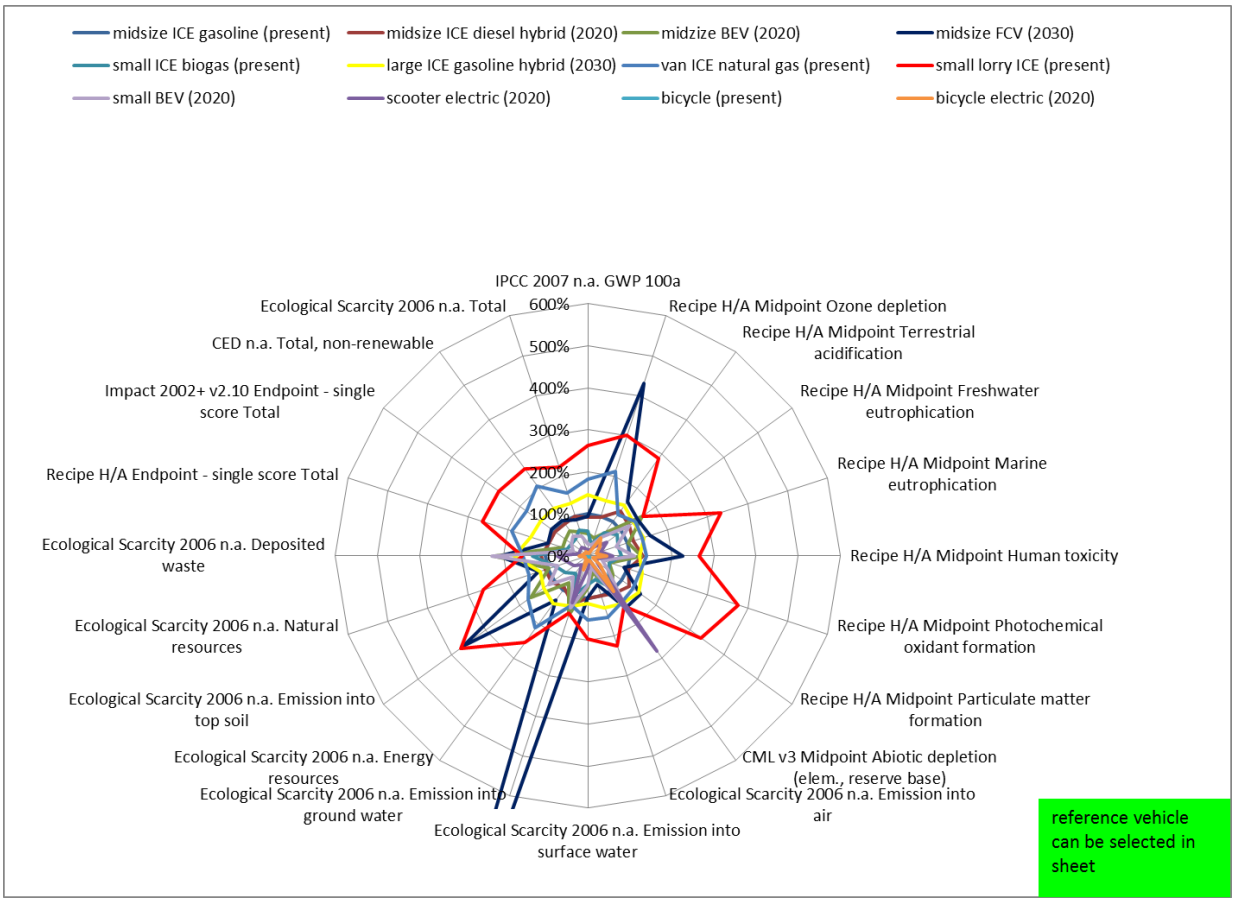


Figure 2.4 Illustration of a comparison of a large range of environmental indicators for the set of vehicles as specified in Figure 2.2. This selection and comparison is not meant to be representative for a set of vehicles fulfilling the same purpose.

2.5.2. LCA results

The following environmental indicators are chosen for the detailed comparative environmental evaluation of passenger vehicles in this chapter:

- Cumulative GHG emissions (Solomon et al., 2007); as indicator for potential negative impacts of global climate change. It is quantified aggregating all airborne emissions weighted with their individual Global Warming Potentials (GWP).
- Particulate matter formation (Goedkoop et al., 2012); as indicator for potential negative impacts on human health. It accounts for primary and secondary particulates. Main contributors are particle emissions as well as NO_x, SO_2 and ammonia emissions. High particulate matter concentrations are often interpreted as a result of high traffic volumes.
- Photochemical oxidant formation (Goedkoop et al., 2012); as indicator for potential negative impacts on human health. This indicator corresponds to the so-called “summer smog”, which is mainly an effect of NMVOC and NO_x emissions and often poses an environmental concern in urban areas with a large number of vehicles used.
- Terrestrial acidification (Goedkoop et al., 2012); as indicator for potential negative impacts on ecosystem quality – an effect of SO_2, NO_x and ammonia emissions.
- Abiotic resource depletion (Oers et al., 2002); as indicator for potential negative impacts on the availability of mineral resources. It aggregates the demand of metal and mineral

resources according to their currently estimated global reserves and rate of de-accumulation, relative to the reference substance antimony (Sb).

This selection of environmental indicators is supposed to represent the most relevant[20] burdens and potential impacts generated by passenger vehicles on human health, ecosystem quality, availability of resources, and climate change. The indicators were selected based on expert judgement of the authors and are supposed to represent those potential damages to human health and ecosystems, for which passenger vehicles are known to substantially contribute due to pollutant emissions. These are all indicators on the so-called "midpoint level" quantifying burdens and not potential impacts. Providing these and avoiding endpoint as well as aggregated indicators including weighting of different impact categories guarantees transparency and helps in avoiding oversimplification and misinterpretation. This procedure is in line with ISO recommendations (ISO, 2006a, ISO, 2006b). A more complete set of indicators (including aggregated ones) will be shown without contribution analysis, i.e. total indicator results like in Figure 2.4.

2.5.2.1. Vehicle specification

Vehicle characteristics and parameters need to be specified in a consistent way for generating a meaningful comparative evaluation for sets of vehicles providing the same (or, at least, similar) functionality.[21] If characteristics and parameters are selected in a biased way, the results of the comparative evaluation of the environmental performance of the vehicles can be misleading and must not be used for decision support (Althaus and Bauer, 2011).

Work package 1 does not employ sophisticated vehicle modeling which would generate vehicle characteristics and parameters based on simulation tools (please see WP2 and WP5). Nevertheless, useful LCA results can be provided based on the characteristics of vehicles available on the Swiss market today, as provided e.g. by (VCS, 2014).

Fuel consumption is the parameter with the most important impact on the LCA results (Althaus and Bauer, 2011). The evaluation can be based on consumption data based on driving cycles, as provided by the car manufacturers, or on "real-world data". The following LCA results are supposed to represent operation of vehicles in daily practice. Fuel consumption of daily driving is in practice higher than based on driving cycles like the NEDC[22] with relative differences between ICEV, BEV and FCEV. According to Mock et al. (2013), "real-world" fuel consumption of ICEV passenger cars is today on average 25% higher than official figures based on the NEDC. The discrepancy can even be much higher for BEV, depending on topography, ambient temperatures, and speed. VCS (2014) uses an average factor of 1.7, i.e. estimates the "real-world" consumption as being 70% higher than NEDC data. Since FCEV are not included there, and FCEV are also not available on the market yet, there are neither NEDC figures for fuel consumption, nor empirical "real-world" factors for calculating realistic fuel consumption based on a sufficiently large sample of vehicles. Therefore, literature data (Hwang,

[20] Relevant in the sense of: "Which are the environmental concerns with relatively large contributions of passenger vehicles?"

[21] Already comparing current and near-future ICEV with BEV violates this condition to some extent, since vehicle ranges and the time needed for fueling/charging substantially differ.

[22] NEDC: „New European Driving Cycle" (NEFZ: „Neuer Europäischer Fahrzyklus"). Used within the EU for officially measuring fuel consumption of passenger vehicles. These figures need to be provided by the car manufacturers.

2013, Hwang et al., 2013, Messagie et al., 2014, Miotti et al., 2015) are used for estimating FCEV hydrogen consumption in the following comparisons.

Further parameters which need to be specified for each vehicle are masses of glider, drivetrain, fuel cell system, and propulsion battery as well as lifetimes of the vehicles as such and fuel cell system and propulsion battery.

In general, LCA results shown in the following sections slightly differ from those published in papers developed in parallel to this report (Bauer et al., 2015, Miotti et al., 2015, Simons, 2016). LCI data used in all these publications are very similar; the main reason for differences in LCA results are differing vehicle specifications in terms of vehicle weight as well as fuel and electricity consumption for vehicle operation. These deviations show the dependency of LCA results of passenger vehicles on vehicle specification and other assumptions. However, the overall conclusions drawn based on the LCA results of all these publications are similar.

2.5.2.2. Base case: medium-sized cars, "near-future"

The time horizon "near-future" is the most appropriate for a comparative assessment of all powertrain technologies. Currently, FCEV are commercially not widely available and therefore, "current" (=2012) would exclude FCEV from the comparison. On the other hand, uncertainties are much higher for "far-future". Medium-sized vehicles ("VW Golf class") configured as ICEV with gasoline, diesel and natural gas, as gasoline and diesel hybrids, as BEV and as FCEV (each with two different sources of electricity for battery charging and of hydrogen, respectively) are chosen as reference technologies for this "base case" evaluation. Plug-in hybrids are not included, since their fuel consumption almost entirely depends on the driving pattern (i.e. whether the vehicles are used for short distances allowing for electric operation of for long ones using the IC engine) and specifying fuel demand would be much more arbitrary than for the other powertrain technologies. Table 2-31 shows the specifications of these vehicles and Table 2-32 the parameter setting.

Table 2-31 Vehicle specification, "Medium-sized cars, near-future".

Define Vehicles here and choose indicators for environmental impacts in sheet "Results_details"

Reset selection

Reference name (user defined)	Vehicle type	Weight / materialization type	Power train type	Emission class	Battery type	Temporal senario	Energy source for vehicle operation (fuel)
ICE gasoline	medium-sized car	standard	ICE	Euro 5	n.a.	near future (2020)	Gasoline
ICE diesel	medium-sized car	standard	ICE	Euro 5	n.a.	near future (2020)	Diesel
ICE natural gas	medium-sized car	standard	ICE	Euro 5	n.a.	near future (2020)	natural gas
Hybrid gasoline	medium-sized car	standard	Hybrid	Euro 5	NiMeH	near future (2020)	Gasoline
Hybrid diesel	medium-sized car	standard	Hybrid	Euro 5	NiMeH	near future (2020)	Diesel
BEV Swiss mix	medium-sized car	standard	battery electric	n.a.	Li-ion	near future (2020)	Swiss consumption mix
BEV European mix	medium-sized car	standard	battery electric	n.a.	Li-ion	near future (2020)	European consumption mix
FCV natural gas SMR	medium-sized car	standard	fuel cell	n.a.	Li-ion	near future (2020)	H2 from natural gas (SMR)
FCV electrolysis Swiss mix	medium-sized car	standard	fuel cell	n.a.	Li-ion	near future (2020)	H2 from electrolysis (Swiss consump

Table 2-32 Vehicle parameters, "medium-sized cars, near-future".

near future "base case"	Total vehicle mass	Fuel cell system mass (incl H2 tank)	Battery mass	Electricity consumption driving	Chemical fuel consumption driving	Total life time distance	Life time battery	Life time fuel cell
	[kg]	[kg]	[kg]	[kWh/100km]	liquid: [l/100km] gaseous: [kg/100km]	[km]	[km]	[km]
ICE gasoline	1400				6	150'000	150'000	150'000
ICE diesel	1450				5.3	150'000	150'000	150'000
ICE natural gas	1450				4.4	150'000	150'000	150'000
Hybrid gasoline	1550		50		5	150'000	150'000	150'000
Hybrid diesel	1600		50		4.4	150'000	150'000	150'000
BEV Swiss mix	1550		200	19.1		150'000	150'000	150'000
BEV European mix	1550		200	19.1		150'000	150'000	150'000
FCV natural gas SMR	1565	190	25		1	150'000	150'000	150'000
FCV electrolysis Swiss mix	1565	190	25		1	150'000	150'000	150'000

All vehicles are assumed to be based on the same glider with a mass of 1200 kg. Various components are added, resulting in the total vehicle masses listed in Table 2-32. Masses of the fuel cell system (140 kg) and the H_2 tank (50 kg) are specified according to Miotti et al. (2015), interpolating between current and year-2030 technology. The mass of the battery of the BEV is calculated with an energy density of 0.114 kWh/kg according to Notter et al. (2010) and a range of 150 km (based on the NEFZ consumption of 12.4 kWh/100km) with an assumed charging cycle efficiency of 90% and a depth of discharge of the battery of 90%. The estimated H_2 consumption of the FCEV is within the range of values used in (Hwang, 2013, Hwang et al., 2013, Messagie et al., 2014, Miotti et al., 2015). Electricity consumption of the BEV as well as gasoline consumption of the ICEV is quantified according to the "2020 scenario" in De Haan and Zah (2013). Fuel consumption of diesel, natural gas and hybrid vehicles is estimated based on VCS (2014) using consumption data of vehicle models similar to the "Golf VII 1.4 TSI ACT DSG" (which has an NEFC consumption of 4.7 l/100km) as well as relative differences between models available with gasoline, diesel and natural gas engines.

Figure 2.5 through Figure 2.9 show LCIA results per km driven with the different vehicles.

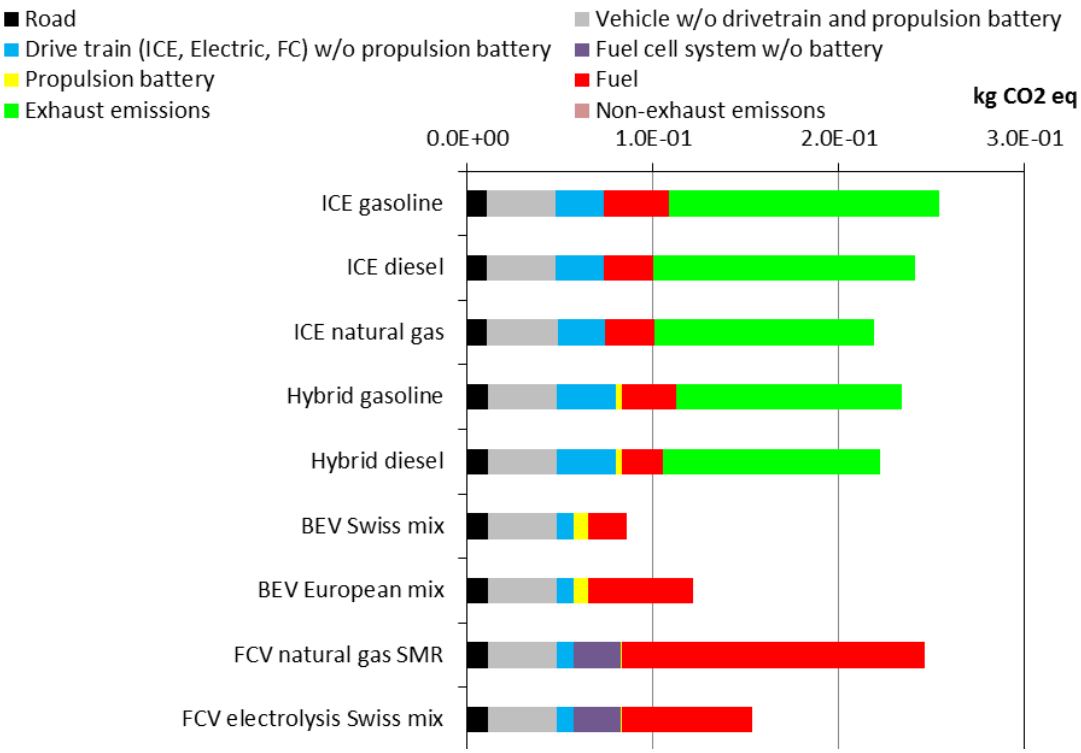


Figure 2.5 Life-cycle GHG emissions per km caused by selected midsize "near future" passenger vehicles as specified in Table 2-31 and Table 2-32.

Among conventional cars the gasoline car shows the highest life cycle GHG emissions among the ICE vehicles, followed by the diesel, gasoline and diesel hybrid and natural gas vehicles. The small battery and the slightly more complex drivetrain of the hybrids does not cause substantial amounts of GHG emissions and therefore, the life-cycle GHG emissions of these vehicles are reduced almost proportionally to the fuel consumption compared to the conventional gasoline and diesel cars. About 40-50% of the GHG emissions of the ICE vehicles are due to other contributions than direct tailpipe CO_2 emissions, mainly from glider and drivetrain production as well as the fuel chain.

The GHG emissions of the BEV and FCEV largely depend on the fuel supply pathway; however, using the Swiss electricity supply mix for either directly charging the battery of the BEV or producing

hydrogen for FCEV results in about 40% lower emissions for the BEV representing the cleanest technology among this selection. Its overall emissions are about one third of those of the ICE gasoline vehicle. The FCEV with hydrogen from steam methane reforming (SMR) of natural gas generates a similar amount of GHG emissions like ICE vehicles.

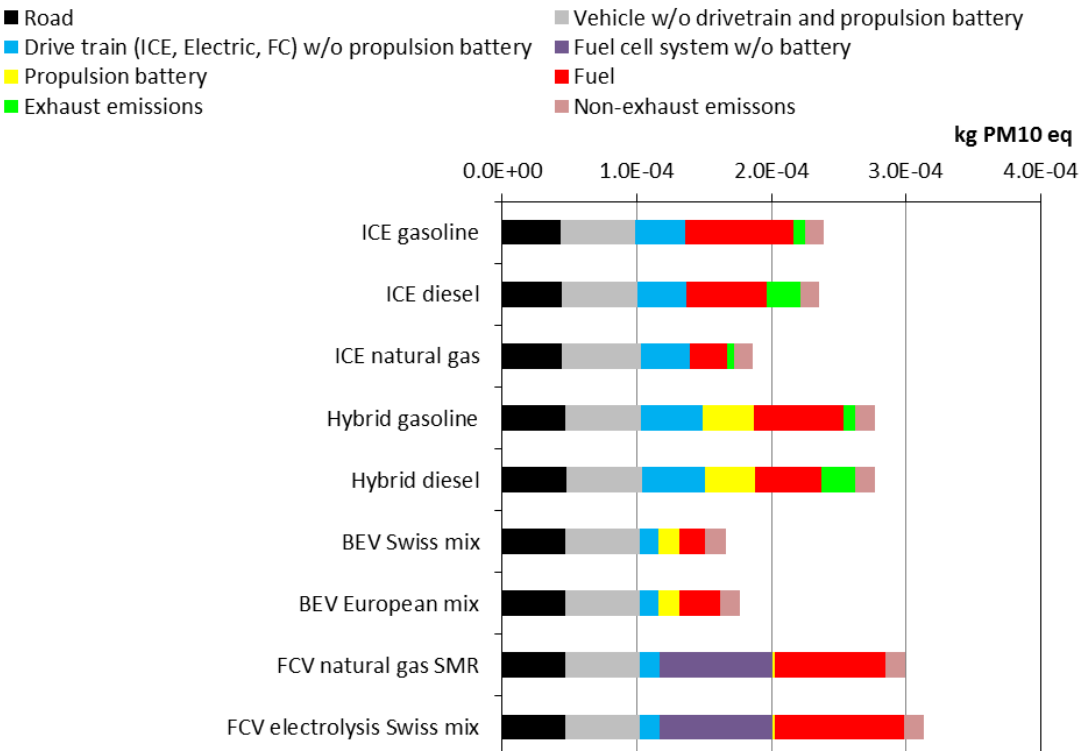


Figure 2.6 Life-cycle particulate matter formation per km caused by selected midsize "near future" passenger vehicles as specified in Table 2-31 and Table 2-32.

Direct exhaust emissions of ICE vehicles with EURO5 emission standard contribute remarkably small amounts of particle and NO_x emissions to the overall life-cycle PM formation. Even for diesel ICE cars, these direct exhaust emissions contribute only about 10% to the total. Other parts of the life cycle generate much higher primary and secondary particles: mainly road and vehicle glider production, the fuel cell system and the fuel production chains. Most of the PM formation is due to mining and processing of metals, which are required for production of vehicles and their components, as well as construction work in case of roads. Fuel cell production seems to generate substantial PM formation, which is mostly due to use of platinum as catalyst. Overall, BEV and the natural gas ICEV cause the lowest PM formation.

Also in case of photochemical oxidant formation, direct exhaust emissions of ICEV (mainly NO_x and NMVOC) contribute only to a small extent to the overall life-cycle emissions, about 20% at most in case of the diesel car. Again, more substantial amounts of emissions are caused by roads, vehicle production as well as fuel supply chains. BEV perform best for this indicator, followed by FCEV and the natural gas ICEV.

Metal mining and processing is a key contributor to emissions causing terrestrial acidification (mainly due to SO_2 and NO_x emissions) – most evident for nickel, platinum and copper, which are used in the hybrid NiMeH battery, the fuel cell system, the electrolyzer and the electricity grid infrastructure. Again, BEV show the lowest burdens, closely followed by the natural gas ICEV.

The most substantial contributors to metal depletion are – according to the method used – construction of vehicles and drivetrains, the fuel cell as well as the electricity grid. Overall, BEV cause slightly less metal resource depletion than ICEV, FCEV slightly more.

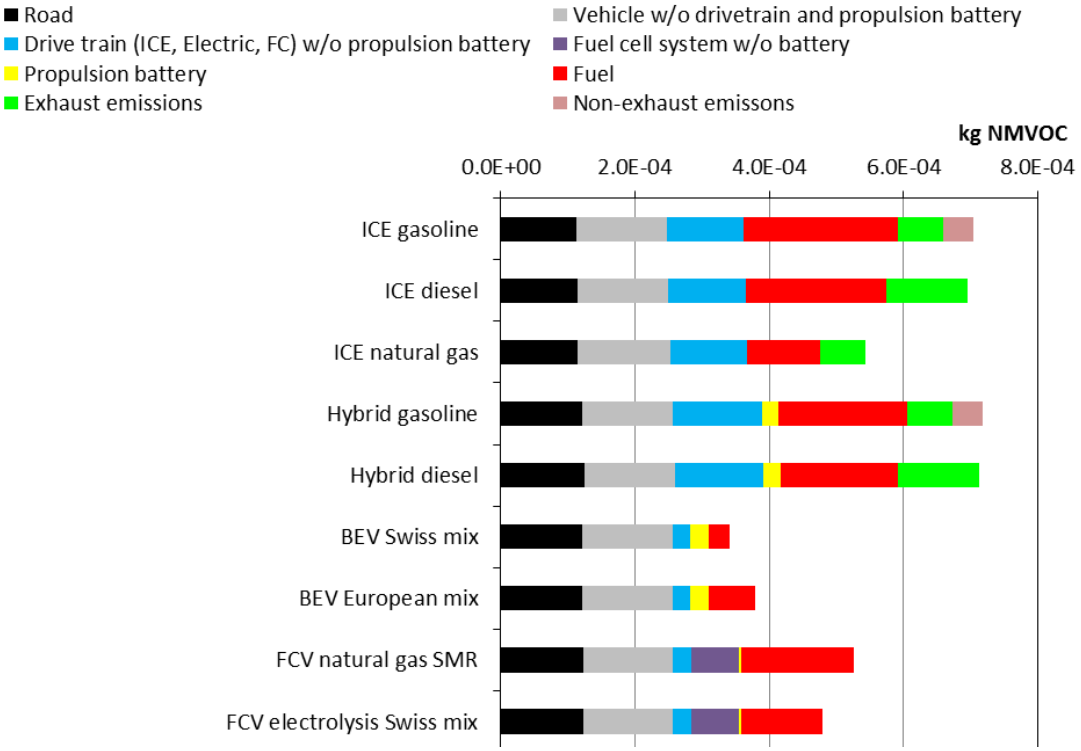


Figure 2.7 Life-cycle photochemical oxidant formation per km caused by selected midsize "near future" passenger vehicles as specified in Table 2-31 and Table 2-32.

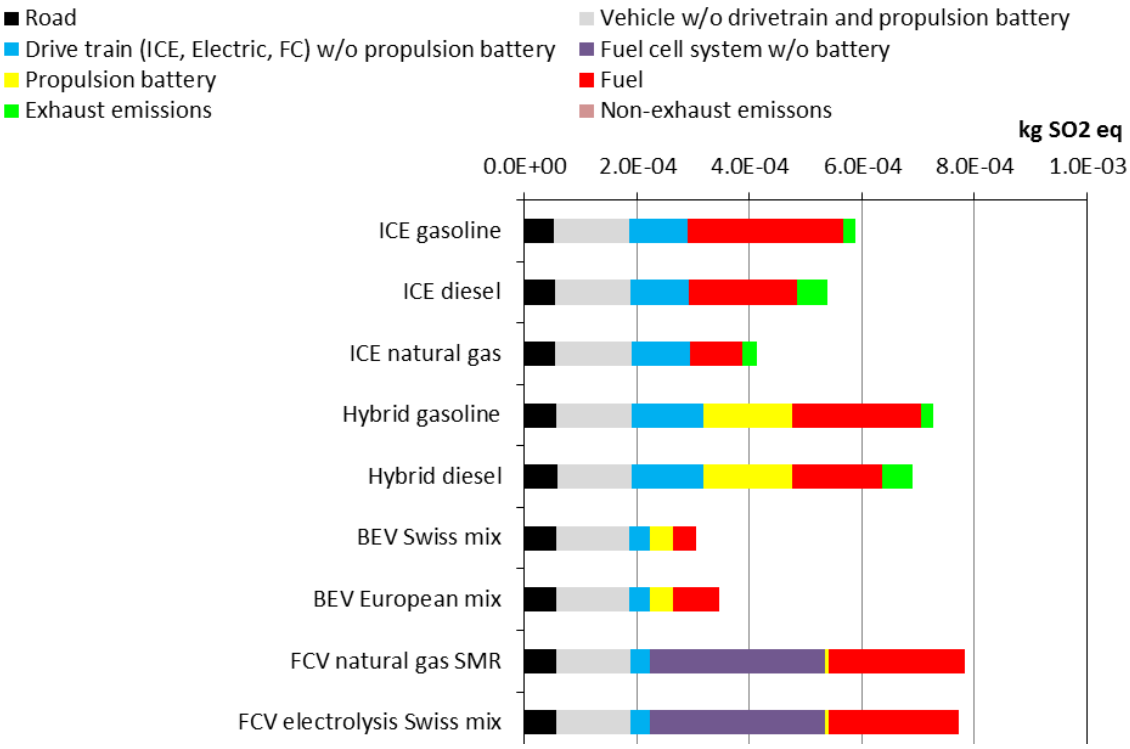


Figure 2.8 Life-cycle terrestrial acidification per km caused by selected midsize "near future" passenger vehicles as specified in Table 2-31 and Table 2-32.

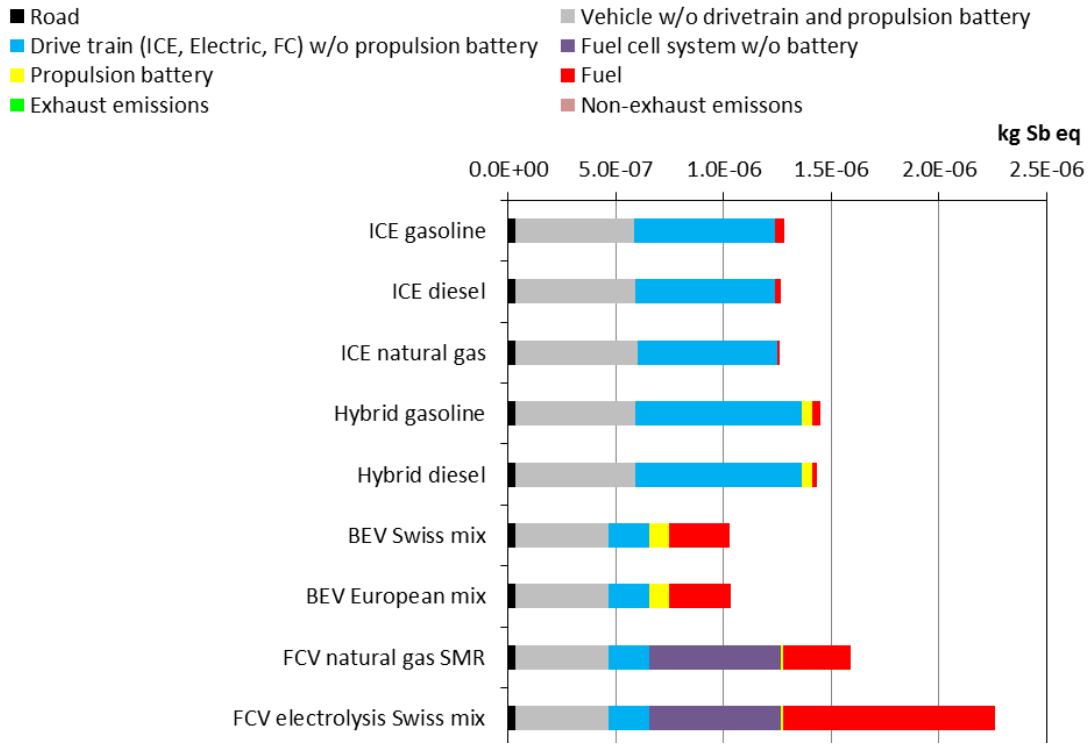


Figure 2.9 Life-cycle abiotic resource depletion per km caused by selected midsize "near future" passenger vehicles as specified in Table 2-31 and Table 2-32.

Comparing the environmental performance of the set of near-future medium-sized vehicles as specified in Table 2-31 and Table 2-32 (with the ICE gasoline vehicle as the reference car with 100% impact for each of the indicators) shows that BEV cause less burdens/impacts than ICEV for the majority of indicators (Figure 2.10). The natural gas ICEV performs better than gasoline and diesel cars for almost all indicators; however, environmental advantages seem to be less pronounced than for BEV. The FCEV with the two most conventional hydrogen production pathways chosen for the base case evaluation show an ambiguous performance with better results than the gasoline ICEV for some indicators, but also with substantially worse results for other indicators.

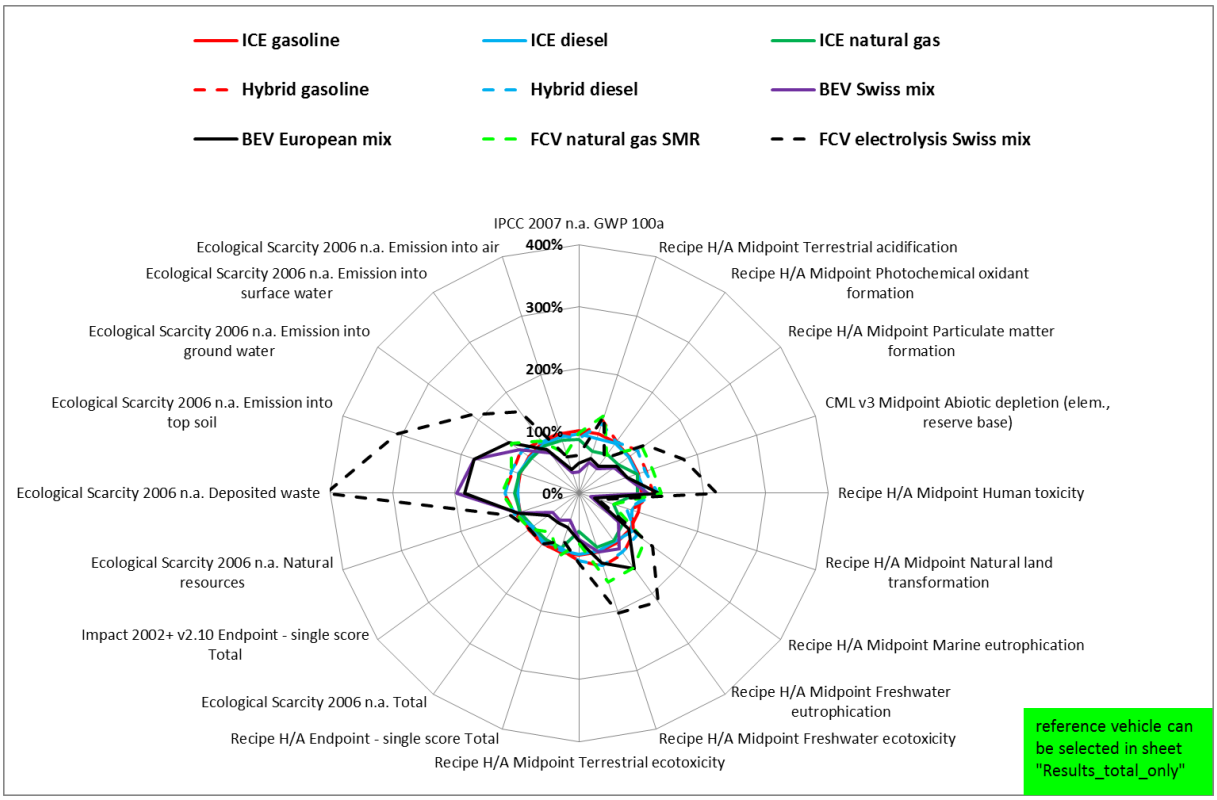


Figure 2.10 Large set of LCA results for the "base case" evaluation: Medium-sized cars, "near-future", as specified in Table 2-31 and Table 2-32.The ICE gasoline vehicle is chosen as the reference car with 100% impact for each of the indicators.

2.5.2.3. Medium-sized BEV, "near-future": impact of electricity used for charging

Depending on the environmental indicator analyzed, the life cycle burdens and potential impacts of BEV can substantially vary depending on the source of electricity used for charging the batteries. Figure 2.11 through Figure 2.15 show the LCA results for medium-sized, "near-future" BEV, charged with electricity from different power generation technologies and electricity mixes. Apart from the power source, the BEV are all identically specified with the same parameter settings as the BEV in Table 2-31 and Table 2-32.

Electricity used for charging the batteries of the BEV shows the highest impact on life cycle GHG emissions per km (Figure 2.11). Using coal power results in the highest emissions, almost as high as those of the gasoline vehicle (see Figure 2.5). On the other end of the spectrum, using renewable electricity or nuclear power – both with very low CO_2 intensity – reduces the overall GHG emissions by about 70% compared to the gasoline car. Using electricity from a natural gas combined cycle (CC) plant for charging the BEV batteries reduces life cycle GHG emissions compared to the gasoline vehicle by about 40%. However, this advantage becomes smaller when comparing with "cleaner" fossil-fueled vehicles, including hybrids (see Figure 2.5).

The impact of the source of electricity for the BEV is much smaller for the other indicators. These are mostly dominated by contributions from other parts of the life cycle than fuel supply, i.e. production/construction and maintenance of vehicle components and other infrastructure such as roads. In general, the overall picture is similar to GHG results: using electricity from renewables or nuclear power generates lower burdens than using electricity from coal and gas power plants. Abiotic

resource depletion represents an exception: metal demand (mainly silver, gold, and copper) for PV modules results in by far the highest resource depletion (Figure 2.15).

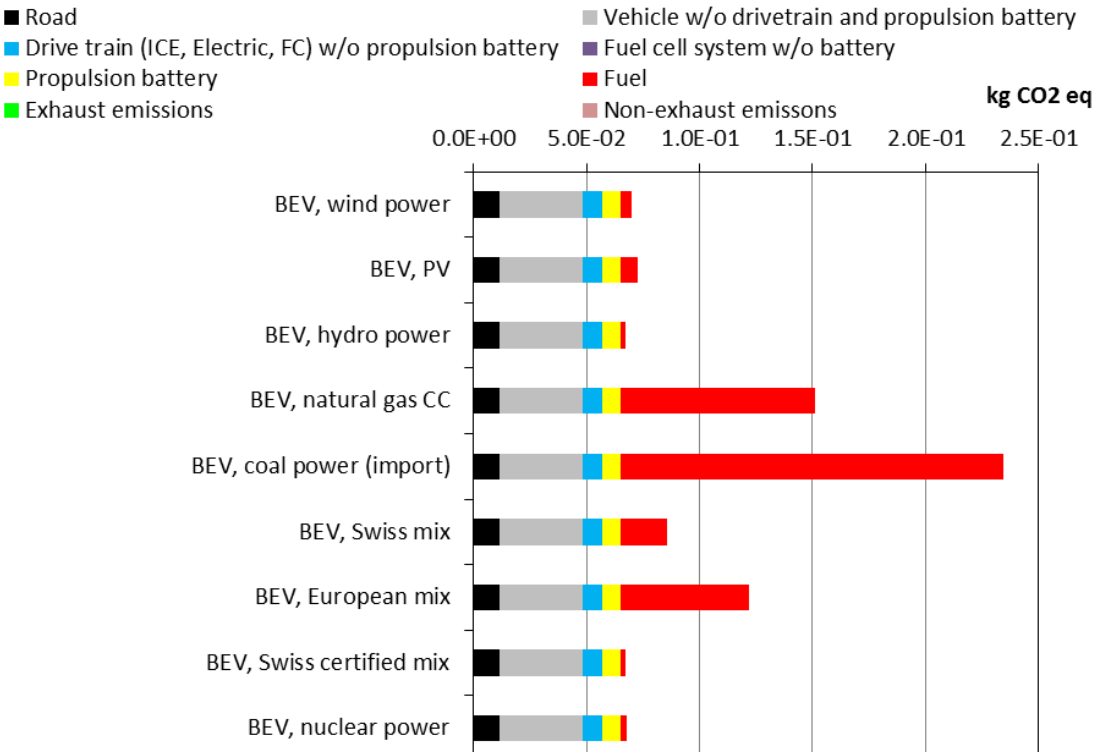


Figure 2.11 Life-cycle GHG emissions per km caused by midsize "near future" BEV.

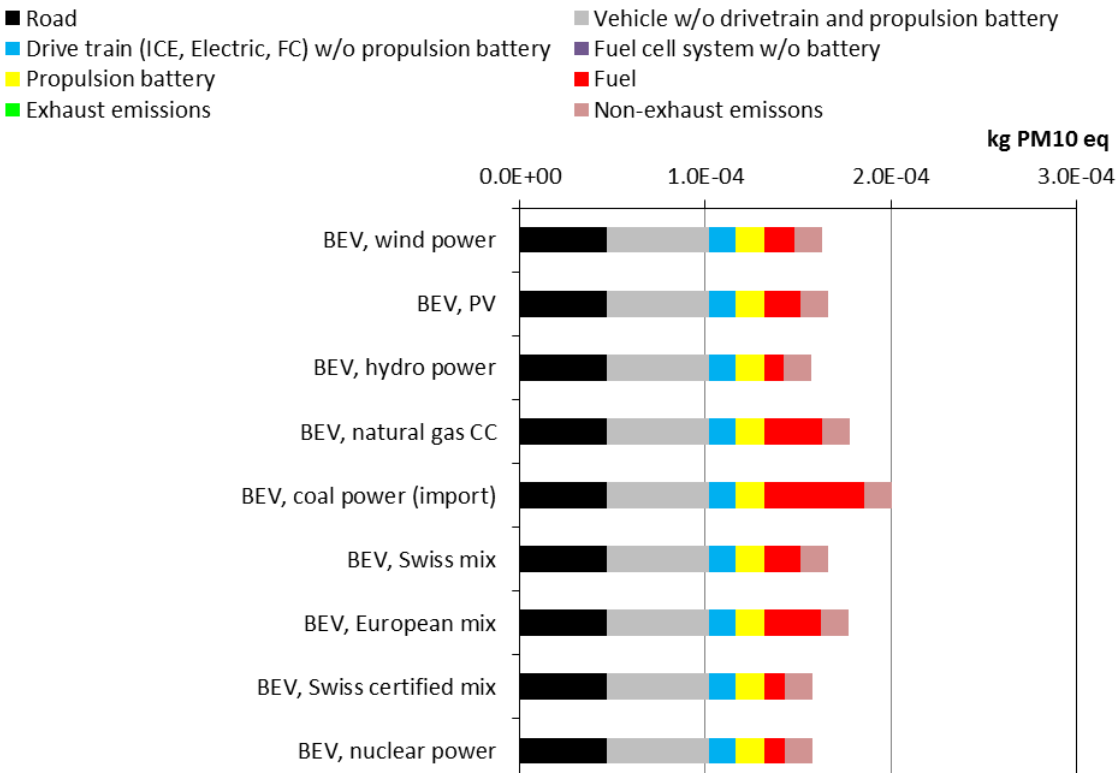


Figure 2.12 Life-cycle particulate matter formation per km caused by midsize "near future" BEV.

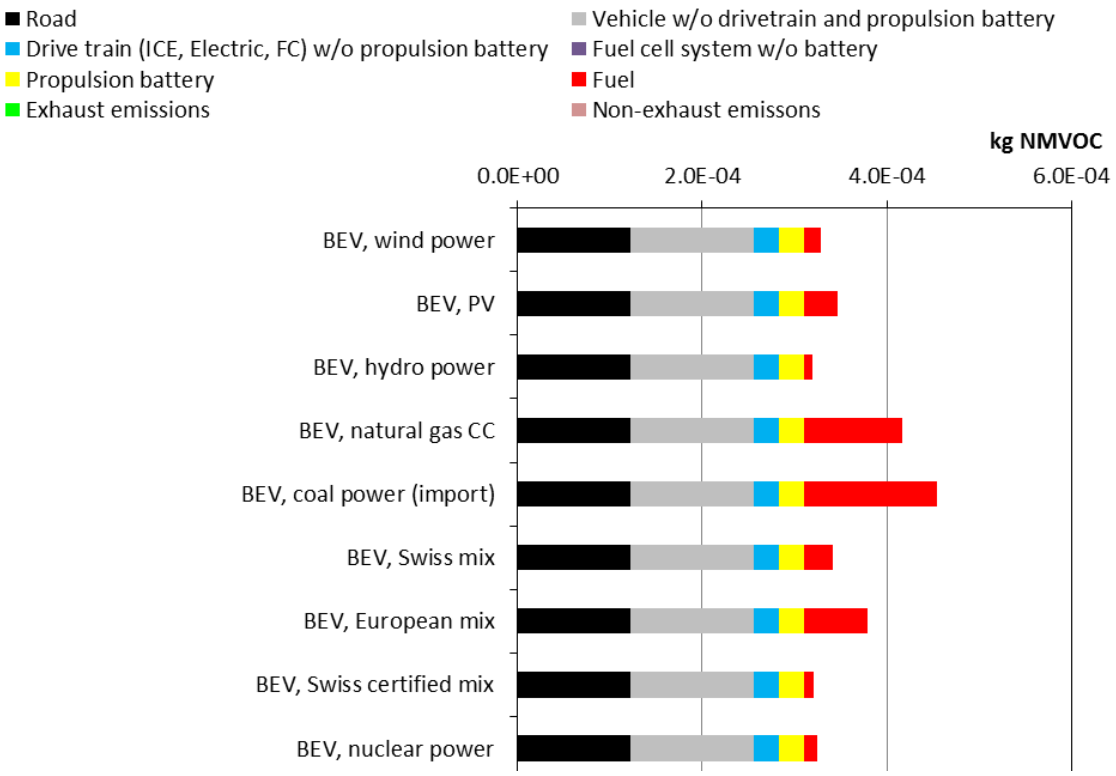


Figure 2.13 Life-cycle photochemical oxidant formation per km caused by midsize "near future" BEV.

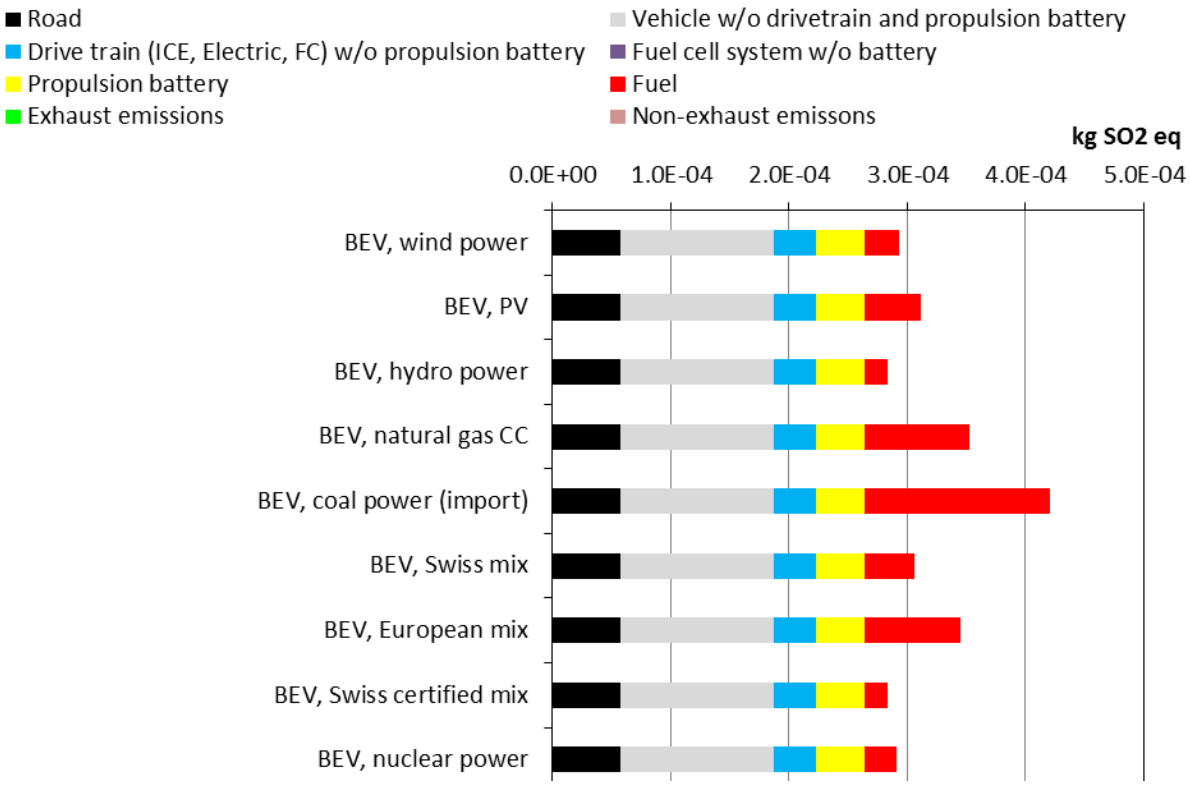


Figure 2.14 Life-cycle terrestrial acidification per km caused by midsize "near future" BEV.

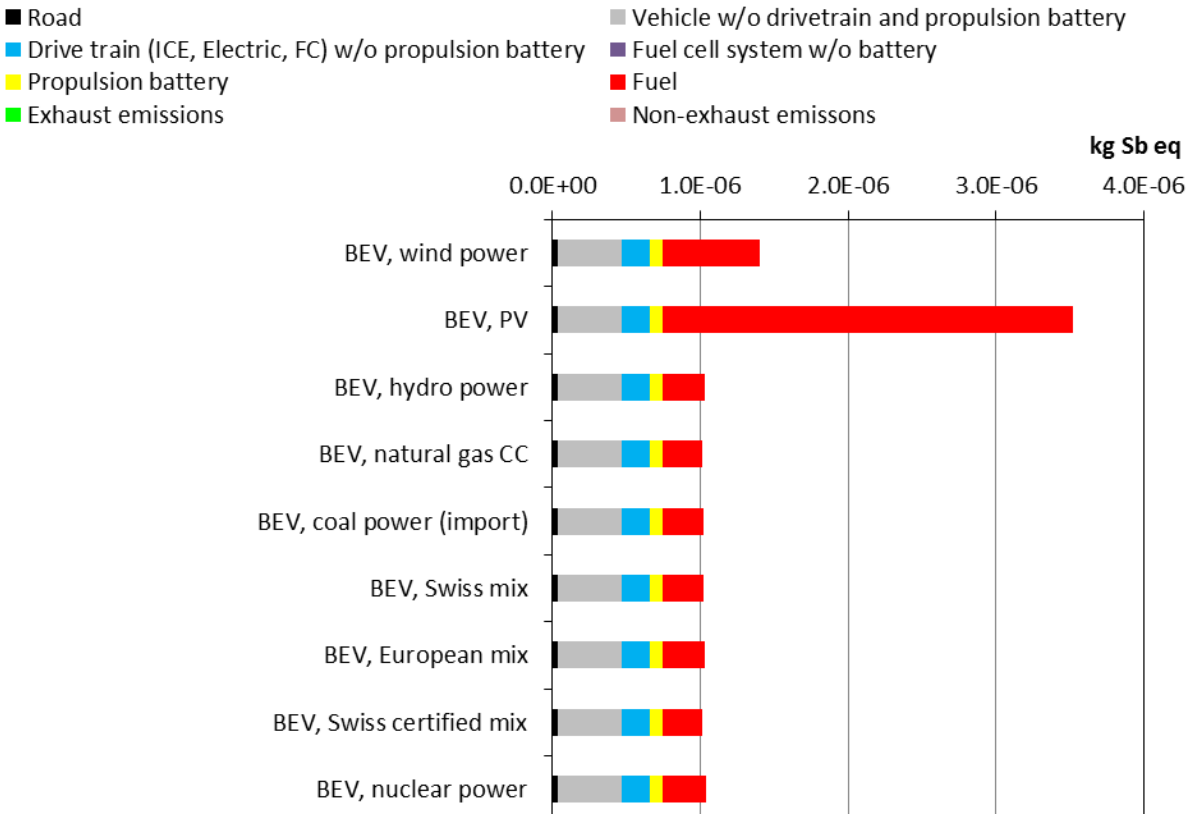


Figure 2.15 Life-cycle abiotic resource depletion per km caused by midsize "near future" BEV.

The evaluation based on the large set of LCIA indicators (Figure 2.16) shows that using wind and hydro power for charging generates in general the lowest burdens. Hydro power is the main contributor to the Swiss certified electricity mix, therefore these results are very similar. Electricity from PV and nuclear causes comparatively higher burdens for some of the impact categories. For most of them, coal power is the worst alternative. BEV using electricity from natural gas CC plants in general cause higher life cycle burdens than those using the Swiss consumer electricity mix.

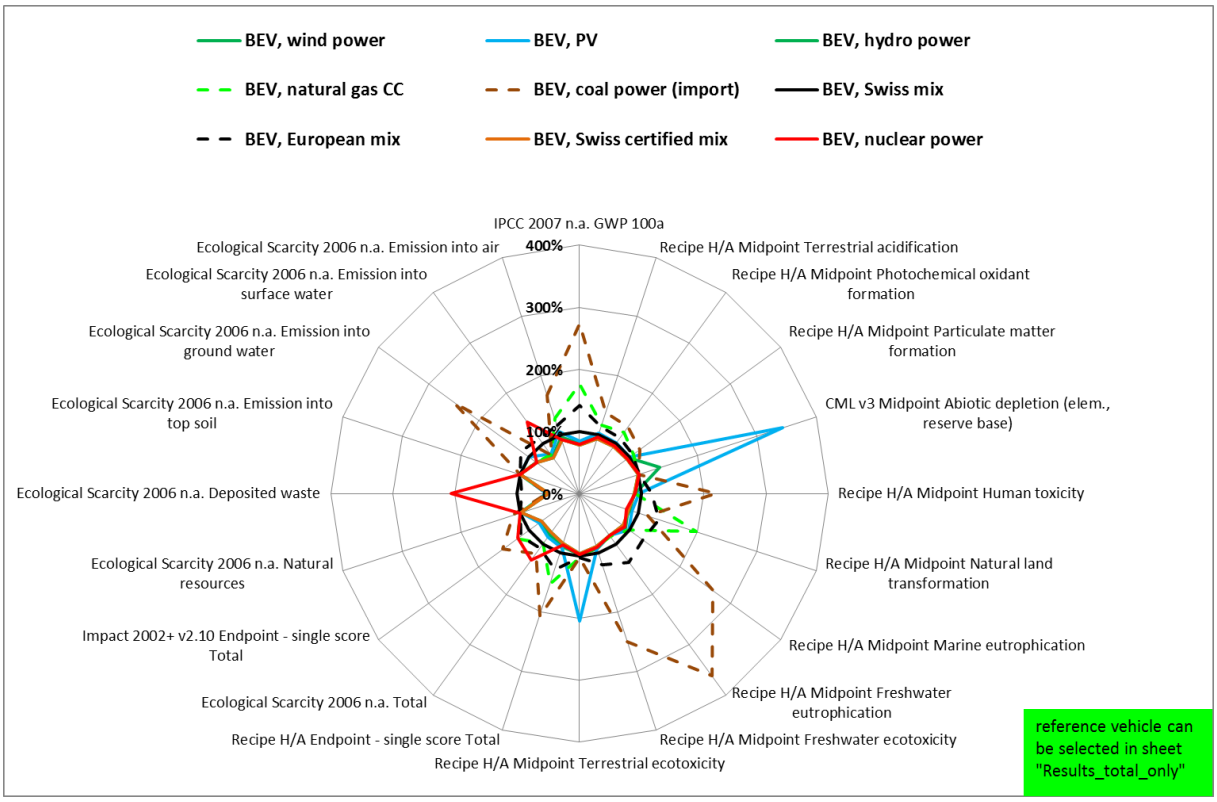


Figure 2.16 Large set of LCA results for the evaluation of BEV: Medium-sized cars, "near-future", as specified in Table 2-31 and Table 2-32, using different power sources for charging of batteries. The BEV using the Swiss consumption mix is used as reference vehicle (=100% for each indicator).

2.5.2.4. Medium-sized FCEV, "near-future": impact of hydrogen production pathway

Depending on the environmental indicator analyzed, the life cycle burdens and potential impacts of FCEV can substantially vary depending on the production pathway for hydrogen used in the FC. Figure 2.17 through Figure 2.21 show the LCA results for medium-sized, "near-future" FCEV, using H_2 from different production technologies. Apart from hydrogen source, the FCEV are all identically specified with the same parameter settings as the FCEV in Table 2-31 and Table 2-32.

As shown in Figure 2.5, the FCEV with H2 from natural gas steam methane reforming (SMR) generates life cycle GHG emissions almost as high as those of the gasoline vehicle. A few H_2 production pathways generate even higher GHG emissions, namely coal gasification as well as electrolysis using the EU mix, natural gas or coal power (Figure 2.17). On the other end of the spectrum, using renewable electricity or nuclear power – both with very low CO_2 intensity – reduces the overall GHG emissions by about 60% compared to the gasoline vehicle.

The impact of the hydrogen source for the FCEV is smaller for the other indicators. These are to a larger extent dominated by contributions from other parts of the life cycle than fuel supply, i.e. production/construction and maintenance of vehicle components and other infrastructure such as roads. In general, the overall picture is similar to GHG results: using hydrogen generated using renewables or nuclear power generates lower burdens than using coal and natural gas, both directly and indirectly via electrolysis. Abiotic resource depletion represents an exception: metal demand (mainly silver, gold, and copper) for PV modules results in by far the highest resource depletion (Figure 2.21).

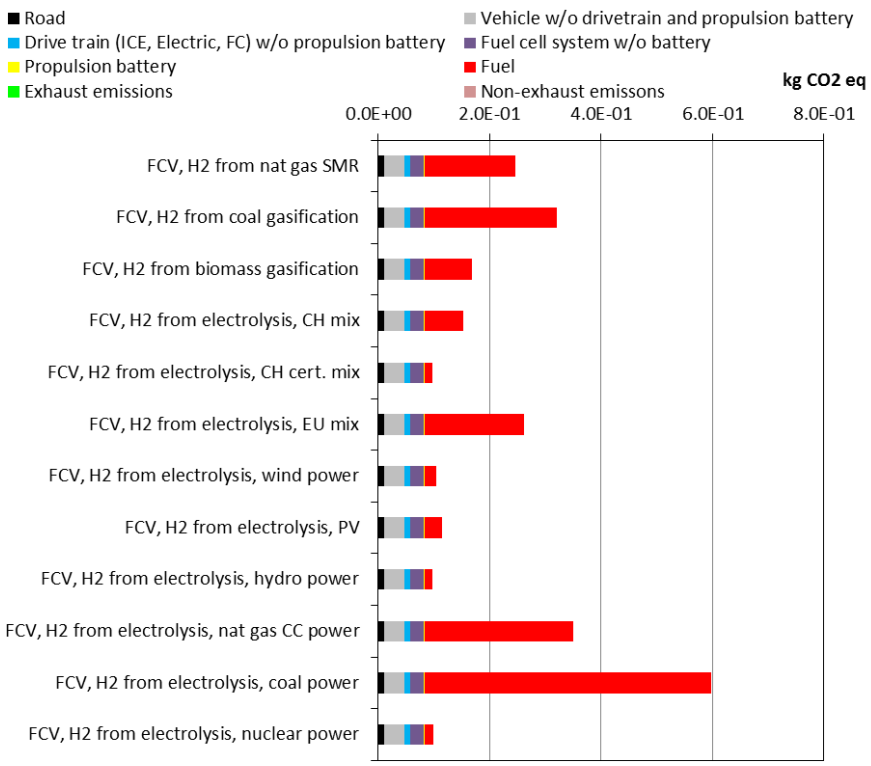


Figure 2.17 Life-cycle GHG emissions per km caused by midsize "near future" FCEV.

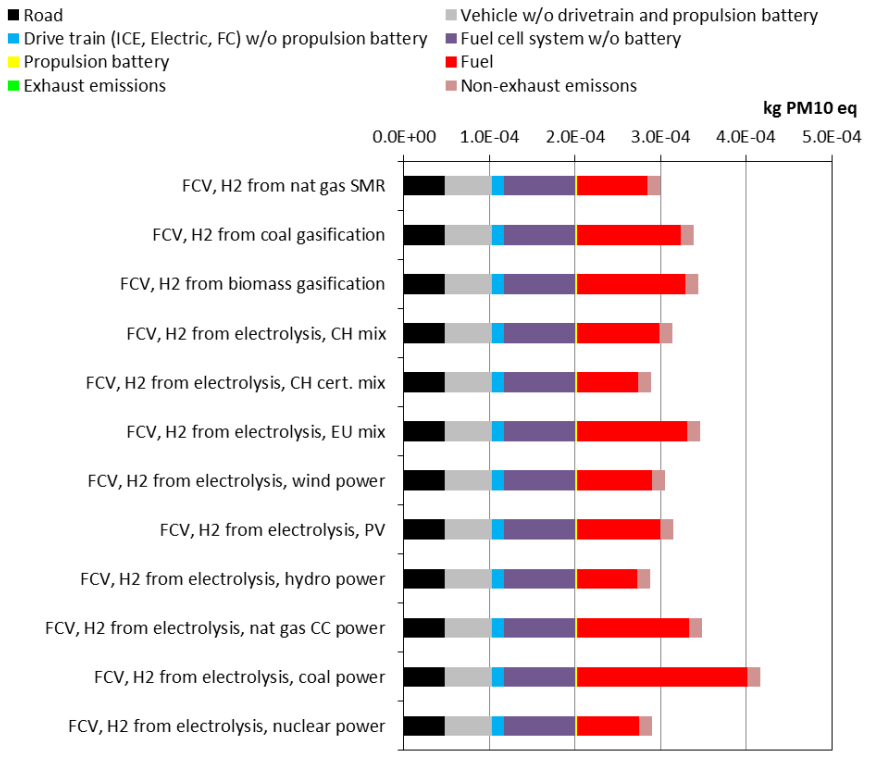


Figure 2.18 Life-cycle particulate matter formation per km caused by midsize "near future" FCEV.

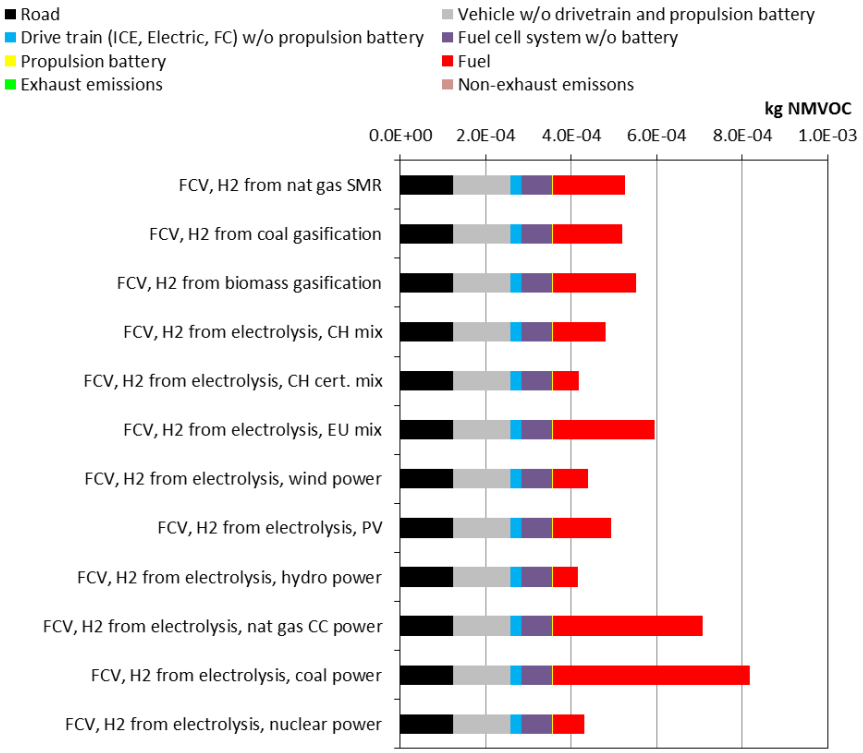


Figure 2.19 Life-cycle photochemical oxidant formation per km caused by midsize "near future" FCEV.

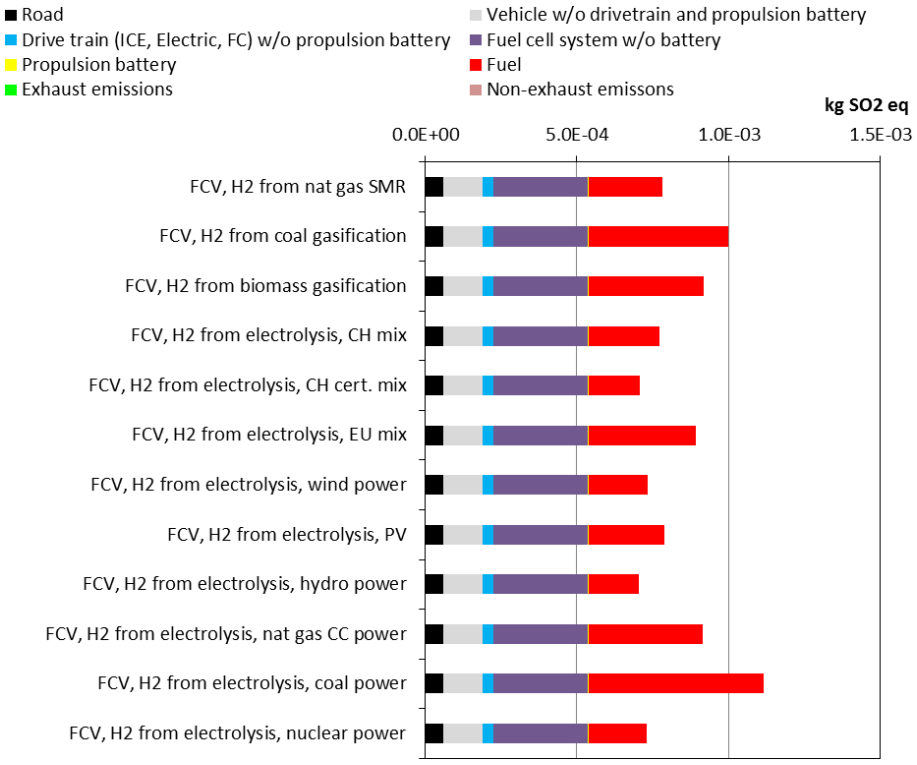


Figure 2.20 Life-cycle terrestrial acidification per km caused by midsize "near future" FCEV.

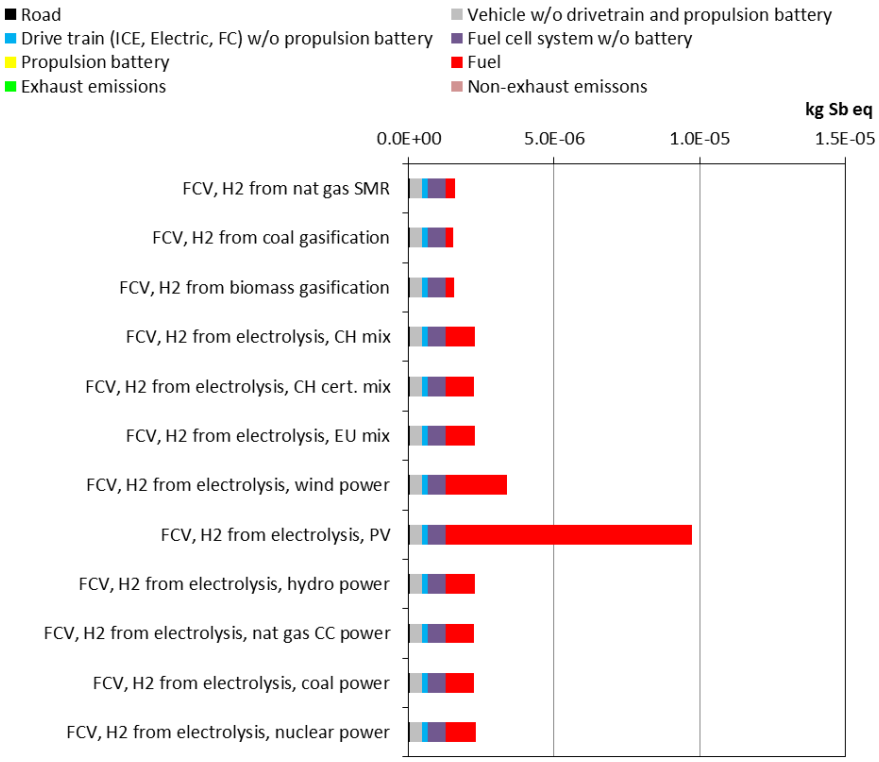


Figure 2.21 Life-cycle abiotic resource depletion per km caused by midsize "near future" FCEV.

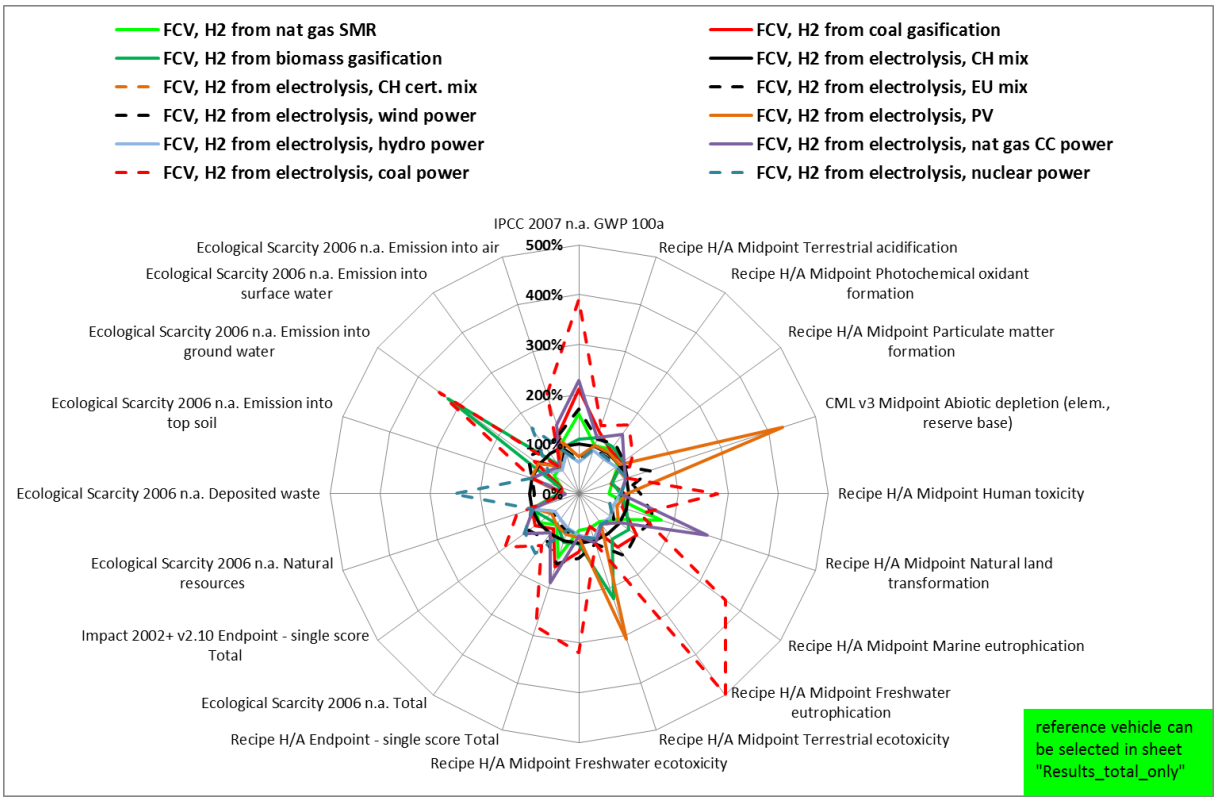


Figure 2.22 Large set of LCA results for the evaluation of FCEV: Medium-sized cars, "near-future", as specified in Table 2-31 and Table 2-32, using different H_2 sources for fuel cell operation. The FCEV using hydrogen from electrolysis with the Swiss consumption mix is used as reference vehicle (=100% for each indicator).

The evaluation based on the large set of LCIA indicators (Figure 2.22) shows that using hydrogen generated via electrolysis based on power inputs from fossil fuels generates by far the highest

impacts for a large number of indicators. Generating hydrogen via electrolysis with wind or hydro power are the best options from the environmental perspective. Electricity from PV and nuclear used for electrolysis causes comparatively higher burdens for some of the impact categories.

2.5.2.5. Medium-sized cars, "near-future" vs. "far future"

Technological progress is supposed to reduce the environmental footprint of passenger vehicles in the future, especially for currently comparatively immature technologies like BEV and FCEV. Also ICEV have shown a substantial reduction of environmental burdens in the past in Europe due to reduction of fuel consumption as well as reduction of tailpipe pollutant emissions – both triggered by tightened legislative regulations. This trend is expected to continue.

These potential improvements and the associated reduction in environmental burdens are evaluated by comparing LCA results for near and far future, i.e. 2020 and "2030 and beyond", respectively. The vehicles and the parameters for the quantification of results are shown in Table 2-33 and Table 2-34.

Table 2-33 Vehicle specification, Medium-sized cars, "near-future" and "far future".

Define Vehicles here and choose indicators for environmental impacts in sheet "Results_details"

Reset selection

Reference name (user defined)	Vehicle type	Weight / materialization type	Power train type	Emission class	Battery type	Temporal senario	Energy source for vehicle operation (fuel)
ICE gasoline, 2020	medium-sized car	standard	ICE	Euro 5	n.a.	near future (2020)	Gasoline
ICE gasoline, >2030	medium-sized car	light Alu	ICE	Euro 6	n.a.	far future (>2030)	Gasoline
ICE diesel, 2020	medium-sized car	standard	ICE	Euro 5	n.a.	near future (2020)	Diesel
ICE diesel, >2030	medium-sized car	light Alu	ICE	Euro 6	n.a.	far future (>2030)	Diesel
ICE natural gas, 2020	medium-sized car	standard	ICE	Euro 5	n.a.	near future (2020)	natural gas
ICE natural gas, >2030	medium-sized car	light Alu	ICE	Euro 6	n.a.	far future (>2030)	natural gas
BEV Swiss mix, 2020	medium-sized car	standard	battery electric	n.a.	Li-ion	near future (2020)	Swiss consumption mix
BEV Swiss mix, >2030	medium-sized car	light Alu	battery electric	n.a.	Li-ion	far future (>2030)	Swiss consumption mix
FCV electrolysis Swiss mix, 2020	medium-sized car	standard	fuel cell	n.a.	Li-ion	near future (2020)	H2 from electrolysis (Swiss consumpt
FCV electrolysis Swiss mix, >2030	medium-sized car	light Alu	fuel cell	n.a.	Li-ion	far future (>2030)	H2 from electrolysis (Swiss consumpt

Table 2-34 Vehicle parameters, Medium-sized cars, "near-future" and "far future".

	Total vehicle mass	Fuel cell system mass (incl H2 tank)	Battery mass	Electricity consumption driving	Chemical fuel consumption driving	Total life time distance	Life time battery	Life time fuel cell
	[kg]	[kg]	[kg]	[kWh/100km]	liquid: [l/100km] gaseous: [kg/100km]	[km]	[km]	[km]
ICE gasoline, 2020	1400				6	150'000	150'000	150'000
ICE gasoline, >2030	1100				4.8	150'000	150'000	150'000
ICE diesel, 2020	1450				5.3	150'000	150'000	150'000
ICE diesel, >2030	1150				4.2	150'000	150'000	150'000
ICE natural gas, 2020	1450				4.4	150'000	150'000	150'000
ICE natural gas, >2030	1150				3.5	150'000	150'000	150'000
BEV Swiss mix, 2020	1550		200	19.1		150'000	150'000	150'000
BEV Swiss mix, >2030	1250		200	16.2		150'000	150'000	150'000
FCV electrolysis Swiss mix, 2020	1565	190	20		1	150'000	150'000	150'000
FCV electrolysis Swiss mix, >2030	1195	125	20		0.66	150'000	150'000	150'000

Reduction in vehicle mass is achieved by using light-weight aluminum construction for the gliders in 2030. Also the weight of the fuel cell system is assumed to be reduced using the average of the two scenarios for 2030 according to Miotti et al. (2015). Battery mass of BEV is not assumed to be reduced, since increasing battery performance, i.e. mass-specific energy density, will be used to increase the vehicle range. With an estimated energy density of 300 Wh/kg in year 2030, the BEV specified for 2030 would have a range of about 370 km. All types of vehicles are expected to increase in their efficiency, i.e. fuel consumption will be lower in 2030 than in 2020. Fuel and electricity demand of ICEV and BEV is reduced according to the expert judgement of the authors. The average hydrogen demand in the two scenarios for 2030 according to Miotti et al. (2015) is used for FCEV. ICE vehicles will comply with EURO6 emission standard in 2030. Results are shown in Figure 2.23 through Figure 2.27.

All vehicles except of the BEV show a reduction in life cycle GHG emissions between 2020 and 2030, mostly due to the reduction in fuel demand. Changes in other parts of the life cycle – vehicle (component) production and road – are not substantial. The reason for the increase in overall GHG emissions of the BEV is the increasing CO_2 intensity of the Swiss electricity mix in 2030 due to assumed hypothetical operation of natural gas CC power plants[23], which cannot be compensated by reduced electricity demand for battery charging.

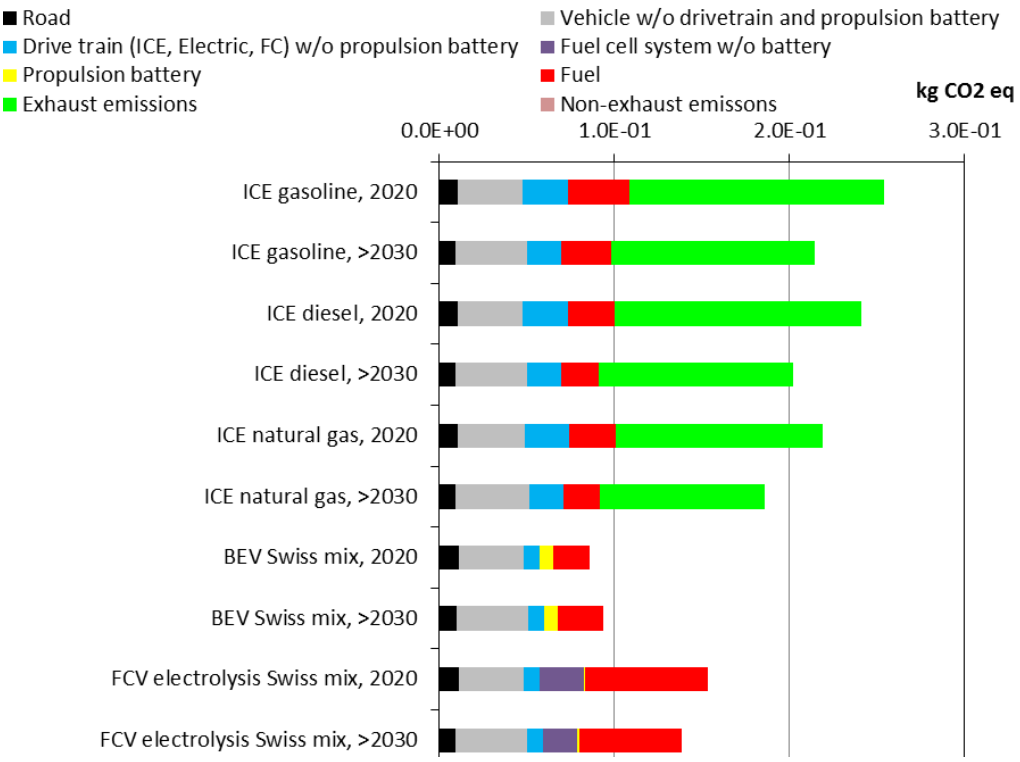


Figure 2.23 Life-cycle GHG emissions per km caused by future midsize vehicles as specified in Table 2-33 Table 2-31and Table 2-34.

FCEV show in general the highest potential for reduction of environmental burdens due to both increasing fuel efficiency (i.e. reduced hydrogen demand) and weight reduction of the fuel cell. Most substantial reductions are achieved for particulate matter formation. Changes for BEV are small and ambiguous with the Swiss electricity mixes used for 2020 and 2030: while the life cycle burdens are slightly reduced for particulate matter formation and photochemical oxidant formation, they are increasing for GHG emissions, acidification and resource depletion due to changes in the electricity mix as well as use of the aluminum based light-weight car body.

The higher the contributions of direct exhaust emissions as well as fuel chain related burdens, the more substantial are the reductions in overall life cycle burdens for the different indicators due to the reductions in fuel demand between 2020 and 2030. The difference between EURO5 and EURO6 emission standards in terms of impact on the overall life cycle results is small, since the contributions of exhaust emissions to overall life cycle results are in general minor.

[23] Natural gas power plants are only one of the possible technologies for generating the electricity currently provided by nuclear power plants after potential nuclear phase-out. Other options are renewables and/or electricity imports. These scenarios are investigated and evaluated in WP5.

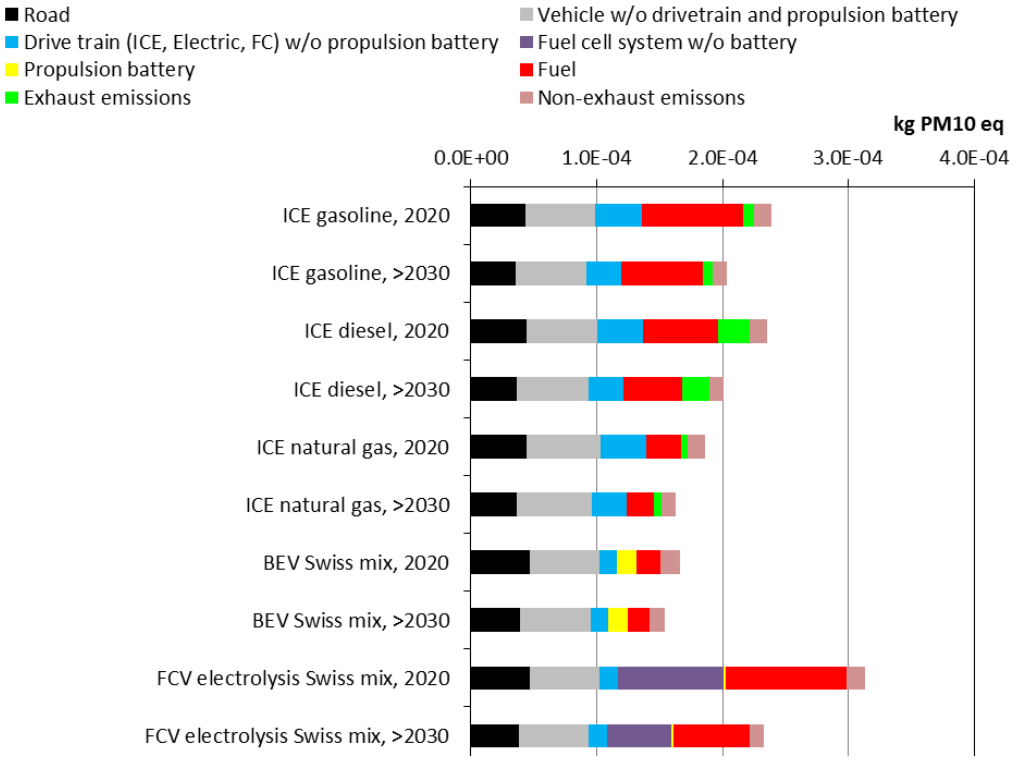


Figure 2.24 Life-cycle particulate matter formation per km caused by future midsize vehicles as specified in Table 2-33 Table 2-31 and Table 2-34.

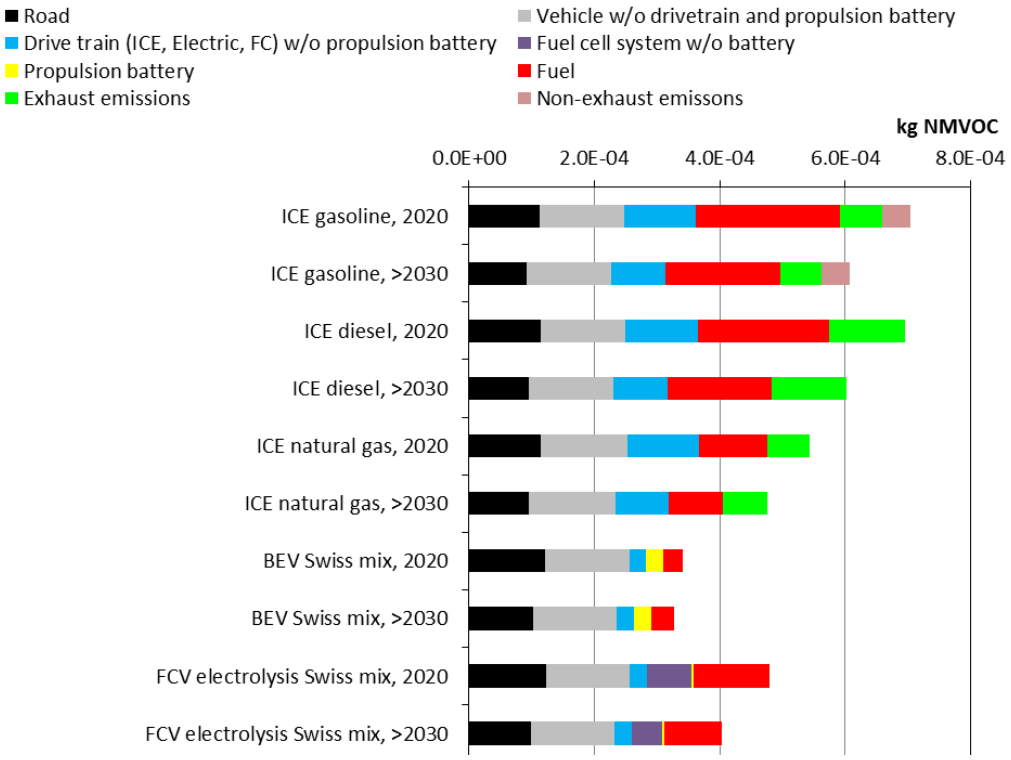


Figure 2.25 Life-cycle photochemical oxidant formation per km caused by future midsize vehicles as specified in Table 2-33 Table 2-31 and Table 2-34.

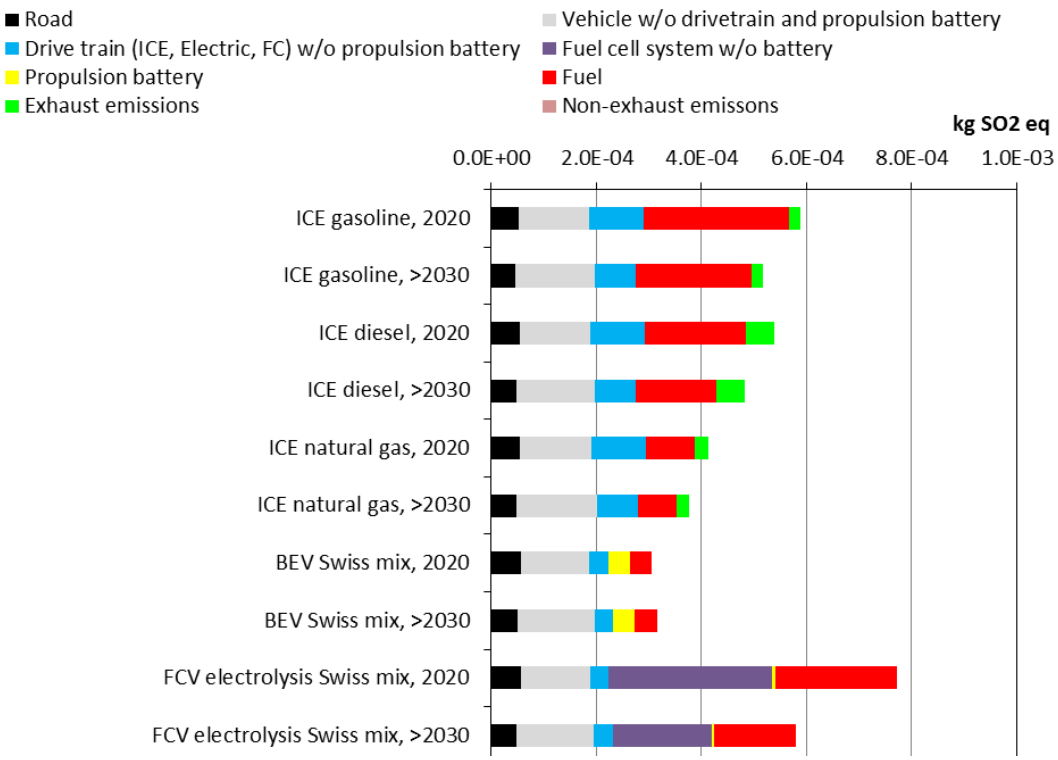


Figure 2.26 Life-cycle terrestrial acidification per km caused by future midsize vehicles as specified in Table 2-33 Table 2-31 and Table 2-34.

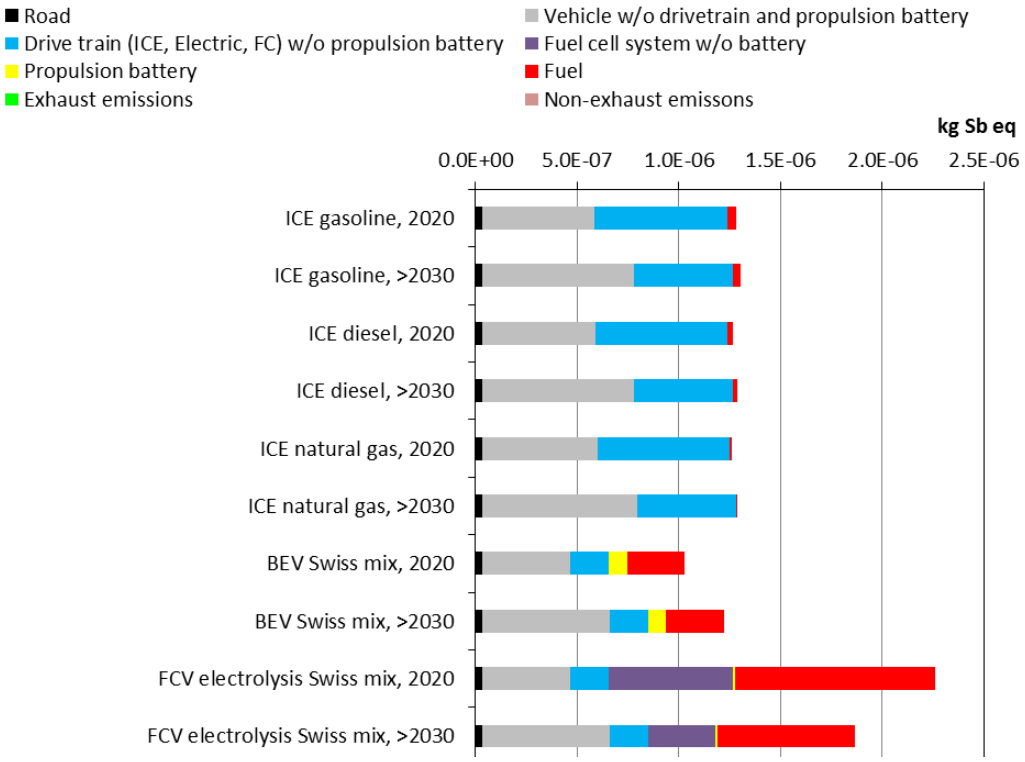


Figure 2.27 Life-cycle abiotic resource depletion per km caused by future midsize vehicles as specified in Table 2-33 Table 2-31 and Table 2-34.

The fact that FCEV show the largest potential for reduction of environmental burdens is obvious in the analysis of the large set of environmental indicators (Figure 2.28). However, the general picture – FCEV with hydrogen produced via electrolysis using the Swiss electricity mix will perform worse for a

number of LCIA indicators than vehicles operated with fossil fuels – will not change. The overall performance of the BEV using the Swiss electricity mix for charging of batteries relative to the ICEV will hardly change between 2020 and 2030.

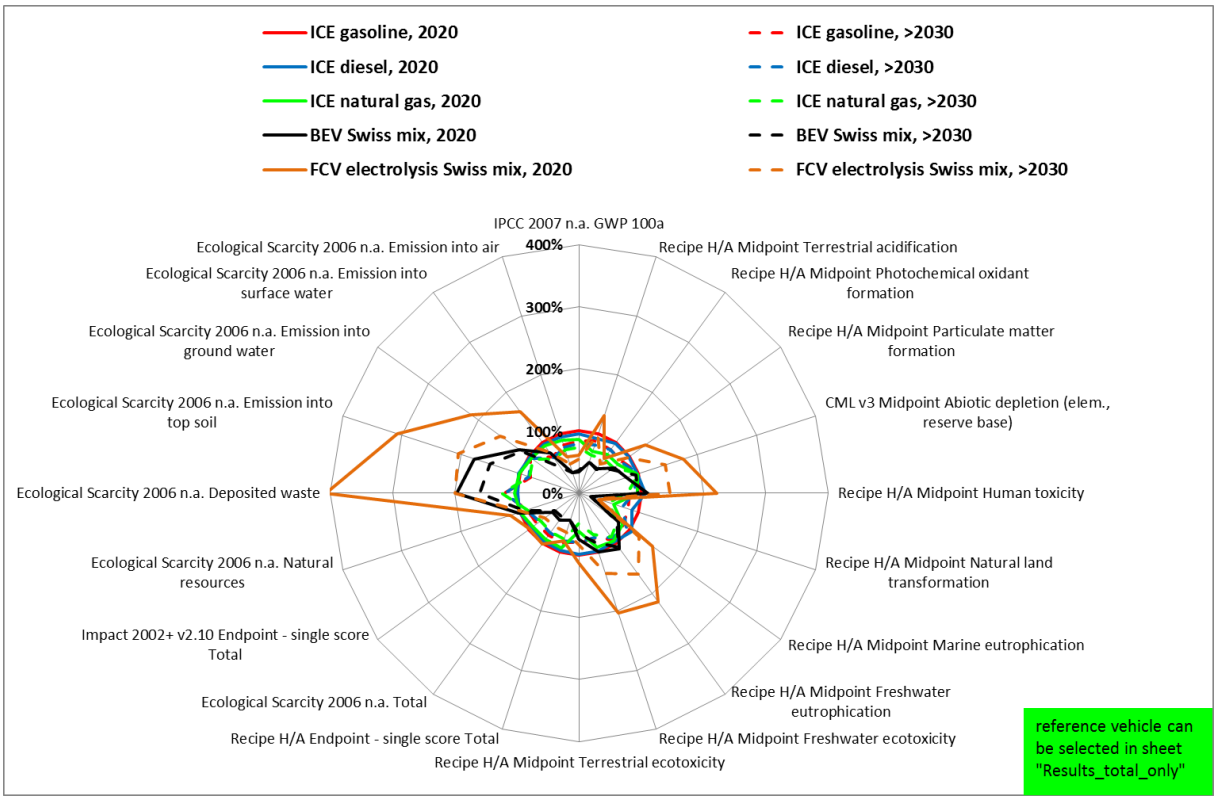


Figure 2.28 Large set of LCA results for the evaluation of midsize cars, as specified in Table 2-33 Table 2-31and Table 2-34. The near future (2020) ICE gasoline vehicle is chosen as the reference car with 100% impact for each of the indicators.

2.6. Conclusions

Based on the LCA results of WP1, the following main conclusions concerning the environmental performance of passenger vehicles can be drawn:

- Battery electric vehicles (BEV) show a better environmental performance than fossil fuel internal combustion engine vehicles (ICEV) for the majority of environmental indicators, as long as they are charged with “clean” electricity, i.e. not from fossil power plants. The most substantial benefits – up to minus 80% – can be observed regarding reduction of potential impacts on climate change, if electricity from renewables or nuclear power is used. At the same time, life cycle GHG emissions are most sensitive concerning the type of electricity used for charging. These observations hold true for the complete time frame of this evaluation, i.e. from today up to 2030.
- Fuel cell vehicles (FCEV) show a mixed environmental performance. As long as the hydrogen for vehicle operation is produced based on “clean” energy resources, i.e. via electrolysis using electricity from non-fossil power plants, they offer advantages for some environmental indicators. Concerning life cycle GHG emissions, substantial reduction of up to minus 60% compared to the gasoline reference ICEV can be achieved in 2020. However, almost independent of the hydrogen production pathway, the LCA results of FCEV are worse than those of fossil fueled ICEV for some environmental indicators. Obviously, FCEV with hydrogen from fossil sources will not provide an environmental benefit. Currently, FCEV are the most

immature among the evaluated technologies and hardly commercially available. Therefore, we expect that the potential for reduction of environmental burdens due to improved technology performance is still high.

- Among the ICEV evaluated, natural gas vehicles clearly generate the lowest life cycle environmental burdens. Conventional natural gas vehicles even cause lower burdens than gasoline and diesel hybrid vehicles[24] for most of the LCIA indicators.
- Progress in vehicle technology development will in general result in reduced environmental burdens, mostly due to increasing vehicle efficiency and reductions in fuel demand. Changes in fuel supply – e.g. electricity mixes with higher shares of fossil power generation or increasing market shares of unconventional fossil fuels – might (over)compensate these environmental benefits and lead to higher life cycle burdens.

However, when interpreting these results, the following limitations of the work need to be kept in mind:

- The LCIA methods applied do not take into account the location of pollutant emissions, i.e. their potential impacts will be assumed to be independent of whether emitted in densely populated areas like city centers or remote locations of e.g. mining of metal ores. Therefore, the benefits of BEV and FCEV in mitigating air pollution in urban areas due to their non-existing tailpipe emissions might be underestimated. However, since the contributions of direct tailpipe emissions of ICEV to overall life cycle results are in general minor, the provided results will still be meaningful.
- LCA results for 2030 and beyond are in general associated with high uncertainties, since a) the future development of passenger vehicles cannot be accurately predicted; and b) a non-negligible fraction of LCI data used for LCA calculations supposed to represent 2030 and beyond actually represent current (or past) technological status. In the context of LCA of passenger vehicles, this limitation seems to be most important for LCI data of fossil fuel chains as well as metal mining and processing.
- This LCA represents an attributional assessment on the level of single vehicle technologies. It does not take into account consequential effects within the economic system and it also does not take into account economic and environmental feedback effects due to potential large-scale introduction of innovative vehicle technologies such as BEV and FCEV.

2.7. Recommendations for future work

LCA related issues, which are associated with high uncertainties, or which could not be sufficiently analyzed within WP1 (and only partially in the THELMA project as such) and deserve further attention in the future, are the following:

- Primary industry data from manufacturers of batteries and fuel cells would substantially reduce uncertainties in these LCI data.
- Establishment of LCI data for specific future battery technologies not considered in this work, such as Li-air or Li-sulfur.
- Establishment of LCI data for future fuel cells explicitly taking into account new materials and manufacturing methods technologies.

[24] In this case, “hybrid vehicles” does not include plug-in hybrids.

- Establishment of LCI data for unconventional and future fossil fuel production, such as oil sands, shale oil and gas, and deep sea reservoirs, which are supposed to increase their market shares in the future.
- Consideration of biofuels.
- Consideration of systemic aspects in addition to the current technology centered perspective and integration of economic interactions.

Acronyms

BE	Battery Electric
BEV	Battery Electric Vehicle
CC	Combined Cycle
E85	Mix of 85% bioethanol, 15% gasoline
EC	European Commission
EoL	End-of-life
FC	Fuel Cell
FCEV (Sometimes FCV)	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NEDC	New European Driving Cycle
NiMeH	Nickel-Metal-Hydride
PM	Particulate Matter
PV	Photovoltaic
SMR	Steam Methane Reforming
Swiss mix	Swiss electricity supply mix (incl. electricity imports)
vkm	Vehicle-kilometer
WP	Work Package
ZEBRA	Zeolite Battery Research Africa

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3. Work Package 2 "Vehicle simulation and powertrain assessment"

Authors: Gil Georges (ETHZ)[25], Johannes Hofer (PSI)[26]

3.1. Introduction

In today's passenger car fleet, electrically propelled passenger cars – including hybrids – are still fairly in the minority. Any assessment of the benefits of electrification will thus have to look into a possibly quite distant future, when alternative propulsion systems presumably will have gained significant market shares. Furthermore, contrary to conventional powertrains, there are no de-facto design standards for electrified powertrains as of yet, especially when it comes to more complex configurations such as hybrid electric architectures.

Yet assessing the benefits of electric mobility obviously requires information on the distance-specific energy demand (in terms of unit energy per unit distance). Obviously that information cannot be obtained empirically – at least not in the breadth required by THELMA, namely for every vehicle in the fleet, from now until the study's time horizon of 2050.

THELMA's Work Package 2 (WP2) addresses this issue through vehicle and powertrain simulation, as detailed in the following sections.

3.2. Objectives

The main objectives of WP2 include the characterization of current and future powertrain technologies and the calculation of energy consumption and other related indicators for different vehicle classes and energy carriers. In particular conventional, hybrid electric (including plug-in hybrids), battery electric and fuel cell vehicles are simulated for assorted driving cycles, representative of real-world driving conditions. In addition, WP2 assessed vehicle costs and coupled vehicle simulation results to life cycle analysis results from WP1 for the assessment of environmental indicators.

After configuring and assessing a large, representative design of current and future vehicles, the technical trade-offs of powertrain electrification are presented in an unbiased manner to allow stakeholders to evaluate the merits of new vehicle propulsion technologies with respect to:

- Energy use
- Performance (acceleration, top speed)
- Utility (range, size)
- Cost (purchase, operating, total)
- Environmental factors (all relevant Life Cycle Assessment (LCA) indicators) [27]

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[26] Current affiliation: ETH Zurich, Architecture and Building Systems, hofer@arch.ethz.ch
[27] Note that proper derivation of LCA indicators falls under the purview of WP1. WP2 provides vehicle configuration and energy demand data, which ultimately translates into the production, operation and decommissioning environmental impact. The results of both WP's can however be combined, as for example used in Bauer, C., J. Hofer, H.-J. Althaus, A. Del Duce and A. Simons (2015).

Besides the direct analysis of the technology criteria, the technology descriptions also serve as inputs to other work packages, in particular WP3 and WP5.

The work package was split between ETHZ-LAV and PSI-LEA. ETHZ-LAV focused on combustion engine vehicles, while PSI-LEA focused on battery electric and fuel cell vehicles. Battery and electric motor models are selected and applied in close cooperation.

3.3. Scope

The mission of WP2 is to derive the technical configuration and energy demand data through simulation for every vehicle in the fleet, from now to 2050. As core methodological element, THELMA-WP2 therefore considers a vehicle as the combination of (1) a powertrain, providing the necessary propulsion power and (2) a glider, which aggregates everything but the powertrain. One particular glider can thus be fitted with various powertrain systems and technologies to explore their respective potential for electrification. For any given glider/powertrain combination, the energy demand further depends on (3) operational boundary conditions, in particular the speed (or more precisely the driving cycle) at which the system is operated, or the ambient temperature during the journey.

In the following, the three building blocks, as illustrated in Figure 3.1 are discussed separately.

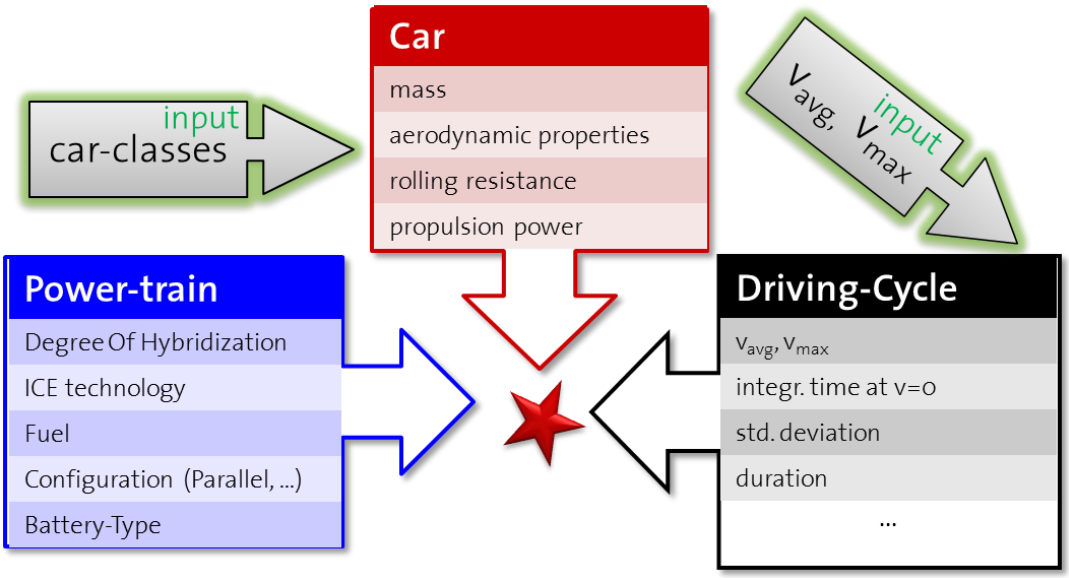

Figure 3.1: THELMA-WP2 vehicle simulation framework. This considers vehicles as combination of (1) a powertrain providing the propulsion power and (2) the glider, as the sum of components that do not belong to the powertrain. The operation of any given vehicle assembly is further defined by (3) the operational boundary conditions, before all the driving cycle.

3.3.1. Vehicle design

3.3.1.1. Characterization of the glider

Looking to Switzerland's streets, the contemporary passenger car fleet is a heterogeneous mixture of various sizes and shapes – which is likely to still be the case 40 years from now. The variety is so large that actually modeling each existing vehicle individually is out of the question – even though energetic powertrain models still only resolve a fairly small part of a modern vehicle's physics. Therefore the fleet is broken down into a manageable number of individual classes, presuming that

class members are so similar to one another that their relevant indicators (those listed in section 3.2) do not differ significantly.

The categorization chosen by THELMA-WP2 is that of car market segments as used by the European New Car Assessment Programme (EuroNCAP) – and often found in car magazines (Mini, Midsize, Compact, and so on). Indeed following Hucho (2007), the industrial design process of a car always targets a specific market segment (i.e. membership of a "vehicle class" is part of a vehicle specification). The car market being as it is, the visual appearance of the product plays a very central role. Therefore, very early in the concept phase, designers will consider the perceived directly competing products. Consequently many pivotal design decisions, in particular the outer dimensions and general aspect of a vehicle, are heavily influenced by already existing designs. It is therefore very likely that individual vehicles marketed as members of a given market are optically not that dissimilar. In fact, as market class is often synonymous with "price class", it is also probable that other customer expectations such as performance attributes (size, acceleration, etc.) are correlated.

Following that rationale, Table 3-1 summarizes the derived vehicle class specification used in WP2. The segments more or less correspond to the widely used EuroNCAP classes, but were actually defined in accordance with the underlying vehicle sales records. Note that the parameter values between certain classes are quite similar. Also, some classes are more relevant than others with respect to sales. Indeed, as visible in Figure 3.2, the mini to midsize segments amounted for roughly 2/3 of all passenger car sales in Switzerland in 2011.

Nevertheless, the definition of individual vehicle classes is somewhat fuzzy. On one hand, class membership may not always be that obvious, especially considering that designers may consciously chose to break with de-facto standards to differentiate their product. Furthermore, the above rationale neither precludes the possibility of class definitions "creeping" over time, nor the possibility of the introduction of new classes. But as modeling thousands of individual vehicles is not an option, the above approach, mimicking the actual industrial design process, is a good compromise.

Table 3-1 Analyzed vehicle classes and important simulation parameters.

	Glider mass (kg)	Power-to-mass ratio (W/kg)	Frontal area (m^2)	Aerodynamic drag coeff. (c_d)
Mini	612	56	1.9	0.34
Small	762	59	2	0.31
Low-Midsize	944	66	2.1	0.31
Midsize	1091	76	2.2	0.31
Up-Midsize	1186	92	2.3	0.3
Luxury	1328	117	2.4	0.3
Compact-MPV	1032	61	2.6	0.32
MPV	1266	65	2.8	0.34
Compact-SUV	1085	70	2.6	0.33
SUV	1442	84	2.9	0.35
Compact-Sport	858	86	2.1	0.33
Sport	917	141	2	0.35
Transporter	1046	51	3.1	0.34

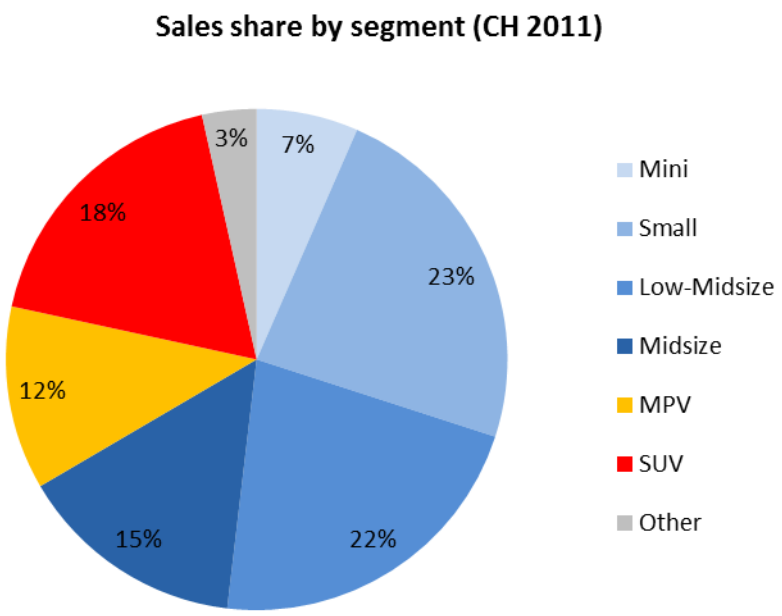

Figure 3.2 Passenger car sales in Switzerland by market segments. Source: IHS Automotive (2013).

3.3.1.2. Characterization of the powertrain

The main objective of WP2 is obviously to investigate powertrain electrification. Note that this is understood in the strictest sense of the word, referring to any architecture whose propulsion effort is sustained by meaningful amounts of electrical power. Beyond the obvious, pure battery electric vehicle, the definition thus encompasses fuel-cell electric systems and internal combustion engine based hybrid electric solutions. That leads to the following technical base options; for a deeper technical discussion of the different powertrains and their operation, see section 3.3:

- Conventional, internal combustion engine based powertrain (ICEV)
- Hybrid electric powertrain (HEV)
- Externally chargeable hybrid electric powertrain → range-extender / plug-in (PHEV)
- Pure battery electric vehicle (BEV)
- Fuel-cell electric vehicle (FCEV)

Within each of those powertrain architectures there are further technology choices. For instance for all solutions featuring an internal combustion engine (ICE) there are different fuels (and by extension thermodynamic combustion processes) available. As a matter of principle there is no exclusive relationship between ICE fuels and vehicle classes (at least this will become unlikely in a 10-30 year future), thus ICE fuels are considered an additional exogenous variable to the powertrain specification (where applicable).

Just as there are different implementations of ICE technology, so are there different electric machines, batteries and power electronics; compared to changing the combustion process in an ICE these constitute however rather smaller interventions, and are therefore not resolved in WP2.

Thus far only the powertrain architecture was specified, i.e. technology choices for individual components and their interconnections were made. What is left is to “size” the components, by

which – as all of them are energy conversion, transmission or storage devices – determining their nominal power output / throughput resp. energy storage capacity is understood.

The envelope of the prime mover, i.e. the primary device used to apply torque to the wheels (there can be more than one) directly defines the drivability of a vehicle. Presuming that at high velocities the aerodynamic drag is by far the dominant dissipative influence a vehicle's top speed v_{top} relates to the prime mover power P_{max} via :

$$v_{max} = P_{max} \cdot \left(\frac{1}{2} \cdot \rho \cdot c_D \cdot A_f\right)^{-\frac{1}{3}} \tag{1}$$

Similarly, disregarding the influence of the tire rolling resistance or aerodynamic drag, the acceleration time t_0 from 0 to v_0 is approximately given by (with m_V being the total vehicle mass):

$$t_0 = \frac{m_V \cdot v_0^2}{2 \cdot P_{max}} \tag{2}$$

As discussed in section 3.3.1.1, the performance attributes of a car are related to its membership to a specific class. Via the above equation the average/representative acceleration timing within a given class can be directly translated to the prime mover's power rating. The fact that the total mass m_V figures in the above equation points to a central trade-off in vehicle design: increasing the electric machine's power output P_{max} also increases its weight; sustaining a certain acceleration target with a larger electric machine is thus only possible with compromising battery size. Figure 3.3 illustrates this as the blue line in the "design space", spanned by the "traction motor size" and "battery size" axes. Using today's electric vehicles as a reference, the battery can then be configured; the battery mass in future vehicle generations is presumed approximately constant in time, so that the autonomy range may grow under the direct action of battery energy density improvements, vehicle light-weighting, or other efficiency improvements.

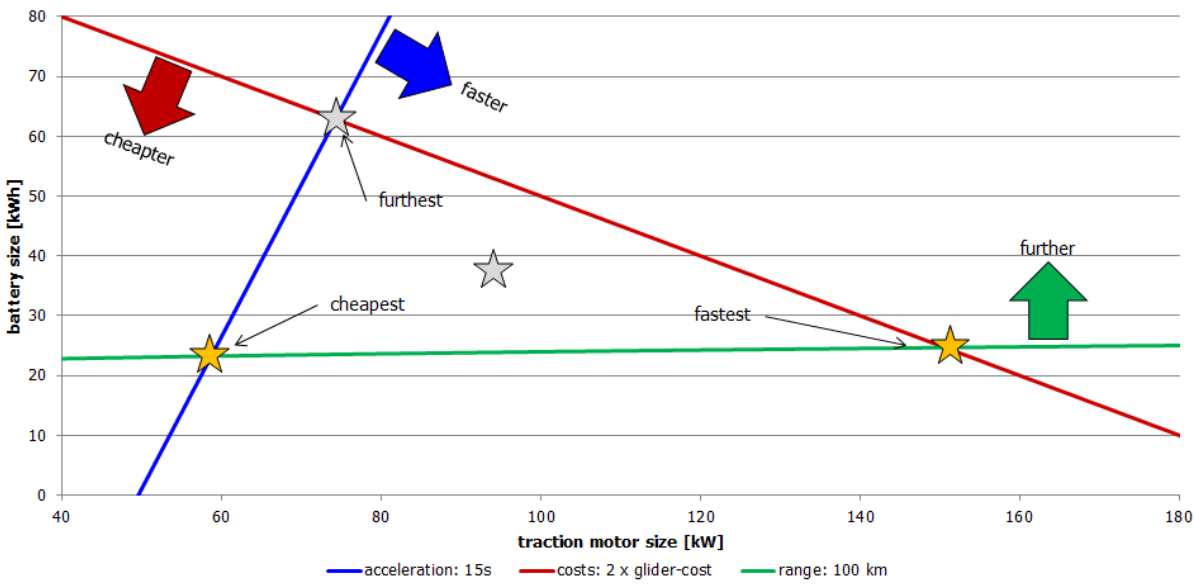

Figure 3.3 Configuration options for a mid-class battery electric powertrain in terms of the installed traction motor and battery size (in kW nominal power output and in kWh effectively available maximum energy capacity respectively). To achieve the class-dependent performance characteristics (in terms of acceleration and nominal range), certain minimum motor (blue line) and battery sizes (green line) are required.

However, since the component choice affects the total mass of a vehicle, it also influences the net propulsion load and the average conversion efficiency (see section 3.3 for more details). Accounting for these feedbacks, the three lines above are just the loci of vehicle configurations with identical performance with respect to acceleration, costs, or range. As the dependencies are roughly linear, there is a clear tendency (see arrows) in which the performance indicators evolve. This is what ultimately allows constraining the design space to the triangular area shown above.

For hybrid electric vehicles, the design process is more complex since the additional energy source augments the dimensionality of the design space. See Figure 3.4. The Degree of Electrification (DOE) measures the relative share of the battery-electric (i.e. non-range-extender) power to the total traction power: a DOE of 0 corresponds to an essentially ICE vehicle, while a DOE of 1 would be a pure-electric vehicle.

There is a minimum DOE (the blue line) below which the vehicle can no longer be operated under city-driving conditions (ARTEMIS Urban cycle) without the ICE. This minimum degree of electrification is given by the battery still providing enough electrical power and energy to enable the vehicle to cover at least 100 km (to be consistent with Figure 3.3) in a city cycle (ARTEMIS urban); lower settings would cause the powertrain to operate in "hybrid mode", hence the resulting car may no longer be truly considered a "range extender" (more a plug-in hybrid with a seriously oversized battery). Note that if the 110 km/h (kph) constraint is coupled with the acceleration constraint of Figure 3.3. (i.e. the resulting range extender is supposed to accelerate all-electrically) much higher DOE values are required.

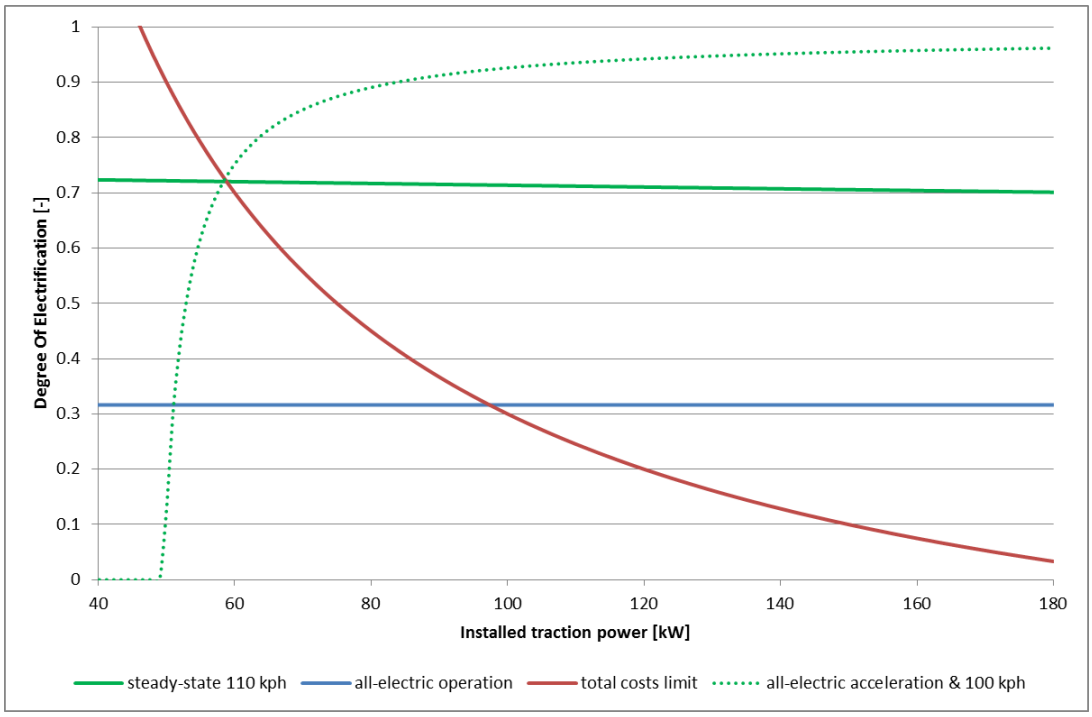

Figure 3.4 Configuration space of a range extended EV powertrain for a mid-class car.

A vehicle design, as described in 3.3.1 is a static description of a propulsion system and its individual energy conversion and storage devices. In the physical world, a driver is controlling the forward velocity of the vehicle by instructing the aforementioned devices to apply a certain torque to the wheels. For doing so, the powertrain generally has to draw on its on-board energy storage system

(within THELMA that can be a fuel/hydrogen tank or a battery). In other words, energy is used to adjust the forward velocity.

Next to direct dynamic simulation, THELMA-WP2 relies on a method known as backward facing simulation, effectively inverting this causal relationship. As depicted by Figure 3.5, it deduces the energy demand that a vehicle must have had, knowing that it moved along previously known velocity profile. The latter is a time-resolved record of its speed versus time profile, as illustrated in Figure 3.6.

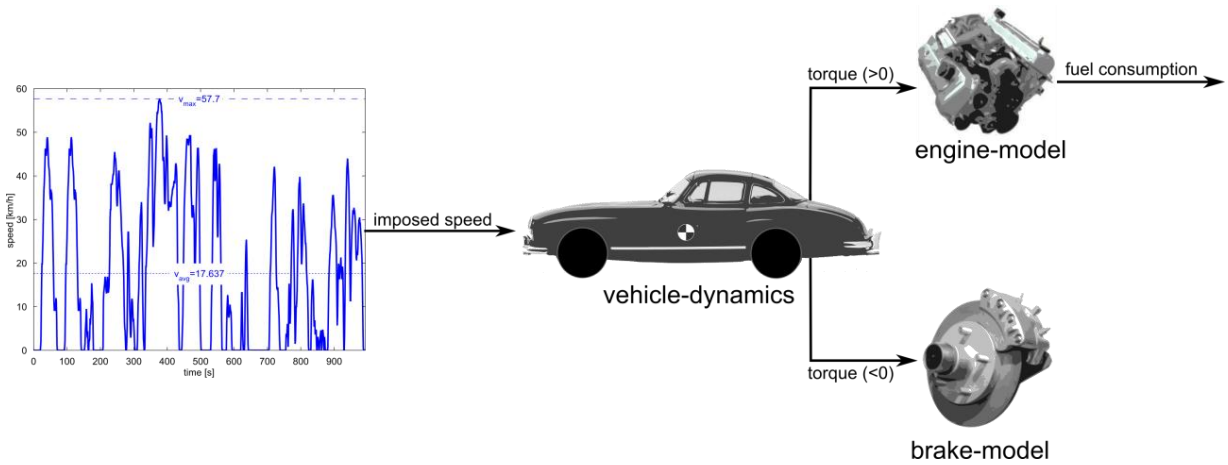

Figure 3.5 Schematic illustration of the backward facing simulation technique, to compute vehicle energy demand based on a certain speed trajectory.

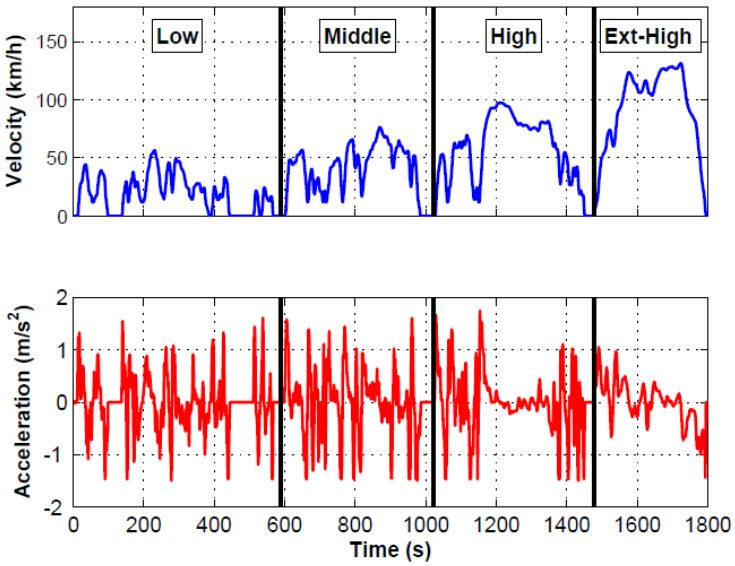

Figure 3.6 The Worldwide harmonized Light vehicles Test Procedure (WLTP) in terms of momentary velocity (blue) and acceleration (red) over the roughly 30 minutes of the test procedure.

3.3.1.3. The physics of longitudinal motion

The forward motion is opposed by various drag forces, namely aerodynamic drag and rolling resistance, whose magnitude is determined both by certain technical attributes of the glider, the tires and the current magnitude of the forward velocity. Also any change in velocity is opposed by inertia. Hence, for speed signal $v(t)$ known a priori (backward facing simulation), it is possible to calculate the necessary propulsion force $F_{prop}(t)$ at any time t:

$$F_{prop}(v(t)) = m_V \cdot \frac{dv(t)}{dt} + F_{aero}\big(v(t)\big) + F_{roll}(v(t)) \tag{3}$$

where:

- m_V is related to the vehicle's total mass
- $F_{aero}(v)$ is the longitudinal aerodynamic force opposing forward motion when traveling at v
- $F_{roll}(v)$ is the total tire rolling resistance opposing forward motion when traveling at v

3.3.1.4. Characterization of the vehicle usage

The total mechanical energy demand of a vehicle over a known driving cycle $v(t)$ is:

$$E_{mech} = \int_0^{t_f} F_{prop}(v(t)) \cdot v(t)\, dt \tag{4}$$

Yet F_{prop} is not necessarily positive; indeed active braking, i.e. decelerating stronger than the natural retardation induced by the various resistive and drag forces is only possible if the powertrain applies a negative F_{prop}. In conventional vehicles, this is achieved through friction brakes, dissipating the returning, negative power. Electrified vehicles on the other hand can instead recuperate the returning power by converting it back to electric power, and storing it in a battery (or other electric energy storage device). A more in-depth analysis of this process, known as brake energy recuperation, can be found in section 3.4.1.1.

For now it is important to note that in the above definition of E_{mech}, negative $F_{prop}(v(t)) \cdot v(t)$ reduce the total energy demand E_{mech}; in fact, provided that $v(0) = v\big(t_f\big)$ it is straight forward to show that the inertial (differential) term of $F_{prop}(v)$ does not contribute to E_{mech}. This is only possible if all recuperated negative power can be losslessly "brought back" to the wheels; which is a technical impossibility. Nevertheless, if such an ideal powertrain could be built, its energy demand would solely be a matter of the average aerodynamic drag and rolling resistance forces (meaning ultimately the average velocity); the acceleration intensity and frequency within $v(t)$ would play no role at all.

In any real powertrain there are losses, and some (or all) of the braking occurs using dissipative braking systems, because certain higher-ranking constraints require so (the battery could e.g. be fully charged). Of course in the worst case of a vehicle incapable of brake energy recuperation (ICEVs), all negative power is lost, so that the mechanical energy demand grows to:

$$E^{+}_{mech} = \int_0^{t_f} F_{prop}(v(t)) \cdot v(t) \cdot H\left(F_{prop}(v(t))\right)\, dt > E_{mech} \tag{5}$$

where $H(x)$ is the Heaviside function, i.e. it is zero if $x < 0$ and 1 if $x > 0$. Consequently, the end-energy demand of a vehicle depends certainly on the average value of $v(t)$, and the more its braking is effectively dissipative (including losses in the recuperation path), the more the acceleration behavior starts to play a role. Next to the vehicle itself, its energy demand is thus strongly dependent on the $v(t)$ it is evaluated against.

Now as explained above, $v(t)$ is the observed consequence of a driver applying a certain acceleration or retardation request to their vehicle. If one were to record the $v(t)$ of all vehicles in a fleet as they go about their day, by the very nature of individual mobility, there would be as many $v(t)$ as there are drivers. Analogously to the categorization of passenger car gliders in section 3.3.1.1, a simplification is necessary. The solution is found in standardized driving cycles, which have been developed primarily by governing agencies (or on their request) as a support framework for emissions legislations.

In THELMA, the Worldwide harmonized Light vehicles Test Procedure (WLTP), New European Driving Cycle (NEDC) and ARTEMIS driving cycles are considered. The WLTP is used as the reference driving cycle. It is based on statistical analysis of driving conditions from the EU, India, Japan, Korea, Switzerland, and USA and is expected to replace the NEDC for emission certification in Europe. In contrast to the NEDC, the WLTP and ARTEMIS are transient driving cycles which involve many continuous changes of velocity representing a more realistic driving pattern, i.e. it's more representative for "real-world" driving than the NEDC, which is underestimating fuel consumption of modern passenger vehicles in daily driving. Nevertheless, at the time of writing the NEDC is the reference of emissions legislation and therefore still relevant. The ARTEMIS driving cycle was shown by independent studies to be very realistic of European traffic conditions (Bassett et al., 2010).

All three driving cycles are part of a testing procedure that makes an assumption on how much of a vehicle's operation occurs on motorways, major rural roads and typically busier urban street networks. As with the MATSim simulation data from WP4 information is available on the actual split factor between those road-types, energy demand figures for each are computed individually. Thus in the end, THELMA-WP2 categorizes the "driving situation" in terms of the three road-types: "urban", "rural" and "motorway".

3.3.2. Drivetrain configuration and simulation

As indicated in section 3.3.1.2, THELMA WP2 considers a wide range of powertrain architectures:

- Conventional, purely internal combustion engine powered systems
- Hybrid electric solutions (internal combustion engine powered):
    - Mild/full hybrids
    - Plug-in/range extending hybrids
- Battery electric systems

Fuel-cell electric systems Table 3-2 summarizes the drivetrain types considered in this study and the corresponding abbreviations. Figure 3.7 illustrates the powertrain configuration and the possible power flows between the main components for the different powertrains.

Table 3-2 Drivetrain types considered in this study.

Drivetrain technology	Abbreviation
Internal combustion engine vehicle fueled by gasoline/diesel/compressed natural gas	ICEV-gasoline/diesel/cng
Hybrid electric vehicle fueled by gasoline/diesel/compressed natural gas	HEV-gasoline/diesel/cng
Battery electric vehicle	BEV
Plug-in hybrid electric vehicle fueled by gasoline/diesel/compressed natural gas	PHEV-gasoline/diesel/cng
Fuel cell electric vehicle	FCEV

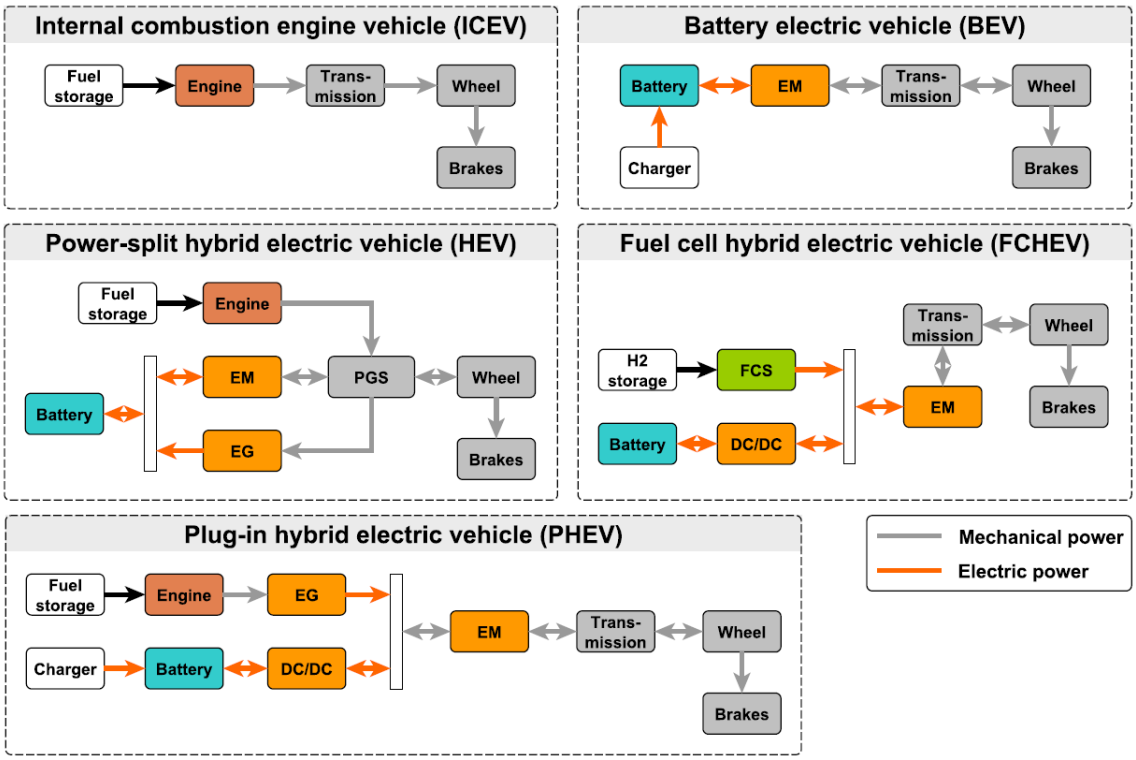

Figure 3.7 Overview of drivetrain configurations analyzed and power flows between the main components. Abbreviations: Electric motor (EM), electric generator (EG), fuel cell system (FCS), planetary gear set (PGS).

Computing the energy demand of a given vehicle is essentially the same for all powertrain systems: starting with the known power demand signal at the wheels, the power flows are traced back through the powertrain up to the initial energy input at the plug or fuel station. All conversion and storage processes are modeled using the quasi-steady state models included in ADVISOR, an open-source vehicle simulation software (Wipke et al., 1999).

Hybrid electric vehicles constitute a special case, as the presence of two covalent (at least in the short term) energy sources requires an active control strategy, deciding upon which source to use at any given moment. For the large-scale simulation, heuristics provided by ADVISOR were used in the interest of reducing the computational load. Nevertheless, a limited data-set using full dynamic optimization was generated – see section 3.4.1.3 for a more detailed discussion.

3.3.2.1. Mass and cost assessment

The characterization outlined in 3.3.1.1 and 3.3.1.2 is sufficient to statically describe the entire system for LCA and later, dynamic simulation. With the size resp. nominal rating of all powertrain components, their mass and cost can be individually estimated. Table 3-3 lists the assumed reference values of the specific masses and costs for the power and energy storage devices (Hofer et al., 2014). It consists of a fixed and variable part in order to realistically evaluate the component mass and cost for different amounts of power and energy. Not yet fully developed technologies (such as batteries and fuel cells) are expected to improve in energy and power density and decrease in cost due to efficiency gains, experience effects, and increase of production volume. The sensitivity of the resulting vehicle criteria to changes of important parameters such as battery energy density is analyzed in detail.

Table 3-3 Fixed and variable mass and cost of the main vehicle components.

	Mass power devices				Cost power devices			
	Unit	**2012**	**2030**	**2050**	**Unit**	**2012**	**2030**	**2050**
Gasoline Engine	kg	60.0	54.0	50.0	$	1000.0	1300.0	1500.0
	kg/kW	0.7	0.5	0.4	$/kW	7.4	9.2	11.0
Diesel Engine	kg	69.0	62.1	57.5	$	1150.0	1495.0	1725.0
	kg/kW	0.8	0.6	0.5	$/kW	8.5	10.6	12.7
CNG Engine	kg	63.0	56.7	52.5	$	1050.0	1365.0	1575.0
	kg/kW	0.7	0.5	0.4	$/kW	7.8	9.7	11.6
Motor and controller	kg	22.0	18.0	15.0	$	500.0	420.0	370.0
	kg/kW	0.9	0.7	0.6	$/kW	28.0	20.0	17.0
Li-ion battery (power)	kg	8.0	6.6	5.0	$	1000.0	600.0	400.0
	kg/kW	1.0	0.8	0.5	$/kW	50.0	32.0	24.0
Fuel cell system	kg	40.0	34.0	30.0	$	10000.0	6000.0	1500.0
	kg/kW	1.1	0.7	0.5	$/kW	400.0	90.0	40.0
	Specific power (kW/kg @80kW)	0.6	0.9	1.1	Specific cost ($/kW @80kW)	525.0	165.0	58.8
ICEV transmission and differential	kg	55.0	50.0	50.0	$	800.0	900.0	1000.0
	kg/kW	0.6	0.5	0.5	$/kW	6.0	6.0	6.0
EV transmission and differential	kg	35.0	30.0	30.0	$	500.0	400.0	300.0
	kg/kW	0.4	0.3	0.3	$/kW	3.0	3.0	3.0
	Mass energy devices				**Cost energy devices**			
Li-Ion battery (energy)	kg	30.0	20.0	15.0	$	8000.0	2500.0	1500.0
	kg/kWh	8.3	4.2	2.7	$/kWh	440.0	150.0	120.0
	Specific energy (Wh/kg @25kWh)	105.3	200.0	303.0	Specific cost ($/kWh @25kWh)	760.0	250.0	180.0
Hydrogen tank	kg	40.0	35.0	30.0	$	1500.0	1200.0	1000.0
	kg/kWh	0.3	0.3	0.3	$/kWh	9.2	8.2	7.3
ICEV tank	kg	10.0	10.0	10.0	$	300.0	300.0	300.0
	kg/kWh	0.1	0.1	0.1	$/kWh	0.6	0.6	0.6
CNG tank	kg	25.0	20.0	20.0	$	800.0	700.0	600.0
	kg/kWh	0.2	0.2	0.2	$/kWh	5.0	4.5	4.0

3.3.3. Other scenario assumptions

Besides the development of components specific mass and cost explained in the previous section, several other parameters influence the simulation of future vehicle indicators. Glider mass, aerodynamic drag, and tire rolling resistance are expected to be continuously reduced by manufacturers in order to reduce vehicle energy use and to fulfill new emission standards. In the baseline scenario, glider mass, aerodynamic drag, and tire rolling resistance are reduced by 0.5 % per year, which equates to a total reduction of ca. 17 % by 2050. This rate of reduction seems realistic

considering historic developments for these parameters and projections used in other studies. Similarly powertrain component efficiencies are assumed to increase over time to account for technical progress.

Due to the high importance of range for purely battery powered electric vehicle performance and cost, the BEV is modeled as a short-range (SR) and long-range (LR) vehicle. The assumed reference BEV driving ranges which can be achieved for a specific driving cycle are indicated in Table 3-4. These values were used as the baseline scenario for BEV configuration. It is assumed that these driving ranges will be possible with the available battery technology at that point in time without excessive battery weight and cost impacts. Obviously also longer ranges are possible, but at increased battery cost, weight, and environmental impacts. For many applications, such as urban and commuter travel, commercial fleets or shared e-mobility a short range vehicle may be sufficient.

Table 3-4 Reference battery electric vehicle ranges.

	2012	2030	2050
BEV-SR	100 km	150 km	200 km
BEV-LR	200 km	350 km	500 km

3.4. Results

The results chapter has been split into three sections: before any large-scale simulation was possible, certain detail aspects of vehicular dynamics and powertrain technology had to be explored; section 3.4.1 covers the most important findings. Section 3.4.2 then gives an overview over the fleet-wide energy and costs assessment, and section 3.4.3 provides a sensitivity analysis on those results.

3.4.1. Central aspects of vehicle dynamics and powertrain technology

3.4.1.1. Active braking and brake energy recuperation

As displayed in Figure 3.8, $F_{prop}(v(t))$ can become negative at any speed if the deceleration is sufficiently strong. In that case the powertrain has to "provide" negative propulsion power, i.e. it has to actively brake. Depending on the driving cycle $v(t)$ this can amount to large amounts of energy. Figure 3.9 compares the amount of returning, negative braking energy (integral of the power over one driving cycle) to the positive "acceleration energy" over various driving cycles. As speed goes up, this ratio drops, as a result of drivers ever more decelerating through coasting, i.e. using the retarding effect of the natural drag forces over that of the braking system.

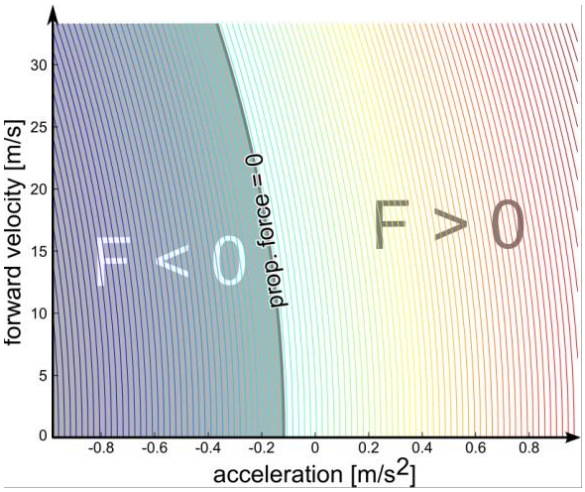

Figure 3.8 Magnitude of the propulsion force as a function of forward velocity and acceleration.

Technically, conventional propulsion systems – incapable of inverting their effective direction - realize negative traction through friction brakes; devices that dissipate the returning mechanical power as heat. Electric machinery used in electrified architectures on the other hand can be put into "generator mode", converting mechanical power into electricity. The latter can be stored back in the battery for later usage – a procedure known as brake energy recuperation, providing a much more efficient energy usage compared to conventional systems.

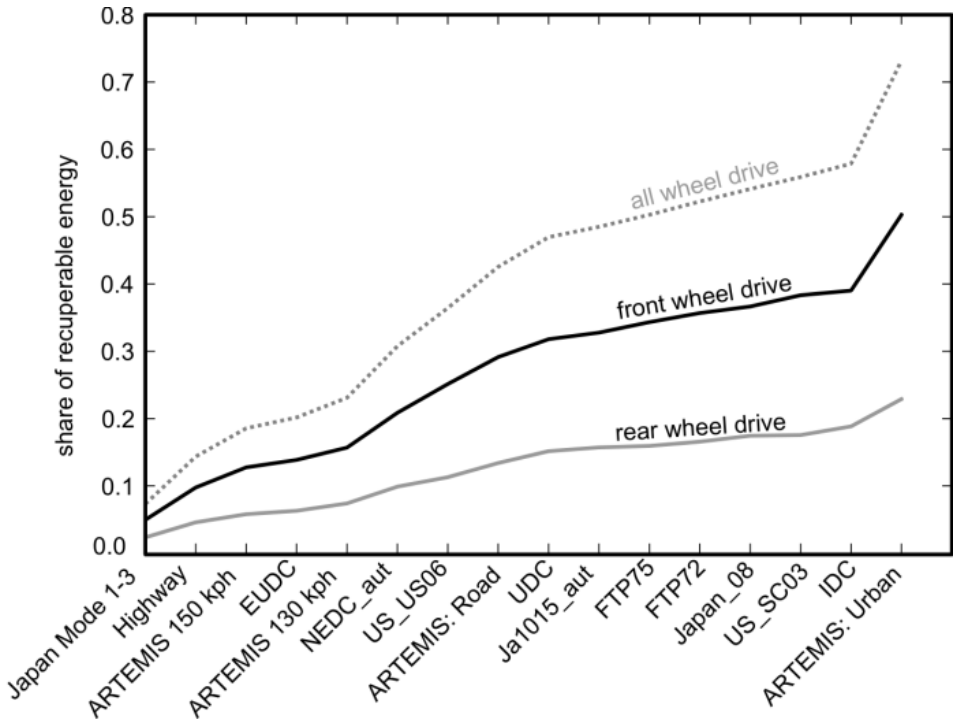

Figure 3.9 Share of the recuperable energy (compared to the positive kinetic energy invested) for 3 different drive configurations and 16 driving patterns.

Naturally there are losses all along the recuperation path, primarily due to mechanical friction as well as conversion losses within the electric machinery and the battery. Furthermore, most vehicles today (and in the foreseeable future) do not feature all wheel drives. For stability reasons, the non-powered axle must still brake as well, so a share of up to 50% (or higher in the case of a rear wheel drive) is lost to friction braking. For different vehicles, the recuperation potential depends primarily on the weight (see Figure 3.10).

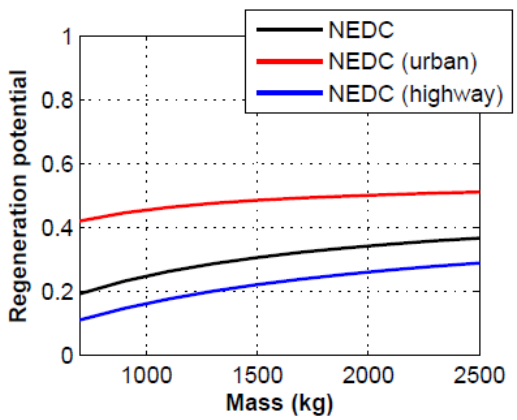

Figure 3.10 Recuperation potential as a function of vehicle mass at constant aerodynamic drag and rolling resistance coefficient.

3.4.1.2. Non-propulsive loads

In modern passenger cars, there is an array of active, i.e. power drawing components that do not or only indirectly contribute to forward motion. This ranges from various electronic controllers to the air-conditioner. While in “tank-to-wheel” terms, electric propulsion is more efficient than internal combustion based solutions as a matter of principle, pure electric systems turn out to be significantly more sensitive to auxiliary loads.

The explanation is that in conventional systems, any auxiliary power (including electrical power) is ultimately supplied using mechanical energy from the prime mover, i.e. the internal combustion engine. The additional constant mechanical load generally pushes the engine to more favorable load points. In electrical systems though, auxiliary power is provided directly by the electro-chemical energy provider, thereby increasing the outgoing electrical current. This has a negative impact on overall energy consumption.

Furthermore, electrical systems lack the steady heat supply of a primary engine coolant loop for heating the cabin, which can easily require several kilowatt of thermal power in winter. Figure 3.11 is a qualitative comparison of both cases (including an additional 4 kW heating load in cold weather for the battery electric system). In the case of the EV, especially at low velocities, the constant auxiliary load can cause the energy demand per kilometer to explode. Note that the completely different shape of the “no aux.” and “1800 W” lines are primarily due to the very high efficiency of the electric drive: under congested conditions, the average power demand may indeed be far below 1800 W.

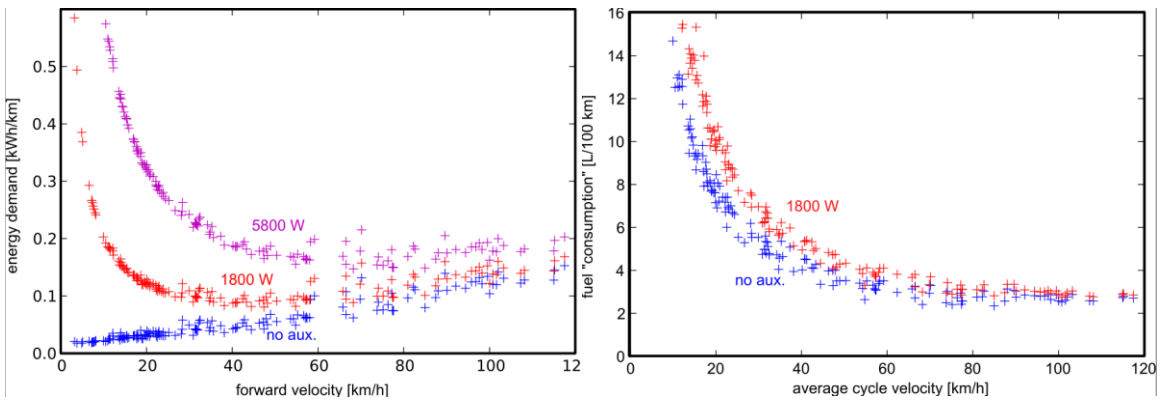

Figure 3.11 Qualitative comparison of the influence of non-propulsive auxiliary loads on the distance-specific energy demand of a battery electric (left) and conventional (right) vehicle. Note that the displayed quantities are the specific energy demand per unit distance, not the overall efficiency.

3.4.1.3. Hybrid vehicle technology

In propulsion systems technology, a hybrid powertrain is generally defined as one featuring at least two independent sources of power. Any number of configurations would be imaginable, but most variants of practical relevance combine a non-invertible (typically chemical) energy converter with an energy buffer device (invertible as a matter of principle).

In the context of THELMA, only two implementations of this are relevant: (1) the “conventional” hybrid electric powertrain, coupling an ICE with a battery and (2), very similarly but often forgotten, fuel-cell based electric powertrains balancing their high voltage system with a battery or supercapacitor array. Just to point out that there are alternative examples of practical importance,

let be mentioned the so called Kinetic Energy Recuperation Systems (KERS), found in racing, that usually rely on a fly-wheel assembly as a high-power, low-energy buffer to provide a short-term electric torque boost to the wheels as well as the pneumatic-hydraulic storage systems found e.g. in construction machinery.

Compared to their non-hybrid counter-parts, these “buffered” hybrids gain efficiency over their non-hybrid counterparts by decoupling the (chemical) energy conversion process from the energy demand at the wheel. More precisely, the power output of the converter does no longer have to exactly match the momentary propulsion and auxiliary power demand – the disequilibrium is seamlessly balanced by the energy buffer – within obvious physical constraints. It is therefore possible to run the converter at an efficiency-wise more beneficial operation point, which may extend to shutting it off completely during particularly unfavorable situations. For example, all hybrids and many modern conventional vehicles shut down the ICE at vehicle stand-still.

The finite capacity of the energy buffer puts a limit to this flexibility though. The device responsible for running the buffer resp. chemical energy converter taking these constraints into account is called energy management system. Quite intuitively, the operation strategy implemented in this device is a key factor in determining a hybrid’s specific energy demand. If the sole target is minimizing the converter’s energy intake though, the resulting optimal control problem can be solved using a non-linear problem solving techniques (the particular approach chosen in THELMA is dynamic programming (Guzzela and Sciarretta, 2013), next to heuristics implemented in ADVISOR).

Of course the presence of both a chemical energy converter and electric propulsion motors enables “plug-in” or “range-extender” variants: since in the relevant cases, the buffer is an electrical storage device, it can be charged using grid electricity. This enables the hybrid to cover certain distances essentially as a pure EV, yet cover larger distances by falling back on its chemical energy converter. The all-electric autonomy range (AER) can be increased with the battery size, yet this also increases production costs and weight – thus practical implementations typically feature AERs of in between 30-50 km – the optimum with respect to CO_2 emissions depends on the electricity mix and life-cycle considerations (Yazdanie et al., 2014). It should be noted (although not accounted in THELMA), that even charging the low energy capacity of a “non-plugin” hybrid can increase overall efficiency, as a battery’s cycle efficiency generally increases with its state of charge.

Controlling a hybrid electric vehicle is a very challenging matter. The employed dynamic programming approach gives a globally optimal solution, yet by the very nature of global optimization, such an algorithm cannot be implemented in an actual car (“global” implies perfect knowledge, which an actual car cannot have as it cannot predict the driver inputs reliably ahead of time). Implementable strategies can thus at best be locally optimizing. A promising variant of such a strategy is the so called adaptive equivalent consumption minimization strategy (A-ECMS) (Guzzela and Sciarretta, 2013), which comes close to the dynamic programming computed ideal. As illustrated by Figure 3.12 though, disturbances such as a non-average initial state of charge can cause excessively large resp. low fuel consumption, which converges towards the same average though after many repetitions. Contrary to conventional vehicles that, when warmed up, reproducibly yield the same fuel consumption on the same driving cycles, hybrids may experience a “break-in” period; note that modifying the driving cycle in between repetitions can be enough to cause a disturbance.

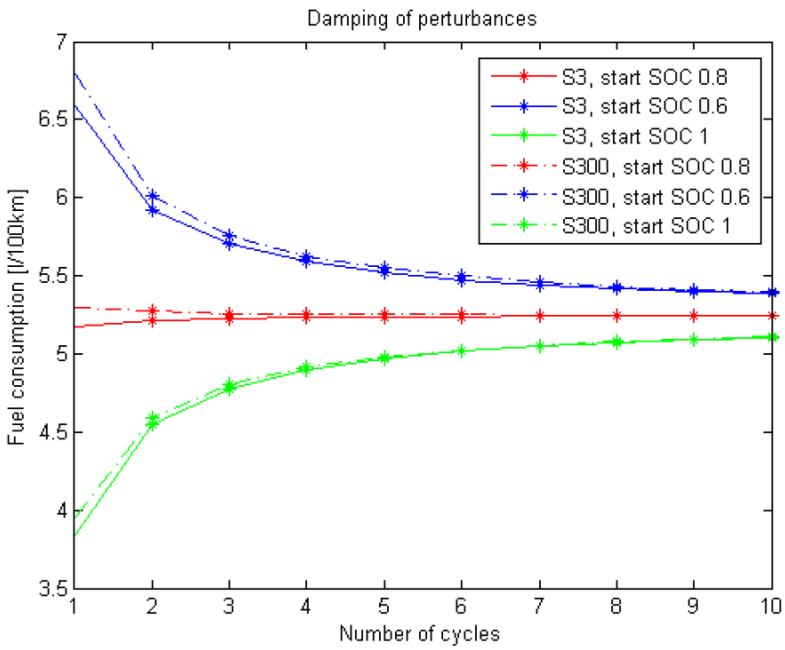

Figure 3.12 Fuel consumption of an A-ECMS controlled hybrid electric vehicle, repeating the same cycle 10 times in a row, starting out at different battery state of charge (SOC) settings.

3.4.1.4. On the scaling of powertrain components

In itself, a powertrain is an energy conversion device, converting some kind of storable, on-board energy supply into mechanical energy (motion). The key trade-off with any such automotive system is that in addition to the payload, the powertrain must additionally provide the energy of moving itself. The higher the payload, the more powerful the powertrain must be to achieve the same performance targets, yet the weight of most powertrain component increases with power (or energy stored).

However, simultaneously, thermodynamic and electric prime movers generally exhibit a decline in efficiency towards low loads (meaning low torque). If a vehicle is heavily loaded, this causes the average conversion efficiency of the prime mover to increase (see red lines in Figure 3.13), as the load-points shift more and more to the part-load region (see Figure 3.14). However, the absolute propulsion power demand also increases (see blue line in Figure 3.13). With most technologies, the latter effect outweighs the absolute energy demand of the prime mover increases with increasing vehicle mass – but sub-linearly. As the payload is presumed constant in THELMA, the weight differences in between different prime movers of same output power is small and their efficiency maps similar, the sensitivity to the chosen efficiency map is secondary (as long as it features a reasonably slow decay towards low loads – which holds in rough approximation as shown in (Guzzela and Sciarretta, 2013)).

On the other hand, if the prime mover is scaled up to higher nominal power ratings (lighter red lines in Figure 3.13), then the share of low-load points increases, resulting in an altogether decreasing average efficiency (while the average energy demand goes up). Simultaneously, the system weight goes up, causing an altogether increased absolute mechanical energy demand. This effect is super-linear.

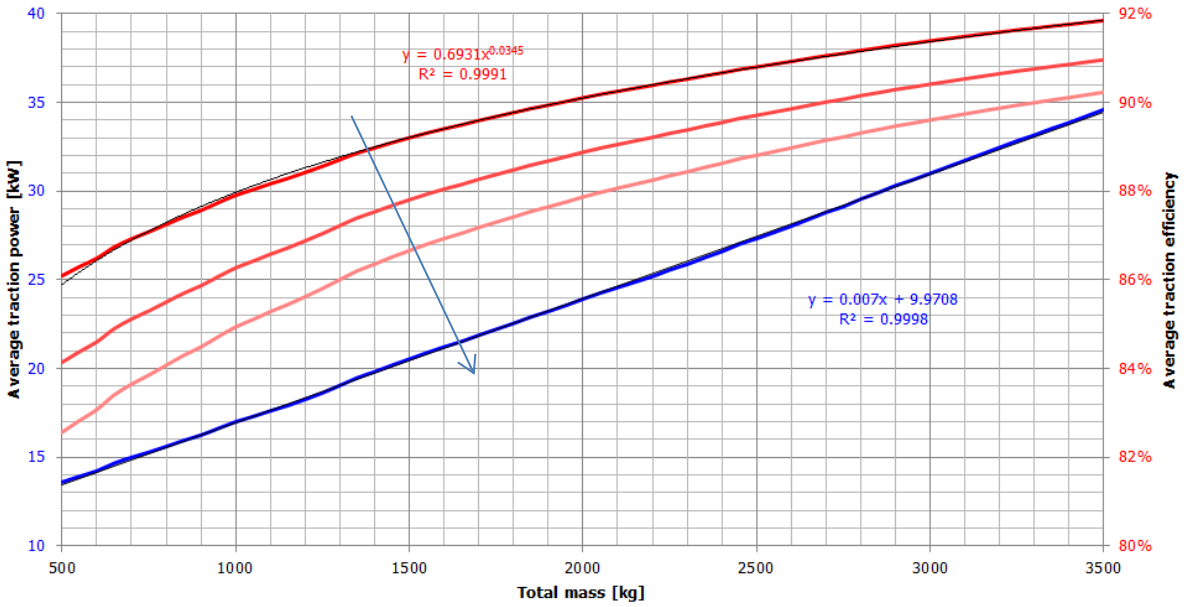

Figure 3.13 Vehicle average traction power and average traction efficiency versus mass. Energy demand prediction of any prime mover model depends on the absolute traction power and average efficiency: the average power requirement (blue line) increases as the system's total weight goes up; yet simultaneously, this pushes the average load point to higher torque regions, increasing the average traction efficiency (red lines, for various motor types). The energy demand increase is therefore not linear.

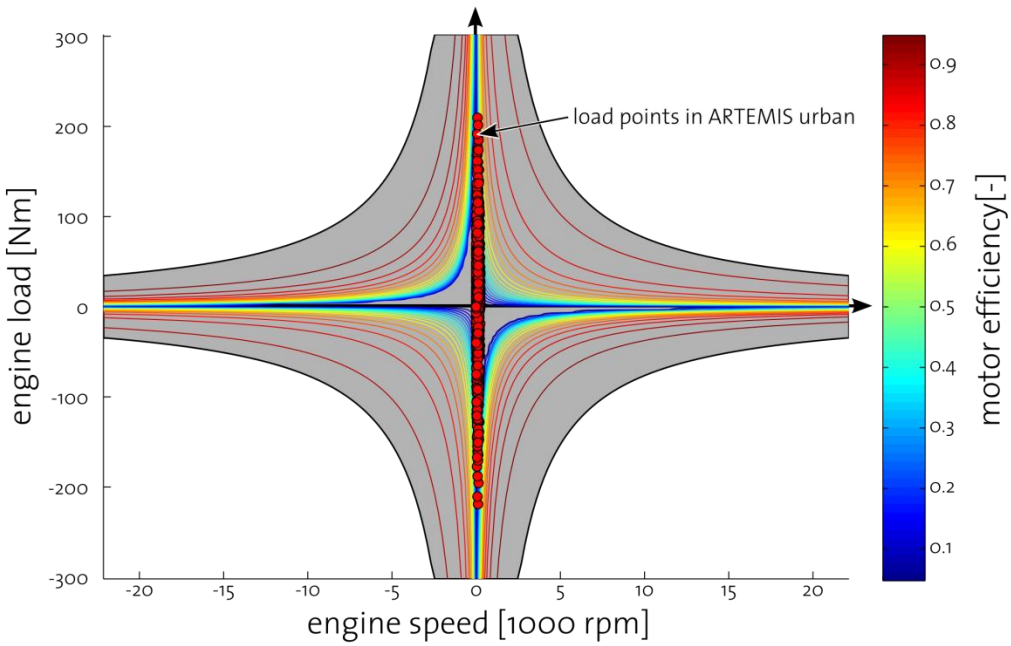

Figure 3.14 Efficiency map of a 4-quadrant electric machine, modeled using the Willans approach. Note the steep decrease of efficiency at very low loads in propulsive mode. Load points stretch out in the map, defining the average efficiency. Scaling the motor pushes the envelope (bounding hyperbolae) towards higher torque and speeds, yet the load points stay the same (disregarding a possible weight increase) resulting in reduced average efficiency.

3.4.1.5. Optimal use of advanced technologies

Many technology options exist to improve vehicle fuel economy and to reduce environmental impacts. Among these are engine efficiency improvements, hybridization, weight reduction, and other options like reduction of aerodynamic drag, rolling resistance and drivetrain losses. All these

technologies have different costs and influence energy use in different ways. An integrated framework on how to best implement those technologies is missing. Within the THELMA project several studies have been carried to analyze the optimal implementation of those technologies (Hofer et al., 2013, Hofer et al., 2012, Wilhelm et al., 2012).

Reducing vehicle weight and improving powertrain efficiency are two fundamentally different ways of reducing fuel consumption and thereby operating cost and emissions. In Wilhelm et al. (2012) a methodology was developed to find the optimum combination of these measures for different marginal technology cost functions describing lightweighting and powertrain efficiency improvement, minimizing vehicle lifetime costs. Analytic solutions for the optimal degree of implementation were given. The study clearly showed the trade-off between investments in lightweighting versus powertrain efficiency technology.

Battery electric vehicles constitute a dramatic improvement in vehicle energy efficiency relative to conventional ICEVs, due to the high efficiency of the electric powertrain. However, their relatively high cost and low range remain the greatest challenges in commercialization. Reducing the energy consumption of electric vehicles allows one to increase range and/or to reduce costs. The main possibility for reducing energy consumption is by vehicle lightweighting with advanced, high-strength and low-weight materials such as high-strength steel, aluminum, or carbon fiber composites. The optimal tradeoff between reduced driveline costs due to smaller and cheaper drivetrain components and the higher costs of producing a lighter vehicle has been investigated in Hofer et al. (2012).

In Hofer et al. (2014) the effect of weight reduction using advanced lightweight materials on the mass, energy use, and cost of conventional and battery electric passenger vehicles was compared. The results show a strong secondary weight and cost saving potential for the BEV due to the high mass and cost of the battery, but a higher sensitivity of vehicle energy consumption to mass reduction for the ICEV due to the relatively low powertrain efficiency and lack of regeneration capability. Generally, lightweighting has a high potential to lower vehicle costs, however, the results are very sensitive to parameters affecting lifetime fuel costs for conventional and battery costs for electric vehicles. Based on current technology cost estimates it is shown that the optimal amount of primary mass reduction minimizing total costs is similar for conventional and electric vehicles and ranges from 22% to 39%, depending on vehicle range and overall use patterns. As an example of this analysis Figure 3.15 shows the breakdown of current ICEV and BEV total costs as a function of glider weight reduction for 150,000 km lifetime driving distance and a BEV range of 150 km. Black points indicate the optimal amounts of weight reduction. The difference between the optimal solutions minimizing manufacturing versus total costs is higher for the ICEV than the BEV due to the relatively low energy consumption and low share of electricity to total costs for the BEV.

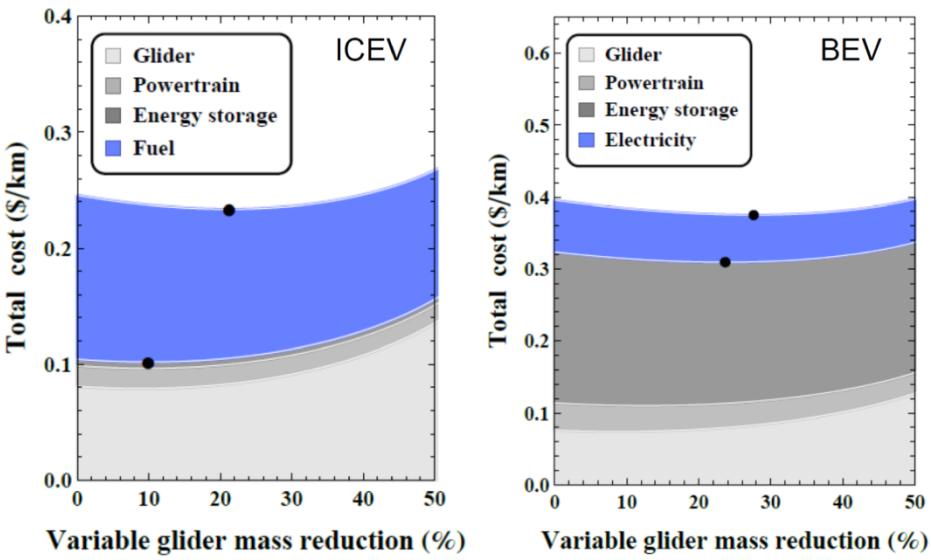

Figure 3.15 Breakdown of ICEV and BEV total costs as a function of glider weight reduction. Black points indicate minimal purchase and total costs.

3.4.2. Indicator results

In this chapter the analysis results of vehicle mass, energy use, and manufacturing cost are compared for various drivetrain types and classes for "state-of-the-art" technology, as well as their presumable timely evolution according to the THELMA-WP2 technology scenario. For the sake of clarity, results are shown only for three vehicle segments in the following section; the full dataset can be found in Appendix A: Selected vehicle indicators by powertrain, class, and year.

3.4.2.1. 2012 – "state of the art"

Figure 3.16 shows the breakdown of vehicle mass, energy use, and cost by drivetrain for a mini, midsize, and Sport Utility Vehicle (SUV) car in 2012. Equivalently (in terms of class-related performance indicators – see section 3.1) combining a given glider (of a certain market segment) with an alternative (i.e.\ electrified) powertrain generally results in a higher total vehicle mass, as compared to the reference ICEV solution. This is primarily due to:

- in HEVs and PHEVs, the motor/generator and the battery,
- in BEVs, the battery,
- in FCEVs, the fuel cell, hydrogen storage, as well as the battery.

Since the same range and performance requirements must be achieved, moving to market segments of higher glider mass prompts an increase of the component cost and weight - in particular regarding the battery and fuel cell. The effect of a change of class on vehicle weight is most significant for the BEV, FCEV, and PHEV, particularly at high electric range. The breakdown by mass reveals a high sensitivity of BEV and PHEV mass to electric range due to the relatively low energy density of current batteries.

As shown in Figure 3.16, the direct vehicle energy use significantly varies by class and drivetrain. Relative to the gasoline ICEV, energy use is reduced by approximately:

- 10-15 % with the diesel ICEV
- 20-25 % with the gasoline HEV
- 40 % with the FCEV
- 45 % with the gasoline PHEV (depending on the electric range and as such the electric driving fraction)
- up to 65-70 % with the BEV (strongly depending on climate conditions).

The absolute change of energy use related to a change of class decreases with powertrain efficiency, i.e. it is highest for the gasoline ICEV and lowest for the BEV. The manufacturing costs of all electric vehicles are today significantly above their ICEV counterparts due to the additional cost of the battery, fuel cell, and electric motor. BEV manufacturing cost is very sensitive to the electric range. Due to the high cost of the fuel cell and battery the effect of a change of class on manufacturing cost is most significant for the FCEV, BEV, and PHEV.

3.4.2.2. Scenario to 2050

Figure 3.17 shows the breakdown of vehicle mass, energy use, and cost by drivetrain for a midsize car in three manufacturing years (2012, 2030, 2050) according to the scenario assumptions described in sections 3.4 and 3.5. As shown on top, the mass of all vehicles is expected to decrease over time due to a lighter glider which induces additional mass reductions of the powertrain and energy storage. Also the increasing power and energy density of the fuel cell and battery lead to overall vehicle mass reductions. The increase of battery energy density also leads to a lower sensitivity of BEV mass to variations of range. Energy use reduces for all drivetrains over time as vehicle mass and other resistance parameters decrease and powertrain efficiency improves. The reductions are strongest for the ICEV and HEV. Today the manufacturing costs for the BEV, FCEV, and PHEV are still much higher than for the ICEV and HEV, but this is expected to strongly decrease in the future due to reductions in battery and fuel cell costs. The sensitivity of BEV and PHEV manufacturing costs to range is lower in the future as the specific mass and cost of batteries decreases.

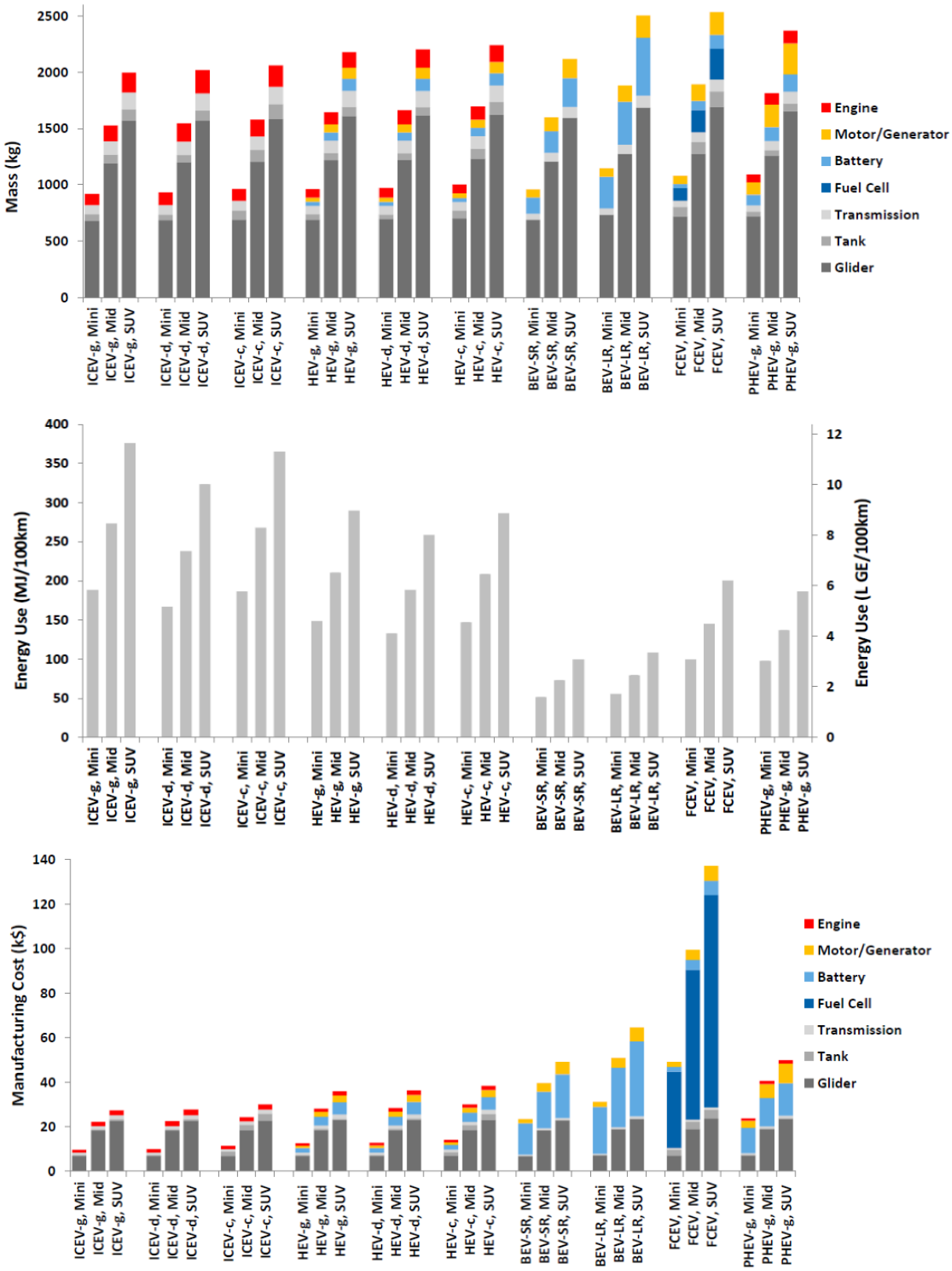

Figure 3.16 Breakdown of vehicle mass, energy use, and manufacturing cost by drivetrain for a mini, midsize, and SUV in 2012.

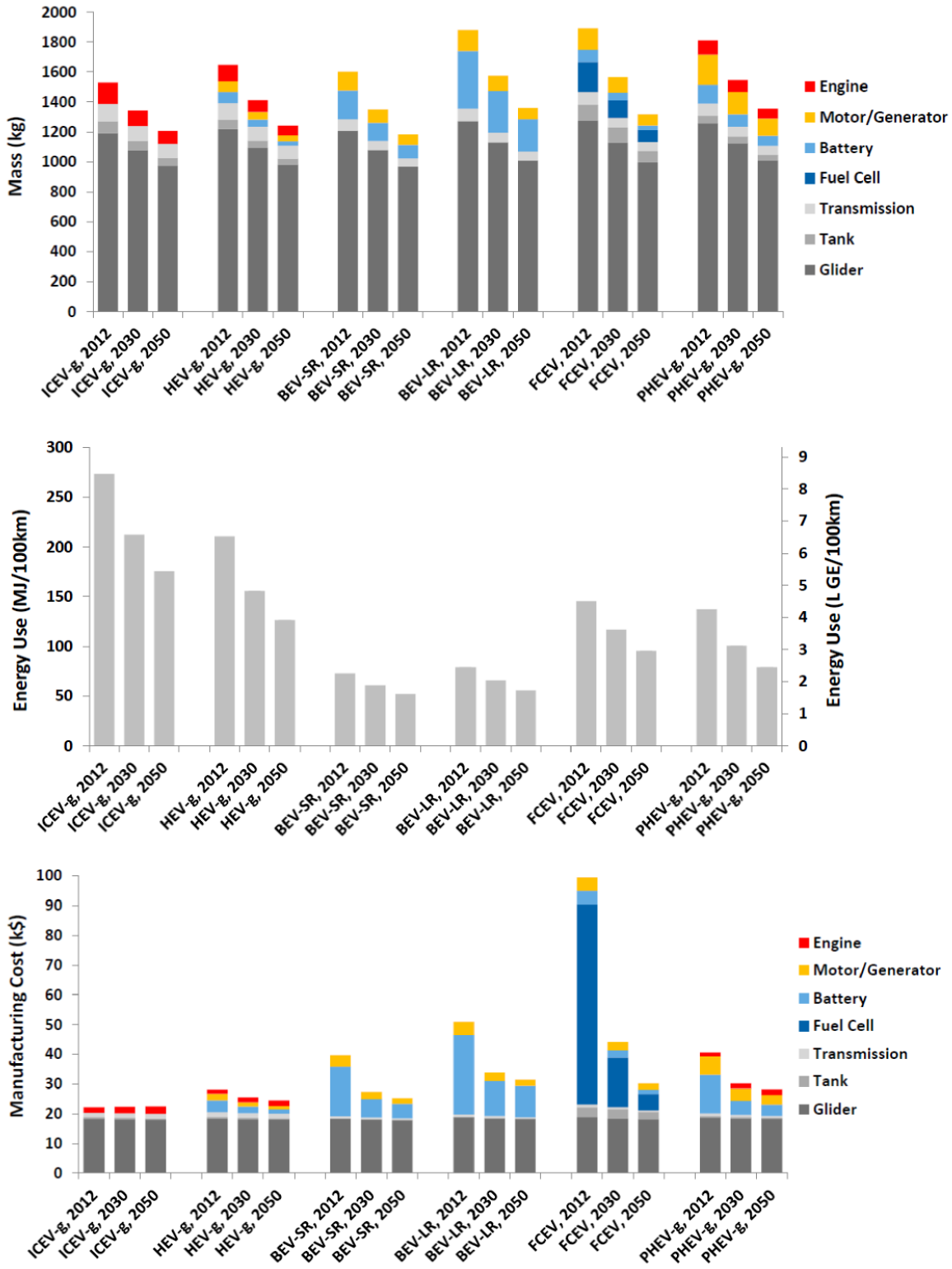

Figure 3.17 Breakdown of vehicle mass, energy use, and manufacturing cost by drivetrain for a midsize car from 2012 to 2050.

3.4.3. Sensitivity analysis

The scenario analysis results presented in the last section involve many highly uncertain assumptions about future developments. Sensitivity analysis helps in understanding which way changes of input parameters influence the results and in assessing the range of possible outcomes. In this section the

sensitivities of BEV criteria as a function of range are investigated. In addition, the most important parameters affecting conventional and electric vehicle total costs are analyzed.

3.4.3.1. Influence of range on battery electric vehicle characteristics

Due to the comparably low energy density of current battery technologies, battery electric vehicle mass and cost are highly sensitive to range. Figure 3.18 shows on the left the required energy storage capacity of a midsize BEV as a function of range for different battery specific energies, where 100 Wh/kg corresponds to the current status of automotive Li-ion batteries. The higher values represent possible future developments using advanced battery chemistries. Interestingly, for current battery specific energy the relation between BEV storage capacity and range is nonlinear due to the feedback of increasing mass on energy use and the additional energy capacity required to achieve a certain range. Note that this effect is much smaller for fuel cell vehicles due to the relatively high specific energy of the hydrogen storage. Figure 3.18 shows on the right the corresponding relation of BEV mass vs. range. It is obvious that above ranges of 500 km, the vehicle becomes extremely heavy. Future advances in battery specific energy may allow higher ranges.

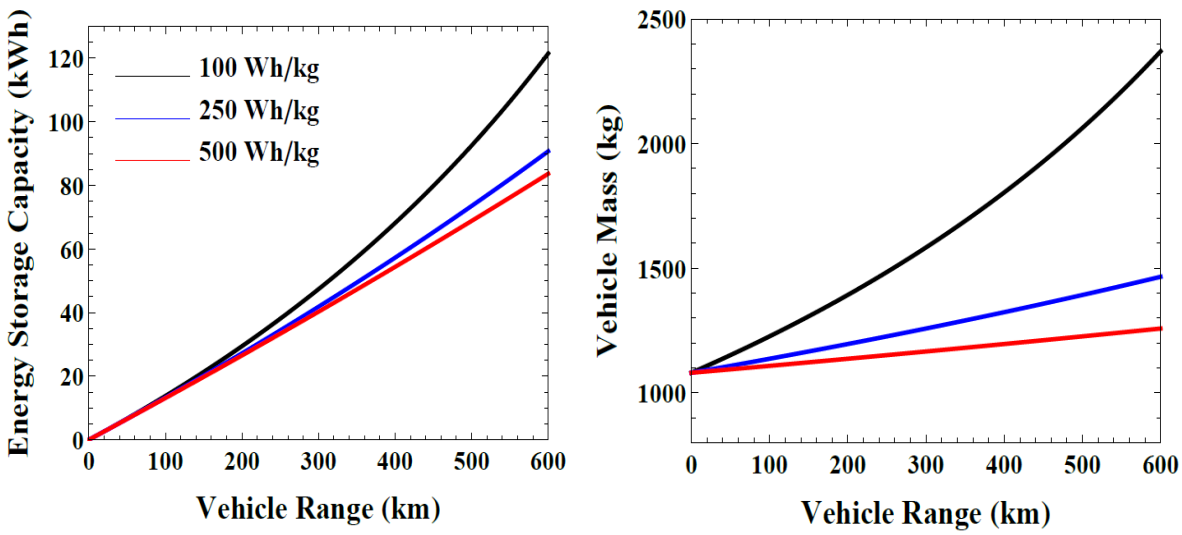

Figure 3.18 Required storage capacity and vehicle mass of a midsize BEV as a function of range for different battery specific energies.

Figure 3.19 shows the effect of a variation of BEV range on manufacturing cost for different battery specific energies and costs. The results show that manufacturing costs are highly dependent on the range and specific cost of the battery. Even though the relation is most sensitive to battery specific cost, there is also an influence of battery specific energy which determines the required energy storage capacity for a certain range.

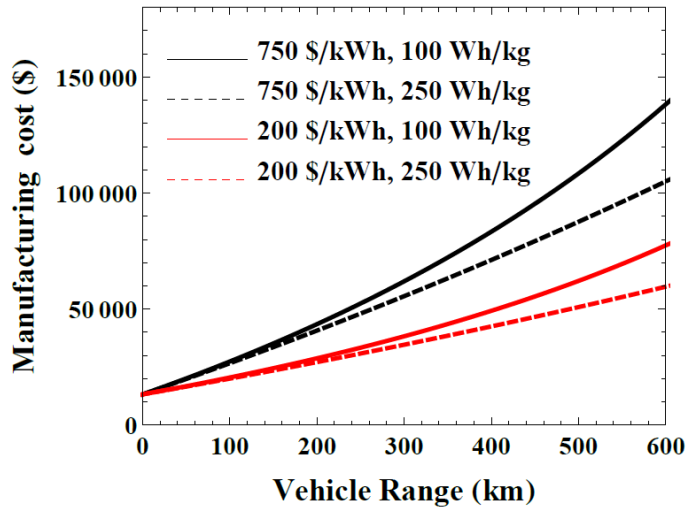

Figure 3.19 Manufacturing cost of a midsize BEV as a function of range for different battery energy densities and specific costs.

3.4.3.2. Sensitivity of total costs

Figure 3.20 shows the sensitivity of total costs relative to changes of vehicle range, specific cost of the energy storage, charging or fueling cost, specific mass of the energy storage, and specific cost of the powertrain. It is always expressed as the change of total cost per percent parameter change relative to the reference total cost. Comparing the sensitivity to these parameter changes for each powertrain separately, it can be seen that BEV total cost is most sensitive to range and the specific cost of the battery, and that the sensitivity to specific battery and energy costs reaches equal levels by 2050. Among the analyzed parameters, ICEV total cost is clearly most sensitive to fuel price and FCEV total cost in 2012 to specific powertrain cost (mainly the fuel cell). Over time the sensitivity of FCEV total cost to specific powertrain cost decreases and to hydrogen cost increases, reaching approximately equal sensitivity by 2050. Comparing the sensitivity to parameter changes among the different powertrains, it is obvious that the BEV is most sensitive to range, the ICEV least sensitive to range and most sensitive to energy costs, the BEV and FCEV are approximately equally sensitive to energy costs, and the FCEV is most sensitive to powertrain costs.

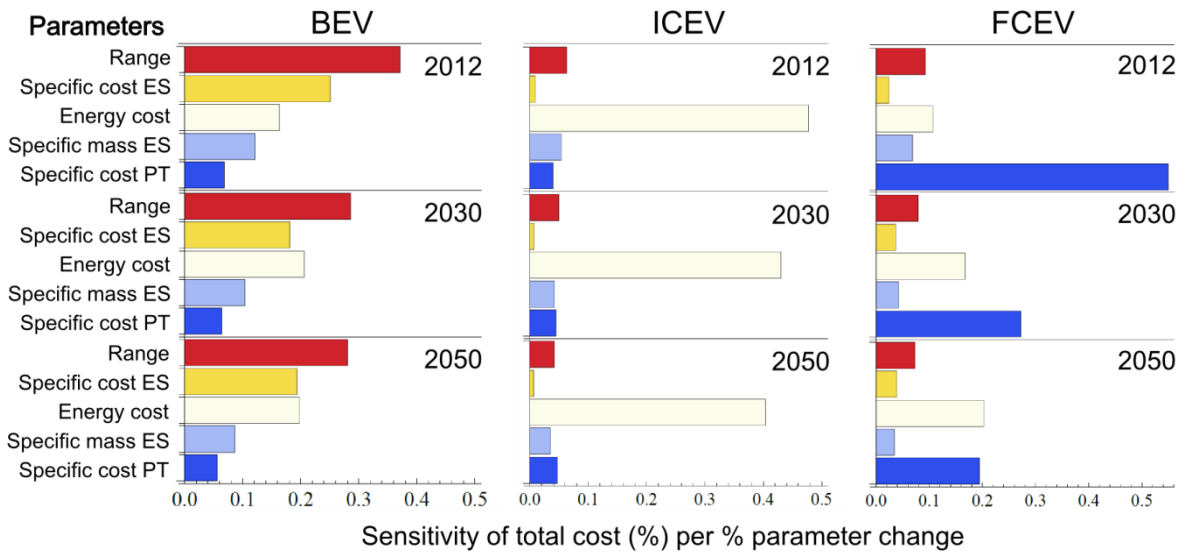

Figure 3.20 Sensitivity of total cost to changes of important parameters by powertrain and year.

3.5. Discussion

Obviously, the time horizon of 40 years of the technology scenario incurs its fair share of uncertainty. Now, as sections 3.4.3.1 and 3.4.3.2 clearly revealed, the technology and economy of batteries are paramount to the commercial success of electric mobility. Reliably predicting how such a still comparatively immature technology will fare over such a long time frame is difficult – at least there is a large range with regards to costs and performance among those published studies that tried to do so.

Historically, most other core automotive components and aspects such as aerodynamics and tire rolling resistance exhibited rather steady improvement curves. Furthermore, again referring to 3.4.3.1, any improvement in the specific energy density reduces the energy demand increasing effect of high autonomy ranges (through the battery mass), the impact may not be as severe as that which could ensue from changing customer expectations. Hence the primary concern may not be so much on the technology development itself, but rather with the ensuing customer expectations.

Indeed a central assumption of the WP2 methodology is that of stable vehicle classes and time-invariant attributes (at least with respect to performance). This allows sizing powertrain components such that the final vehicle assembly achieves the average performance criteria of its glider's market segment. Break-through innovation, resource scarcity or perhaps changes in the social significance of the car as a transportation mode are just a few examples of what could lead to fundamentally altered customer expectations, perhaps even a complete redefinition of the market segmentation itself – with far reaching consequences for the validity of the results at hand.

3.6. Conclusions

In general, ICEVs have an edge both in terms of costs and performance over all considered alternative technologies, as long as energy and all the involved sustainability implications do not play the core role.

Now concerning the performance, i.e. the acceleration and top speed, in particular, section 3.1 declared those attributes as exogenous variables to the WP2 methodology. They are thus not assessed directly, but rather imposed by a vehicle's membership to a given market segment. The fact that it was possible to apply all powertrain options to all vehicle classes without sacrificing the corresponding class performance targets indicates that fleet-wide electrification is indeed technically feasible, even with today's technology. Economically that may not be the case though, since especially the "higher-end" segments exhibit up to twice the production cost over their respective ICEV variant in the model year 2012.

Whether or not FCEVs and BEVs with relaxed design parameters could compete in the market place is beyond the scope of WP2. Yet it has been shown that the electrification premium in "lower-end" segments is over-proportionally lower (due to the lower glider weight – see 3.4.3.1). It is therefore likely that, contrary to the usual dynamics of automotive technology markets, full electrification (via FCEV or BEV solutions) may diffuse in through low price segments – while the heavier, expensive variants may still rely on ICE technology (which includes HEVs).

With regards to environmental factors, the reader is referred to WP1, as the results presented herein do not account for the energy chains behind the manufacturing, operation and decommissioning of a particular vehicle. Nevertheless, sections 3.4.2 and 3.4.3 clearly revealed that concerning costs, ICEV

are by far the most effective solution, as long as energy prices are relatively low. Electric mobility thus directly compromises performance and comfort with energy usage.

Similar findings apply to the autonomy range. Interestingly FCEVs and BEVs offer mutually exclusive benefits here: boosting the range of an FCEV is rather cheap, as is increasing the power of a BEV; doing the opposite may be exorbitantly expensive in both cases though. A future, electrified individual mobility system may thus depart from the “one-fits-all” general purpose car solution the ICEV is today, and instead feature a wide variety of powertrains, tailored to cover a very specific driving situation. This could have deep repercussions to the way cars are operated and sold.

3.7. Recommendations for further work

A very challenging but worthwhile endeavor is pushing the same analysis from individual mobility to road-freight transportation. Indeed the demand for freight transportation (in terms of ton kilometers per year) increased by 50% over the last 30 years (Bundesamt für Statistik, 2012). Both the operation patterns and machinery are more complex, due to the commercial and the much more energy intensive nature of heavy-duty transportation.

Acronyms

A-ECMS	Adaptive Equivalent Consumption Minimization Strategy
AER	All-Electric Autonomy Range
BEV	Battery Electric Vehicle
DOE	Degree of Electrification
EG	Electric Generator
EM	Electric Motor
ETHZ	Swiss Federal Institute of Technology In Zurich
ETHZ-LAV	ETHZ Aerothermochemistry and Combustion Systems Laboratory
EuroNCAP	European New Car Assessment Programme
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FCS	Fuel Cell System
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine
KERS	Kinetic Energy Recuperation Systems
LCA	Life Cycle Assessment
NEDC	New European Driving Cycle
PGS	Planetary Gear Set
PHEV	Plug-In Hybrid Electric Vehicle
PSI	Paul Scherrer Institute
PSI-LEA	PSI Laboratory for Energy Systems Analysis
SUV	Sport Utility Vehicle
WLTP	Worldwide harmonized Light vehicles Test Procedure
WP	Work Package

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4. Work Package 3 "Power System Modeling"

Authors: Thilo Krause[28]; Marina González Vayá[29] (ETHZ)

4.1. Introduction

Work Package 3 addresses the effects of electric mobility on the power system. In particular it aims at evaluating the influence of higher penetration rates of electric vehicles on transmission and distribution grids as well as on the generation portfolio (González Vayá, 2015). In doing so, WP3 studies whether electric mobility will increase congestion in the grid, eventually leading to a need for investments on the transmission and/or on the distribution level. Moreover, WP3 deploys different Electric Vehicle (EV) charging concepts in order to assess if intelligent control strategies can be used to minimize possible adverse effects on transmission and distribution grids, as well as on the generation portfolio. Complementary research targets questions concerning the aging of transmission and distribution assets, the aging of the cars' batteries as well as the potential to provide ancillary services with electric vehicles. Figure 4.1 depicts a schematic of the models and tools used in WP3. In the following, it serves as basis for outlining the research work of WP3.

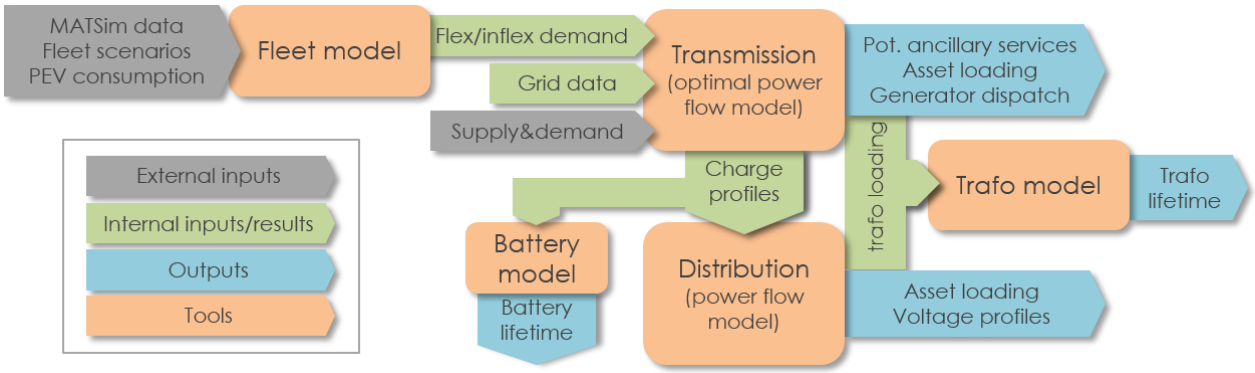

Figure 4.1 Overview of the Simulation Model used in WP3, depicting external inputs from other Work Packages (grey), internal inputs / results (green), outputs (blue) and tools used (orange).

Crucial input for Work Package 3 are the results from the traffic simulation in conjunction with the fleet scenarios and EV consumption models. The inputs and the fleet model are described in Section 4.4. Together with the demand and the grid data, as well as the supply and demand scenarios they form the basis for the transmission simulation tool / the optimal power flow model (Section 4.5). The main internal outputs of the latter model are the transformer loading and the charging profiles, which are used to assess the transformer lifetime using a dedicated model (Section 4.8). Similar to the assessment of the transformer lifetime, the charging profiles are utilized to evaluate the cars' battery lifetime relying on the battery model detailed in Section 4.7. Major results of WP3 are an assessment of the potential for providing ancillary services with EVs (Section 4.5.4), the asset loading (see Section 4.5.7.3) on the transmission and distribution level, as well as the generation dispatch (see Section 4.5.7.2) and the voltage profiles in the distribution grid (see Section 4.6). Based on these outputs Section 4.5.7.1 analyses the future need for transmission investments.

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4.2. Specific objectives

In short, the objective of WP3 is to account for the role of and requirements on the electric grid depending on the various options for electric mobility. This includes an analysis of the impacts on the electric system dispatch, the transmission and distribution constraints and the costs due to the presence of new charging loads from electric vehicles. A key question involves customer decisions on when to charge their vehicles. These charging strategies will also be compared with centralized control based on minimizing utility cost.

4.3. Scope

The model as well as the research work in WP3 is confined to the Swiss power system. The transmission model was built on data provided by the Swiss transmission system operator (swissgrid). Although, the power systems of the neighboring countries are not represented in detail, the effects of electricity imports / exports are considered. For the distribution model exemplary data from BKW Energie has been deployed. Although the analysis targets mainly Switzerland, the developed tools are generic, and thus, can be ported to analyze other countries or systems. The authors would like to thank Swissgrid AG and BKW Energie AG for the provision of data and the friendly collaboration.

4.4. Fleet model

This module describes the charging behavior, and therefore the electricity demand, of the EV fleet under different charging scenarios.

4.4.1. Inputs

The main inputs to this model from other WPs are described in the following.

4.4.1.1. Individual driving patterns from transport simulation Multi-Agent Transport Simulation Model (MATSim) (WP4)

The transportation simulation determines, for each of the modeled vehicles, the arrival and departure times of each trip, the parking location (geographic coordinates), the type of activity performed at the parking location (e.g. home or work), and the total distance traveled during each trip. The timing of the trips is given in terms of continuous values, and is transformed into discrete (hourly) time steps for the power system simulations. It is assumed that an EV can potentially charge if it is parked for the complete duration of a discrete time step. MATSim sometimes generates trips with very short distances. All trips with distances below 100 m were omitted. This particular MATSim simulation comprises 10% of the population. Therefore the vehicle parameters are scaled with the factor 10 so that each vehicle represents 10 vehicles in practice.

4.4.1.2. EV penetration and fleet composition scenarios (WP5)

The fleet scenarios defined in WP5 determine which fraction of the overall fleet is expected to be electrified by a given time horizon. Moreover, they define for specific agents of the transportation simulation MATSim (see 4.4.1.1) the vehicle class, the vehicle model year and the battery size. In total, three different penetration scenarios are considered, each assuming a 30%, 60% or 90% absolute electrification of the fleet by 2050. However, the horizon considered in the simulation is the year 2035, and therefore the penetration at this time horizon is lower.

4.4.1.3. EV energy consumption models (WP2)

Based on the driven distances from the transport simulation MATSim (see 4.4.1.1), the energy consumption needs to be determined. For this purpose, the following inputs are used:

- The fractions of the total driving distance, as given by MATSim for each trip, that are performed on one of the following driving cycle types: urban, suburban or highway.
- The energy needed for propulsion per distance driven for a specific vehicle class, model year, battery size and driving cycle type (urban, highway, rural).
- The energy needed for auxiliaries per time driven for a specific vehicle class, model year, battery size and season (summer, winter, intermediate season).

4.4.2. Geographic mapping

Based on the geographic coordinates of the parking locations reported by MATSim (see 4.4.1.1), a mapping to particular network nodes is performed, to determine where the charging load of a vehicle or group of vehicles occurs in the grid.

At the transmission system level, first the subset of network nodes that are potential load nodes is determined, based on Swissgrid's data. Second, the vehicles are mapped to the closest network node

At the distribution system level, first, out of the geographic locations from MATSim, covering the whole of Switzerland, the subset of locations pertaining to the region where the distribution network is located is determined. Second, the vehicles parking in this subset of locations are mapped to the closest network node.

4.4.3. Charging scenarios

Here we define the different charging scenarios considered in the simulations. We distinguish between uncontrolled, i.e. inflexible, charging and controlled, i.e. flexible, charging (González Vayá and Andersson, 2012, González Vayá et al., 2012, González Vayá and Andersson, 2015). Within flexible charging, a further distinction can be made between indirectly controlled charging and directly controlled charging.

4.4.3.1. Uncontrolled charging

In this scenario, it is assumed that vehicles start charging at the nominal charging rate, assumed to be 3.5kW, as soon as they are parked, and until their batteries are full or until they depart for the next trip. Therefore charging is inflexible and charge profiles can be directly determined out of driving patterns, as well as physical characteristics such as the battery size and the nominal charging rate.

4.4.3.2. Indirectly controlled charging

Here we assume that a time-of-use (TOU) tariff is used to incentivize EV drivers to defer their charging to low-load hours. We assume a two-part tariff, with the higher tariff from 6:00 to 22:00, as it is currently the case, e.g. in Zurich (ewz). In this case the EVs try to postpone charging as much as possible to the low-tariff period, and charge during the high-tariff period only when urgently needed.

For a multi-part tariff, the response of an EV to this tariff can be determined based on its cost-minimization problem:

$$\text{minimize}_{P_{vt}} \quad \sum_t ToU_t P_{vt}^{\mathrm{V}} \Delta t \tag{1}$$

$$\text{subject to} \quad E_{vt}^{\mathrm{V}} = E_{v(t-1)}^{\mathrm{V}} + P_{vt}^{\mathrm{V}} \eta_v^{\mathrm{V}} \Delta t - E_{vt}^{\mathrm{V,cons}} \quad \forall t \tag{2}$$

$$0 \leq P_{vt}^{\mathrm{V}} \leq P_{vt}^{\mathrm{V,max}} \quad \forall t \tag{3}$$

$$E_{vt}^{\mathrm{V,min}} \leq E_{vt}^{\mathrm{V}} \leq E_{vt}^{\mathrm{V,max}} \quad \forall t \tag{4}$$

$$E_{vt_0}^{\mathrm{V}} = E_{vt_{\mathrm{T}}}^{\mathrm{V}} \tag{5}$$

The objective function (1) represents the costs of charging based on the given TOU tariff ToU_t at time step t and the chosen charging power P_{vt}^{V} of vehicle v at time step t, with time step duration Δt. Equation (2) describes the evolution of the energy content E_{vt}^{V} of the battery, based on the energy at the previous time step, the charging power P_{vt}^{V}, the charging efficiency η_v^{V} and the energy consumption during driving $E_{vt}^{\mathrm{V,cons}}$. Constraints (3) and (4) set bounds on the power and energy of the EV. If a vehicle is connected at a given time step, then $P_{vt}^{\mathrm{V,max}}$ is equal to the nominal charging rate, otherwise it is zero. Note that therefore in (2) only either P_{vt}^{V} or $E_{vt}^{\mathrm{V,cons}}$ can be positive. The bounds $E_{vt}^{\mathrm{V,min}}/E_{vt}^{\mathrm{V,max}}$ are given by the minimum/maximum state-of-charge settings of the battery and the battery capacity. Finally, (5) ensures that enough energy is purchased throughout the time horizon, i.e. the energy content at the beginning and at the end of the day is identical. Otherwise, due to cost minimization, the battery would tend to be depleted, i.e. charging would be shifted to a time period beyond the optimization horizon, since the corresponding costs are not taken into account in the cost function.

To determine the overall demand at a network node n at a given time, the charging powers of all vehicles connected to that node are aggregated

$$P_{nt}^{\mathrm{A}} = \sum_v u_{vnt} P_{vt}^{\mathrm{V}} \quad \forall t, \tag{6}$$

where $u_{vnt} = 1$ when vehicle v is connected to node n at time step t, and $u_{vnt} = 0$ otherwise.

4.4.3.3. Directly controlled charging

In this case it is assumed that a so-called aggregator can directly control EV charging. The aggregator needs a representation of the fleet's demand, to be incorporated as a set of constraints in the Optimal Power Flow (OPF) problem, described later in Section 4.5. Since this demand is flexible, i.e., not fixed, it is not sufficient to forecast a demand profile, but a model that represents the set of feasible demand profiles is needed. For this purpose, the fleet can be modeled as a virtual battery(González Vayá et al., 2015), with a set of constraints on the aggregation's charging power and on the energy state of the virtual battery. To derive the parameters of the aggregated virtual battery, a bottom-up approach is adopted, based on the driving patterns and characteristics of individual EVs.

Starting at the individual EV level, it is possible to define upper and lower possible trajectories, $E_{vt}^{\mathrm{V,up}}$ and $E_{vt}^{\mathrm{V,low}}$, for the energy in the battery of vehicle v at time step t. The upper value of the energy content is calculated assuming that charging starts as soon as the vehicle parks. For this purpose, we assume that the battery reaches the highest allowed state-of-charge (SOC) at some point in time. The lower values are calculated assuming charging is deferred as much as possible, given that the vehicle

should depart with enough energy in the battery for the forthcoming trip. The lower values are calculated with foresight, e.g. when there are two consecutive trips with only a short parking break between them, this is considered when computing the required charging during the parking break preceding the two trips. Moreover, since we assume that the battery reaches the maximum SOC charge at some point, the SOC cannot drop more than the normalized cumulative energy consumption over the day from this reference, unless the vehicle-to-grid (V2G) mode, i.e. discharging to the grid, is used. We assume that the SOC stays between 20% and 80% to reduce battery degradation.

Figure 4.2 shows how the upper and lower trajectories are determined for a particular vehicle. It can be seen that the upper SOC trajectory is equal to the maximum SOC value (0.8) most of the time, except after the trips, when it starts increasing immediately at the maximum predefined charging rate. The vehicle considered in Figure 4.2 does not use the full battery capacity for its daily trips, therefore the minimum SOC it will reach without V2G is much higher than the actual minimum SOC of 0.2. Finally, the lower SOC trajectory for the V2G case is equal to 0.2 most of the time, and increases before the trips to make sure there is enough energy before departure. The lower energy trajectory corresponding to the V2G case is denoted with $E_{vt}^{\text{V,low,V2G}}$.

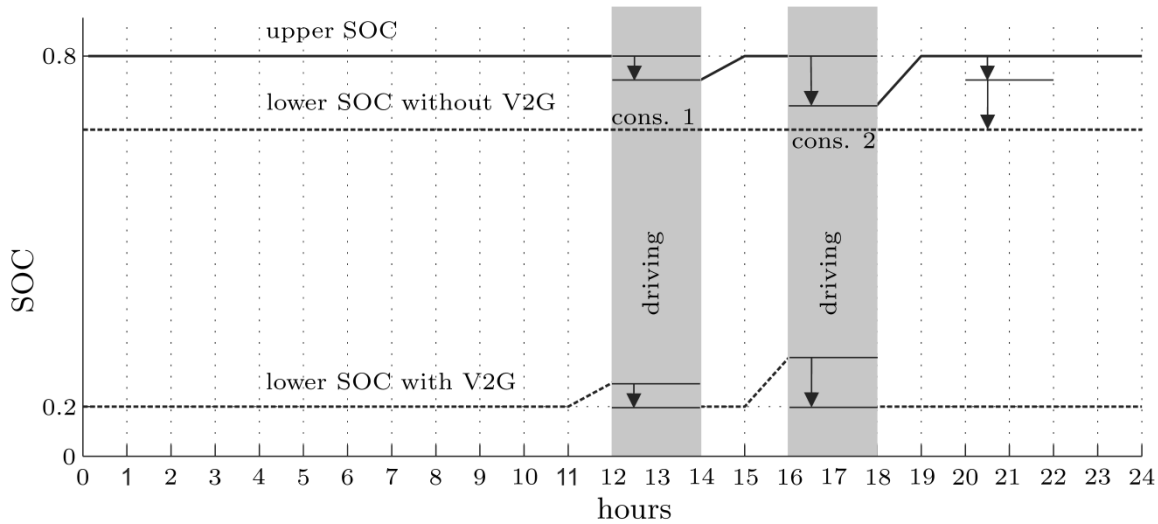

Figure 4.2 Example of the upper and lower SOC trajectory computation for an individual vehicle.

Similarly, the upper and lower power values of a vehicle at a given time step $P_{vt}^{\text{V,up}}$ and $P_{vt}^{\text{V,low}}$ can be computed. The upper value is equivalent to the upper bound defined in 4.4.3.2 $P_{vt}^{\text{V,up}} = P_{vt}^{\text{V,max}}$. The lower value of the charging power when the vehicle is connected is either zero or whatever is necessary to fulfill the trip energy requirements (inflexible charging). This inflexible charging can be derived by comparing the upper and lower energy bounds at subsequent time steps: If $E_{v(t-1)}^{\text{V,high}} < E_{vt}^{\text{V,low}}$, this implies that some charging is required at time step t. When the vehicle is disconnected, both the lower and upper power bounds are equal to zero. In the V2G mode, the lower trajectory corresponds to the negative available charging capacity, $P_{vt}^{\text{V,low,V2G}} = -P_{vt}^{\text{V,max}}$, or to zero in the case of inflexible charging requirements.

Based on these descriptions at the individual vehicle level, an aggregated model of a virtual battery at each network node can be derived. The following equations describe the aggregated virtual battery model:

$$E_{nt}^{\mathrm{A}} = E_{n(t-1)}^{\mathrm{A}} + P_{nt}^{\mathrm{A}} \eta_{nt}^{\mathrm{A}} \Delta t + E_{nt}^{\mathrm{A,arr}} - E_{nt}^{\mathrm{A,dep}} \quad \forall n, \forall t \tag{7}$$

$$P_{nt}^{\mathrm{A,min}} \leq P_{nt}^{\mathrm{A}} \leq P_{nt}^{\mathrm{A,max}} \quad \forall n, \forall t \tag{8}$$

$$E_{nt}^{\mathrm{A,min}} \leq E_{nt}^{\mathrm{A}} \leq E_{nt}^{\mathrm{A,max}} \quad \forall n, \forall t \tag{9}$$

$$E_{nt_0}^{\mathrm{A}} = E_{nt_T}^{\mathrm{A}} \quad \forall n \tag{10}$$

The energy content of the virtual battery E_{nt}^{A} at a particular node n stands for the aggregation of the energy contents of all EVs plugged in at that node at a given time step. The dynamics of this variable are defined by Eq. (7). They are determined by the aggregated charging power at a given time step P_{nt}^{A}, the aggregated charging efficiency η_{nt}^{A}, and by the positive/negative energy contributions of arriving/departing vehicles, $E_{nt}^{\mathrm{A,arr}}/E_{nt}^{\mathrm{A,dep}}$. The power and energy of the virtual battery should be within certain bounds as defined by Eqs. (8) and (9), respectively, and the energy level should be the same at the beginning t_0 and end t_T of the time horizon (10)

The aggregated parameters $E_{nt}^{\mathrm{A,arr}}$, $E_{nt}^{\mathrm{A,dep}}$, $E_{nt}^{\mathrm{A,min,(V2G)}}$, $E_{nt}^{\mathrm{A,max}}$, $P_{nt}^{\mathrm{A,min,(V2G)}}$, $P_{nt}^{\mathrm{A,max}}$ and η_{nt}^{A} are determined out of the individual EV parameters:

$$E_{nt}^{\mathrm{A,max}} = \sum_{v} u_{vnt}^{V} E_{vt}^{\mathrm{V,high}} \,;\; E_{nt}^{\mathrm{A,min,(V2G)}} = \sum_{v} u_{vnt}^{V} E_{vt}^{\mathrm{V,low,(V2G)}} \quad \forall n, \forall t \tag{11}$$

$$P_{nt}^{\mathrm{A,max}} = \sum_{v} u_{vnt}^{V} P_{vt}^{\mathrm{V,high}} \,;\; P_{nt}^{\mathrm{A,min,(V2G)}} = \sum_{v} u_{vnt}^{V} P_{vt}^{\mathrm{V,low,(V2G)}} \quad \forall n, \forall t \tag{12}$$

$$E_{nt}^{\mathrm{A,arr}} = \sum_{v} u_{vn(t-1)}^{V} \left(u_{vn(t-1)}^{V} - u_{vnt}^{V}\right) E_{v(t-1)}^{\mathrm{V,high}} \,;\; E_{nt}^{\mathrm{A,dep}} = \sum_{v} u_{vnt}^{V} \left(u_{vnt}^{V} - u_{vn(t-1)}^{V}\right) E_{v(t-1)}^{\mathrm{V,low}} \tag{13}$$

Eqs. (11) and (12) state that the power and energy bounds of the individual vehicles contribute to the aggregated bounds of a particular node when these vehicles are connected to that node during that time step, i.e. the variable denoting their connection status is equal to one, $u_{vnt}^{V} = 1$. The departure and arrival energy is estimated using the upper energy bound at the time of departure or arrival, respectively (13). The charging efficiency is set to $\eta_{vt}^{\mathrm{V}} = 0.92$ for all vehicles, and therefore the aggregated charging efficiency η_{nt}^{A} is also equal to this value.

4.4.4. Outputs

Figure 4.3 gives and overview of key characteristics that shape the charging profiles: the number of connected vehicles, arrivals, as well as departures over time.

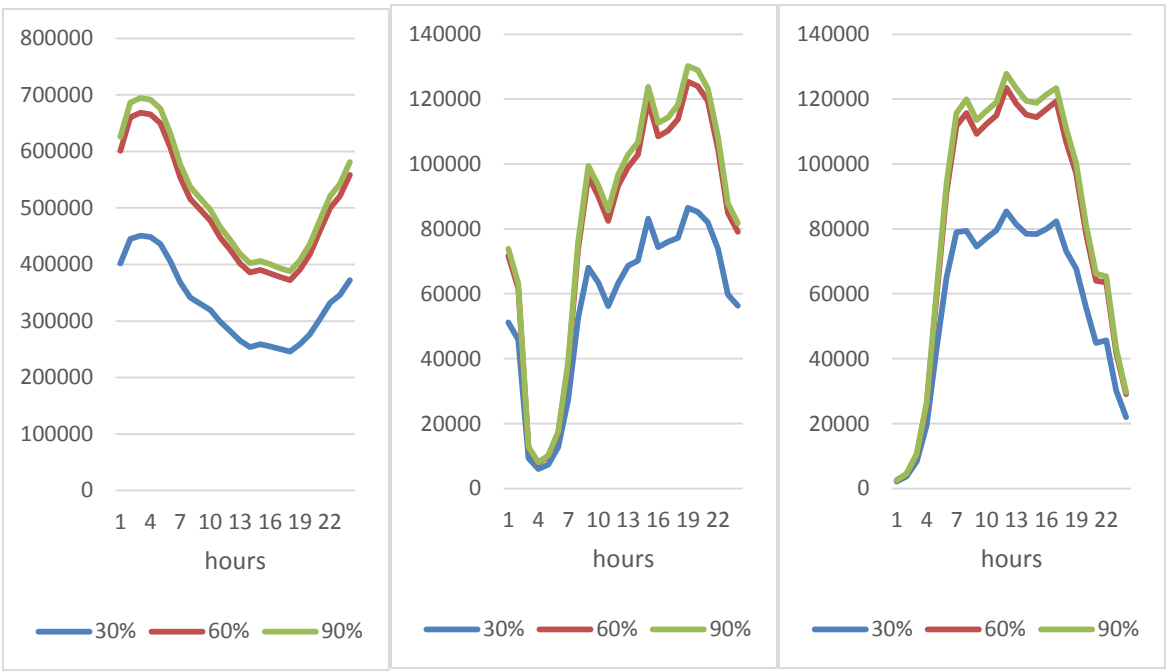

Figure 4.3 Number of connected vehicles (left), arrivals (middle) and departures (right) for different penetration levels.

4.4.4.1. Uncontrolled charging

Figure 4.4 shows the charging profiles under uncontrolled charging. They are related to the patterns of arrivals, see Figure 4.3. For that case charging takes place when vehicles arrive at work in the morning, and at home or other locations later during the day, especially in the evening, when most vehicles are connected, see Figure 4.3. It can be seen that the winter load is slightly higher than the summer load, because of the increased consumption of auxiliaries due to heating demand.

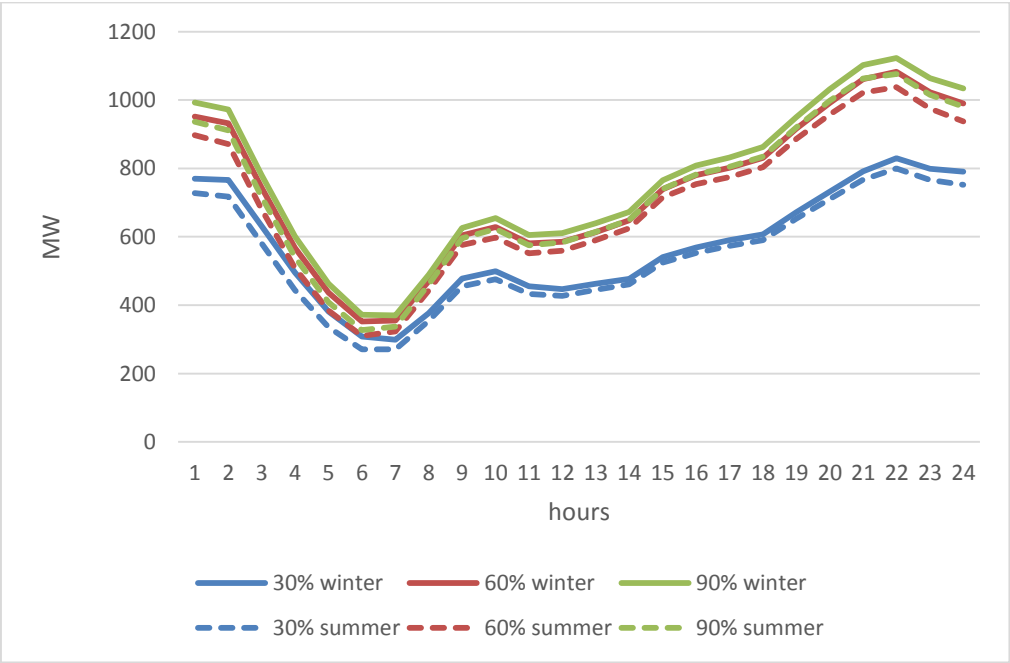

Figure 4.4 Charging profiles for uncontrolled charging, for different EV penetrations and seasons.

4.4.4.2. *Indirectly controlled charging*

Figure 4.5 shows the charging profiles as a response to the TOU tariff. Since the low tariff starts at 22:00, demand increases at this time, and vehicles continue charging until their batteries are full or until the high tariff period starts, at 6:00. Note that this approach induces a significantly higher peak demand as uncontrolled charging, since the EV load loses diversity, i.e. it is concentrated during the times of low prices.

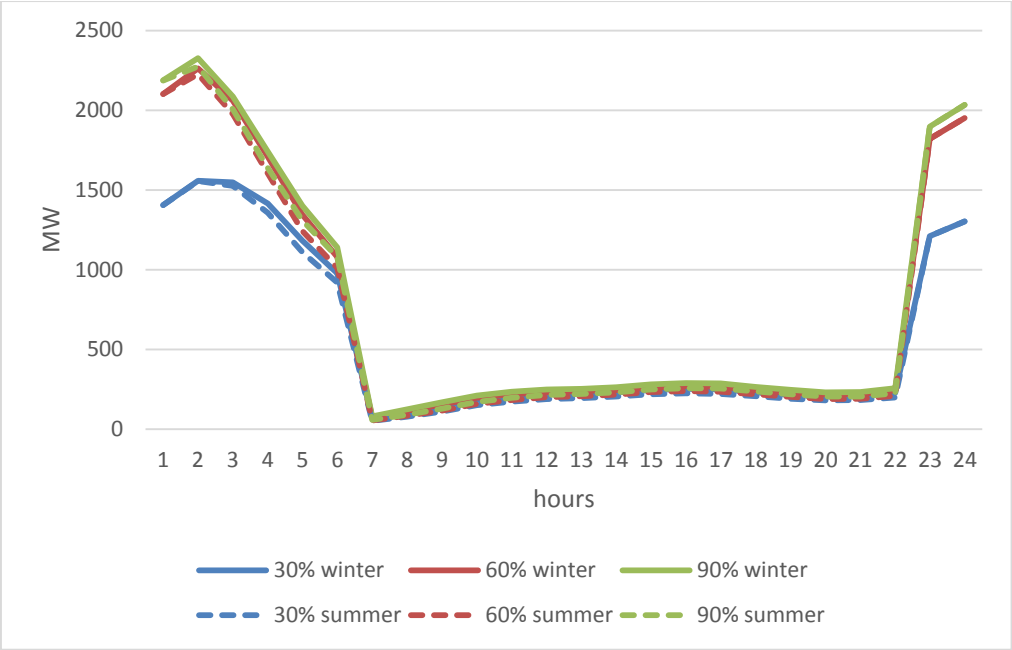

Figure 4.5 Charging profiles for indirectly controlled charging (TOU), for different EV penetrations and seasons.

4.4.4.3. *Directly controlled charging*

In this case there are no predefined charging profiles, but the set of feasible charging profiles is given by equations (7)-(10). The upper and lower bounds on energy ($E_{nt}^{\mathrm{A,max}}, E_{nt}^{\mathrm{A,min}}$) and power ($P_{nt}^{\mathrm{A,max}}, P_{nt}^{\mathrm{A,min}}$) are shown in Figure 4.6. It can be seen that these bounds are closely related to the number of vehicles connected over time, see Figure 4.3. The actual charging profiles depend on the system's demand and supply scenarios, since they are an outcome of a cost minimization problem. Some examples will be shown in 4.5.7.2.

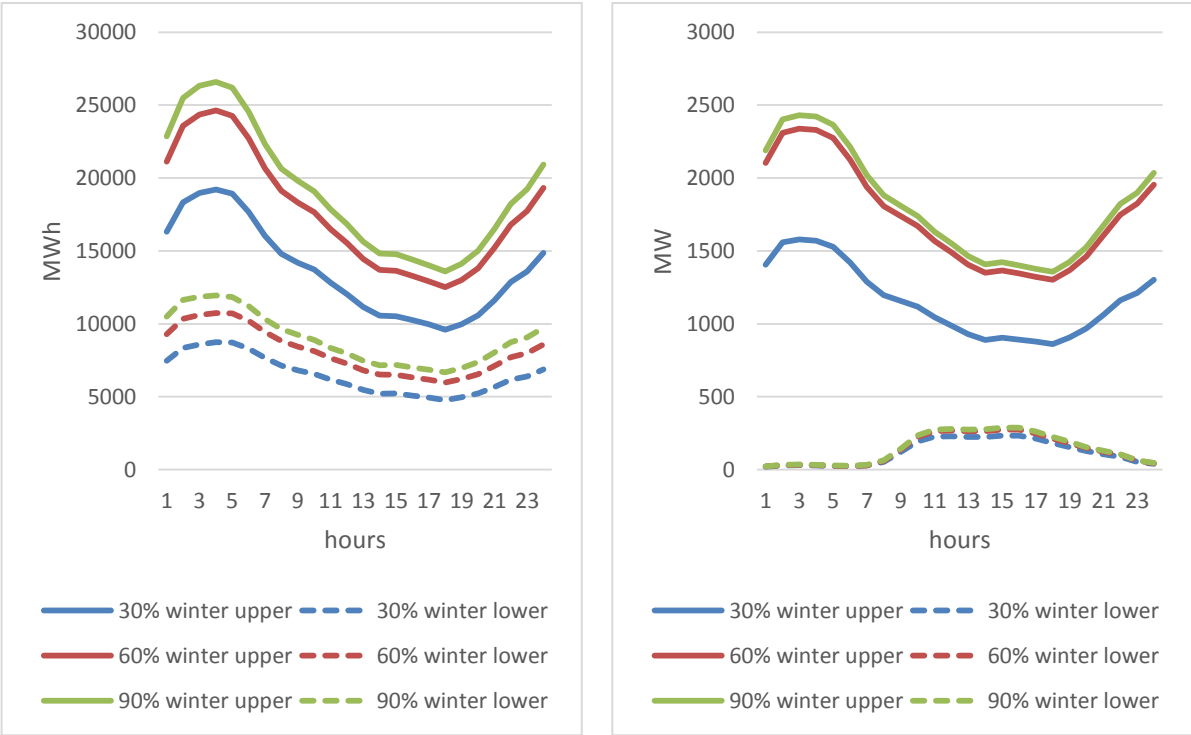

Figure 4.6 Energy (left) and power (right) bounds for directly controlled charging, for different penetrations.

4.5. Transmission system (Task 2 and 4)

4.5.1. Inputs

4.5.1.1. Supply and demand scenarios (WP5)

Within WP5, PSI has defined three supply scenarios (Base, Nuc - nuclear, RES - renewable energies), combined with three demand scenarios (NEP - new energy policy, POM - political measures, BAU - business as usual), see WP5 for more details (Hirschberg et al., 2012, Ramachandran and Turton, 2012). Under the policy measures defined in the NEP scenario demand declines almost immediately, and becomes significantly lower by 2050 than today. The measures currently under consideration in Switzerland as part of the Energy Strategy 2050 would yield demand in 2050 around the current level (POM scenario). Without these measures (BAU scenario), demand would continue to increase. Regarding supply scenarios, the Base supply scenario is the base-case supply scenario, whereas Nuc assumes no nuclear phase out, i.e. investments in new nuclear power plants are allowed. The renewable energy sources (RES) scenario has a stronger focus on renewable energy sources. On the supply side, the total installed capacity and costs for different generation technologies, as well as typical profiles of the production of these types of generation technologies in different seasons are provided. The generation technologies considered are the following:

- Gas: Base / CHP / Flexible
- Nuclear
- Hydro: Storage / Pumped / Run of the river
- Renewables: Geothermal / Solar / Wind / Waste / Other

On the demand side, typical daily demand profiles for the different seasons are defined. This is also the case for exports/imports from/to Germany, Italy, Austria and France.

4.5.1.2. *Network model*

The Swiss transmission system operator, Swissgrid, has provided a model of the transmission network, including topology as well as line and transformer parameters. The currently planned network extensions (Swiss Federal Office of Energy, 2009) have been added to the present model, see Figure 4.7. For new lines, the values assumed for the line capacity and the line reactance are based on the estimated length of the line and typical line parameters. The plans in (Swiss Federal Office of Energy, 2009) only consider the time horizon up to 2015, whereas the simulation corresponds to the year 2035.

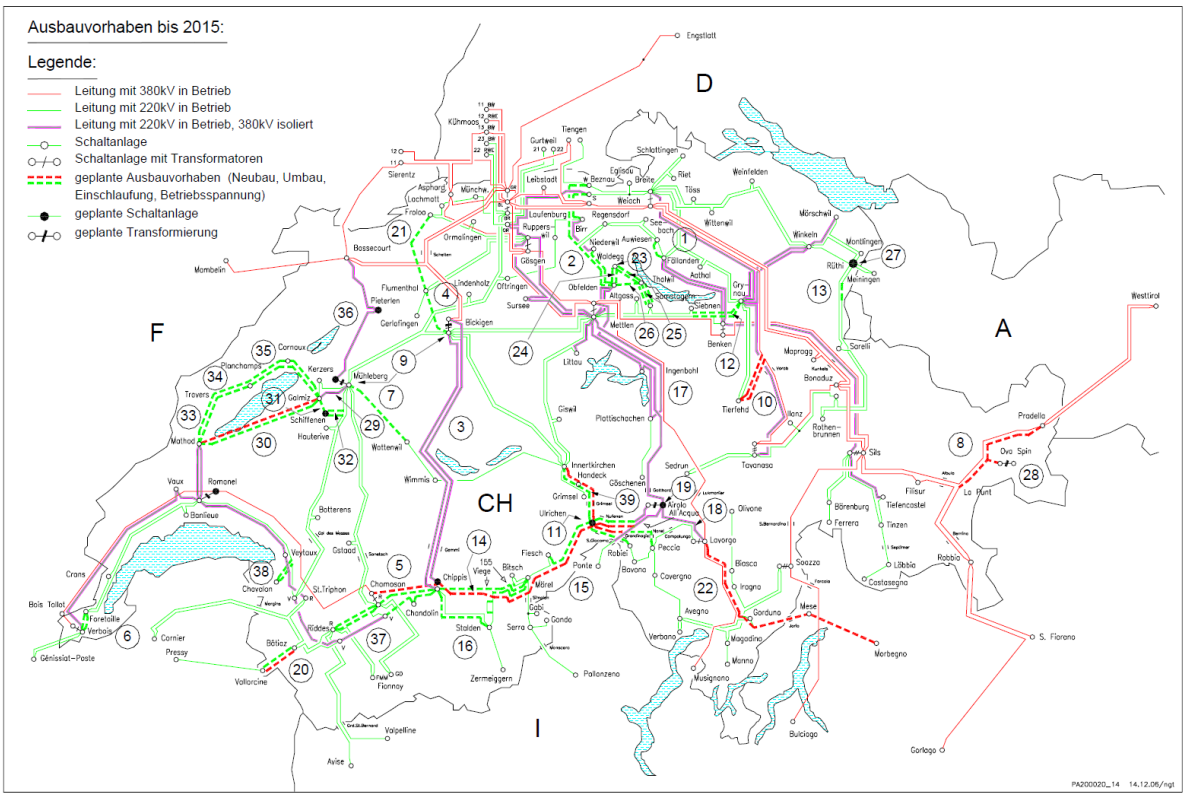

Figure 4.7 Current high voltage network and planned extensions up to 2015.Source: Swiss Federal Office of Energy (2009).

The network model comprises 272 lines (of which 37 are tie lines), 20 transformers, and 199 nodes. From those nodes, 37 are in the neighboring countries, and 88 are considered load nodes, i.e. they feed an underlying medium voltage network. The loading limits of the lines are defined differently depending on the time of the year; typically a value is given for the winter (highest), fall/spring (intermediate), and summer (lowest).

4.5.1.3. *Integration of different power sources and demand into the model*

To be able to integrate the inputs from WP5 into the grid simulation, a pre-processing is required. An important aspect is the geographic mapping of the different technologies. For larger power plants, such as hydro, gas, and nuclear power plants, as well as waste incinerators, the (potential) geographic position is determined and they are assigned to the corresponding network node. The list of hydro power plants in Switzerland is published by the Swiss Federal Office for Energy (2013). Most of the hydro power plants reported in Swiss Federal Office for Energy (2013) were considered. The potential future locations for gas power plants and the location of waste incinerators were provided

by PSI. The production of other minor sources such as wind, “other renewables”, geothermal and gas-CHP (Combined Heat and Power), is directly subtracted from total demand. A more detailed approach is used to map the solar power generation to the network nodes (see below).

Some of the technologies needed additional modeling assumptions as described in the following:

a) Solar: The aggregated Swiss-wide photovoltaic production profile defined in the scenarios is assigned to individual network nodes with weights proportional to the building area of the closest municipality (Gemeinde) multiplied by the yearly global radiation of the closest weather station (Theodoulou, 2013). The underlying assumption is that the presence of photovoltaic panels is related to the available rooftop area, and their actual output is related to the radiation. The building area of each municipality, which is published by the Swiss Federal Statistical Office (2007), is used as a proxy for the rooftop area. Only the subset of network nodes that are considered load nodes is taken into account in the assignment. The photovoltaic (PV) generation technology is included in the model with zero marginal costs and is considered curtailable.
b) Storage and pumped hydro: A constraint is set in the optimization so that the total daily production of each of these two technologies is equal to the amount defined in the scenarios, i.e. the production of this technologies is not only power-, but also energy-constrained. The costs assigned to storage and pumped hydro in the dispatch model are not the actual production costs, but an estimation of their opportunity costs. It is assumed that power plants with a lower energy/power ratio (peaking plants) bid higher prices, and therefore they are dispatched fewer hours. Since storage and pumped hydro plants fill the gap between base gas power plants and peak gas power plants, it is assumed they bid costs in-between those values. The bid prices are scaled linearly with the historical energy/power ratio for each individual plant, as given by the statistics (Swiss Federal Office for Energy, 2013).
c) Run of the river hydro: The total amount of energy from this technology is also set equal to the amount defined in the scenarios. The individual maximum power for a given season is set so that the total power of this type of plants is equal to the power profile given by the supply scenarios. Individual power values for each plant are scaled according to the amount of energy that the plant produces for a given season, as given by the statistics (Swiss Federal Office for Energy, 2013). Since run of the river plants can store small amounts of water, they are allowed to increase/decrease their production by 20% throughout the day. The total amount of energy produced per day corresponds to that defined in the scenarios.
d) Waste: The individual maximum power for a given season is set so that the total power of this type of plants is equal to the power profile from the supply scenarios. The power of each power plant is scaled according to its CO_2 emissions, provided by the PSI.
e) Baseload plants (nuclear, waste and gas base plants): A constraint is set so that the power of nuclear, waste and gas base plants is constant throughout the day.
f) Exports and imports: A constraint is set that specifies the amount of power flowing through a border with one of the neighboring countries according to the supply and demand scenarios: An inequality constraint states that imports/exports can be as high as the value given in the supply and demand scenarios, but not higher. To make sure that the result is as close as possible to the PSI scenario results, imports and exports are assigned a negative cost in the cost function. Therefore there is an incentive to import and export as much as possible

within the bounds defined by the scenarios, i.e. there is a soft constraint on the amount of imports and exports. We did not introduce this as a hard constraint because it led to infeasibilities (asset overloads) in some cases.

g) EV load: Part of the load defined in the demand scenarios corresponds to an estimate of the EV charging load. Since the EV load is modeled in detail in the THELMA project, the scenario-specific charging demand is subtracted from the total demand given in the scenarios. The EV demand is then modeled explicitly as explained in 4.4.3.

4.5.2. Optimal power flow problem formulation

To analyze the impact of the charging demand on the network and the electricity supply, an Optimal Power Flow (OPF) is performed (González Vayá and Andersson, 2012, González Vayá et al., 2011). Within this framework, the optimal, i.e. welfare maximizing, dispatch of supply and demand is decided, taking into account load, generator and network constraints. Thereby the power generated by each generator P_{gt}^{G} and the power consumed by each load P_{lt}^{L} and by the EV aggregation P_{nt}^{A}, at a given time step is established, as well as the resulting power flows on lines and transformers. Since some of the constraints that need to be considered introduce a link between different time steps, we perform a multi-period OPF, comprising a full day with hourly time steps. The OPF performed here is a DC-OPF, which is a common simplified form of the OPF, where some approximations are adopted for the physical power flow equations, e.g. losses are neglected. The resulting mathematical problem is a linear programming problem:

$$\min_{P_{gt}^{\mathrm{G}}, P_{nt}^{\mathrm{A}}, E_{t_0}^{\mathrm{A}}} \sum_{t} \sum_{g} P_{gt}^{\mathrm{G}} \, c_{gt}^{\mathrm{G}} \tag{14}$$

$$\sum_{l} P_{lt}^{\mathrm{L}} + P_{nt}^{\mathrm{A}} = \sum_{g} P_{gt}^{\mathrm{G}} \quad \forall t \tag{15}$$

$$P_{gt}^{\mathrm{G,min}} \leq P_{gt}^{\mathrm{G}} \leq P_{gt}^{\mathrm{G,max}} \quad \forall t, \forall g \tag{16}$$

$$\left| \sum_{n} D_{nl} \left(\sum_{g \in \Omega_n} P_{gt}^{\mathrm{G}} - \sum_{l \in \Omega_n} P_{lt}^{\mathrm{L}} - P_{nt}^{\mathrm{A}} \right) \right| \leq P_{l}^{\mathrm{L,max}} \quad \forall t, \forall l \tag{17}$$

In this OPF the costs of generation are minimized, given the marginal costs (or opportunity costs for storage and pumped hydro) of each generator c_{gt}^{G} (14). Constraint (15) establishes the balance of demand and supply in the system and (16) enforces the generator output limits. The loading limits of network assets are enforced by (17), using a formulation based on power transfer distribution factors D_{nl}. The reference load, i.e. the load without EV charging, is considered inflexible. This means that P_{lt}^{L} is an exogenous input to the problem. The EV aggregation's load P_{nt}^{A} is also exogenous in the cases of uncontrolled charging and indirectly controlled charging, as explained in 4.4.3. When directly controlled charging is considered the fleet's charging schedule P_{nt}^{A} and initial energy content $E_{t_0}^{\mathrm{A}}$ become optimization variables and Eqs. (7)-(10) are included as constraints in the OPF problem.

In addition to the standard DC-OPF Eqs. (14)-(17), and the fleet's Eqs. (7)-(10), when appropriate, some additional constraints were added to the power output of some power plant types, to incorporate the restrictions described in 4.5.1.3.

4.5.3. Defining individual charging set-points

In the case of directly controlled charging, the result of the OPF only gives a set of aggregated charging profiles $P_{nt}^{\mathrm{A,max}}$, not individual profiles. Therefore a second step is needed to distribute the aggregated profile into individual profiles. This is done by assessing the charging urgency of each vehicle at each time step and charging the vehicles which need charging more urgently first. The urgency depends on the time left until departure in conjunction with the time needed to charge to the required SOC, as well as the SOC in conjunction with the current SOC. The SOC is set to reach the maximum value at some point.

4.5.4. Ancillary services

When an aggregator directly controls charging, there is the possibility to use the flexibility of EV charging to provide ancillary services, such as frequency regulation, for the transmission system operator (TSO). Here we specifically analyze the provision of secondary frequency control (González Vayá and Andersson, 2013b, González Vayá and Andersson, 2013a, Marmolejo, 2011, Avramiotis, 2012), also called automatic generation control (AGC) or load frequency control (LFC). In this case, the entities providing this service offer a given capacity to the TSO, and the TSO makes, in real-time, up and down regulation requests in proportion to this capacity. Currently, the participants in this market need to provide a symmetric amount of up/down regulation for the period of one week. For a generator, providing up/down regulation means increasing/decreasing the power output. For the aggregator, providing up/down regulation means decreasing/increasing charging. Additionally, up regulation can be provided by discharging the batteries. There is a distinction between two cases: i) V2G, where discharging can take place, and ii) unidirectional charging, where charging can only be modulated or interrupted, but no discharging can take place.

Although using V2G allows offering higher capacities for regulation, it could come at the cost of additional battery cycling and therefore degradation of this expensive asset. Note that the V2G mode is not considered in the optimal dispatch described in Subsection 4.5.2, whereas it is potentially attractive to use it for the purpose of offering ancillary services. The reason is that ancillary services have a capacity remuneration, i.e. a remuneration for being available as a reserve, in addition to an energy remuneration, i.e. a remuneration for the energy actually delivered upon request. In the OPF, the only benefit from using V2G is price arbitrage, which usually does not compensate for the additional degradation costs (Kristoffersen et al., 2011, González Vayá et al., 2011).

4.5.5. Assessing the regulation capacity potential

Additional constraints need to be added to the OPF to assess if the fleet can offer a given regulation capacity. The total load of the fleet should follow a profile given by the sum of the day-ahead charging schedule, as computed in the OPF, and stochastic requests for a given amount of up or down regulation from the TSO. To model the fact that the aggregator needs to reserve a given power and energy flexibility, which depend on the offered regulation capacity C^R, to be able to respond to these random requests, additional equations are added to the previously introduced fleet Eqs. (7)-(10). For this purpose, we distinguish between the V2G case and the unidirectional case.

Unidirectional:

$$\sum_n P_{nt}^A + C^R \leq \sum_n P_{nt}^{\mathrm{A,max}} \quad \forall n, \forall t \tag{18}$$

$$\sum_n P_{nt}^{\mathrm{A,min}} \leq \sum_n P_{nt}^{A} - C^R \quad \forall n, \forall t \tag{19}$$

$$\sum_n E_{nt}^{A} + C^R \eta_{nt}^{\mathrm{A}} \Delta t \max_s \left(\sum_t \delta_{st}^R \right) \leq \sum_n E_{nt}^{\mathrm{A,max}} \quad \forall n, \forall t \tag{20}$$

$$\sum_n E_{nt}^{\mathrm{A,min}} \leq \sum_n E_{nt}^{\mathrm{A}} + C^R \eta_{nt}^{\mathrm{A}} \Delta t \min_s \left(\sum_t \delta_{st}^R \right) \quad \forall n, \forall t \tag{21}$$

V2G:

$$\sum_n P_{nt}^{\mathrm{A}} + C^R \leq \sum_n P_{nt}^{\mathrm{A,max}} \quad \forall n, \forall t \tag{22}$$

$$\sum_n P_{nt}^{\mathrm{A,min,V2G}} \leq \sum_n P_{nt}^{\mathrm{A}} - C^R \quad \forall n, \forall t \tag{23}$$

$$\sum_n E_{nt}^{\mathrm{A}} + C^R \eta_{nt}^{\mathrm{A}} \Delta t \max_s \left(\sum_{\tau=1}^{\tau=t} \delta_{s\tau}^R \right) - \Delta E^{\mathrm{A}} \leq \sum_n E_{nt}^{\mathrm{A,max}} \quad \forall n, \forall t \tag{24}$$

$$\sum_n E_{nt}^{\mathrm{A,min,V2G}} \leq \sum_n E_{nt}^{F} + \frac{C^R \Delta t}{\eta_{nt}^{\mathrm{A}}} \min_s \left(\sum_{\tau=1}^{\tau=t} \delta_{s\tau}^R \right) - \Delta E^{\mathrm{A}} \quad \forall n, \forall t \tag{25}$$

The set of equations (18)-(25) describes the fact that the energy and power of the aggregation of EVs should stay within feasible bounds when perturbed from their reference values E_{nt}^{A} and P_{nt}^{A} due to the regulation requests, $\delta_{s\tau}^R$ in p.u., given it has offered a capacity C^R to the TSO.

First, we describe the constraints with unidirectional charging. Constraint (18) ensures that the aggregator can provide regulation down with the full contracted regulation capacity C^R in addition to the total scheduled charging power across all nodes $\sum_n P_{nt}^{\mathrm{A}}$. Similarly, it should be able to reduce the total scheduled charging power by the full contracted regulation power without violating its power lower bound (19). Since this lower bound is non-negative (no V2G), this means that the scheduled charging power cannot be lower than the contracted regulation up capacity.

Concerning the energy trajectory, it should stay within the energy bounds, coping with the worst-case possible cumulative energy deviations (across the scenarios s) due to providing regulation down power (20) and regulation up power (21). The worst case up and down deviations, $\min_s(\sum_{\tau=1}^{\tau=t} \delta_{s\tau}^R)$ and $\max_s(\sum_{\tau=1}^{\tau=t} \delta_{s\tau}^R)$ respectively, are derived empirically from regulation signal time series.

The equations with V2G (22)-(25) are similar to those without V2G (18)-(21). The main differences are, a) the values for the power and energy lower bounds, $P_{nt}^{\mathrm{A,min,V2G}}$ and $E_{nt}^{\mathrm{A,min,V2G}}$, b) the use of the discharging efficiency in (22)-(25) and c) the introduction of a shift in the energy reference, $-\Delta E^{\mathrm{A}}$, which is a decision variable. This shift represents a deviation from the reference assumption where vehicles are considered to reach the maximum SOC at some point in time. To provide more regulation capacity it might however be beneficial to operate around a lower SOC.

4.5.6. Computing individual responses

With the setup described above it is possible to verify if an EV fleet can potentially provide a certain amount of regulation. As a second step, we compute how the regulation requests are broken down into individual charging set points.

To provide regulation, the aggregator has to respond to a signal from the TSO which has a typical time resolution in the range of several seconds. In an ideal setup with unlimited communication and computational capabilities, the aggregator would be able to obtain vehicle statuses, calculate new set points for each vehicle and send those set points to the individual vehicles in real time. However, in practice this type of approach would probably prove impractical due to delays in communication and data processing.

For this reason we propose a decentralized approach in which decisions to change the charging set point are made by the individual vehicles. This approach has the following characteristics:

- The aggregator broadcasts a signal to the vehicles which is recalculated with each new value of the AGC signal.
- Vehicles respond to this signal according to their capabilities.
- The aggregator can measure the aggregated response.
- The vehicles send information to the aggregator on a longer time scale, in the range of several minutes.

The broadcasted signal contains a probability with which vehicles should increase charging, decrease charging or discharge by a predefined power. This probability is calculated by the aggregator based on its knowledge on the number of vehicles available to perform each of the actions. When an EV receives the signal, it verifies whether it is capable of responding without violating its constraints. If this is the case, the EV responds to the signal only if the result of a Bernoulli trial, with probability of success equal to the broadcasted probability, is positive. The EV maintains the new charging set point until the next scheduled information update takes place. The only information that an EV needs to exchange with the aggregator is its capability to increase/decrease charging or discharge by the predefined amount of power for the time period extending to the next scheduled information update. Although a decrease in charging and discharging are equivalent in terms of their contribution to up regulation, discharging has a negative impact on battery lifetime since it increases cycling. Therefore we distinguish between these actions and prioritize charging reduction over battery discharge whenever this is possible.

Although with this type of scheme it is not possible to perfectly follow the regulation signal, the response is still accurate enough.

4.5.7. Results

4.5.7.1. Requirements for network expansion

From the OPF, it is possible to assess if the available network infrastructure is sufficient to cover the needs of generators and consumers. If the OPF problem is infeasible, and becomes feasible when line/transformer constraints are relaxed, then additional investments in the network are required. The OPF tool is however not an investment planning tool, and cannot be used to estimate the optimal investment in infrastructure. In all simulated scenarios a feasible solution was found,

implying that the introduction of EVs should in principle not pose a problem for the transmission network. Note however that no security constraints were considered in the OPF.

4.5.7.2. Dispatch profiles

In total, 324+36 OPF simulations were performed (4 seasons x 3 supply scenarios x 3 demand scenarios x 3 EV penetrations x 3 charging scenarios, plus the reference cases without EV 4x3x3x1x1). Therefore we can only show detailed results for a reduced number of the simulations performed.

First, we compare the results of different supply scenarios. Figure 4.8, Figure 4.9 and Figure 4.10 show the supply and demand mix for the POM demand scenario, directly controlled charging and 90% EV penetration on a typical winter day. It can be seen that in the Base supply scenario an important part of the baseload is provided by gas, whereas this role is played by nuclear power in the Nuc supply scenario. In the Res supply scenario a variety of renewables, predominantly solar, replace gas and nuclear power. Also, the ratio of exports vs. imports is much lower in this scenario. It can be seen that in all cases, with directly controlled charging, most of the EV load is shifted to the night hours, when demand is lower.

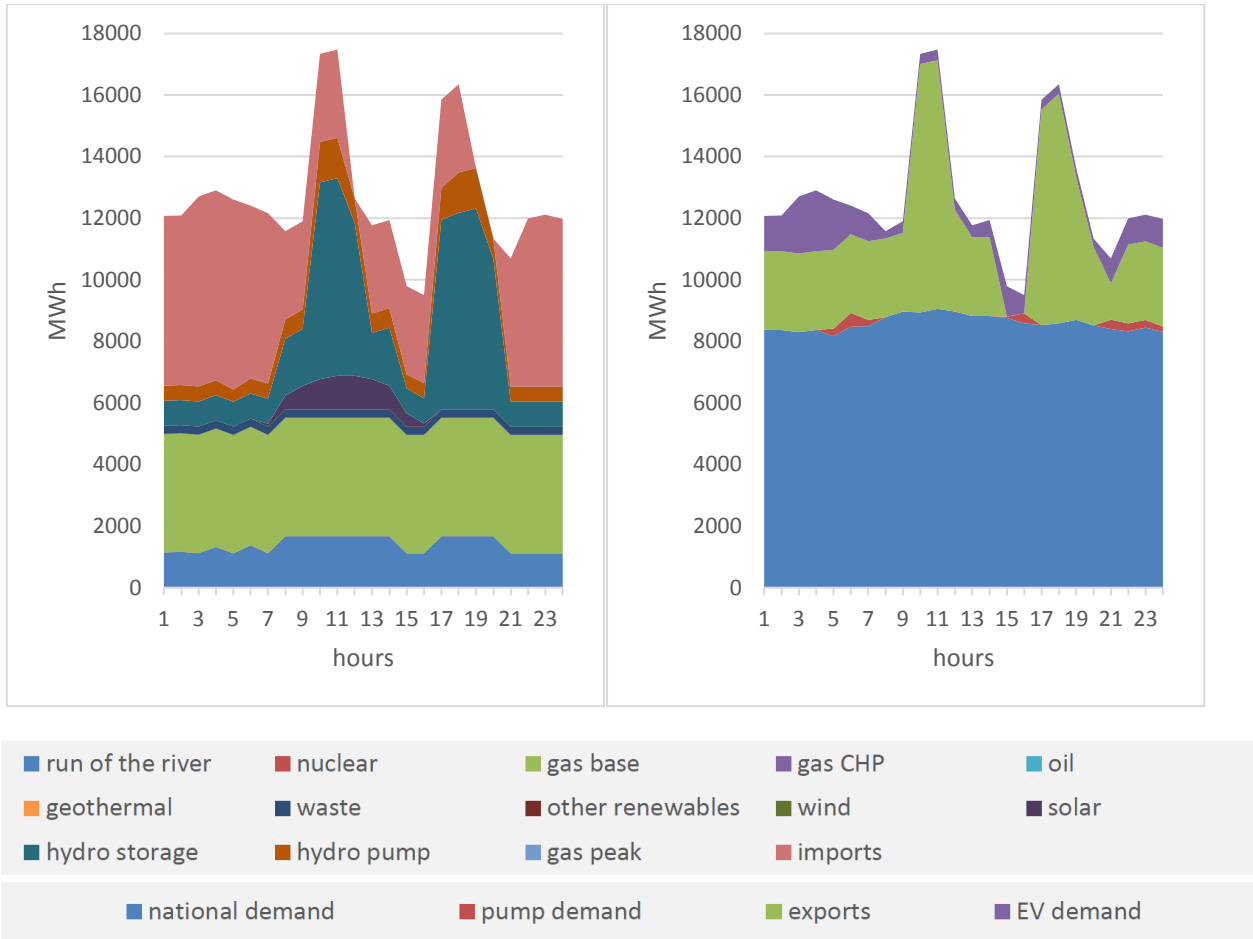

Figure 4.8 Supply (left) and demand (right) mix for the scenario POM-Base/directly controlled charging/90% EV penetration/winter.

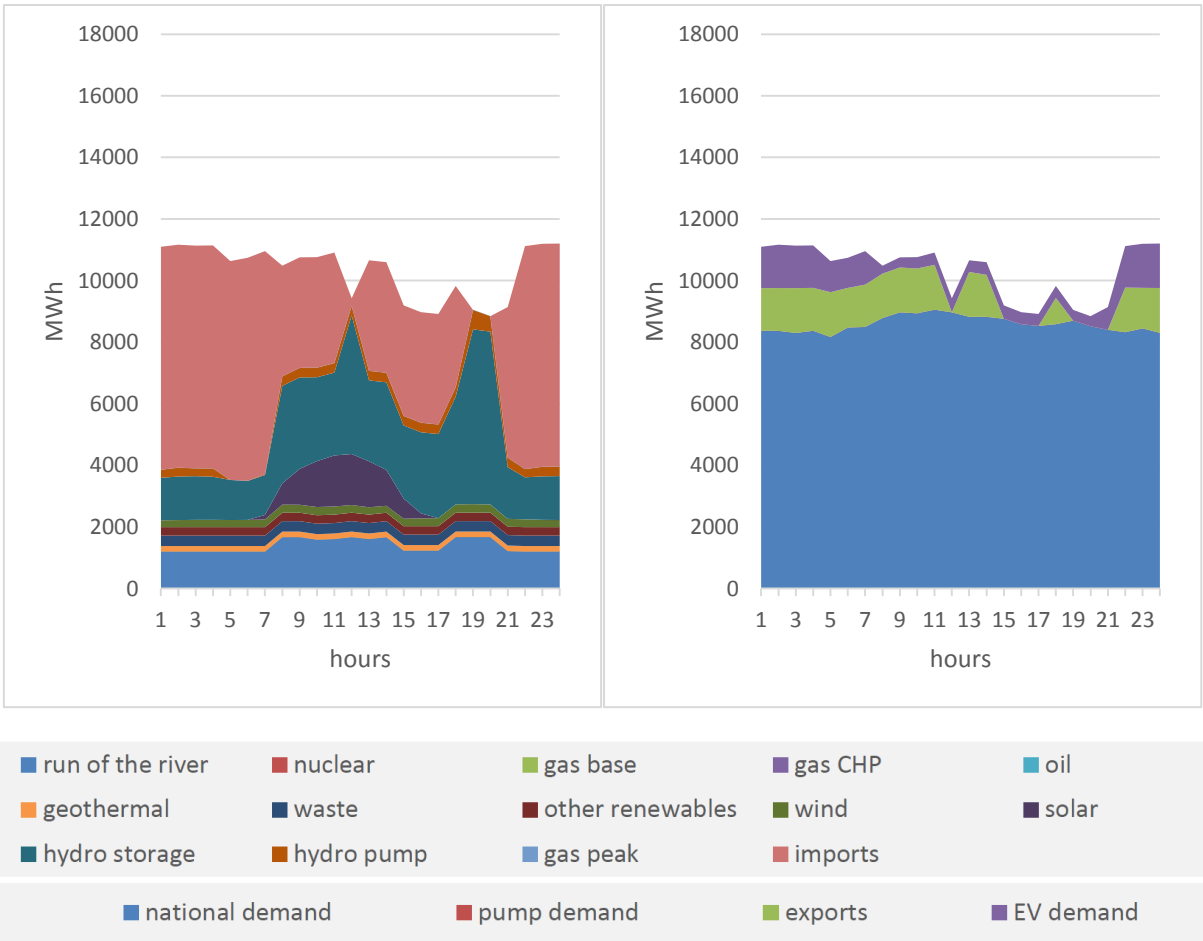

Figure 4.9 Supply (left) and demand (right) mix for the scenario POM-Res/directly controlled charging/90% EV penetration/winter.

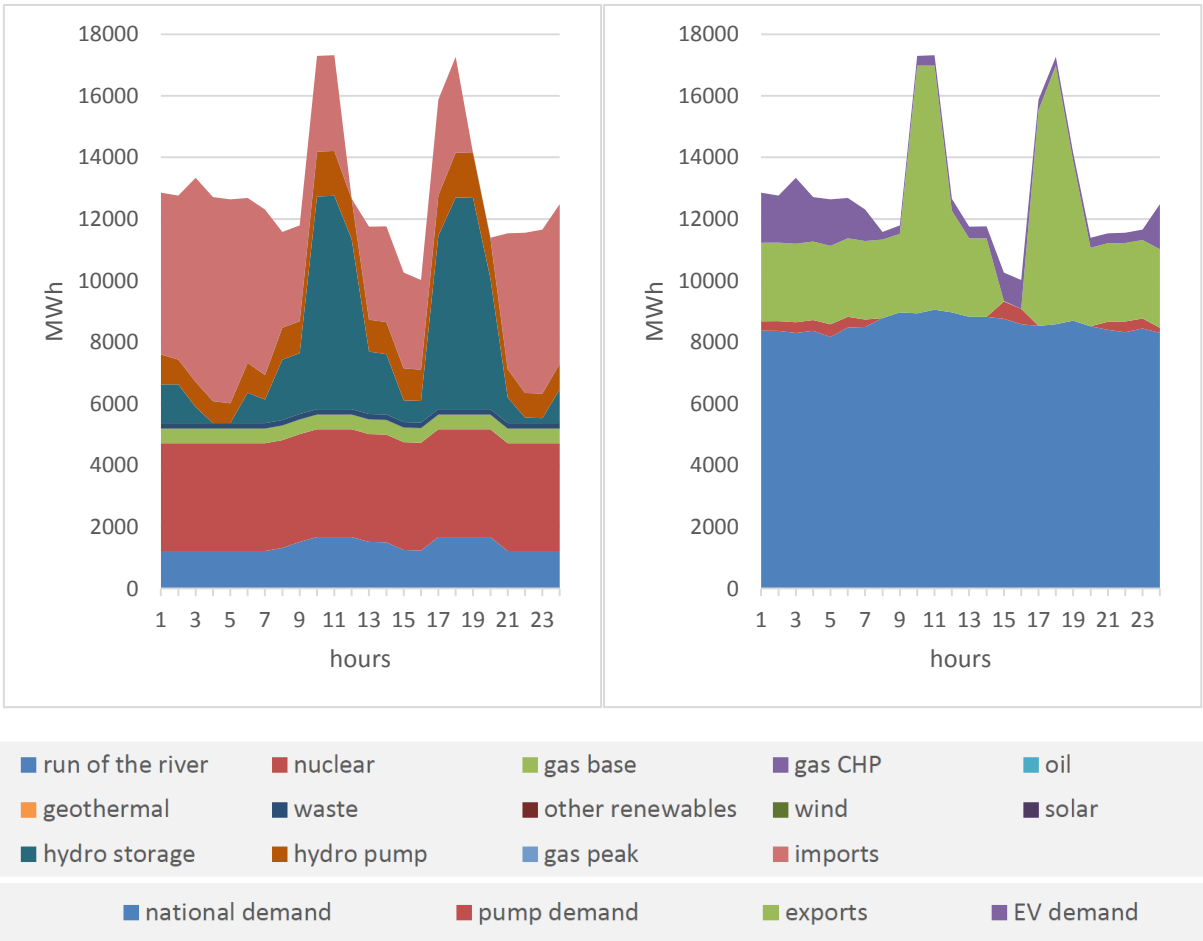

Figure 4.10 Supply (left) and demand (right) mix for the scenario POM-Nuc/directly controlled charging/90% EV penetration/winter.

Second, we analyze the seasonal effects, comparing a typical winter day with a typical summer day for the POM-Base scenario, directly controlled charging and 90% EV penetration, see Figure 4.8 and Figure 4.11. It can be seen that solar production is higher than in the winter, as well as exports.

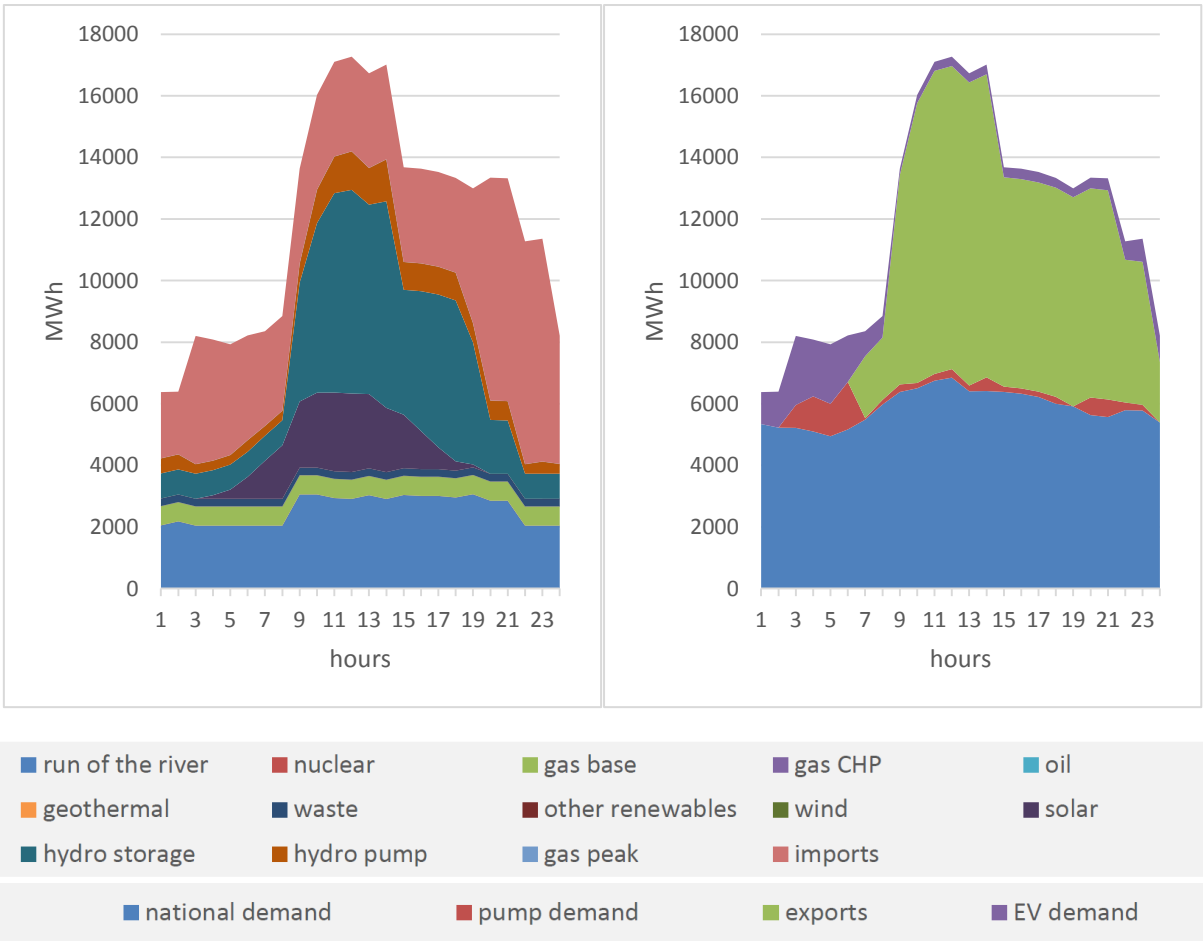

Figure 4.11 Supply (left) and demand (right) mix for the scenario POM-Base/directly controlled charging/90% EV penetration/summer.

Third we analyze the effect of the different charging scenarios, comparing the results of directly controlled charging, uncontrolled charging and indirectly controlled charging, for the POM-Base scenario, 90% EV penetration on a winter day, see Figure 4.8, Figure 4.12 and Figure 4.13. The total amount of energy provided by each type of source does not change, only the timing of hydro production. This is related to the fact that the amount of energy provided by hydro has a fixed value, and to the assumption that import and export patterns are exogenous. If imports/exports were modeled exogenously, we could expect a small change in the composition of supply.

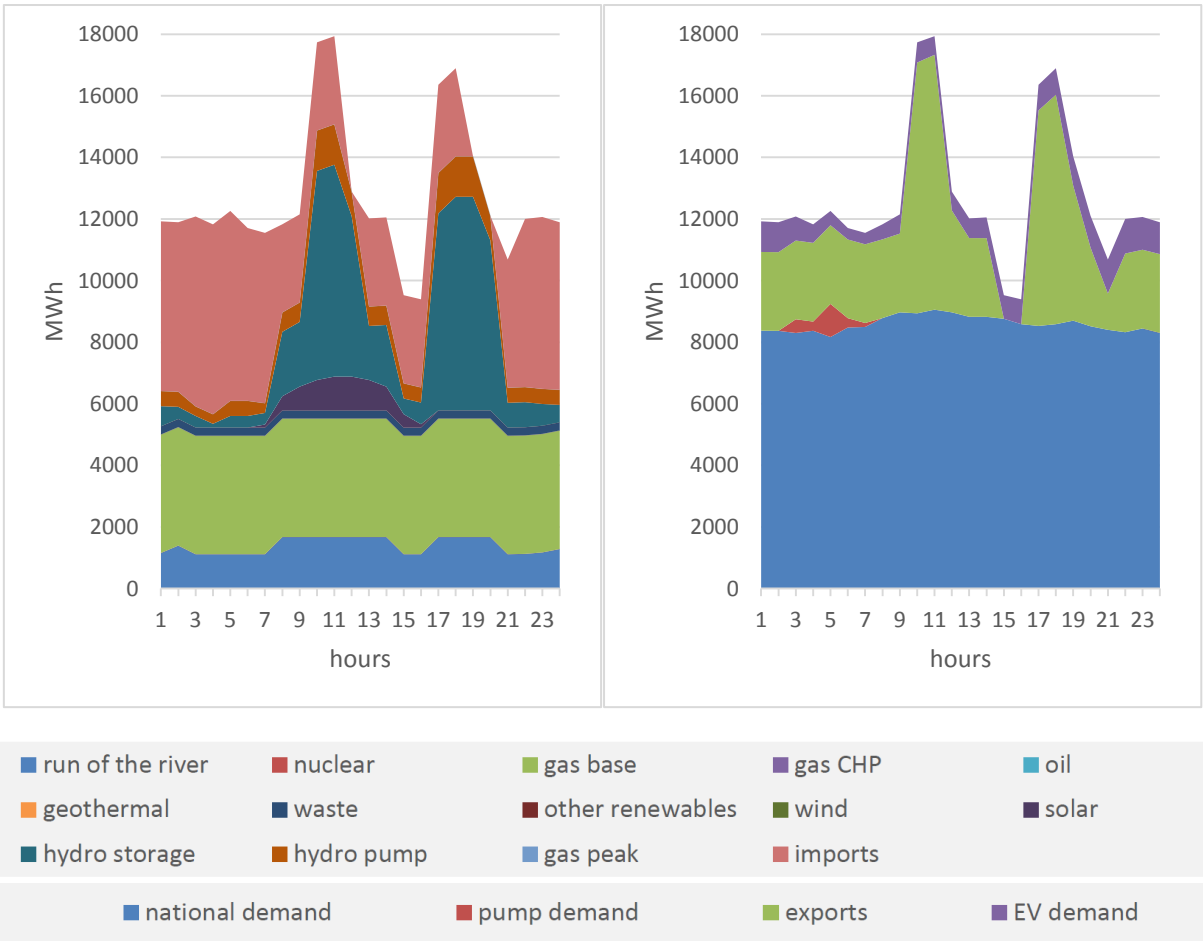

Figure 4.12 Supply (left) and demand (right) mix for the scenario POM-Base/uncontrolled charging/90% EV penetration/winter.

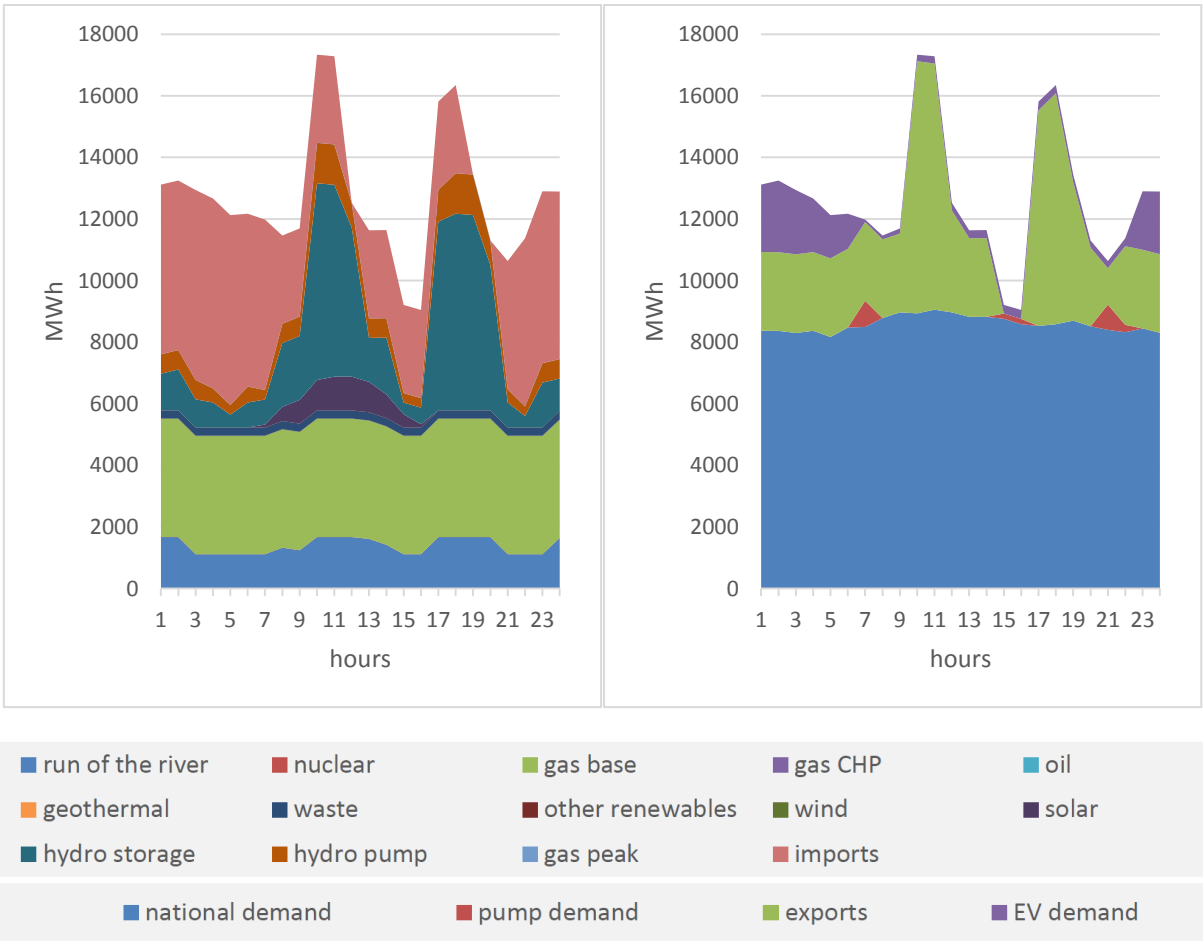

Figure 4.13 Supply (left) and demand (right) mix for the scenario POM-Base/indirectly controlled charging/90% EV penetration/winter.

Next, we explore the sensitivity of the results to the demand scenarios. Previous results were shown for the POM demand scenario. Figure 4.14 and Figure 4.15 show the results for the BAU and NEP demand scenarios, respectively, on a winder day, for 90% EV penetration and directly controlled charging. Due to the higher demand in the BAU scenario compared to the POM scenario, production from peak gas power plants and more imports are needed. In the NEP scenario, where demand is lower than in the POM scenario, the output of base gas power plants is reduced.

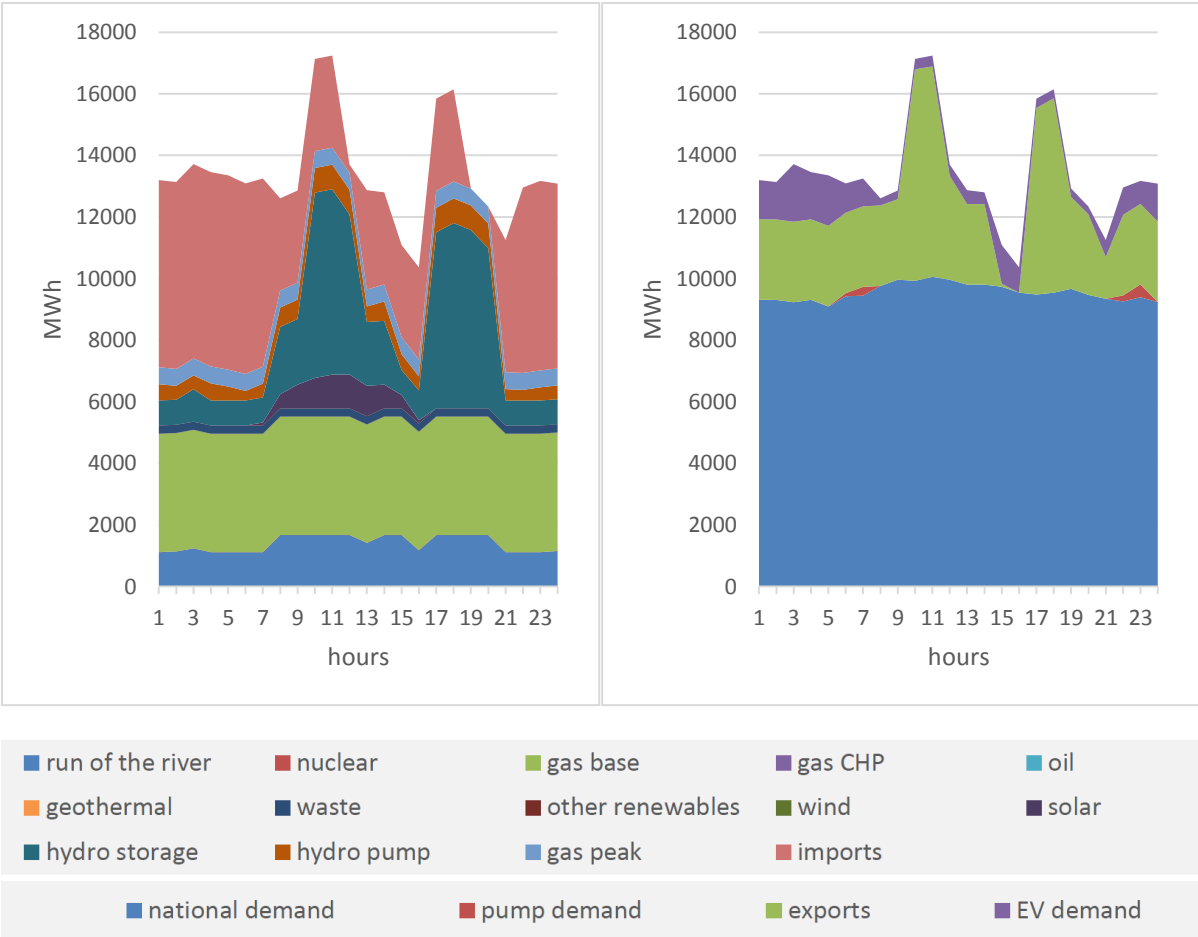

Figure 4.14 Supply (left) and demand (right) mix for the scenario BAU-Base/directly controlled charging/90% EV penetration/winter.

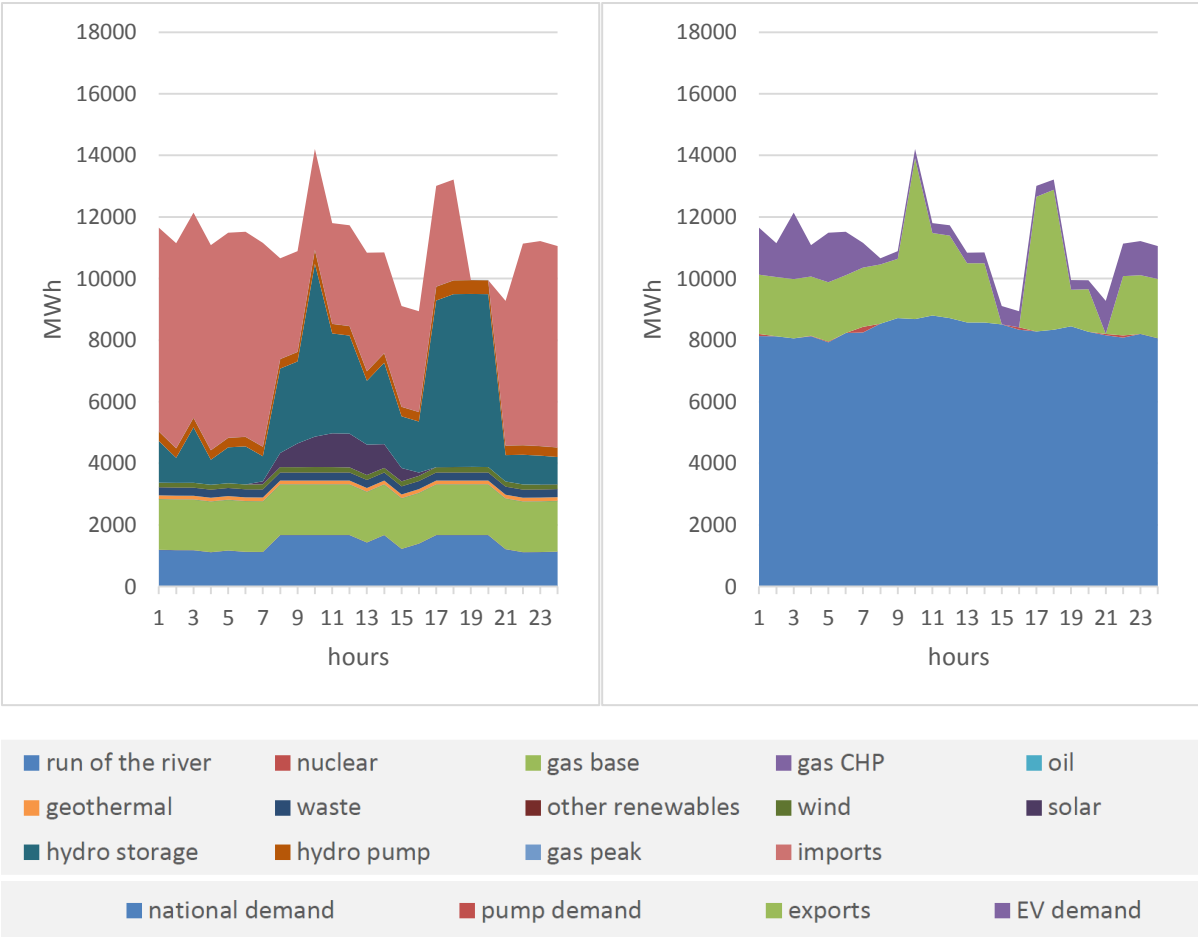

Figure 4.15 Supply (left) and demand (right) mix for the scenario NEP-Base/directly controlled charging/90% EV penetration/winter.

Further, the impact of the different EV penetrations is analyzed, in Figure 4.16 and Figure 4.17, for the POM-Base scenario and directly controlled charging. The impact of EV penetration has an insignificant impact on results, since EV demand only represents a minor fraction of demand. The reduced EV demand leads to a lower share of gas base plants in the supply mix.

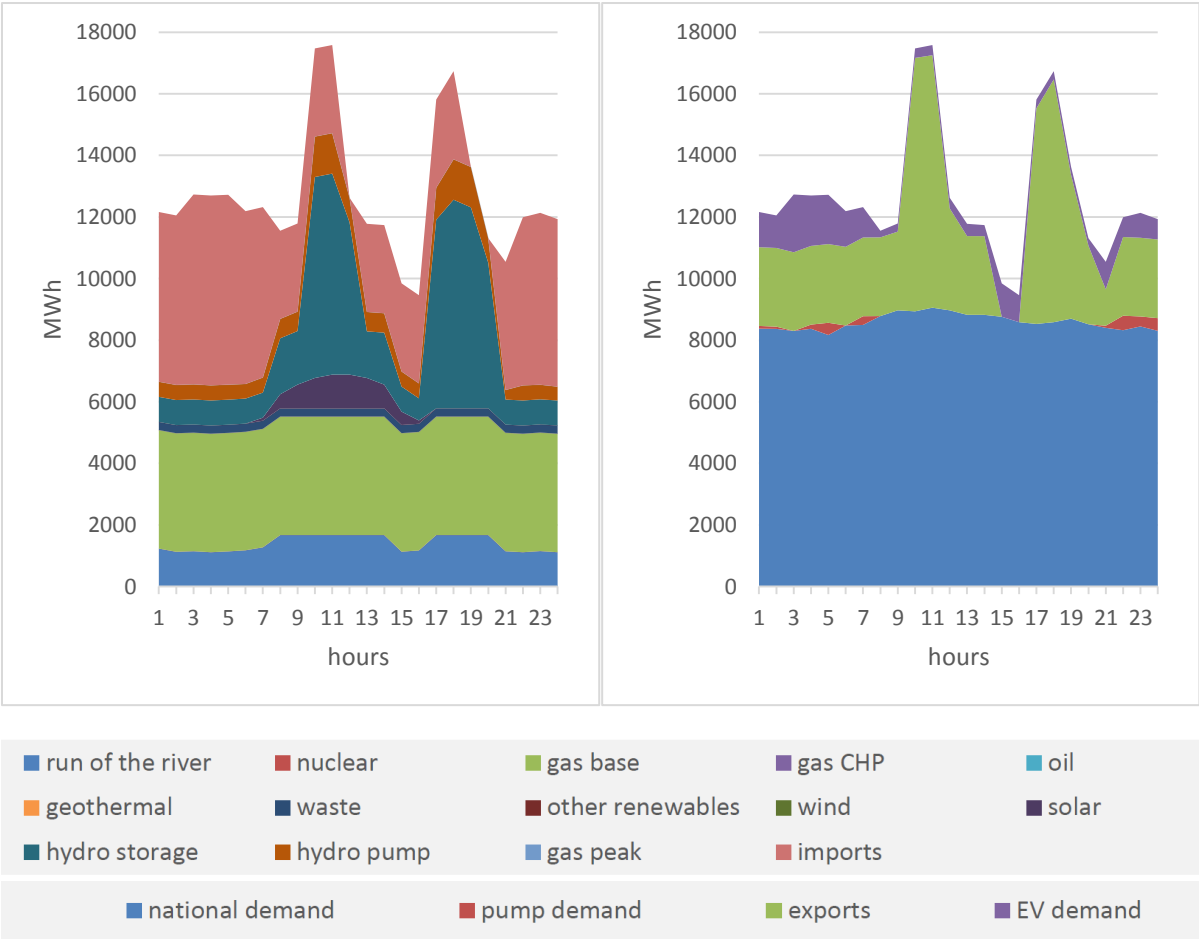

Figure 4.16 Supply (left) and demand (right) mix for the scenario POM-Base/directly controlled charging/60% EV penetration/winter.

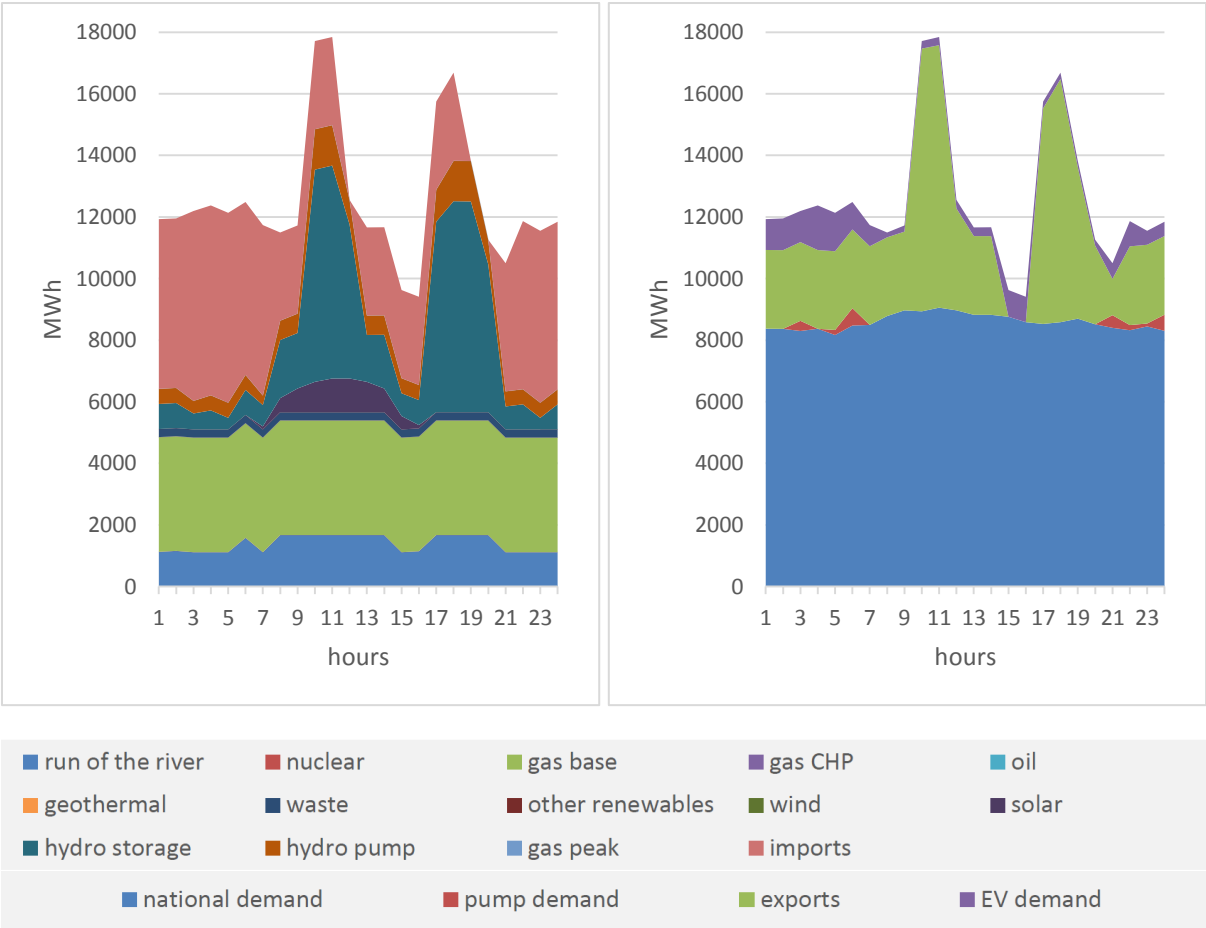

Figure 4.17 Supply (left) and demand (right) mix for the scenario POM-Base/directly controlled charging/30% EV penetration/winter.

We also compare the results of the no-EV penetration case with the different EV cases to establish the marginal technologies that cover the EV demand. In the Base supply scenarios these are primarily gas baseload or peak plants, and partly solar and waste. In the RES supply scenarios the marginal technologies are waste and solar. In the Nuc supply scenarios the marginal technologies are primarily, nuclear and gas baseload, and partly waste and solar. An increase in solar generation in the mix compared to the no-EV case means that more of the solar production potential can be used, i.e. less solar power needs to be curtailed compared to the case without EVs. In some cases the presence of EV charging leads to more curtailment of solar power, typically in the uncontrolled or indirectly controlled charging scenarios. This can be due to internal congestions created by the exogenous EV demand.

4.5.7.3. Asset loading

The increase in average asset (lines and transformers) loading is minor, around 0.01% additional loading, for all of the EV penetration scenarios, compared to the no EV penetration case.

4.5.7.4. Ancillary service potential

For the controlled charging scenario we establish the available potential to provide secondary frequency control, by increasing the provided capacity in 10 MW increment steps until the problem becomes infeasible. Since this potential depends primarily on the charging flexibility, and not on the demand and supply scenarios, we perform this analysis for the POM-Base scenario only. Results are

reported in Table 4-1 and Table 4-2, with and without using V2G, respectively. Given that the currently required capacity for secondary frequency control is 400 MW, it can be seen that a substantial portion of this service could potentially be provided by EV fleets, especially if V2G is used. The reported capacities correspond to approximately 0.4 kW per vehicle with V2G and 0.3 kW without V2G, i.e. around 10% of the nominal power of the EV.

In some of the scenarios, when V2G is available, the potential is slightly higher in the summer, where EV demand is lower because of the lower consumption of auxiliaries. This can be interpreted as demand being more flexible in the summer. Without V2G we find the opposite, the potential is sometimes higher in the winter. This is because without V2G, total charging needs to be at least as high as the offered capacity at all times. In this case it can be more beneficial to have a higher total demand, as it is the case in the winter.

Although V2G allows for a higher potential, it could lead to higher battery degradation costs, further analyzed in section 4.7.3.

Table 4-1: Potential to provide secondary frequency control using V2G.

EV penetration scenario	Winter	Summer
30%	190 MW	200 MW
60%	260 MW	260 MW
90%	280 MW	290 MW

Table 4-2: Potential to provide secondary frequency control without using V2G.

EV penetration scenario	Winter	Summer
30%	140 MW	140 MW
60%	190 MW	190 MW
90%	200 MW	190 MW

4.6. Distribution system (Task 1)

4.6.1. Inputs/system description

BKW provided a model of its 16 kV distribution network embedded in the power flow software Neplan. Also load measurements at the feeders for the year 2013 were provided, as well as the peak power at individual nodes. The feeder-level profiles were scaled down to the downstream nodes according to the nodes' peak power. To determine the projected load (active and reactive) in 2035, the 2013 profiles were scaled according to the load evolution of the given demand scenario (NEP, POM, BAU). Moreover, the total PV production of the distribution network considered was obtained from the total PV production in Switzerland, by considering the irradiance and area values of the municipalities covered by the distribution network in relation to those values for the totality of municipalities. The total PV production of the distribution network was distributed to the individual nodes in proportion to their load. The charging load results computed in the transmission system simulations described in Section 4.5 were mapped down to the distribution network. Then, the vehicle load was added to the projected future load, and power flow simulations were run with Neplan.

A schematic representation of the grid can be seen in Figure 4.2. The network comprises 1487 nodes, 3632 lines and 29 transformers (from 16 kV to 50 or 132 kV).

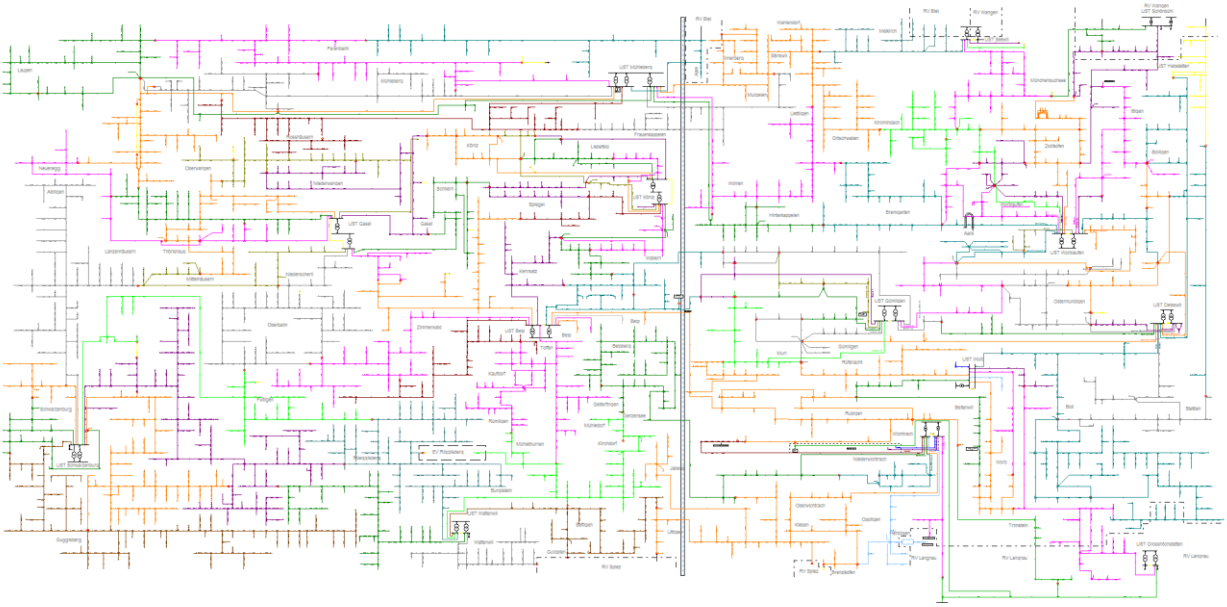

Figure 4.18 Schematic representation of BKW's 16kV network

4.6.2. Results

Since the distribution grid simulations are computationally expensive, we focused on the controlled charging scenario(González Vayá et al., 2012), and only simulated the other charging scenarios for a subset of the demand/supply scenarios (POM-Base/POM-Nuc/BAU-Res).

Figure 4.19 shows the number of vehicles parked in the simulated distribution network and in the whole country. It can be seen that patterns are similar. However, for the distribution network there is a more pronounced peak in the morning than at national level.

Figure 4.20 shows the aggregated net[30] load profiles of the distribution system nodes for the POM-Base demand/supply scenario combined with the 90% EV scenario, for a winter and summer day. The PV production within the network is also depicted. Note that the structure of the demand without EV is different to the national demand, which is shown in section 4.5.7.2. Since the directly controlled charging is optimized taking into account the supply/demand characteristics of the whole country, it does not necessarily lead to optimal outcomes at the distribution level. As can be seen in Figure 4.20, the total load is sometimes higher with directly controlled charging than with uncontrolled charging. This is because load is "synchronized" through controlled charging, i.e. the simultaneity of EV loads is increased during some hours, compared to uncontrolled charging, which is related to the random process of EV arrivals. With indirectly controlled charging, the synchronization effect becomes more pronounced, leading to increased peaks. With directly controlled charging this effect could be mitigated by introducing additional layers of control (hierarchical control) which would also address issues at the distribution level. However, this problem would persist with indirectly controlled charging. Therefore TOU tariffs would not be suitable at high EV penetrations

[30] Net load: the PV production has been subtracted from the actual load.

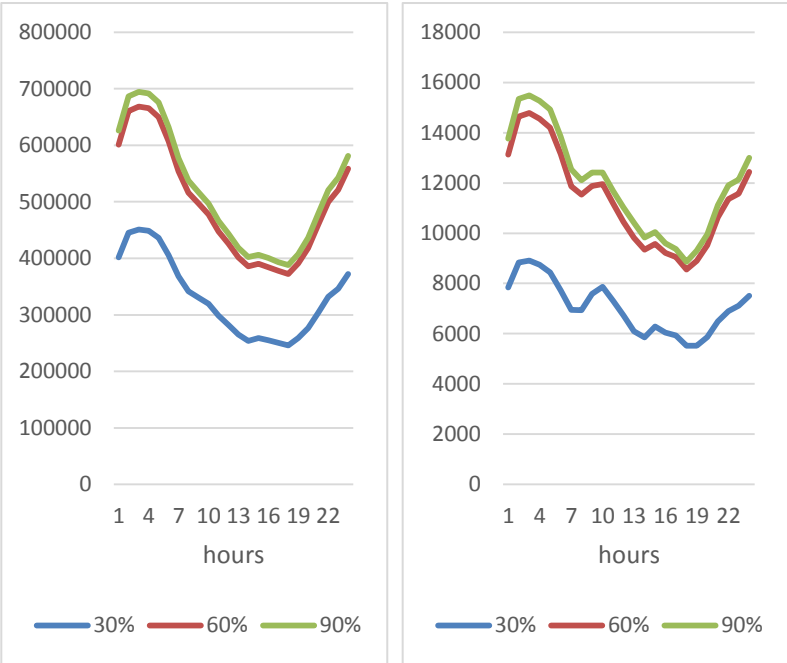

Figure 4.19 Number of connected vehicles in Switzerland (left) and in the simulated distribution area (right).

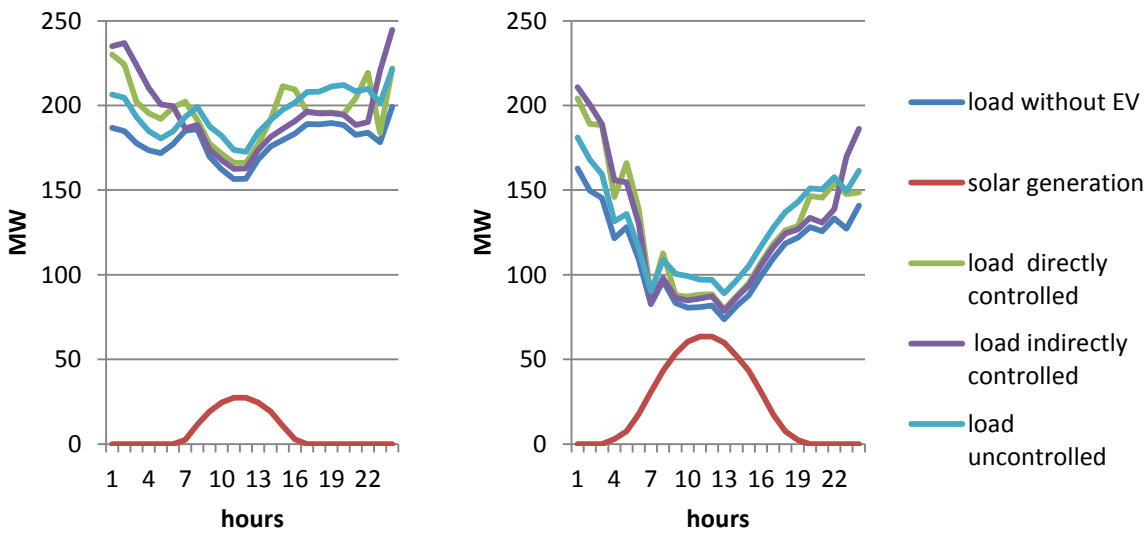

Figure 4.20 Net load profiles for the POM-Base/ 90% EV scenario, for different charging types on a winter (left) and summer (right) day. The load profiles are the net load profiles, i.e. they already incorporate the PV production as negative load.

From Table 4-3 and Table 4-4, displaying the increase in line and transformer loading, it can be seen that the impact of EV charging on infrastructure is minor, on average. Figure 4.21 and Figure 4.22 show the loading of individual lines and transformers, respectively, on a winter day for the POM-Base scenario, with no EVs and with directly controlled charging. It can be seen that, with respect to the no EV case, loading increases especially at night. The impact on some lines is minor, whereas others are more affected. This is related to the spatial distribution of charging vehicles. Figure 4.23 and Figure 4.24 show the loading of lines and transformers, respectively, on a winter day for the POM-base scenario with uncontrolled charging and indirectly controlled charging. With indirectly controlled charging loading peaks occur at night, whereas with directly controlled charging the loading increase is more evenly distributed. Table 4-5 shows in which scenarios overloads occur. In all

cases only a single line is concerned and it occurs in the winter, when demand is highest. Note that the indirect control and direct control charging scenarios were only run for a subset of supply/demand scenarios, so results are not completely comparable: Although more cases with violations are listed for direct control, this is just because this charging approach was thoroughly analyzed. However, Table 4-5 already indicates that indirect control (TOU tariff) is the approach that can potentially lead to more problems, since it presented overloads for all instances simulated at the 60% and 90% EV penetration scenarios in winter. This can be explained by the high EV load simultaneity during low-tariff hours. It is also interesting to note that at some scenarios overload occurs with the 60% EV penetration scenario but not with the 90% EV penetration scenario (e.g. POM-Base and direct control). This shows that overload with direct control is a matter of how the EV load is shaped because of the general country-wide supply/demand characteristics, and that it could also be shaped in a way that does not cause problems at the distribution level. Table 4-4 also gives an insight on why overloading occurs more often with controlled charging. It can be seen that although the mean increase in loading is practically the same in all scenarios (since an almost identical amount of energy is charged in each of them for a given day), the standard deviation is higher for directly controlled charging and even more for indirectly controlled charging, indicating a less smooth load profile (more peaks).

Table 4-3 Increase in loading due to EV charging (directly controlled charging scenario).

	Penetration scenario		
	30%	60%	90%
Lines (mean/s.d.)	0.4% / 1.2%	0.6% / 1.7%	0.6% / 1.7%
Transformers (mean/s.d.)	1.1% / 2.2%	1.6% / 3.3%	1.7% / 3.4%

Table 4-4 Increase in loading due to EV charging (POM-Base/POM-Nuc/BAU-Res).

	Penetration scenario								
	30%			60%			90%		
	No control	Direct control	Indirect control	No control	Direct control	Indirect control	No control	Direct control	Indirect control
Lines (mean/s.d.)	0.4% / 0.9%	0.4% / 1.2%	0.4% / 1.3%	0.6% / 1.2%	0.6% / 1.7%	0.6% / 1.8%	0.6% / 1.2%	0.6% / 1.7%	0.6% / 1.8%
Transformers (mean/s.d.)	1.2% / 1.5%	1.1% / 2.2%	1.1% / 2.4%	1.7% / 2.1%	1.6% / 3.3%	1.6% / 3.7%	1.8% / 2.2%	1.7% / 3.4%	1.7% / 3.8%

Table 4-5 Line overloads due to EV charging. Uncontrolled charging and indirectly controlled charging were only simulated for the demand-supply combinations POM-Base/POM-Nuc/BAU-Res.

Season	EV penetration	Charging scenario	Demand scenario	Supply scenario	Overloaded lines	m to be replaced
winter	60	direct control	NEP	Base	1	322
winter	60	direct control	NEP	Res	1	322
winter	60	direct control	POM	Base	1	322
winter	60	direct control	POM	Res	1	322
winter	60	direct control	BAU	Base	1	322
winter	60	direct control	BAU	Nuc	1	322
winter	60	direct control	BAU	Res	1	729
winter	90	direct control	NEP	Base	1	322
winter	90	direct control	NEP	Res	1	322
winter	90	direct control	POM	Nuc	1	729
winter	90	direct control	POM	Res	1	729
winter	90	direct control	BAU	Base	1	322
winter	90	direct control	BAU	Nuc	1	322
winter	90	direct control	BAU	Res	1	729
winter	60	no control	BAU	Res	1	322
winter	90	no control	BAU	Res	1	322
winter	60	indirect control	POM	Base	1	322
winter	60	indirect control	POM	Nuc	1	322
winter	60	indirect control	BAU	Res	1	729
winter	90	indirect control	POM	Base	1	729
winter	90	indirect control	POM	Nuc	1	729
winter	90	indirect control	BAU	Res	1	729

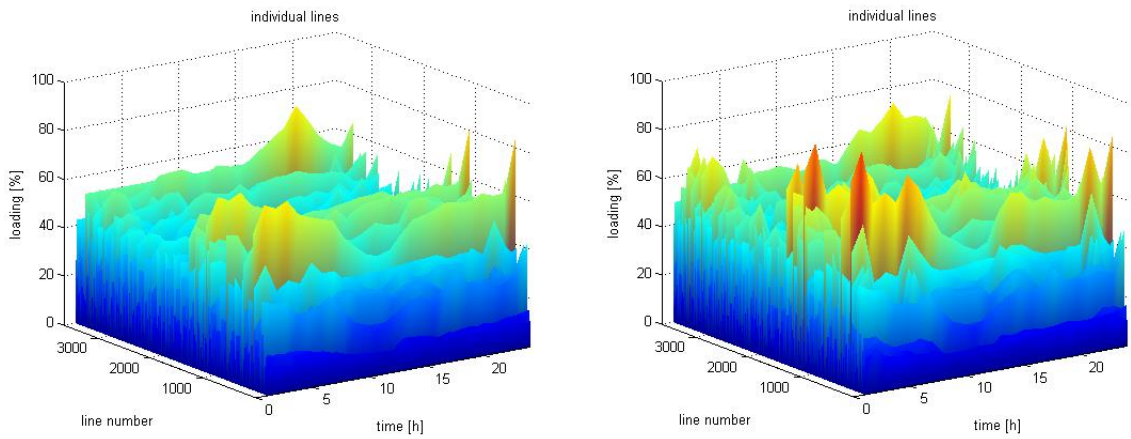

Figure 4.21 Line loading without EVs (left) and in the 90% penetration scenario (right), for the POM-Base scenario with controlled charging on a winter day.

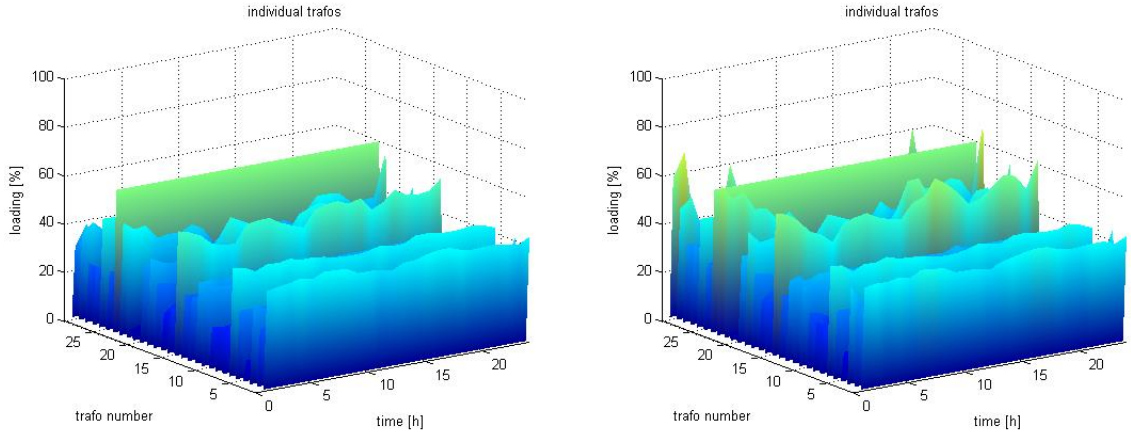

Figure 4.22 Transformer loading without EVs (left) and in the 90% penetration scenario (right), for the POM-Base scenario with controlled charging on a winter day.

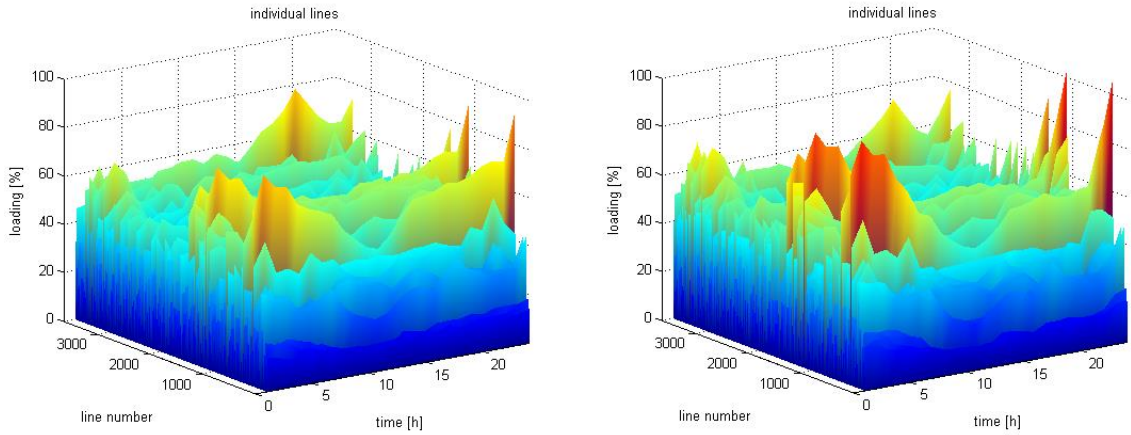

Figure 4.23 Line loading with uncontrolled charging (left) and with indirectly controlled charging (right) in the 90% penetration scenario, for the POM-Base scenario on a winter day.

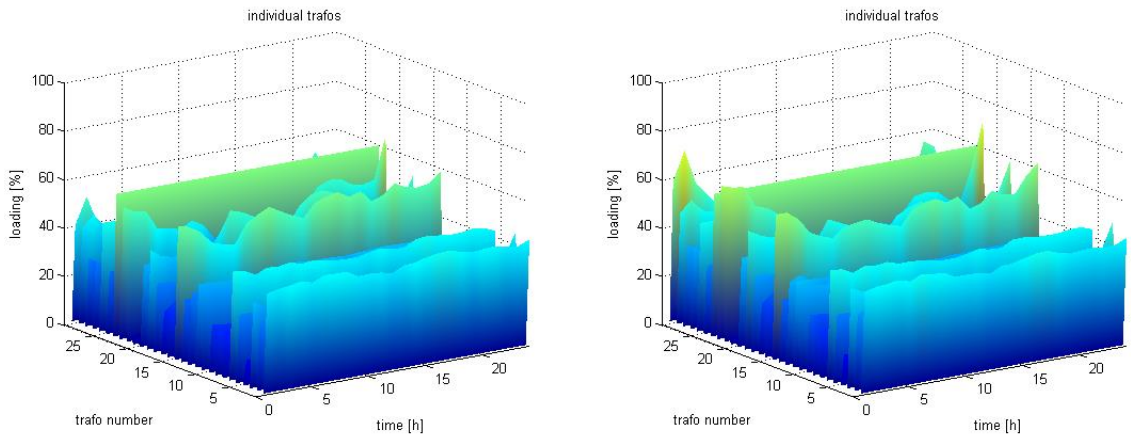

Figure 4.24 Transformer loading with uncontrolled charging (left) and with indirectly controlled charging (right) in the 90% penetration scenario, for the POM-Base scenario on a winter day.

In none of the cases an under voltage was identified, i.e. a drop by more of 5% from the nominal voltage. Therefore voltage problems do not seem to be a major concern. Note that the results shown here are for a particular network, results could be different for other distribution networks that are currently closer to their limits. The network simulated was not heavily utilized, so it could easily host

a large number of EVs without major concerns. However, local congestions can occur at areas with higher EV density.

4.7. Battery model (Task 3 and 5)

4.7.1. Inputs

The SOC profiles for each vehicle are derived from the transmission system simulation, see 4.5.3 and 4.5.6. Out of these and some battery parameters introduced in the next subsection, battery degradation can be computed.

4.7.2. Battery degradation model

To assess battery degradation we use the model proposed in(Millner, 2010), based on crack propagation (Karagiannopoulos, 2012). Battery damage is typically represented by a single parameter, denoted L in the following, running from 0, for a new battery, to 1, when no capacity is left. The end of life of a battery is usually defined as the time when the capacity of the battery is reduced to 80% of its original capacity *(*$L = 0.2$).

The factors defined in Table 4-6 are computed according to the model proposed in Millner (2010) to take into account battery degradation.

Table 4-6: Input parameters for battery degradation model

The average SOC	The normalized deviation of the state of charge from its mean over a cycle period	The effective number of throughput cycles
$SOC_v^{\text{avg}} = \frac{1}{T}\sum_{t=1}^{t=T} SOC_{vt}$	$SOC_v^{\text{dev}} = 2\sqrt{\frac{3}{T}\sum_{t=1}^{t=T}(SOC_{vt} - SOC_v^{\text{avg}})^2}$	$N_v = \frac{1}{2}\sum_{t=1}^{t=T}\frac{\lvert P_{vt}^{\text{V}}\rvert \Delta t}{C_v^{\text{V}}}$

The additional ageing incurred in a cycle ΔL_v is given by the equation

$$\Delta L_v = \left(K^{\text{co}} N_v \mathrm{e}^{\left(\frac{SOC_v^{\text{dev}}-1}{K^{\text{ex}}}\frac{T^{\text{nabs}}}{T^{\text{a}}}\right)} + 0.2\frac{t^{\text{cycle}}}{t^{\text{life}}}\right) e^{\left(\frac{K^{\text{soc}}\left(SOC_v^{\text{avg}}-0.5\right)}{0.25}\right)}(1 - L_v) e^{\left(K^{\text{temp}}\left(T^{\text{a}}-T^{\text{nabs}}\right)-\frac{T^{\text{nabs}}}{T^{\text{a}}}\right)}, \quad (26)$$

Where K^{co}, K^{ex}, K^{soc}, and K^{temp} are battery parameters, T^{a} and T^{nabs} are the battery and nominal temperatures in Kelvin and t^{cycle} and t^{life} the duration of the cycle and the battery shelf life. Since the battery temperature is not known, we make the simplifying assumption that it is equal to the nominal temperature $T^{\text{a}} = T^{\text{nabs}}$ and therefore do not to consider the temperature-related degradation. The equation above simplifies to:

$$\Delta L_v = \left(K^{\text{co}} N_v \mathrm{e}^{\left(\frac{SOC_v^{\text{dev}}-1}{K^{\text{ex}}}\right)} + 0.2\frac{t^{\text{cycle}}}{t^{\text{life}}}\right) e^{\left(\frac{K^{\text{soc}}\left(SOC_v^{\text{avg}}-0.5\right)}{0.25}\right)}(1 - L_v). \quad (27)$$

It can be seen that high and low average SOC are penalized, as well as large deviations of the SOC from the average SOC. We define ageing acceleration as the ratio between ΔL_v and $0.2\frac{t^{\text{cycle}}}{t^{\text{life}}}$, which would be the degradation due purely to the passing of time, without using the battery, at 0.5 average SOC.

4.7.3. Results

As explained in 4.5.3, when no reserves are provided by the fleet, it is assumed that the maximum SOC, 0.8 in our simulations, is reached at some point. To be able to provide reserves, the aggregator will schedule a lower average SOC, see 4.5.5. Moreover, to respond to the frequency regulation requests (AGC signal) by the TSO, the SOC dispatched in real time will deviate from the scheduled SOC, see 4.5.6. These different average SOCs for the fleet are shown in Figure 4.25. The SOC deviations to respond to the AGC signal were computed for 7 samples of daily AGC signals. It can be seen that deviations from the scheduled profile are minimal for these samples

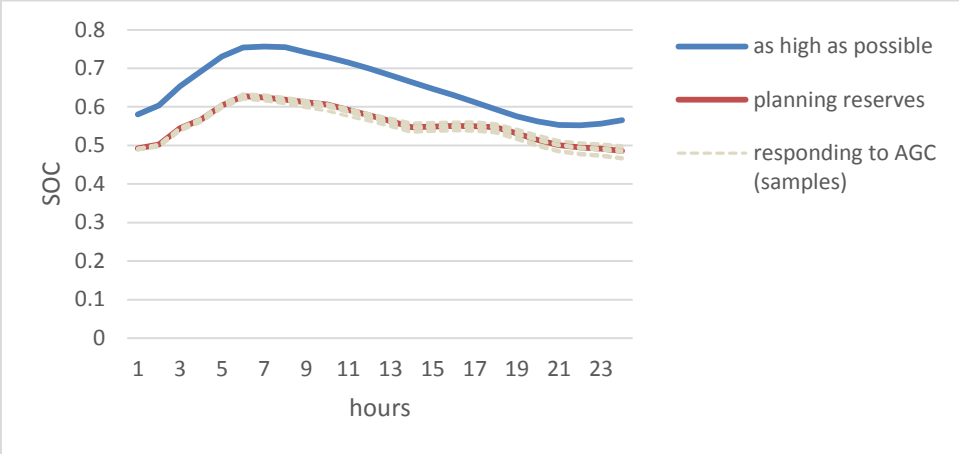

Figure 4.25 Average SOC across the fleet.

Table 4-7 shows the ageing acceleration for the different cases. The total amount of provided reserves corresponds to the values reported in Table 4-1 for each of the cases. It can be seen that actually providing reserves leads to lower battery degradation. This is because the average SOC will be closer to 0.5, whereas without providing reserves, the SOC is kept as high as possible by assumption. We set this reference because a high SOC is more convenient for users: They have a lower risk of having a battery without enough energy when spontaneously deciding to drive. If battery degradation were the major priority, then the battery degradation could be reduced by a different charging policy optimization. The effect of degradation when responding to AGC, compared with the ageing with the reference SOC scheduled when planning reserves, is not visible at least for the 7 samples analyzed. It is possible that for some days with more extreme AGC requests the impact is larger, but in general it does not seem to be a problem.

Table 4-7 Ageing acceleration with and without AGC provision

EV penetration scenario	Winter			Summer		
	as high as possible	planning reserves	responding to AGC	as high as possible	planning reserves	responding to AGC
30%	2.2	1.6	1.6	2.1	1.5	1.5
60%	2.2	1.6	1.6	2.1	1.6	1.6
90%	2.2	1.7	1.7	2.2	1.6	1.6

4.8. Transformer model (Task 3)

4.8.1. Inputs

The main inputs to this model are the loading profiles of the transformers modeled in the transmission system model (220 kV/380 kV transformers) and the distribution system model (16 kV/132 kV and 16 kV/50 kV transformers), described in sections 4.5 and 4.6, respectively.

Moreover, the season-dependent ambient temperature also needs to be taken into account. For the transmission network, the average seasonal temperatures of the weather station situated closest to the transformer were computed. For BKW's distribution network the weather station located in Bern was chosen as a reference for the temperature. Figure 4.26 shows the summer temperature profiles.

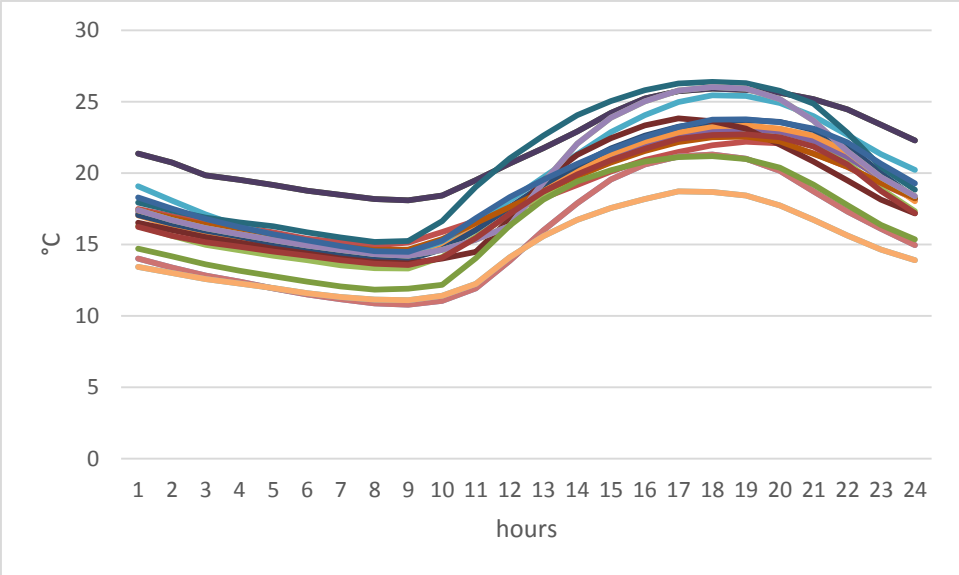

Figure 4.26 Summer ambient temperature profiles for transformers at different locations.

4.8.2. Transformer degradation model

The transformer degradation model (Konzak, 2011) is based on IEEE and IEC standards (Institute of Electrical and Electronics Engineers, 2012, International Electrotechnical Commission, 2005). First, the hot-spot temperature of the transformer needs to be computed. Then, the degradation is computed based on this temperature.

The hot-spot temperature is computed given the loading of the transformer, the ambient temperature and a set of transformer parameters. For this purpose the equations in Appendix C of the IEC standard (International Electrotechnical Commission, 2005) were used. Typical power transformer parameters for the ONAN cooling class were selected from Table E.1 in International Electrotechnical Commission (2005). This is the typical cooling class of BKW's transformers. For the sake of simplicity, the same parameters were used for the transmission system transformers, in spite of the fact that their cooling class is unknown.

Once the hot-spot temperature is determined, the transformer loss of life is computed with the following equations from the Institute of Electrical and Electronics Engineers (2012).

The ageing acceleration factor F_t^{AA} is obtained from the hot-spot temperature θ_t^{H} at time t with the exponential relation

$$F_t^{\mathrm{AA}} = \exp\left(\frac{1500}{273+110} - \frac{1500}{273+\theta_t^{\mathrm{H}}}\right). \tag{28}$$

The loss of life for a representative day is computed as:

$$LOL = \frac{\sum_{t=1}^{24} F_t^{\mathrm{AA}}}{\text{normal insulation life [h]}} \tag{29}$$

4.8.3. Results

4.8.3.1. Transmission grid

The transformers analyzed in this case are the transformers between the two voltage levels of the transmission system, i.e. 220 kV and 380 kV. We do not have information on the transformers to lower voltage levels. The model explained in this section assumes that the "normal" ageing, leading to an ageing acceleration factor of 1 at nominal loading, occurs at 20°C ambient temperature. Since temperatures in Switzerland are lower on average in most locations, even in the summer (see Figure 4.26), we obtain average acceleration factors much lower than 1. Note the exponential relationship between ageing and temperature of (8). For the transmission system the ageing was found to be in all cases lower than 0.05. Therefore the thermal insulation ageing does not seem to be a relevant factor in the replacement of the transformers, and comparisons between the no EV and EV penetration cases to assess potential additional costs due to earlier transformer replacement are thus irrelevant.

4.8.3.2. Distribution grid

Here the 16 kV/132 kV and 16 kV/50 kV transformers were analyzed. Due to low temperatures and low loading (see Figure 4.22), the ageing acceleration factors are even lower than in the transmission grid simulations, and therefore the comparison between no EV and EV scenarios is not meaningful.

4.9. Restoration (Task 6)

Restoration is the process of re-establishing a stable electric system after a blackout. Although different restoration strategies exist, in general terms, the following steps are gone through: first the blackstart-capable generator(s) re-energize the transmission system, or parts of it operated as islands, then loads and other generators are connected, and finally synchronization takes place.

It can be noted that the restoration process typically starts in the transmission system, thanks to generators with specific characteristics to be able to conduct this task. Since vehicles are located at the distribution network, their contribution to the restoration process cannot be comparable with that of traditional generators. However, EVs can help mitigate a phenomenon that occurs during restoration, specifically when loads are reconnected, and that presents a challenge for this process: Cold-load pickup (CLPU) (Zigkiri, 2013). CLPU refers to the phenomenon whereby the load, when reconnected after an interruption, can be significantly different in size and character than before the interruption: Residential load is typically higher after reconnection, whereas industrial load is typically lower (Agneholm and Daalder, 2000). The load increase can be partially explained by the loss in load diversity. For example, thermostatically controlled loads could all be activated after the interruption if they have moved outside their temperature deadband during that period.

Similarly to what has been explained in the context of ancillary services in 4.5.4, in the load-reconnection phase of restoration the EV charging/discharging could be controlled in order to follow

a given profile. This profile would be given by the difference between the normal load and the post-blackout load, thereby compensating the CLPU effect.

Further, there exist new approaches that propose a restoration process at the level of microgrids (Moreira et al., 2007).

Definition of microgrid from U.S. Department of Energy (Office of Electricity Delivery and Energy Reliability, 2011)
A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.

Within the microgrid restoration process, EVs could play an important role(Gouveia et al., 2013). However, specific voltage and frequency regulation strategies, coordinating the flexible resources of the microgrid need to be defined. EVs could be an important player in maintaining the frequency at acceptable levels with an active power/frequency droop controller, i.e. the EVs would adapt their charging or even discharging in accordance to the measured frequency. This droop control is active during the normal operation of the microgrid, and is modified in the restoration phase, so that the reference power consumption of the droop is zero. Thereby EVs can reduce the frequency deviations and the need to use of other storage devices during restoration. The implementation of this method was out of the scope of THELMA, but we refer to Gouveia et al. (2013) for detailed simulation and experimental results.

4.10. Conclusions

The results reported of WP4 suggest that, under the conditions assumed in the demand, supply and EV penetration scenarios, EVs could be integrated into power systems without any major impact for the electricity supply side, as well as the transmission and distribution networks. EV demand would represent a small share of total demand and does therefore not affect the supply mix significantly nor does it have a major impact on the power flows at the transmission system level. Distribution networks have different characteristics (e.g. rural vs. urban networks) and loading situations. Moreover, the penetration of EVs could be higher in specific areas than in others. Therefore, for distribution networks, the impact assessment should be done on a case by case basis. Moreover, EV charging is a very flexible load that can be shaped to reduce the costs of generation, to avoid congestions and even to provide network ancillary services. EVs could for example contribute significantly to the provision of frequency regulation. EVs could also potentially play a role in system restoration after a blackout.

4.11. Recommendations for Future Work

First, it would be interesting to integrate the needs of the distribution network in the controlled charging approach. This could be done by introducing additional control loops within a hierarchical control framework.

Second, it would be interesting to model imports and exports as endogenous parameters within the model, e.g. by assuming electricity prices for the neighboring countries.

Finally, it would be interesting to develop a more detailed battery degradation model. Within the project it was only possible to use a model available in the literature.

Acronyms

AGC	Automatic Generation Control
BAU	Business As Usual
CHP	Combined Heat and Power
EV	Electric Vehicle
LFC	Load Frequency Control
MATSim	Multi-Agent Transport Simulation Model
NEP	New Energy Policy
OPF	Optimal Power Flow
POM	Political Measures
PSI	Paul Scherrer Institute
PV	Photovoltaic
RES	Renewable Energy Sources
SOC	State of Charge
TOU	time-of-use
TSO	Transmission System Operator
V2G	Vehicle to Grid
WP	Work Package

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5. Work Package 4 "Case Studies"

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5.1. Introduction

Work Package 4 examines mobility on several scales. It examines mobility and how it relates to household consumption, and performs two small scale community case studies. Furthermore, it uses the Multi-Agent Transport Simulation Model (MATSim) to simulate current and future individual mobility.

Energy is a key factor for economic and societal development. However, the dependence of today's energy systems on fossil or on other non-renewable energy sources causes a range of adverse environmental impacts. The built environment with its associated heating and cooling loads, as well as the mobility sector are major energy consumers. In Switzerland, about 80% of the heating systems are based on fossil fuels and 96% of the mobility energy demand is covered by oil products or natural gas (Swiss Federal Office for Energy, 2012). Therefore, assessing and understanding environmental footprints of housing and mobility is essential to identify strategies for a sustainable development of urban settlements and for the abatement of negative energy-related effects. This analysis should preferably be done on a household level as many decisions, e.g. about the choice of private vehicles or heating systems, are taken on this level.

Furthermore, household consumption, apart from governmental consumption, is the main driver of worldwide economy. Consequently, approximately 72% of greenhouse gas (GHG) emissions are directly or indirectly related to household demand (Hertwich and G.P.Peters, 2009). But then, from an urban planning and policy making point of view, the household-based analysis has to be extended to a district or municipality perspective. It is at these levels that many important decisions are made, concerning, e.g. regulations for building design, the construction of district heating networks, or the financial support for electric vehicles or for private refurbishment initiatives. As a consequence, there is a need for regionalized bottom-up models which aggregate household focused analyses in order to reach an effective level of political decision making.

Many existing regional environmental studies, such as analyses focusing on countries and whole economies, typically do not build on the evaluation of single households' behavior. Previous models which attempt to analyze and evaluate the environmental impacts of anthropogenic systems and especially of household consumption are primarily based on input-output-analyses (Hertwich and G.P.Peters, 2009, Hertwich, 2011, Tukker et al., 2006, Jungbluth et al., 2011). Even though these approaches allow for a comprehensive environmental evaluation of consumption of national average citizens and for the identification of the environmentally most relevant consumption areas, they are

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not able to capture the variation in behavior of different households within a region or a municipality.

A suitable method for environmental analyses is life cycle assessment (LCA), because this methodology is able to assess resource uses and emissions along the supply chain which is attached to each household purchase. A holistic view in terms of a life cycle based approach is a substantial prerequisite in order to perform comprehensive environmental assessments and to derive design opportunities for more sustainable urban energy systems. Building on the concepts of LCA, life cycle optimization is a powerful tool which can assist in revealing the theoretically best way for the improvement of a specific urban energy system. In contrast to traditional comparative LCA, life cycle optimization offers the advantage of not only comparing different alternatives but to find environmentally optimal solutions, e.g. in the context of scenarios of future energy supply.

Work Package 4 (WP4) uses transportation data generated by the Multi-Agent Transport Simulation Model (MATSim) to perform small scale community case studies. The LCA of mobility patterns on the household level is enhanced with analyses of housing. This leads to a holistic picture of diverse household consumption patterns. The LCA model is capable of not only assessing the current situation but also future changes in mobility supply (such as the introduction of electric vehicles), by incorporating behavioral modeling into MATSim. Multiple advances in this field have been achieved. A fleet choice model for households has been implemented in MATSim for all of Switzerland. This model predicts the number of cars in a household, the type of these cars and the usage of the cars measured in vehicle miles travelled per year. All predictions are based not only on socioeconomic household characteristics but also on fuel price. This makes the model a useful tool in forecasting the prospective fleet composition. Another long-term investment decision model for homeowners was established. Using a multiple discrete-continuous choice approach, it predicts household reductions in the transportation, housing, or other sectors when overall energy consumption is constrained. The output data of this extended MATSim is processed by the LCA model and used for prospective optimization of consumption supply under regional constraints. MATSim runs were also performed in collaboration with WP 3, based on test data containing patterns on energy consumption for each electric vehicle and each trip, as well as detailed information on parking location, parking times and activity types (e.g. work, home, education, etc.). At a later stage of the project, the scope of WP4 has been widened to include the forecast of future mobility patterns and travel demand in Switzerland for 2030 using MATSim. Following the same scheme as for the rest of WP4, these forecasts are used in WP4 for environmental assessment of future mobility in regional case studies, and in WP 3 and WP 5 to estimate the geographical and temporal distribution of additional loads on the electric grid due to Electric Vehicle (EV) penetration into the Swiss fleet. For this purpose, a new MATSim population of agents was created, based on the latest forecasts by the Swiss Federal Statistics Office, in particular the medium scenario for 2030 of 8.7 million inhabitants. Population distribution on the municipal level is based on predictions made by the Federal Office for Spatial Development. Population data is enhanced with information on driver's licenses and household income trends that influence car choice and transportation spending. Transport infrastructure in 2030 is also implemented into MATSim based on national and cantonal projects to which the relevant administration has committed. Future population, car ownership, individual mobility spending and transport infrastructure are then used in MATSim to generate future Swiss mobility demands and patterns.

5.2. Objectives

WP4 was subdivided in three tasks reflecting three specific objectives. Task 1 had the objective to integrate energy supply and demand into an energy system model for Swiss municipalities. The primary focus was the environmental assessment and optimization of future energy systems, with a focus on electric mobility.

To expand the multi-agent based transport model MATSim, representing travelers as agents, by a financial household-budget allocation model to better simulate individual mobility demand for various activities and the associated energy requirements for transportation was the main objective of Task 2.

With task 3, work package 4 includes also the development of a 2030 Switzerland scenario for the agent-based micro-simulation MATSim and dedicated policy runs specified within the capabilities of MATSim by the PSI.

The objectives of task 1 can be further subdivided in 3 sub-objectives which are: (i) the assessment of individual mobility as well as the evaluation of its impacts on the environmental footprints of households on a regional as well as local level, and (ii) its relevance in the broader context of household consumption. In order to achieve these objectives, current household consumption patterns were analyzed by two modules being both based on LCA methodology. Besides the environmental assessment of mobility behavior, a predictive building stock model was developed to evaluate the environmental footprint of individual housing. As a further goal of WP4, (iii) the application of optimization tools shall reveal environmentally optimized scenarios for future energy systems of Swiss municipalities. Building upon the assessment of current housing energy demand, a LCA based optimization approach was elaborated in order to minimize building related environmental impacts by optimizing the energy supply through alternative technologies and refurbishment measures.

To achieve the objectives of task 1, it was necessary to create a model framework that would accurately reflect patterns in the interdependency of household expenditure categories to be able to make predictions how price and expenditure (or income) changes influence the total household budget. That was done in task 2. Therefore, the main objective of task 2 was to create a model able to predict the share and amount of household expenditure on transport and communication of a given household, based on its geographical and socio-economic characteristics as well as on the expenses of other categories. Such a model could be applied for example to assumed changes in prices or expenditures in certain household categories and a prediction for the expenditures on transport or communication could be derived from that, which is assumed to affect overall travel demand. A hypothetical example of such a mechanism could be, that an increase in alcohol and tobacco prices (e.g. through taxes) would increase the expenditure of said category and negatively influence the transportation category (e.g. through an income effect that would leave less money in the budget for transportation), which would depress travel demand. The simulation MATSim was used as a platform in which the model was implemented. It was therefore necessary to further develop MATSim which translates in two additional sub-objectives. The first regards the assignment of car types to the agents in MATSim. A household structure had to be created, since cars are generally shared between household members. The second was to create interfaces in order to be able passing the MATSim output to the power system model developed by the Power Systems Laboratory of ETHZ (ETHZ-PSL) within WP3.

Task 3 dealt with the forecast of future mobility patterns and travel demand in Switzerland for 2030. The main objective here was to be able to perform the same kind of analyses as for the scenario representing the present situation (2005 later updated to 2010). This implied the creation of a population of agents for MATSim, which represented the Swiss population in 2030 and the extension of the road network to reproduce foreseeable 2030 conditions.

An important aim of WP4 is a close linking of the developed models and real world conditions. Therefore, all of the developed models and tools were applied to case studies. Working with primary data within these case studies not only allowed for the consideration of local restrictions and supported thus the development of more realistic models, but it allowed also for the evaluation and validation of submodules such as the housing energy demand model.

The results of all subtasks contribute finally to the overall goal which is the development of a decision-support framework and analysis tool for energy-related decision-making and policy measures on a regional level.

5.3. Scope

The scope of the research was different for the different tasks. In particular, the extensions of MATSim and the models attached to it had a larger scope than the LCA based models, which rather focused on specific case studies. In a way, the scenarios for task 1 where cut out from the Swiss scenario.

5.3.1. Task 1

Even though mobility, housing and nutrition are almost equally important consumption areas with regard to their environmental impacts (Jungbluth et al., 2011, Jungbluth et al., 2012), the focus of this work package lies only on the housing and mobility sector. To calculate and assess all emissions and resource uses along the supply, use and disposal chains of a product or a service related to housing and mobility, the methodology of life cycle assessment was applied.

Temporal Scope

The temporal scope was generally the year 2010 except for future mobility scenarios which were based on predictions made for the year 2030. The temporal resolution of the applied models was on an hourly basis. This implied the flexibility to aggregate data over any discretionary time frame.

Case studies

Within the scope of this work package, two Swiss municipalities served as case studies for the application and the evaluation of the developed models.

1. Wattwil (SG)

This mid-sized municipality is situated in the eastern midlands of Switzerland in the canton of St. Gallen. Wattwil has around 8000 inhabitants living in 3238 households and in 1332 buildings. This case study substantially contributed to the development of the housing energy demand model. Furthermore, the optimization extension of the LCA model was also elaborated considering the local constraints of this municipality. The application of the LCA based optimization approach required however the following assumptions: the population of the municipality was presumed not to grow (as projected for this municipality), the building park would remain constant (since there were no

new building areas planned) and the demand for per-capita living space would remain constant as well.

2. Zernez (GR)

Zernez is a small municipality located in the Swiss Alps. Analogously to the case study of Wattwil, the household consumption comprising housing and mobility was environmentally evaluated. Moreover, a survey was conducted in the municipality in order to gather data on fuel oil consumption, used amount of wood chips and logs as well as on district heating and electricity demand (Wagner et al., 2015). Furthermore, the municipality supported the establishment of a database containing also detailed information on installed heating systems and different building characteristics. This unique set of data for each household and each building facilitated an in-depth evaluation of the applied housing energy demand model. Moreover, future mobility scenarios which were developed within THELMA-project were applied to the municipality of Zernez.

5.3.2. Task 2 and task 3

Temporal scope

The household expenditure model was estimated for the year 2010. For Task 3 the temporal scope is extended to 2030.

Territorial scope

All the models implemented and the simulation MATSim, cover the whole of Switzerland.

5.4. Data

LCA studies in general and our LCA model in particular rely on life cycle inventories. They exist for a multitude of consumption related activities and they include upstream processes and waste treatment. Ecoinvent, a well renowned life cycle inventory database, includes in its version 2.2 for instance 50 datasets for the generation of heat and 40 datasets for different means of private transportation (ecoinvent, 2012). These numbers will further increase in the future and also cover activities from other areas of consumption, which will allow detailed assessment of household consumption.

As a prerequisite to perform a life cycle assessment of individual mobility and housing, the corresponding demands had to be estimated. Space heating, hot water production and electricity were assessed using simplified energy balances and building-specific data as well as climate databases. Climatic data was generated with Meteonorm version 7 (Meteotest, 2012). Hourly outdoor temperature as well as direct horizontal and diffuse horizontal radiation were used as inputs for the calculation of space heat demand in buildings. All residential buildings situated within the borders of the spatial selection were considered for housing demand modeling. The data describing the buildings was extracted from the Federal Register of Buildings and Dwellings (FRBD) (Swiss Federal Statistical Office, 2013). The FRBD contains up-to-date data of all buildings and dwellings in Switzerland. The data we used were geographic references (i.e., longitude and latitude, altitude above sea level), building characteristics (i.e., year of construction, number of stories, number of apartments, energy source used for space heating and hot water supply), and characteristics of the building's apartments (i.e., total floor area, number of rooms). The building-specific data derived from FRBD was then supplemented and combined with statistical data from Wallbaum et al. (2010).

Mobility demands of households were deduced from the results of MATSim. The aggregation on household level was achieved by the assignment of MATSim-agents to household members based on information from the Swiss National Census (Swiss Federal Statistical Office, 2000)

For the household expenditure model, the data used in the analysis is data gathered by the Swiss Federal Office of Statistics (FSO) on a yearly basis between the late 90s and 2010. Every year around 3000 representative households were interviewed and surveyed in a mandatory survey about all their income sources and expenditures. The households had to fill out a very detailed diary about all incomes and expenses for all its members during one month. The main income categories are:

1. Income from employed labor
2. Income from self-employed labor
3. Income from renting
4. Income from wealth
5. Income from social benefits
6. Other transfer income

The main expense categories are:

1. Food and non-alcoholic beverages
2. Alcohol and tobacco
3. Clothes and shoes
4. Housing and energy
5. Furniture and general household expenses
6. Healthcare
7. Transportation
8. Communication
9. Entertainment and Culture
10. Education
11. Hotels
12. Other goods and services
13. Insurance (including social insurance programs)
14. Donations
15. Taxes and fees

On the most detailed level, the data used is divided in a total of about 500 income and expenditure categories. This level of detail is clearly too high for our purposes, and the main scope of the model lies in the above shown main categories and its interdependencies. However, where we assumed a possible impact of a certain subcategory, its separate influence was tested (e.g. in the case of the expenditure in restaurants as a subcategory of food and beverages as a possible effect on transportation). Apart from the income and expenditure part, the data has also a lot of information on socio-economic characteristics, especially on household composition and profession. However, geographical information is very limited due to data protection laws, which limits the reach of the model substantially, as geographical information is of special importance in a transportation focused model. Note also that a key assumption for the estimation of the model is that a) the behavioral mechanisms underlying household expenditure patterns kept stable over time and will also in the future and therefore the data can be treated as a single dataset; and b) the period is long enough to

have variability in the data and therefore the dataset is suitable to detect how patterns were modified by households according to given exogenous changes. The dataset is made of a representative sample of Swiss households.

The MATSim population is based on the work of (Müller and Axhausen, 2013). Two major datasets and a classification of municipalities were used for generating the synthetic population:

- Register survey: This dataset describes the full population of Switzerland at a certain day of 2010. It contains the spatial location at the hectare level in addition to basic socio-demographics available from the civil registry.
- Microcensus 2010: The latest version of the survey on mobility behavior in Switzerland which includes, among others, extended socio-demographics as well as information on mobility behavior (activities and detailed trips).
- Municipality classification: Official classification (22 types) of Swiss municipalities according to commuter movement, occupation, housing conditions, wealth, tourism, population, and role in the Central Place Theory (the theory which tries to explain the spatial distribution of a system of cities, derived from the pioneer work of Christaller, 1933). A coarser version of this classification with nine levels is used.

For the road network, a detailed transport network of 2010 conditions is the standard for MATSim (Balmer et al., 2010). This was updated through a list of extension projects for which the federal and cantonal governments have firmly committed themselves (Swiss Federal Office for Spatial Development, 2010); this information is publicly available.

For the public transport supply, the National Transport Model, which includes the expected schedule for 2030, was used (Swiss Federal Office for Spatial Development, 2010).

The qualitative estimation of future travel patterns is based on analyses made on current and past travel patterns. This has been done looking at Swiss travel diaries surveys from 1994 to 2010 (ARE, 1995, 2001, 2007, 2012).

5.5. Methodology

5.5.1. Modeling individual travel demand

For travel demand modeling, the activity-based multi-agent transport simulation MATSim was used in this project. The basic idea of MATSim is that travel demand can be predicted by simulating daily life of persons and particularly the spatiotemporal occurrence of out-of-home activities (Balmer et al., 2006). The agents represent the actual individuals traveling or carrying out activities in a specific region. At the start of the simulation, each agent is located at his home. S/He has a list of activities to perform (a plan); for example, s/he has to go to work, then shopping and finally to a leisure activity before coming back home. All these plans correspond to the initial transportation demand, which, in the case of Switzerland, has been created based on the Swiss Microcensus (Swiss Federal Statistical Office and Swiss Federal Office for Spatial Development, 2012). During a simulation run, in which a day is repeatedly simulated, each agent tries to optimize its plan, through a trial and error process. At each iteration, it is possible for example to change route, means of transportation (car, public transportation, walk and bike), activity scheduling and location of leisure and shopping activities. This is done through a score, which is assigned to each executed plan according to the utility provided to the agent. The agent will try to keep the plans with the better scores and discard the worse during

the process. It should be noted that transportation duration takes into account interactions with other agents, which can lead to a high density of traffic and even traffic jams. So, travel times can diverge even substantially from free-flow travel times. The behavior of the system "emerges" from the simulation as a consequence of individual agents' behavior. More details about the conceptual framework and the optimization process of the MATSim toolkit can be found in (Balmer and Rieser, 2009). A schematic representation of the process is displayed in Figure 5.1.

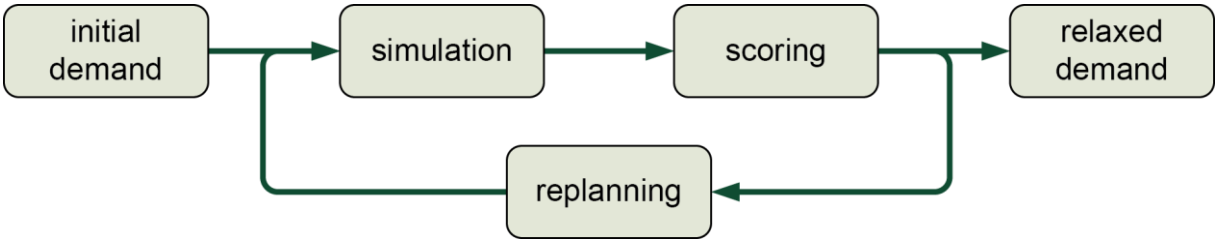

Figure 5.1 Co-evolutionary simulation process of MATSim

The iterative process described, will come to a point where agents are not able anymore to increase their score by changing their plans. This point, called *relaxed demand* in the MATSim context, corresponds to user equilibrium. The demand obtained is completely disaggregated, that is, at individual level. This can be used in this form or aggregated in any form is needed as it was the case in the work presented in this paper. More information on the development of the MATSim model with a Swiss specific scenario for 2030 may be found in Appendix B.

5.5.2. Multiple discrete-continuous extreme value decision model

The methodology used for the household expenditure model was a MDCEV, a Multiple Discrete-Continuous Extreme Value Decision Model. This methodology is part of the family of utility maximizing decision models. That means that we assume the households to define their share of expenditure for each category as a rational decision that maximizes their utility. The MDCEV framework assumes parameters which define the utility of each category based on whether the category was chosen by the household (Discrete) and on the amount of money spent on it (Continuous) and estimates the parameters using the data available. The parameters show which socio-economic or other characteristic has an influence on the probability and amount spent on each category. Assuming shares of other categories as an explanatory variable for a given category allows estimating the interdependency and dynamics of the categories.

5.5.3. LCA model for the assessment of individual household consumption

Large parts of the chapters 5.5.3.1, 5.5.3.2 and 5.5.3.3 were published as Saner et al. (2013), Saner et al. (2014), and Froemelt and Hellweg (2016).

5.5.3.1. Modeling the housing energy demand

As a prerequisite for the assessment of environmental impacts from housing, estimates of the energy demand for space heating, hot water production and electrical appliances are needed. For this reason, a housing energy demand model based on simplified energy balances was set up according to SIA 380/1 (Swiss Society of Engineers and Architects, 2001). Climatic data, statistical census and dwelling register data are the foundations of this model.

We calculated the heating energy demand (Q_h) for each building based on its hourly heat flux balance. Thus, to determine Q_h, we subtracted thermal gains from the losses. As thermal gains, we

counted solar gains (Q_S) via windows and internal gains because of occupancy (Q_{iP}) and electricity use (Q_{iEl}). Thermal losses were losses due to thermal transmission through the building envelope (Q_T) and losses due to ventilation (Q_V). This approach is in accordance with the Swiss standard SIA 380/1 (Swiss Society of Engineers and Architects, 2001) for thermal energy calculations in buildings published by the Swiss Society of Engineers and Architects (SIA) and is formulated in equation (1).

$$Q_h = \sum_{t=t_{begin}}^{t_{end}} (Q_{T,t} + Q_{V,t}) - \eta_g (Q_{s,t} + Q_{iP,t} + Q_{iEl,t}) \quad (1)$$

Herein, t denotes the hour, t_{begin} and t_{end} are the boundaries for the analyzed period, and η_g is the degree of utilization for heat gains, which depends on the thermal storage capacity of the building mass. The heat transfer coefficients (U-values) for the determination of the transmission losses (Q_T) were taken from (Wallbaum et al., 2010), who reported these coefficients for four different building components (roof, wall, floor, and windows) and distinguished their U-values according to year of construction of the building and year of renovation of the specific building component. The areas of the four components were calculated from the area of the building surface. The Federal Register of Buildings and Dwellings (FRBD) does not contain information on the shape of the buildings. Hence, by means of a correction factor and a so-called building envelope factor (Dettli et al., 2007), each building was simply modeled as a cube with a square base and an assumed share of window area of 18% (Jagnow et al., 2002). Calculations for ventilation losses (Q_V) draw on hourly differences between outdoor and ambient room temperature as well as on standard values for hourly air exchange flows. While computations for solar gains (Q_s) were based on climatic data, glass properties and took shading of nearby buildings into account, the modeling of internal gains due to occupancy (Q_{iP}) and electricity use (Q_{iEl}) relied on specific values provided by SIA 380/1 standard (Swiss Society of Engineers and Architects, 2001).

Apart from heating and electricity demand, we also calculated the energy demand for the supply of hot water (Q_{ww}) for each household. Hereby again, we relied on standard values (Swiss Society of Engineers and Architects, 2001).

Although FRBD is rather comprehensive, some data such as the renovation year of specific building parts, roof inclination, or specific heat supply technology was not available. We therefore assumed that the unknown parameters were stochastic. For instance, the FRBD holds information on the energy source used for space heating and hot water production. It distinguishes between oil, coal, natural gas, electricity, wood, heat pump, solar collectors, and heat from a district network. Yet, wood, for instance, can be further differentiated into heat from logs, chips or pellet incinerating systems. Therefore, we used statistical data and applied stochastic modeling to determine the detailed heating supply technology. Then, in preparation for the life cycle assessment, we linked the space heating and hot water demands per apartment with the respective activity in ecoinvent 2.2 (ecoinvent, 2012) representing a specific heating system technology.

The extensive dataset of final energy consumption available in the case study of Zernez enabled a detailed evaluation of this housing energy demand model (Wagner et al., 2015). For a building-wise comparison of model results and empirical database, the space heating demands of 133 buildings in Zernez were computed. In order to account for uncertain parameters, Latin Hypercube sampling was applied and for each building, the results of 1000 simulation runs were averaged. But also the collected data on final energy consumption had to be processed for the comparison. Several

assumptions (e.g. on energy contents, conversion efficiencies, domestic hot water needs, and electricity demand for lighting/appliances) had to be made in order to convert the collected empirical data into annual net space heating demand per building. These assumptions were chosen in a manner to cover the uncertainty of these net space heating demands derived from the collected empirical data. This resulted in a range for each building spanning from a minimum value – which represents an underestimation – to a maximum value which is likely to overestimate the "real" space heating demand.

The buildings considered for the evaluation comprised only residential buildings and among them, only buildings with reliable and unambiguous data entries.

5.5.3.2. Modeling the land-based mobility demand

Mobility demand for land-based traffic modes was evaluated based on results of MATSim. At the moment no weekend or intraweek model for Switzerland is implemented in MATSim. Therefore, we approximated yearly mobility patterns with 365 workdays. As the average travel distance for weekends equals the average travel distance for workdays this assumption is justifiable (Swiss Federal Statistical Office and Swiss Federal Office for Spatial Development, 2012). The output data from a MATSim simulation contains the details of selected plans together with detailed output of the traffic simulation for each agent. These plans state when agents left a specific location, for how long and how far they drove and what mode of transport they used. Hence, we calculated the mobility demand (in terms of traveled kilometers) of each agent and each mode of transport and aggregated the traffic demand on household level by assigning MATSim-agents to household members. This assignment was based on characteristics of the agents and characteristics of households and household members, both derived from the Swiss National Census (Swiss Federal Statistical Office, 2000). For the life cycle assessment, activities from ecoinvent 2.2 (ecoinvent, 2012) were allocated to the chosen transportation modes by means of stochastic modeling. The fleet composition was obtained by implementing the MDCEV decision model of task 2 (Jäggi et al., 2012).

Household data from the Swiss National Census 2000 (Swiss Federal Statistical Office, 2000) is subject to data protection and thus its geographic reference does not exactly coincide with the geographic reference of buildings in the FRBD. Therefore, each household was assigned to the nearest building and within the building to an appropriate apartment, that is, an apartment with enough rooms to hold all members of the household. If an apartment was already occupied by another household then our model looked for another available apartment to avoid double occupancy. After this step, we knew for each household the housing and land-based mobility demand. These demands were then fed into a life cycle assessment model which is capable of applying all common life cycle impact assessment methods provided by ecoinvent (ecoinvent, 2012) (e.g., ReCiPe (Goedkoop et al., 2012) midpoint indicators) in order to determine environmental impacts.

5.5.3.3. Optimization extension

The model for the life cycle assessment of individual household consumption was extended by optimization methods aiming at minimizing environmental impacts from housing. Therefore, the extended model should find optimal refurbishment strategies and optimal energy supply technologies for residential buildings. As a case study, the municipality of Wattwil was chosen. The application to a real case enabled the consideration of realistic local restrictions such as capacity

limits and resource-supply constraints, as well as site-specific factors such as the possibility to join a district heating network, to exploit groundwater heat pumps or to install solar panels or collectors.

In order to quantify potential savings in environmental impacts by refurbishment and thus a reduction of heating demand, four building renovation measures (floor, roof, wall, and window refurbishments) were included in the model assuming that all refurbishments would meet best available standards. The possible space heat and hot water supply technologies were oil, gas, and wood heaters (chips, logs, pellets), heat pumps (brine-water, air-water), district heat (wood chips), and polymer electrolyte membrane (PEM) fuel cell systems (co-generation of heat and electricity fueled by gas). Hot water could additionally be partly supplied by solar collector panels. Electricity demand could be supplied by electricity from local photovoltaic (PV) panels (ribbon-Si) mounted on roof tops, Proton Exchange Membrane (PEM) fuel cells or electricity from the Swiss grid. For electricity from PV, it was assumed that 50% of the rooftops in the case study municipality could be equipped with panels and that PV panels could only occupy the residual roof area after subtracting the area of the solar collectors from the total roof area. PEM fuel cells could only be run with natural gas or purified biogas and thus only in buildings with a connection to the gas network. Ground source heat pump systems were only allowed for buildings situated in designated areas.

Furthermore, the year was divided into twelve time steps, i.e. months, to be able to account for temporal constraints (e.g. unusable surplus heat from solar collector systems in summer).

Environmental impacts were assessed for two midpoint categories from the ReCiPe Method (Goedkoop et al., 2012) with particular relevance for energy supply systems: climate change (kg CO_2-eq) and particulate matter formation (kg PM10-eq). While climate change is currently the environmental dimension receiving the highest political attention and an indicator of the fossil fuel intensity of products, we chose particulate matter formation as a second indicator as we expected trade-offs with climate change, especially in the context of using wood energy.

In order to minimize several life cycle impact categories at once in a multi-objective optimization, we applied the fuzzy linear programming extension of the general matrix-based LCA developed by Tan et al. (2008). According to this approach, the optimization problem is converted to the maximization of the degree of satisfaction that can be obtained for all objectives simultaneously.

5.5.3.4. Application to case studies

To illustrate the application of the household consumption LCA, we carried out case studies for two Swiss municipalities, Zernez and Wattwil. In both cases, the environmental impacts of housing demand and mobility behavior of the individual households in the respective municipality were assessed. A detailed empirical dataset on final energy consumption at household level allowed for an in-depth evaluation of the housing energy demand model in the case of Zernez. In Wattwil, the households were further analyzed. According to their environmental footprints the households of Wattwil were categorized in four groups. Cluster analysis for each group of households then allowed for further data reduction without losing information on differences in the households' environmental footprints. We used hierarchical clustering applying Ward's method as linkage criterion (Backhaus et al., 2006). As parameters for the cluster analysis, we used aside from life cycle impact results different household characteristics such as household size, income, age of household members, and highest education.

Furthermore, Wattwil was also selected as a case study for the LCA based optimization approach to optimize refurbishment of buildings and energy supply under environmental criteria, given the local restrictions.

Future mobility scenarios which were developed within different work packages of the THELMA-project were applied to the municipality of Zernez. The investigated future mobility behavior of households corresponds to the "Baseline 2030"-scenario which was elaborated within task 3. For this scenario, an adapted synthetic population for 2030 and an updated road network was considered. The underlying fleet composition was again derived by means of the MDCEV decision model developed in the scope of this work package. However, in the framework of these future mobility scenarios, the resulting base fleet was combined and supplemented by the fleet scenarios provided by WP 3. The fleet scenarios of WP 3 comprise a 30%-, 60%- and a 90%-penetration level scenario of battery electric vehicles (BEV) by 2050. For the establishment of these scenarios, MATSim-agents were identified which are likely to purchase a specific BEV-type at a certain point in time. Therefore, by assigning MATSim-agents to household members, it was possible to identify the households which will replace their conventional cars by one or more battery electric vehicles. It has to be noted that, owing to the focus on the year 2030 instead of 2050, lower penetration levels apply for the case study in Zernez. Furthermore, the indicated BEV penetration levels are valid for the whole of Switzerland and might be substantially different for the municipality under investigation. More information on the development of the Matsim 2030 model may be found in Appendix B.

For the purchase of a BEV by a MATSim-agent, eight different electric vehicle classes (luxury, midsize, upper midsize, mini, small, sport, SUV and vans), two battery sizes (short and regular range) as well as three electric vehicle model years (2012, 2020 and 2030) were distinguished within the fleet scenarios of WP 3. The combination of these 48 different BEV-types with the results of the life cycle assessment of vehicles in WP 1 allowed for a detailed analysis of the environmental consequences of the future introduction of individual electric mobility.

5.6. Results

Although the LCA analysis was defined as task 1, as previously mentioned, the results shown here follow a rather different order. The logic is that the household model, and the MATSim scenarios and output, were indeed inputs for the LCA analysis and therefore are presented first hereafter. The further developments of MATSim to include 2030 scenarios as well as the application of future mobility scenarios to a case study come as last.

5.6.1. Household expenditure models

The results of this research using Decision Modeling Methodology are parameters that show the influence of explanatory variables that tell us what drives a household's expenditure share of a given category. In the context of this research project, different model configurations were tested and two main models were estimated: a) A general model that predicts the share of the 15 main categories (and the transportation category as one of them) and estimates parameters for the influence on these categories and b) a specific model that predicts the share of sub-categories within the transportation and communication category, such as public transportation, private transport, telecommunication, internet, etc., and estimates the parameters that define its utility.

The results of the models however show that the shares of expenditure of all the categories seem to date almost independent of the observed household characteristics and of the expenditures of other

categories. So far, with the tested methodology no significant patterns or correlations could be found that would explain and predict the share of any of the categories, including transportation. Neither socio-economic nor the limited available geographical variables can explain the households expenditure shares sufficiently. The reasons could be that the shares are influenced by other variables that are not in the dataset, that we have not yet found the proper model specification or that the amount a household spends on a category are not subject to rational decision making but more individualistic and irrational. The later would mean the approach of trying to predict travel demand based on the amount of money spent on transportation would prove very difficult.

5.6.2. Travel demand

Travel demand was modeled at both Swiss national level and at local level for two selected municipalities (Wattwil and Zernez). The MATSim simulation and its extensions for electric vehicle modeling were used to model energy demand by the various types of vehicles, which included modeling of electricity demand. The output of the simulations was used both for country-wide electric grid and supply analysis (WP3 and WP5) and for life cycle assessment in the mentioned local scenarios, where the environmental footprint of households was assessed. Scenarios for 2005, 2010 and 2030 were simulated. The 2005 scenario was the original basis scenario, while the 2010 scenario is an update which has been created in parallel with the setup of the 2030 scenario.

Since the scenario for 2010 did not previously exist, it was necessary to gather newer data and use a rather standard MATSim scenario creation process. The process is of scarce relevance in the context of this project and therefore, is not documented here. Conversely, the creation of a scenario for 2030 implies several challenges and the whole process, with the several results obtained along it. This is documented in a separate paragraph at the end of this chapter.

5.6.2.1. MATSim extensions

MATSim was further developed to meet the needs of the case studies and to be able to make certain predictions of the energy consuming infrastructure and the traffic demand for future scenarios. The cost structure of electric vehicles (high purchase/investment costs, low energy/running costs) substantially different than that of internal combustion vehicles needs extensions in MATSim that reflect the consumer behavior regarding car choice and investment decisions. Another part of MATSim that was further developed was parking, which is crucial for the loading patterns of electric vehicles.

5.6.2.2. Fleet choice model

To assign car types to the agents in MATSim according to the household expenditure model described above, a household structure had to be created, since cars are generally shared between household members. The households have certain characteristics, such as number of persons, ages, children, income, that determine fleet choice. The census data (Swiss Federal Statistical Office, 2000) is the basis for all agents in MATSim. Characteristics needed for the car choice model that were not included in the census, such as income and number of cars, were extrapolated from the Microcensus (Swiss Federal Statistical Office and Swiss Federal Office for Spatial Development, 2012). Another sub-model based on the Microcensus calculated the annual VMT (Vehicle Miles Travelled) per household. The fleet choice model then made a forecast for every household how many vehicles this household owns what car types the vehicles are and how many kilometers per years are travelled with each car.

5.6.2.3. Parking model

At the time the THELMA project started, the parking model in MATSim was too simplistic. There was no constraint on the parking supply side, so that any number of cars could be parked everywhere. Furthermore there was no notion of parking price in the model. And also walking distances to/from the parking were not modelled, so that the agents directly drove to the destination location and parked there. These shortcomings had several implications: As the parking supply did not have any limitations, agents could drive to a shop, even if in reality there would be a shortage of parking, which could potentially trigger further changes in behavior, such as change of travel mode. Furthermore trade-offs, e.g. between walking distance and price were not possible at that time. In the meantime a parking model was developed for MATSim, which incorporates all these features, so that agents encountering a supply shortage in parking can react to it. Especially for EVs the module also allows to specify, if an EV needs charging – in that case the agent will only make a trade-off between parking where a charging plug is available.

5.6.2.4. Energy consumption and charging of electric vehicles

As part of another project (related to electric vehicles) called *ARTEMIS (Waraich et al., 2014)*, several additions to MATSim have been made. This includes the implementation of energy consumption and charging of EVs and PHEVs with interfaces to a power systems simulation tool and several interfaces for exchanging the MATSim output with the ETHZ-PSL. Furthermore MATSim runs were performed with test data and forwarded to ETHZ-PSL containing pattern on energy consumption of electric vehicles for each trip. In the dataset also detailed information of parking location, parking times and activity type (e.g. work, home, education, etc.) for each agent were contained. Furthermore, simulation data for the municipalities of Wattwil and Zernez were filtered out from a MATSim run. This contained detailed data both on the daily plan of agents living in the selected communities and their travel both inside and outside the municipalities.

5.6.3. LCA model for the assessment of individual household consumption

Large parts of the findings presented in this chapter were published as Saner et al. (2013), Saner et al. (2014), and Froemelt and Hellweg (2016)

The building-wise comparison carried out in the case study of Zernez is depicted in Figure 5.2a. The model's 95% confidence intervals overlap with the empirical database range for 65 out of 133 buildings. Yet, this figure shows clearly that simulated heating demands largely deviate from database entries for some individual buildings. A detailed analysis revealed that these deviations can be explained by the variability in occupants' behavior, construction types of old buildings, only occasionally occupied holiday flats, and problems of representativeness in the underlying statistical databases.

Nevertheless, Figure 5.2b demonstrates that on an aggregated level, cumulative and total heating demand are well reflected by our energy demand model. The cumulative curves of the annual heating demand shall visualize a building stock perspective. The red line in Figure 5.2b illustrates the cumulated average model results, while the blue lines display the database range. The model's line is plotted closely and more or less parallel to the database curves pointing to a good model performance at a building stock scale.

As a conclusion, the applied model is not able to simulate single buildings always accurately, but it is able to reproduce the overall characteristics of the residential building stock's space heating demand on different levels of aggregation.

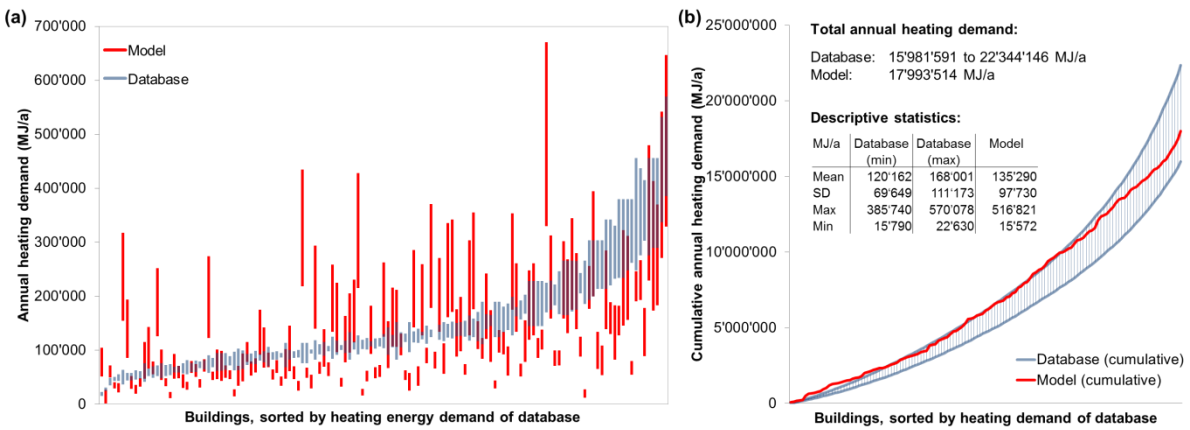

Figure 5.2 (a) Building-wise comparison of the 95% confidence intervals of the annual space heating demand estimated by the housing energy demand model with the empirical database range; (b) Cumulative annual heating demand of buildings sorted by ascending heating demand according to the mean of the empirical database range. The cumulative curve of the model was built by accumulating the simulated heating demands corresponding to the sorted buildings. [SD = Standard deviation; Database (min) = minimum of empirical database range; Database (max) = maximum of empirical database range]

Figure 5.3 shows the median life cycle greenhouse gas (GHG) emissions in metric tons for housing and land-based mobility consumption for the two case study municipalities, Zernez and Wattwil. Although all common life cycle impact assessment methods could be applied by our model, we chose to present the results only in CO_2 equivalent emissions assessed according to the ReCiPe method (Goedkoop et al., 2012) (ReCiPe midpoint impact category: climate change). We found by applying the Kruskal–Wallis test (Kruskal and Wallis, 1952) that there was no significant difference between the different samples calculated with Monte Carlo simulation. Thus, the results of the median sample are representative and suitable for further discussion. The blue bars in Figure 5.3 represent GHG emissions induced by commuting, shopping, and leisure purposes by different means of land-based traffic modes and the use of their infrastructure. GHG emissions induced by space heating, hot water, electricity consumption and building infrastructure are depicted in yellow. The resulting GHG emissions are normalized by the number of people living in the household and ranked from the lowest to the highest emitters.

The median value for life cycle GHG emissions over all households in Wattwil was calculated as 3.12 t CO_2-eq and in Zernez as 3.86 t CO_2-eq per person per year. Hence, 50% of households in the respective municipality emit less and the other 50% emit more than these values. The mean values amount to 4.30 t CO_2-eq and 4.40 t CO_2-eq per person and year for Wattwil and Zernez respectively. These values are comparable to the Swiss average for housing and land-based mobility consumption in 2005, but slightly below (4.76 t CO_2-eq per person (Jungbluth et al., 2012)). The lower average values in the two case studies are mainly due to the large share of buildings heated by wood or, especially in Zernez, directly by the low-carbon Swiss electricity mix. The findings suggest that GHGs are not emitted equally, and that a small share of households in both cases is responsible for a large amount of GHG. This is supported by the cumulative relative impact results also presented in Figure 5.3.

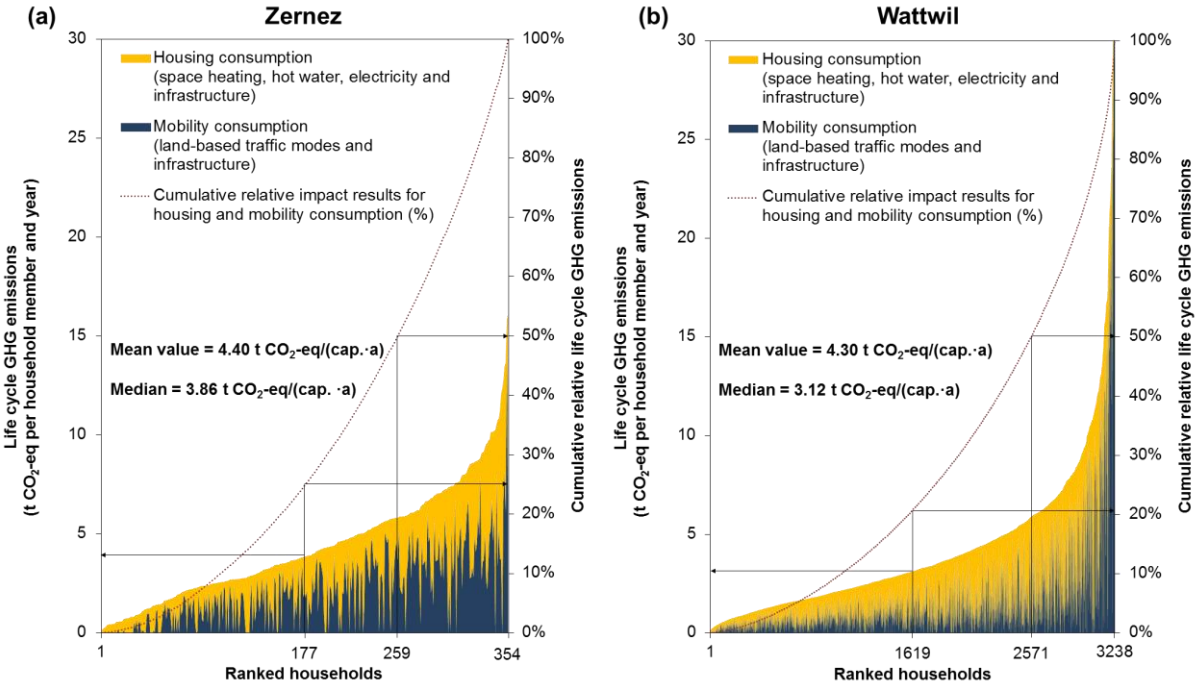

Figure 5.3 Life cycle greenhouse gas emissions of individual households in Zernez (a) and Wattwil (b) in the year 2010 induced by housing and mobility. The impact results per household have been normalized by the respective number of household members and ranked from smallest to largest value.

It is shown that in Wattwil 20% of the households and in Zernez approximately 25% of the households with the largest impacts are responsible for about 50% of GHGs stemming from housing and mobility. The mean values for housing amount to 2.35 t CO_2-eq in Wattwil and 2.22 t CO_2-eq per person and year in Zernez. For mobility purposes, an average household member emits 1.94 t CO_2-eq in Wattwil and 2.18 t CO_2-eq per year in Zernez. Although, housing impacts are more equally distributed among households than mobility impacts, these two consumption areas are apparently equally important in terms of climate change.

In the case of Wattwil, a detailed analysis of the impacts was conducted. The spatial distribution of impacts in Figure 5.4 (environmental impacts within one raster cell of 100 x 100 m were averaged for the reason of data privacy protection) shows that for some areas in the municipality we find differences between the impacts of housing and land-based mobility. One of these areas is marked by a light blue circle. The finding suggests that these households live either in poorly insulated buildings or use fossil fuels for space heating. However, they generate a smaller demand of motorized individual transportation than other households. This might be explained by the fact that we find these households located in the old town near the train station. The inverted phenomenon is marked by a pink circle, where households are located which have high mobility impacts, but low impacts from housing. These two examples support findings of other authors who state that environmental impacts of households are often subject to trade-offs between the different consumption categories (Girod and De Haan, 2009, Girod and De Haan, 2010).

For subsequent cluster analyses (CA), groups of households were derived by investigating the impact result distribution. Group A consists of households that are below 1 t CO_2-eq per capita and year, households that emit less than the median value (i.e., 50th percentile or 20% of cumulative emissions) were assigned to group B, households that contribute between 20% and 50% belong to group C, and households that contribute more than 50% to the cumulative impact result (i.e., the 80th percentile)

were attributed to group D. By applying cluster analyses, we were able to reduce several hundred individual households to 3–4 clusters per group. The most relevant results of the CA are presented in Table 5-1. The first group (A) of clusters represents 9.5% of all households in Wattwil. Cluster A1 consists of small households of elderly people and clusters A2 and A3 are formed by families with children. The apartment area per person is rather small (average for group A is 47 m^2 per person) and the buildings are rather old, however, the apartments are heated by low GHG emitting heating systems. Impacts from mobility are very low because of low demand for motorized private transportation and only moderate demand for public and non-motorized private transportation. The group not only comprises households of elderly people, who tend to have lower demands of mobility, but also clusters of young families. This finding suggests that these households have either short or no commuting distances (e.g., farmers).

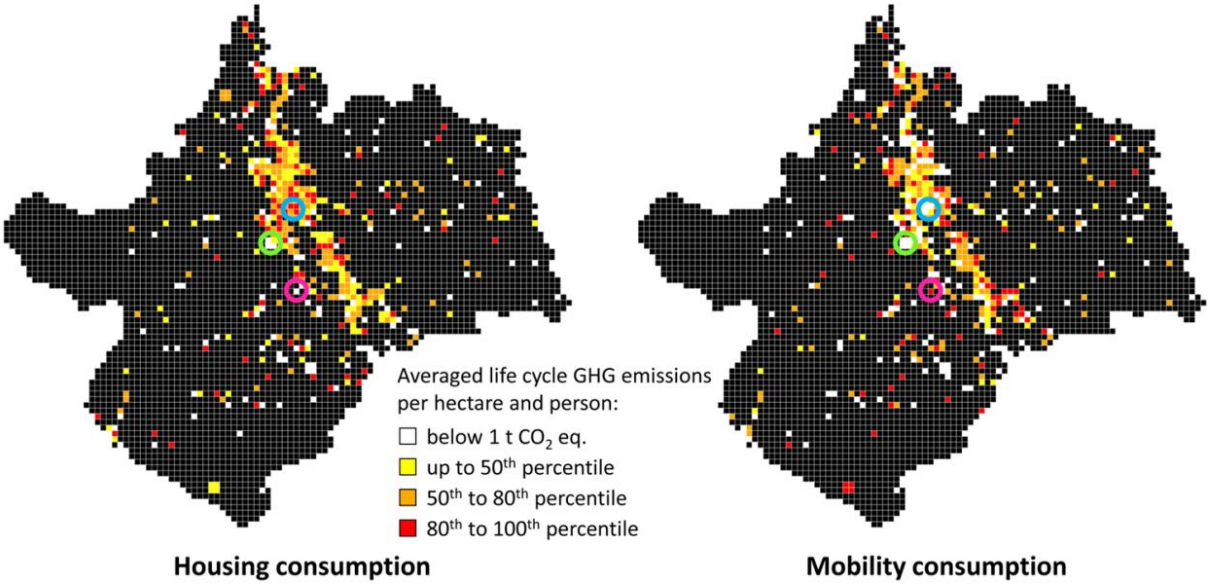

Figure 5.4 Rasterized maps of Wattwil showing averaged life cycle GHG emissions per hectare graduated into four classes. (map data: FSO GEOSTAT/swisstopo). Blue and pink circles indicate areas where housing and mobility impacts are significantly different. Green circle indicate areas where housing and mobility impacts are both on a similar level.

Households in group B either perform very well in housing (B1, B3) or mobility (B2, B4). The rather moderate emissions from housing stem from a higher share of wood and natural gas fueled (14% and 36%, respectively) heating systems and the small living area per person. Most B-clusters have moderate demand for motorized private transportation or high demand for public transportation. Group C consists of three clusters (C1, C2, and C4) with GHG emissions dominated by housing operation and one cluster (C3) with high impacts from mobility. The emissions of one category are often two to three times higher than the emissions of the other. Group D is formed by households that consume large amounts of fossil fuel for heating (share of oil heating approximately 66%) and transportation purposes. This group is responsible for 50% of the cumulative GHG emissions induced by households in the case study municipality, meaning that if their impacts could be halved, the cumulative impacts of Wattwil would be reduced by 25%. The emissions from housing are high, because the households of group D use large apartment areas (on average 92 m^2 per person) and heat with fossil fuels.

Table 5-1 Clusters of similar households and the most relevant household characteristics. GHG emissions per capita and year induced by housing operation and land-based mobility, as well as the distance to city center. All values are presented as average values of cluster.

cluster name	no. of persons per household	max. age of the oldest person in the household	min. age of the youngest person in the household	housing operation impacts (t CO_2-eq per person and year)	mobility impacts (t CO_2-eq per person and year)	apartment area (m^2 per person)	no. of apartments per building	distance to city center (km)
A1	1.5	70	66	0.4	0.2	82	3	1.13
A2	4.6	46	10	0.2	0.5	23	3	1.36
A3	3.5	38	14	0.5	0.2	36	8	1.39
B1	1.6	55	51	0.5	1.3	78	3	1.25
B2	3.3	40	14	1.3	0.7	34	7	1.33
B3	4.6	45	10	0.7	1.2	24	6	1.37
B4	2.0	67	57	1.7	0.4	46	9	1.06
C1	2.0	56	46	3.0	1.1	60	8	1.06
C2	1.4	73	71	3.5	0.7	75	8	1.11
C3	3.5	46	19	1.2	3.0	34	7	1.31
C4	1.3	40	38	3.1	1.1	91	7	1.12
D1	1.2	62	61	5.6	3.2	111	9	1.17
D2	3.1	49	24	2.6	6.4	50	9	1.20
D3	1.3	34	31	6.2	8.1	100	7	1.07

Furthermore, the LCA model was extended by an optimization module whose objective function aims at minimizing CO_2-emissions and particulate matter formation at the same time by finding optimal refurbishment strategies and energy supply technologies for buildings. Figure 5.5 shows the results of the application of this optimization model to Wattwil in two maps. The left map shows the impact results for the reference case, whereas the right map shows the results of the multi-objective optimization. In both cases, the highest GHG emissions are in the center of the municipality due to the higher population density and bigger buildings. Additionally, in the reference system, the heating systems of the buildings in the city center rely mainly on fossil fuels, whereas buildings in the outskirts of the municipality are mainly heated with wood. In the optimal case, GHG emissions are distributed more equally than in the reference case. GHG emissions above 32 t CO_2-eq per hectare are rare. Locally increased GHG emissions can be explained by a switch of the energy supply system from a purely wood based system with low GHG emissions to another system (e.g. heat pumps) in order to achieve a better trade-off between GHG and particulate matter emissions.

In the optimal case, GHG emissions are reduced by more than 75% compared to the reference case, from 11824 to 2664 t CO_2-eq. Also, particulate matter emissions are reduced by more than 50% from 10.7 to 5.12 t PM10-eq. This means that due to the refurbishment of buildings and due to the changing structure in energy supply, the impacts from both impact categories decrease. The multi-objective optimization applied here searches for the best consensus between the two objectives and therefore leads to a fundamentally different portfolio of hydronic energy supply systems in the municipality than in the reference case.

The distribution of energy supply systems is depicted in Figure 5.5 (bottom) for the reference case (left) and the optimal case (right). In the reference situation, the most common supply systems in the city center are oil boilers and gas furnaces, thereby 1156 t of light fuel oil and 1418 Nm^3 of gas are used per year. In the outskirts, wood incineration is predominant (11 m^3 of wood chips and 4583 m^3 wood logs). Only in some cases the most frequent systems are direct electric boilers and heat pumps. The total electricity use for housing purposes is 4.76 GWh per year. Solar collector panel installations, delivering auxiliary heat for hot water generation, are very rare in the municipality. In the optimal case, however, solar collectors are installed to the fullest possible extent. The distribution of the space heat supply systems is rather homogeneous and heat pump systems (brine-water or air-water)

as well as wood chips are preferred. Heat pumps are predominant in the areas where drilling boreholes for heat exchanger tubes is allowed. Wood chips incineration systems are predominant in the other areas. In total, 8452 m^3 of wood chips and only 418 m^3 of wood logs are used. The total electricity demand for housing purposes almost quadruples due to the installation of heat pump systems and amounts to 16.4 GWh per year (50% electricity from PV and 50% from the grid delivered from outside the municipality). In addition to this drastic shift of heat supply technologies from a fossil fuel dominated portfolio to a portfolio consisting of mainly heat pumps and wood chips incineration systems, roofs, windows and walls would need to be refurbished in more than 65% of the municipality's buildings (optimal refurbishment rates are 67% for roofs, 81% for walls and 68% for windows, and only 5% for floors).

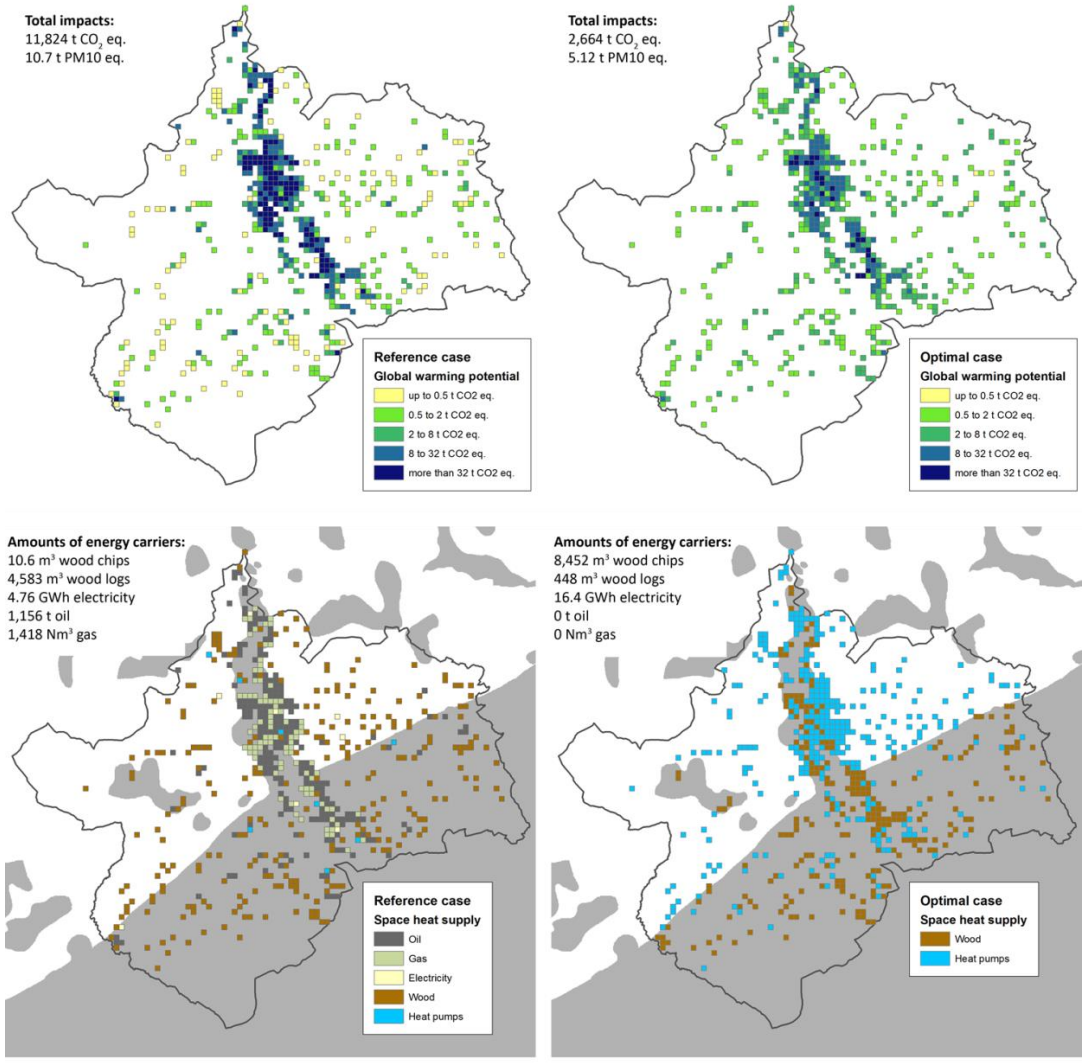

Figure 5.5 Results for the energy supply of buildings in the municipality of Wattwil for the reference case (left) and the multi-objective optimal case (right), aggregated per hectare. Top: annual life cycle GHG emissions. Bottom: distribution of hydronic energy supply systems. Each pixel depicts the most frequent system per hectare. (In the gray shaded areas only air-sourced heat pumps are allowed, borehole heat exchangers are prohibited due to groundwater protection).

The full potential of the environmental impact reductions will hardly be achieved in reality, particularly in the short term, e.g. because of financial constraints and social acceptance, which were not taken into account in this study.

5.6.4. Travel demand 2030

The creation of a 2030 scenario was a challenging task to many respects. The main steps of the process and the results obtain along it are described hereafter. This section is largely based on Ciari et al. (2013).

5.6.4.1. Mobility pattern analysis

In order to evaluate past and present mobility patterns and figuring out how they are expected to evolve in the future, Swiss travel diaries surveys from the last three decades were analyzed (Swiss Federal Statistical Office and Swiss Federal Office for Spatial Development, 2012). In addition, a literature review on teleworking and teleshopping was carried out since those two aspects are supposed to play a major role in future mobility patterns. The survey on the population's travel behavior is called Microcensus and is conducted every five years since 1974 by the Federal Office for Statistics together with the Federal Office for Spatial Development. A cohort analysis of various mobility variables was performed, but also the activity chain organization and the peak spreading patterns were investigated. Figure 5.6 shows exemplary one mobility variable which was studied within the cohort analysis. It illustrates the share of people owning a driving license for the respective cohorts.

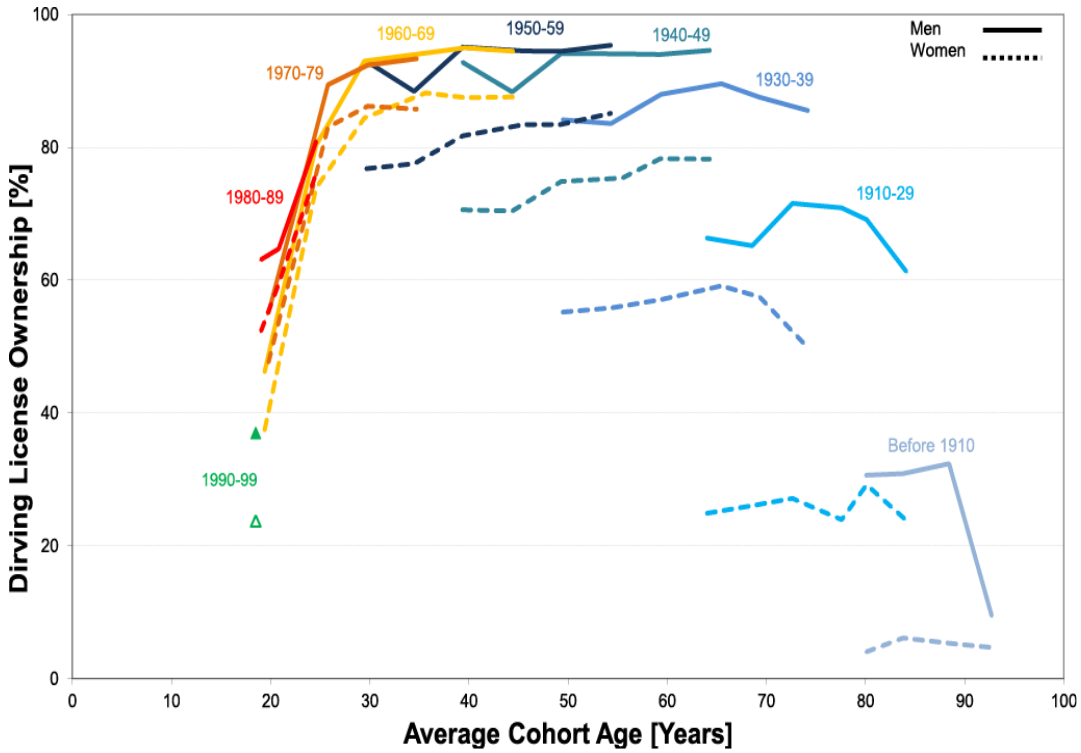

Figure 5.6 Driving license ownership across cohorts. Source: Ciari et al. (2013).

The six points within each cohort represent the development in the course of the evaluated Microcensi. It is seen that for the older cohorts, the proportion of the driving license holder is overall significantly lower than in the younger cohorts. The share of men who own a driving license is much higher than women of the same age. The trend among younger people go to a maximum share of driving license ownership of approximately 90-95% for men and about 80-85% for women, where a plateau is reached that starts decreasing again only after 30 years. Younger generations reach the plateau (saturation) much faster than older generations. The first figures for the 90-99 cohort are rather low and suggest a possible departure from automobility by the younger generations. The data

from Microcensus was also used for a “peak spreading analysis”. This looks at the peaking patterns in departures of trips going-to and returning-from different activity purposes in the Swiss micro-censuses. For this analysis, only the departure times of the trips were considered. Here in Figure 5.7 the pattern for trips with any kind of activity purpose are shown.

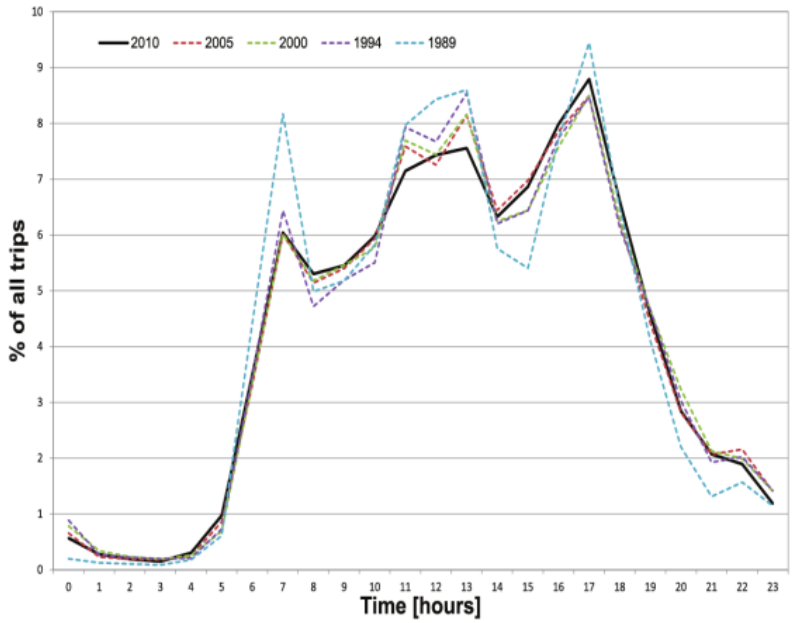

Figure 5.7 Peak spreading for all activities together.

The development of the peak patterns is fairly stable across the different micro-censuses. Three peaks can be distinguished. The first one, also the lowest one, centered at 7 hours driven by the people leaving for work. The second peak/plateau occurs between 11 and 13 hours, and the last peak, the highest, occurs at 17 hours. In summary, the main finding of the analysis is that travel behavior did not change substantially in Switzerland in the span of time analyzed. There are some changes in license owner-ship, car ownership, and public transport subscriptions. The peak analysis did not show substantial tendency of the peaks to flatten out. The number of out-of-home activities and home-to-home journeys for the same age groups across cohorts is fairly stable, although the time spent at activities is slightly decreasing.

In order to figure how activity patterns could change in the future, the research also focused on telework and teleshopping, which are considered two phenomena which might heavily impact future travel habits. To this purpose, a literature review, looking at both international and Swiss studies, was made. Regarding teleworking, among the studies reviewed, one addresses the future growth of teleworking in Switzerland (Nilles et al., 1976). This forecast is based solely on the analysis of the general demographic data for Switzerland since no survey data on the actual number of teleworkers in the country was available. The forecast describes the likely number of people who have jobs suitable for relatively frequent telework, including both home – and telework-center – based telework. Under these assumptions the potential teleworkers in Switzerland in 2030 would be 1.4 Million.

Clearly, this number in itself tells only a part of the story. It is of utter importance to understand how the behavior of teleworkers actually changes. Typically, we can have reduction or substitution of trips, as compared to the previously adopted commuting pattern. Reduction means that a net

decrease of travel is observed, while substitution means that instead of going to work the person might go for other trips with different purposes but not necessarily reduce his/her travel. The availability of a car, which previously was not, might also influence the behavior of other household members. As a short summary of the results found in the study reviewed, it was found that:

- Niiles et al.(1976): substantial reduction in one-way commuters from 108 tele-centers.
- Balepur et al.(1998); Mokhatarian and Varma,(1998): low substitution, if at all.
- California Pilot Telecommuting Project, several studies: 20% reduction in total travel for telecommuters, no increase in non-work travel, no substantial changes in travel of telecommuters' household members.
- Koenig et al.(1996), California Pilot Telecommuting Project: reduction of total travel by 27%, increase of non-work-related trips by 0.5 trips/person, but reduction on non-commuting VMT by 5.3 miles! More frequent but shorter non-commuting trips.
- Mokhtarian et al.(2004), 63% reduction on VMT in telecommuting days, trips per day slightly increase.
- De Graaf, (2004): telecommuting and actual commuting can be clearly considered as substitutes and that working at home substitutes around 20% of the total travel.

It is safe to say that, in general, in the short term telecommuting leads to reduction of the various travel characteristics (e.g., VMT, Passenger Miles Travelled (PMT), morning-peak hours, emission, and number of commuting trips). Commuting and working at home act as substitutes. Moreover, at home work and total travel seem to be substitutes too. The substitution effect between total travel and telecommuting is estimated to be rather substantial, namely around 20% (on working-from-home days). Teleworkers substitute their activities across the week (temporal substitution), which partly offsets the decrease of travel demand. This compensation is estimated to 40%.In the long term, however, telecommuting impacts are still blurred. Some studies suggested that in the long term the values of the telecommuting substitution for commuting would be much lower due to the induced travel demand and residential relocation.

Teleshopping is a much better documented phenomenon than teleworking. This is probably because the elements characterizing teleshopping are relatively easy to measure statistically through surveys. For example, the Swiss Federal Statistical Office (FSO) carries out a detailed survey of internet usage, which gives good estimates on the number of online shoppers. Figure 5.8 reports the estimate of the number of persons in Switzerland making internet shopping and online-banking. This is based on an estimate of the group of "internet intensive users".

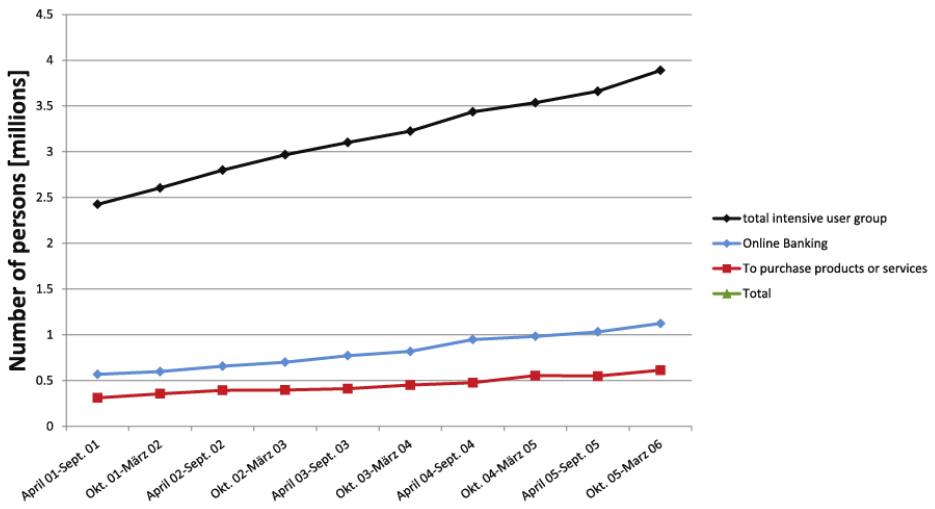

Figure 5.8 Number of internet intensive users, online banking users and online shoppers. Source: (2001-2006, FSO).

The FSO provides a forecast of future diffusion of this behavior too. This is made using a simple logistic model for the growth of the intensive internet users group and assuming that the proportion of online-banking users and online shoppers within this group does not change. The result can be seen in Figure 5.9.

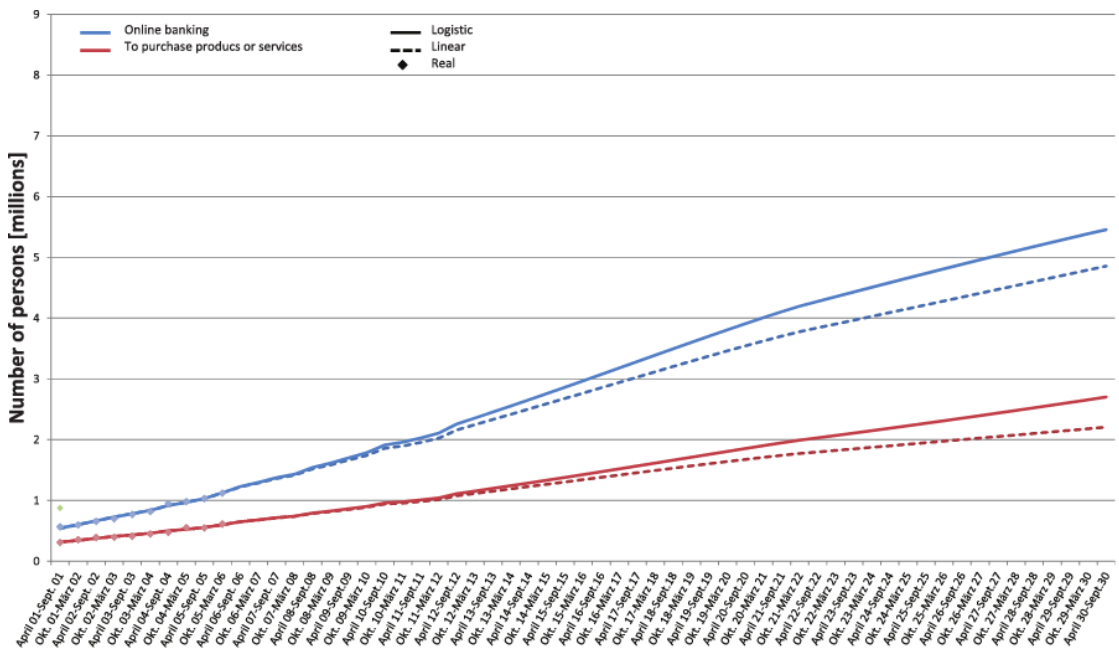

Figure 5.9 Number of online banking users and online shoppers. (forecast, FSO).

The forecast shows that by 2030 almost the entire Swiss population over 14 years of age would use such services. Similar as for teleworking, we tried to find out in the specific literature how teleshopping would impact people's travel behavior. A short summary of the conclusions of the analyzed studies tells:

- The majority of studies shows that teleshopping is no substitute for travel and might be a complement to traditional shopping activities.
- Mud et al. (2001) have concluded that shopping via the Internet does not eliminate travel and most likely even generates additional shopping trips.

- Casas et al. (2001)showed that Internet shoppers do not travel less and in some cases travel even more than non-Internet shoppers.
- Tacken (1990) found that teleshoppers tend to save shopping time and traveled distance.
- Two studies from Germany did find a substitution effect as well: Luley et al. (2002) found reduction in the frequency of trips, while Lenz (2003) found 10% reduction of total shopping travel due to teleshopping.
- Farag et al. (2004)claimed that teleshopping complements store shopping.
- "E-shopping will substitute for store shopping at the margin, but both forms of shopping will probably continue to expand and co-exist. Thus, the dominant relationships between e-shopping and store shopping will not be replacement of the latter by the former, but interactive augmentation and modification of both" (Moktharian, 2004).

Despite expectations that teleshopping could potentiality substitute for traditional shopping, the majority of studies have found that the teleshopping impact is more likely to be complementarity rather than substitution. On the other hand, studies on other maintenance teleactivities (e.g., telebanking, telemedicine) report about a substitution effect (Andreev et al., 2010).

5.6.4.2. Adaption of the transportation networks

There are two separate networks for private and public transport. For the private transport network for 2010, a detailed navigation network from 2010 was implemented. The resulting network includes over 1.3 Mio links and over 600000 nodes. It was updated to the conditions in 2030 by adding the extension projects for which the federal and cantonal governments have firmly committed themselves. Due to the complexity of timetable construction for 2030, the public transport network of the National Transport Model of the Department of the Environment, Transport, Energy and Communications (DETEC) was used. For that purpose, the network was converted to MATSim which showed to be quite difficult because the National Transport Model is modeled within a macroscopic transport simulation whereas MATSim belongs to the group of microsimulations. Figure 5.10 shows the combined network in 2030. The private transport network is marked in grey, the public transport network in red. It can be seen that the private transport network is finer than the public transport network.

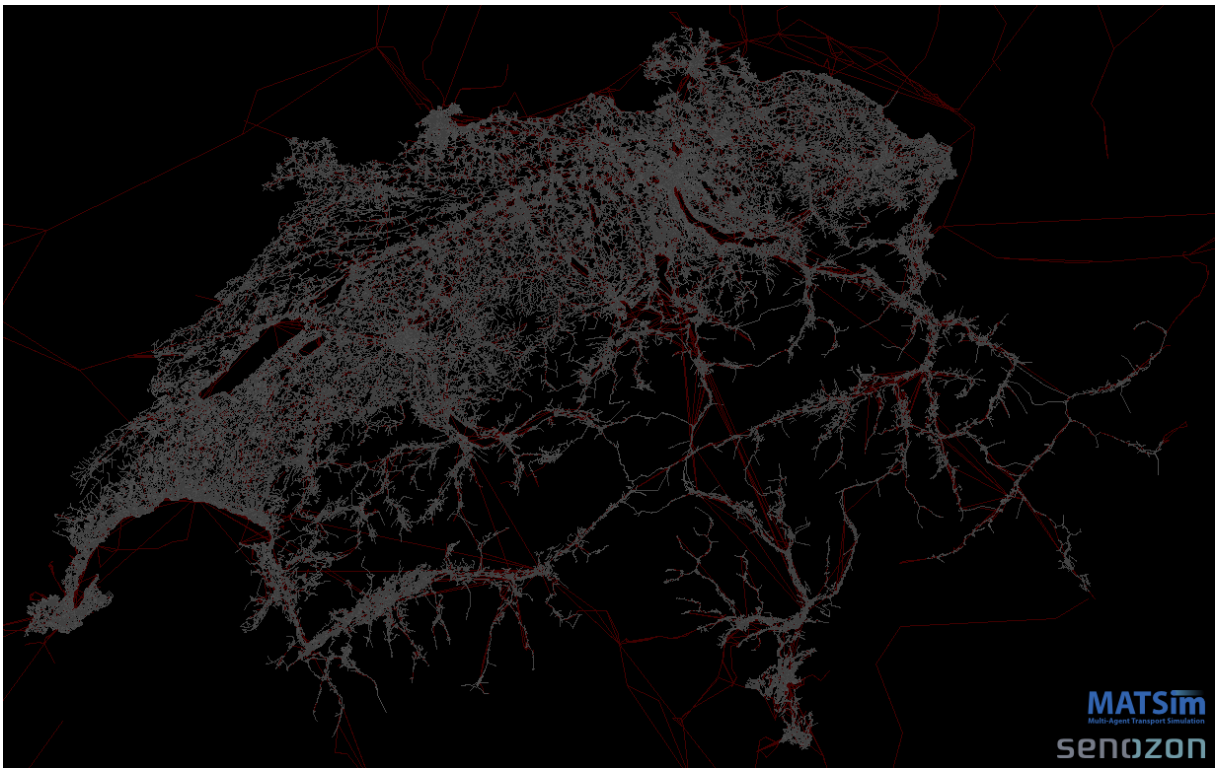

Figure 5.10 Multimodal transport network in 2030. (private transport: grey, public transport: red).

5.6.4.3. Agent's population

The population generation process consisted of two stages. In the first stage, survey calibration was used to reweight a person sample with activity schedules to reflect postulated changes in the frequency of certain activity types (according to the scenario). The second stage combined this calibrated dataset with the register survey data by means of statistical matching based on the attributes age, gender, and the nine-level classification of Swiss communes. All in all, 5 different 10% sample populations were generated:

- Baseline population of 2010
- Baseline population of 2030
- Population of 2030 assuming 20% less work trips
- Population of 2030 assuming that 20% of the shopping trips are replaced by leisure trips
- Population of 2030 combining the former two hypotheses

Table 5-2 gives an overview of the different 10% sample populations. In general, the MATSim population only contains persons with transport demand. Therefore, people staying the whole day at home or toddlers are excluded and the (up scaled) population size is smaller than the number of inhabitants in Switzerland.

Table 5-2 Overview of population files.

Population	Size	# Activities			
		Work	Shopping	Leisure	Education
Baseline 2010	736894	496388	316447	677363	150747
Baseline 2030	794871	486103	354472	738153	156208
2030 "Home office"	790916	385789	354145	737735	156730
2030"Delivery"	796667	484323	284393	884913	157060
2030 "Combined"	793370	386270	283705	884919	156594

For all these scenarios MATSim has been run. The "Combined" scenario has been chosen as the one to work with in WP3 and WP5, whereas in WP4, the "Baseline 2030"-scenario has been selected.

5.6.5. Application of future mobility scenarios to a case study

The "Baseline 2010"-mobility scenario, which is also presented in Figure 5.3, and the "Baseline 2030"-scenario were both applied to the case study in Zernez. The "Baseline 2030"-scenario was joined with the fleet scenario which assumes a nationwide BEV penetration level of 60% by 2050. The Swiss electricity mix was chosen for the operation of BEV in both scenarios. This is a significant simplification indeed. But this assumption shall facilitate the interpretation of the comparison of the present and the future scenario since the effective future electricity mix is not known. However, it might be assumed that a more carbon intense electricity mix decreases the benefits of the introduction of BEV with regard to climate change and vice versa.

Figure 5.11 compares the life cycle GHG emissions of these two mobility scenarios. Just as in Figure 5.3, the emissions are normalized by the household size and ranked in ascending order. For the sake of consistency, the same Monte-Carlo-sample as shown in chapter 5.6.3 was used for all future mobility scenarios. However, only impacts from mobility demand are considered, whereas impacts induced by housing are disregarded for this comparison. According to the model results, the mean value of 2.18 t CO_2-eq per person and year in 2010 decreases by approximately 54 % to 1.01 t CO_2-eq in the considered future scenario (Figure 5.11). Moreover, it can be observed that the mobility impacts are less equally distributed among households in the future scenario. 16% of the households with the largest impacts are responsible for 50% of the GHG emissions stemming from mobility. However, as can be deduced from Figure 5.11b, also BEV-owning households are among these 16% of the largest GHG emitters.

In order to capture the effect of battery electric vehicles on GHG emissions, the "Baseline 2030"-scenario was also run without taking the introduction of BEVs into consideration. Figure 5.12 shows that the reduction of GHG emissions observed in Figure 5.11 is obviously not only caused by the replacement of conventional cars by BEVs. The different mobility behavior simulated in the "Baseline 2030"-scenario compared with the "Baseline 2010"-scenario exhibits a large impact on GHG emissions in the case study of Zernez. Apparently, the mean value of GHG emissions decreases by 35% only due to this change in mobility behavior. The replacement of conventional cars by battery electric vehicles leads to a further reduction of the mean GHG emissions by about 25% to 29% (see Figure 5.12).

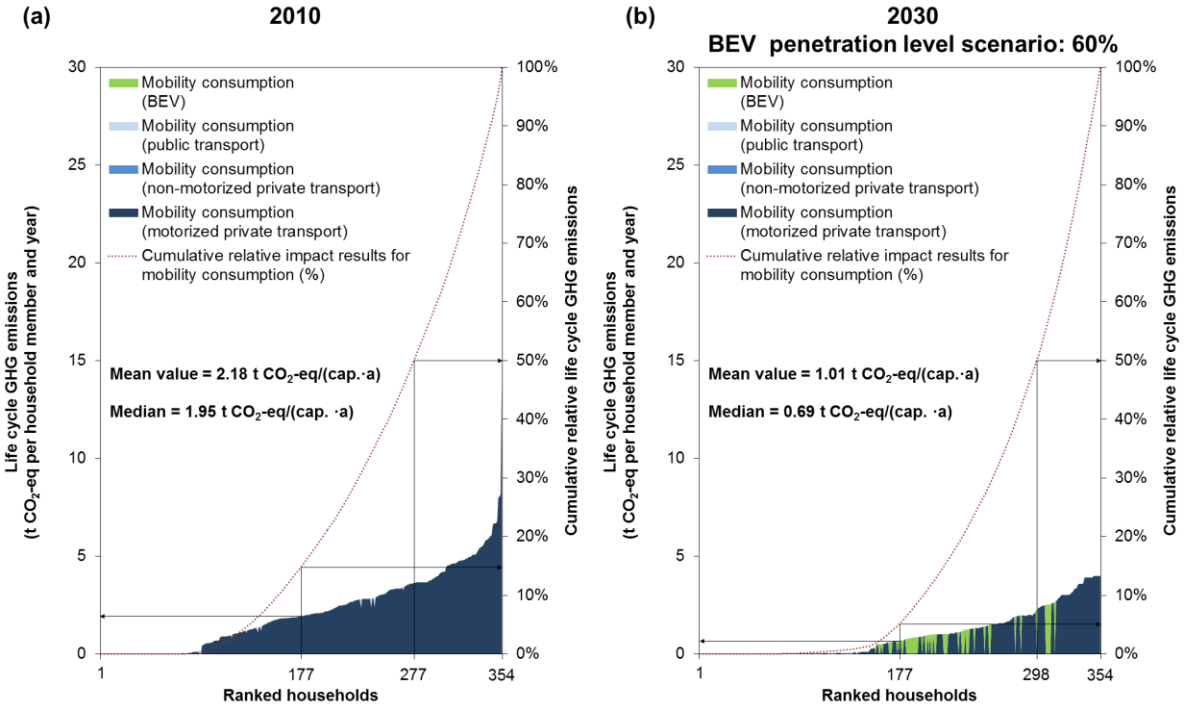

Figure 5.11 Life cycle greenhouse gas emissions of individual households induced by mobility in the case study of Zernez. The impact results per household have been normalized by the respective number of household members and ranked from smallest to largest value. (a) "Baseline 2010"-mobility scenario, corresponding to the scenario used for Figure 5.3. (b) "Baseline 2030"-mobility scenario combined with a fleet scenario assuming a nationwide BEV-penetration level of 60% by 2050.

Interestingly, no further decrease of the mobility impacts can be stated with higher BEV penetration levels. This has several reasons and originates also from model and scenario assumptions, which often become visible in such small case study municipalities. The small amount of agents simulated in Zernez can be divided into two distinct groups. The fleet scenario which assumes a 30%-penetration of BEVs by 2050 identifies already many MATSim-agents in Zernez as prospective BEV-purchasers. These agents feature the necessary criteria defined in WP 3 in order to belong to a class of agents which will buy BEVs at an early stage and regardless of mainstream trends. The second group of agents acts also independently of mainstream trends, but will not buy BEVs in any of the fleet scenarios. In consequence of this circumstance, the ratio of households owning at least one BEV is constant in all three penetration scenarios and amounts to 15%. Differences between these three fleet scenarios and especially the slight increase of GHG emissions in the 90%-penetration scenario arise mainly from two reasons. First of all, there are households, which will possess more than one BEV in scenarios with higher BEV-penetration. If a household complements its BEV-fleet with a BEV which is less environmentally benign, this will understandably result in higher mobility impacts. Secondly, the BEV purchased by a MATSim-agent is different in the three fleet scenarios. Consequently, if for instance, an agent buys a Sport Utility Vehicle-BEV in the 90%-penetration scenario, whereas the same agent is assigned a midsize BEV in the 30%-penetration scenario, this will inevitably cause higher impacts in the 90%-scenario.

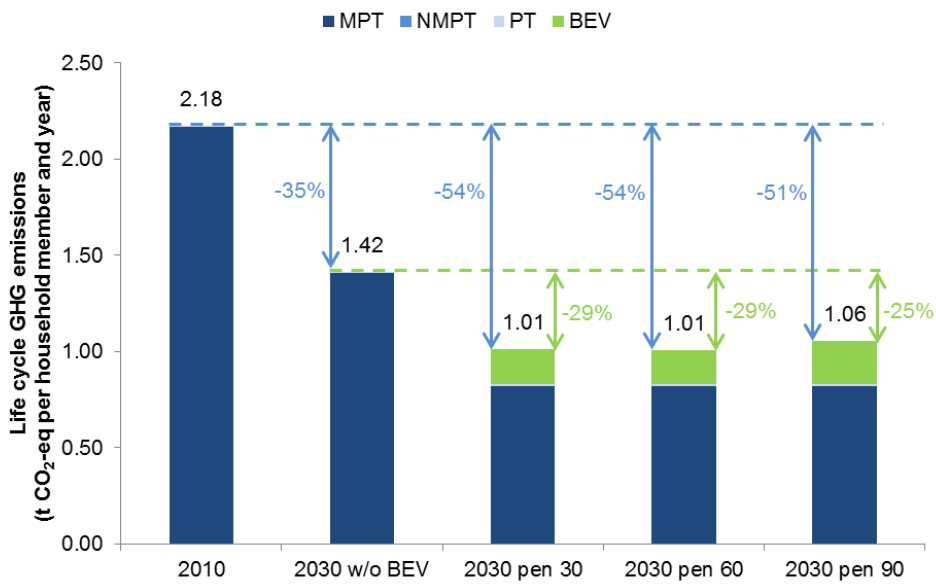

Figure 5.12 Mean values of greenhouse gas emissions for different mobility scenarios applied to the case study of Zernez. Scenarios: 2010 = "Baseline 2010"-Scenario; 2030 w/o BEV = "Baseline 2030"-Scenario without consideration of BEV introduction; 2030 pen 30, 60, 90 = "Baseline 2030"-Scenario combined with a fleet scenario assuming a nationwide BEV-penetration level of 30%, 60% and 90% by 2050. Abbreviations: MPT = motorized private transport; NMPT = non-motorized private transport; PT = public transport; BEV = battery electric vehicles.

Although such a small case study municipality shows the limits of the developed scenarios and models, the presented results reveal that a change in mobility behavior and the introduction of battery electric vehicle are able to substantially reduce greenhouse gas emissions caused by mobility.

5.7. Conclusions

The applied housing energy demand model worked well on an aggregated level in the case study of Zernez. The model evaluation indicates that the housing demand model might be a promising basis for further investigations of the building stock in urban areas. However, it is less suited for the analysis of individual buildings.

The use of well-established and publicly accessible databases facilitates a fast performance and an easy setup of the applied LCA model without antecedent excessive data acquisition. In contrast to previous models for environmental analyses, this model is able to quantify environmental impacts at the level of individual households. The application of this LCA model to the two case studies showed indeed the potential of a regionalized bottom-up analysis of the environmental footprints of households.

The results of the case studies revealed that housing and mobility are comparably important areas in the context of household consumption and responsible for a large share of the environmental impacts induced by household demand. In terms of GHG emissions and for the situation in Wattwil and Zernez, we can conclude for housing that we can only achieve low impacts by a combination of small demand and almost low-carbon supply. Therefore buildings should be refurbished. Furthermore, the living area per capita has a strong impact and it is advantageous to keep it at moderate levels. Wood heating and heat pump systems have a favorable impact on GHG emissions. The disadvantage of the former is the relatively high emission load of particulate matter and that of the latter is the augmented use of electricity. The presented optimization approach is able to assist in

such trade-off-situations. The results of the optimization model can help policy makers to identify the most effective measures for improvement at the decision making level, e.g. at the building level for refurbishment and selection of heating systems or at the municipal level for designing district heating networks. Although the high reduction potentials of GHG and PM emissions found in the case of Wattwil are very encouraging in view of sustainable future energy supplies, they should be seen as long-term targets for environmental improvement potentials rather than realistic goals for the near future, because in our computations substantial aspects of reality such as limited financial resources and social acceptance were not considered.

For today's land-based mobility, the benefits of the future introduction of electric mobility could be demonstrated by the application of mobility scenarios to the municipality of Zernez. However, we cannot switch immediately to a low-carbon supply. Alternatives to internal combustion engines like plug-in hybrid, battery electric, or fuel cell cars are now made ready for the market, but still have deficiencies in range and necessary infrastructure. Thus in the short-term, impacts from mobility can only be significantly reduced by a change in mobility behavior and particularly by a reduction of motorized private transportation and an increased use of public transport. However, this is often not possible because of long commuting distances. This emphasizes the great importance to bring living and working places closer together in order to reduce GHG emissions in the long-term.

The presented LCA model and its application to case studies revealed that analyses of emissions on household level are able to support the identification of targeted measures aimed at lowering environmental impacts caused by household consumption. Finally, the results can be helpful to identify pathways to meet political goals, such as the intended energy turnaround in Switzerland (switching to a more efficient energy supply with high share of renewables after phasing out nuclear power).

The described approach of using household expenditure data has proven difficult. Neither utility maximizing decision modeling nor standard statistical tools helped formulating an unambiguous interpretation. The data used in this research however is very rich and detailed despite limited geographical information due to privacy protection. The insight that household expenditures cannot be easily predicted but are partially irrational is also valuable.

Firstly, household expenditures show very little correlation among each other and in respect to socio-economic variables. Household expenditure are, apart from food that is a function of the number of people to a large degree, of a pronounced individual and random nature. Secondly, transportation expenditure, for both modes, have a very different set of explanatory variables than the other categories. Both are relatively independent of household composition and income but instead on car ownership and residential location. The analysis showed that every household has its own lifestyle and makes decision based on personal preferences that can be interdependent from each other and different from other, apparently similar, households. In other words, the relationship between different expenditure categories does not seem perfectly rational (or its rationality is not captured by the model used) but travel demand generation seems fairly rational as clear dependency on the supply and possibilities of a given transportation network a household faces could be observed.

Travel behavior did not change substantially in Switzerland in the span of time analyzed (1994 to 2010). The number of out-of-home activities and home-to-home journeys for the same age groups

across cohorts is fairly stable, although the time spent at activities is slightly decreasing. Some change has been observed, however, in license ownership, car ownership, and public transport subscriptions. In all microcensi, it is possible to observe saturation in the number of persons with driving license and car ownership. In the newest microcensus the level at which this saturation happens is slightly lower than before and it happens a bit slower too. This means that even if the percentage of people having a driving license is more or less the same as in the previous survey, some persons are getting the license later in their life course. This result can be interpreted in various ways. On the one hand it might reflect a reduced interest in driving and owning a car by newer generations, as already found by other researchers in previous studies (Goodwin, 2011). In support of this view there is also the impressive growth of the number of public transport subscriptions which more than doubled in the last 20 years. This trend is particularly strong among younger generations and more affluent people. The peak analysis did not show substantial changes either. The only noticeable difference through the years is a tendency of the peaks to flatten out. The peaks are still there and at similar time of the day but are not as high as they used to be. A possible interpretation is that people have learned, at least in part, how to avoid congestion if they are not bounded to a particular time. The literature research on teleworking and teleshopping showed that a much larger diffusion in the next 10 to 20 years is expected for both activities. We were not able, though, to answer the question to which extent this will influence individuals' mobility behavior in the future. It is still unclear if these activities will substitute some activities, therefore reducing travel – as many researchers and planners hope – or if they have a rather complementary role at best or they even generate additional travel as some studies on the topic assessed. Looking at the analyses made, a "business as usual" scenario is still a safe scenario. If the trends emerged in this study will go on in the next years, mobility patterns in 2030 will probably not depart substantially from current patterns. Nevertheless, there are some hints that the society is, slowly but steadily, moving on from a car centered mobility to a more varied and possibly complex mobility style and also to different ways to carry out activities. The scenario called here "combined" scenario reflects this trend.

The relevance of the enhancements in MATSim goes beyond the context of the THELMA project. In fact, the fleet choice model, the parking model, the ability to account for energy consumption, the electric charging of vehicles, have transformed MATSim into a tool capable of dealing with a whole series of problems which could not be addressed in its previous versions. This opens up the way to applications of the software which go beyond the domain of transportation alone. Finally, the creation of a MATSim scenario for 2030, taught us a number of important lessons. A model which simulates travel behavior of a whole country at individual level comes at the cost of being data intensive. In Switzerland the necessary data is relatively easy to gather, at least if the goal is simulating a scenario temporally located in the present. Setting up a scenario located in a relatively distant future, the amount of available data on which one can rely is much scarcer. This forced the modelers to take new ways, and make a further effort in order to have plausible estimations of how future mobility could look like. This is a valuable exercise which also adds a new dimension to the simulation tool which was until now used for short term predictions.

5.8. Future work

There are also other factors than housing and mobility contributing to overall household environmental impacts. Food and clothing are the third and fourth most important consumption categories and further work should focus on implementing household demand models for them. Hence, this would lead to a more complete LCA-based picture of household environmental impacts.

More Swiss municipalities should be investigated in the way we demonstrated for Wattwil and Zernez. This would allow comparing the different distribution profiles of household environmental impacts against each other. Low-impacting communities could be identified and factors like short commuting distances could be derived from the analysis of their community structure. The results should be used to establish long-term roadmaps that focus on promoting these factors.

The investigation of future mobility scenarios should also be applied to further municipalities in order to gain a better grasp of the large scale implications of electric mobility. Furthermore, the present work only examines the Swiss electricity mix. However, the underlying electricity mix strongly affects LCA results for BEV. Therefore, future work should focus on a more comprehensive analysis of possible future electricity mixes. Moreover, the penetration of BEV should not only be judged by greenhouse gas emissions, but also by other environmental indicators.

The presented optimization approach remains to be limited in the sense that neither economic aspects nor the willingness of households to take action regarding the installation of new technologies and the refurbishment of their homes were taken into consideration. Further research is therefore necessary to take these factors into account and investigate, e.g., cost-optimal options to reduce environmental impacts. Further model improvements could comprise the consideration of future technology development, implementing mobility-related optimizers, taking into account building park renewal rates and changes in population number, and changed demand in e.g. living space. Even though the presented optimization model was tailored for the case study of Wattwil, it is conceivable to adapt this model to other regions and constraints, given the availability of data.

Future work in the field of household expenditure as related to travel demand, next to the search of better model specifications of the given methodology, would have to consist of designing and implementing surveys that explicitly relate income and expenditure for certain categories and transportation with reported trips and travel demand generation. That would make it easier to make a model that would function as a stronger link between the above mentioned general expenditure data and specific travel generation, which would allow a better usage of said data set.

On the MATSim side, in the near future, it will be attempted to consolidate the improvements that this project brought to the software. An important factor will be to apply the simulation to other similar problems (i.e. involving energy consumption calculation, use of electric vehicles, etc.) in order to get more experience with these new tools. This is a crucial aspect when such complex modeling systems are used. At the same time, some of the enhancements were based on ad-hoc solutions because of the unavailability of some household characteristics in the current MATSim population specification. Therefore work will be pursued on the generation of a population where all the necessary attributes would be available as a standard. Finally, it was originally planned to have week-days and week-end scenarios. This was not possible because the data which was planned to be used as the basis for the associated set up proved to be inadequate. This could be addressed possibly by employing new techniques, gathering new data, or creating suitable datasets by means of a specific survey.

Acronyms

BEV	Battery Electric Vehicle
CA	Cluster Analysis
DETEC	Department of the Environment, Transport, Energy and Communications
ETHZ	Swiss Federal Institute of Technology in Zurich
ETHZ-PSL	ETHZ Power Systems Laboratory
EV	Electric Vehicle
FRDB	Federal Register of Buildings and Dwellings
FSO	Swiss Federal Statistical Office
GHG	Greenhouse Gas
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
MATSim	Multi-Agent Transport Simulation Model
MDCEV	Multiple Discrete-Continuous Extreme Value Decision Model
PEM	Proton Exchange Membrane
PMT	Passenger Miles Travelled
PV	Photovoltaic
VMT	Vehicle Miles Travelled
WP	Work Package

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6. Work Package 5 "Analysis integration"

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6.1. Purpose of integration analysis

The purpose of Work Package 5 (WP5) is to integrate the results of work packages 1 through 4 so that it will be possible to rank both individual vehicle designs and complete transportation scenarios from best to worst, based on their overall sustainability. This means designing a structured set of indicators for measuring different aspects of sustainability in cooperation with the other work packages, generating additional indicators that have not been supplied by other work packages, and integrating the results for the full set of indicators using both cost benefit analysis and multi-criteria decision analysis (MCDA). Work Package 5 also played an integrative or coordinating role in the design phase of the research, e.g. to insure consistency in criteria and indicator definitions, option selection, and scenario design, framing the analysis in terms of scope and boundaries, and coordinating key data assumptions.

The expected results include:

- Single technology rankings of individual vehicle designs
- Scenario rankings of national scenarios based on electric vehicle use and power grid interactions

Section 6.2 introduces two basic approaches to sustainability assessment. In section 6.3 a wide spectrum of quantitative interdisciplinary technology indicators is presented. For some indicators extensive simulations were carried out allowing state-of-the-art quantifications. This includes for example estimation of location-dependent environmental impacts linked to Life Cycle Inventories (LCI) and used for the estimation of environmental external costs. The indicators were then used in the assessment of sustainability of current and future car technologies based on two methods of aggregation of performance indicators, i.e. total cost approach (covering internal and external costs) and MCDA. In Section 6.4 the complex methodology and data flows behind the assessment of sustainability of car fleet options is presented, followed by the corresponding aggregated results. In the main part of this chapter some core results are presented including selected examples of indicator values both on the level of current and future technologies and for the fleet options. A full set of numerical results is provided in appendices.

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6.2. Approaches to sustainability assessment

The key element of WP5 is the integration of the broad range of criteria used to measure different aspects of sustainability. Two complementary approaches are used in the THELMA project, i.e. total cost analysis and Multi-criteria Decision Analysis (MCDA).

Total cost analysis – Total cost analysis is based on taking as many different sustainability criteria as possible and converting (valuing or monetizing) them to a cost basis, so that they can be aggregated into the total monetary value. Direct costs (also called internal costs) born by the vehicle owner, are combined with indirect costs (also called external costs) that are born by society as a whole (e.g. health care costs due to air pollution).

This total cost approach has the advantage of being conceptually simple, and produces vehicle and scenario rankings that are unambiguous. Its merits for cost-benefit assessment are undisputable. However, stakeholders do not always agree on the choice of methods used to monetize the externalities and the values obtained, so final rankings are often controversial. There are two main issues with total cost analysis in the THELMA context:

- First, not all criteria relevant to sustainability are easily monetized. In particular, social criteria are scarcely included in the total cost approach.
- Second, the benefits (in case cost-benefit analysis is pursued) as well as the costs of vehicles can be difficult to monetize. The services provided by different classes of vehicles are hard to compare based solely on a person*km or kg*km basis. Since the total cost approach builds on a vehicle km basis cost comparisons between different vehicle classes should be done with caution.

Multi-criteria analysis – The second approach to the integration of sustainability criteria is to use multi-criteria decision analysis, combining in a structured manner the data on vehicle or scenario characteristics (indicators) with stakeholder preferences. Multi-criteria decision analysis is a field of analysis that can supply a range of tools to help people choose between alternatives in a way that is consistent with their preferences for multiple criteria.

MCDA is typically used for complex problems that have no clear optima. Instead there are trade-offs between competing objectives, and different stakeholders can rationally choose different alternatives or solutions, based on their different preferences that are reasonably linked to their own interests. In fact, vehicle choice is a common example for MCDA applications, based on a buyer's different preferences for criteria like initial cost, fuel economy, performance, safety, appearance, etc.

MCDA is needed because the complexity of many problems simply exceeds human cognitive capacity to consistently balance competing objectives. Research has shown that most people can balance on the order of seven different, competing objectives. The problem of judging the sustainability of future transportation options far exceeded the bounds for consistent, unaided decision making.

MCDA is more than just choosing an appropriate algorithm for solving a specific type of problem. Instead, it is best used as part of a complete process to inform and assist decision-makers.

Such a process would include the following steps:

1. Determine stakeholder groups (optional)
2. Establish criteria and indicators (with stakeholder input if feasible)
3. Select the technological alternatives (with stakeholder input if feasible)
4. Quantify the technology- and country-specific indicators
5. Analyze the MCDA methodology requirements
6. Develop and/or select the most suitable MCDA method(s)
7. Implement and test the selected method(s)
8. Elicit stakeholder preferences or establish a set of preference profiles reflecting priorities of various types of stakeholders, and provide individual MCDA results
9. Analyze aggregated results and sensitivities to various preference profiles, and draw conclusions

As indicated above it is possible to bypass initial stakeholder inputs (steps 1, 2, 3 and 8) if the analysts are sufficiently familiar with the problem at hand, stakeholders' concerns and the various positions represented in the mobility debate.

As the THELMA partner responsible for MCDA, PSI has extensive experience in specifying, co-developing and testing MCDA methods for ranking discrete alternatives. This includes a web-based software application for interactive elicitation of preferences that provides immediate feedback of stakeholder rankings, and different MCDA solver algorithms.

Like cost-benefit analysis, MCDA also has advantages and disadvantages. On the plus side, it provides a learning process that can familiarize stakeholders with the relative strengths and weaknesses of competing technologies (i.e. there are trade-offs, but "no free lunch"). MCDA can guide informed debate and decision making in a way that is structured and fact-based. MCDA also addresses many criteria simultaneously (or in parallel), rather than sequentially, including social and other factors that are difficult to monetize.

On the minus side, MCDA is a complex and time-demanding process that requires agreements on the criteria set and hierarchy, and on the associated indicators. Social indicators are explicitly included, but their quantification is not always robust.

Research Questions – The research questions to be answered by Work Package are not so much theoretical or methodological as substantive, i.e. what are the most sustainable options for future mobility? This encompasses a number of subsidiary questions that are expected to be answered within this task, including:

- What is the representative criteria set?
- What are the values for the indicators in WP5?
- What are the results for the cost and MCDA rankings?
    - What are the 'best' vehicle designs, and what common elements do they have?
    - What are the relative strengths and weaknesses of the top alternatives?
    - What are the total impacts of the various strategies?
- How do the cost and MCDA rankings compare?
- How robust are the rankings to preferences?
- How robust are the rankings to uncertainties in indicators (e.g. GHG costs, etc.)?

6.3. Assessment of sustainability of current and future car technologies

This subchapter contains the discussion of criteria and indicators for the assessment of car technologies, description of the approaches used for the estimation of technology performance indicators and technology specific environmental external costs. Furthermore, the numerical estimates of the indicators are provided.

6.3.1. Criteria and indicators for sustainability evaluation

The problem of planning the future Swiss transportation system is like most important and complex problems, in that there is no single, clearly optimal solution. Rather there are many different possible alternatives that will produce different tradeoffs between a wide range of criteria in the areas of environmental, economic and social concern. Stakeholders and decision-makers with different interests and values will find different alternatives or strategies to be the best, based on their own preferences.

The purpose of multi-criteria decision analysis is to aid decision-makers in finding their own best strategies, and to inform and assist debate between multiple stakeholders. It does this by providing an analytic structure that can help decision-makers overcome the inherent cognitive limitations present when there are tradeoffs between too many different criteria for too many alternatives.

MCDA should be well suited to the dimensions of the problem being considered, that is, the number of criteria and alternatives that are being weighed. MCDA should preferably also be transparent and easily understood by the decision-makers using the results, and provide clear information on the criteria tradeoffs, the sensitivity of the ranking of alternatives to criteria preferences (and data assumptions), and whether there are robust solutions that perform well under a range of preferences and/or assumptions, even if they may not be the 'best' in every case.

The MCDA process generally follows a sequence of steps, which can be generically described as 1) selection of decision criteria for the problem in question, 2) selection of the set of alternatives (transportation technologies in the present case), 3) the selection of specific indicators to measure the criteria for these alternatives, 4) quantification of indicators based on quantitative analysis and qualitative assessment, 5) normalizing these indicators across the range of alternatives, 6) weighting the criteria based on decision-maker preferences, and 7) combining indicator and preference information by some particular algorithm, to 8) provide a ranking of alternatives for each decision-maker. The scaling and ranking methods may be non-linear or include the possibility of vetoes, but understandable transparency is often preferred to complex methods that are theoretically more advanced.

Within THELMA the MCDA process is strongly based on PSI's experience with a range of large, state-of-the-art studies primarily conducted in the area of energy supply. The goal is to pragmatically include participant input and comments in reducing the indicator set to increase clarity and reduce complexity and controversies.

The THELMA project is a bottom-up analysis that starts with a range of vehicle technologies and explores their implications for the personal transport system. This means that we have developed two parallel sets of indicators for both individual technologies (vehicles) and national fleet scenarios. The indicators for both vehicles and the fleet fall into the three classic pillars of sustainability, i.e. the

areas of environment, economy and society. In both cases, a set of good indicators should ideally be 1) measurable (or quantifiable), 2) technology specific, 3) logically independent, 4) balanced, 5) manageable (representative, but not exhaustive), 6) consistent, 7) based on intended use(s), 8) related to policy goals, and finally 9) they should actually be available or possible to produce.

The following documentation goes through the two parallel sets of indicators in the order mentioned above, i.e. environment first, followed by economy and society. Each area is introduced, and then the specific indicators are described. In some cases (environment) the vehicle and fleet indicators are the same, and only vary in the units used, i.e. on a per kilometer basis for each vehicle, and on a total basis for the whole fleet. For the economic indicators the purchase and operating cost are given for each vehicle, but these are only combined into total cost for the overall fleet to reduce the number of indicators. For the social indicators, the health and safety indicators are given with different units for both vehicles and the fleet, but the security of energy supply is only estimated for the whole fleet, and two key vehicle characteristics (range and time to refuel or recharge) are given for the individual member of society who is the vehicle owner.

Environment

All indicators representing the environmental dimension within the MCDA are based on Life Cycle Assessment (LCA), i.e. the quantified indicator results cover the complete life cycles of the vehicles including production, use and disposal of vehicles as well as fuel production. The indicators are quantified using the life cycle inventories developed and the Life Cycle Impact Assessment (LCIA) methods applied in WP1 of the THELMA research project.

The selection of indicators is based on experience gained in previous research projects and MCDA activities, such as the NEEDS (www.needs-project.org) and the CARMA (www.carma.ethz.ch) projects. In both projects, PSI was (together with partners) responsible for LCA as well as MCDA (Hirschberg et al., 2007, Simons et al., 2008, Schenler et al., 2009a, Volkart et al., 2013). The selected indicators represent today's major concerns from the environmental perspective, namely climate change, use of non-renewable resources (energetic and non-energetic), and impacts on ecosystem quality.[42] Together with the human health indicator, which is part of the social area in this MCDA, the environmental indicators completely cover the wide spectrum of environmental issues usually dealt with in commonly used LCIA methods. We refrain from using one fully aggregating LCIA indicator, since this a) would contradict the philosophy of MCDA, i.e. allowing the users to express their own priorities through subjective indicator weighting; and b) is not recommended in comparative LCA by scientific ISO 14040 and 14044 standards (ISO, 2006a, ISO, 2006b).

The environmental indicators used are the following:

1. <u>Greenhouse Gas (GHG) emissions</u>

   This indicator provides cumulative life cycle GHG emissions according to Intergovernmental Panel on Climate Change (IPCC) methodology (100a time horizon) (Solomon et al., 2007). The single GHG are weighted with their Global Warming Potential (GWP) and summed up to the total. The indicator represents potential impacts of global warming on human health, ecosystems, and the society, as a result of anthropogenic GHG emissions (e.g. rise of sea level, spread of diseases,

[42] Impacts on human health as an effect of pollutant emissions are represented by a separate indicator in the social area.

extreme weather events, etc.). The main source of GHG emissions in the mobility sector is the combustion of fossil fuels, either in internal combustion engines for direct propulsion, or in other parts of the life cycles of vehicles, e.g. fuel production in terms of electricity or hydrogen. The most important GHG is CO_2. Others are CH_4, N_2O, and HFCs.

Cumulative GHG emissions are measured in terms of [kg CO_2-eq.].

2. Primary energy use (non-renewable)

   This indicator provides cumulative life cycle non-renewable primary energy use, i.e. the demand for fossil and nuclear primary energy carriers (mainly oil, coal, natural gas and uranium). Primary energy content of the different energy carriers is used for quantification according to (Hischier et al., 2010). Despite of the fact that this indicator does not take into account the different scarcity of primary energy carriers (which is, on the other hand, hardly quantifiable) its use is in line with several commonly used LCIA methods (Frischknecht et al., 2009, Jolliet et al., 2003).

   Primary energy use (non-renewable) is measured in terms of [MJ-eq.].

3. Use of metal and mineral resources

   This indicator provides cumulative life cycle demand of metal and mineral resources. It's quantified according to the LCIA method "CML, abiotic depletion" (Guinée et al., 2002), without fossil fuels and uranium in order to avoid overlaps with the primary energy indicator. It takes into account the scarcity of the single metals and minerals in terms of ultimate reserves and current extraction rate relative to the reference substance iron ore. Economic or political constraints potentially affecting the availability of metals and minerals are not taken into account.

   Use of metal and mineral resources is measured in terms of [kg Fe-eq.].

4. Impacts on ecosystems

   This indicator provides cumulative life cycle impacts on ecosystem quality. It's quantified according to the LCIA method "ReCiPe (H, A)" (Goedkoop et al., 2012) without impacts of climate change in order to avoid overlap with the indicator measuring GHG emission. The indicator considers impacts of land use, acidification and eutrophication, and ecotoxicity as a consequence of direct land use and emissions of pollutants to air, soil and water bodies.

   Impacts on ecosystems are measured in terms of [species-year], representing the “disappeared fraction” of species resulting from the burdens mentioned above.

Economy

All indicators representing the economic dimension within the MCDA are based on discounted net present values of costs estimated for the manufacturing and operation of the vehicles that compose the overall fleet. Fixed capital costs are estimated for a wide range of vehicles based on their design, i.e. the base vehicle, type of drivetrain, key component sizes, and other options like light-weighting. Variable operating costs were modeled based on drivetrain simulation using representative driving cycles. Purchase and operating costs for all vehicles are then summed up for total fleet costs, based on a model of fleet composition.

Although many more interesting economic indicators could be produced, these were selected as the key, minimum subset of indicators based on prior sustainability-related work in both the energy and transportation areas, such as the NEEDS project (www.needs-project.org) and the AGS project Transition to Hydrogen. PSI was responsible in these projects for coordinating and producing key economic indicators, as well as MCDA and integrative analysis (Wokaun and Wilhelm, 2011, Wilhelm et al., 2011, Wilhelm et al., 2012, Schenler, 2010)

The economic indicators used are the following:

5. Purchase Cost

This indicator is generally recognized as one of the most important factors for individual purchasing decisions. It is calculated for each individual vehicle design, based on the vehicle class, size, type of drivetrain, size of major components (e.g. batteries), and other technology choices like light-weighting. The cost of vehicle production is estimated, assuming full production economies of scale for emerging technologies, and then a margin for overhead, distribution and profit is added. If the battery for an electric vehicle is not expected to last the full life of the vehicle, its replacement cost is also included.

Purchase cost is measured in Swiss Francs [CHF] for each vehicle.

6. Operating Cost

   This indicator is other dominant vehicle cost, i.e. the variable fuel and/or charging cost to operate the vehicle, based on vehicle type, energy use, and forecast fuel and electricity prices. The operating cost is an internal cost, paid by the owner, and does not include any external costs due to environmental or health damages. Other operating costs, including maintenance, insurance, taxes, etc., have been omitted as less significant for THELMA's purposes in vehicle comparison.

   Operating cost is measured in Swiss Francs per vehicle kilometer [CHF/vkm] for each vehicle.

7. Total Internal Cost

   This indicator includes the total fleet purchase cost and energy (fuel and electricity) cost based on the sum of the individual fleet vehicles. These costs are calculated for each year up to 2035 or 2050, and then discounted back to the present to give the total net present value for each scenario. This cost also includes any additional grid costs quantified in WP3. All of these costs are internal (or private) costs paid by the customer, on either the individual or societal level, and do not include external costs due to emissions or health impacts.

   Total cost is measured in Swiss Francs [CHF] for the entire fleet.

Social

The indicators represented within the social dimension are divided into two major areas. The first area includes the safety and risk indicators that are based on environmental impacts and accidents within related fuel chains that are of broad interest to society, as well as the risk of interruption to energy supply. Several different measures of health risks are included, based on the differences between normal operation and severe accidents, and differing public perceptions based on typical versus maximum accident size. These indicators are quantified by environmental impact analysis using air transport and damage modeling, by statistical analysis of historic fuel chain accident data

and by expert judgment of the different factors affecting energy supply interruptions. PSI has extensive experience with estimating such indicators for the relevant energy chains, based on prior projects such as NEEDS (Hirschberg et al., 2007, NEEDS, 2009, Schenler et al., 2009a) and the quantification and assessment of a wide range of energy chains (Burgherr et al., 2012, Burgherr et al., 2008, Burgherr et al., 2013).

The second area includes measures of vehicle utility that are of interest to the public as individuals (car buyers). These indicators are based on individual vehicle design characteristics that are of particular interest for EV's, i.e. driving range and recharging time. Other vehicle performance characteristics (e.g. acceleration, braking or handling) have been dropped as they are very largely correlated with the different vehicle classes. PSI experience in such vehicle-related MCDA, including societal, as well as cost and environmental indicators is based on the AGS project Transition to Hydrogen (Wokaun and Wilhelm, 2011).

The social indicators used are the following:

8. Average mortality

   This indicator measures the normal mortality associated with vehicle operation and its entire life cycle. Because supply chain deaths are often premature mortality associated with chronic illnesses, this indicator is measured in Years Of Life Lost (YOLL), indicating the reduction in years of life from the otherwise normal lifespan. Mortality and morbidity are strongly correlated, and the mortality indicator generally dominates so only mortality is used in this case.

   Average mortality is measured in [YOLL/km] for each vehicle, and in total [YOLL] for the fleet.

9. Expected severe accident mortality

   Severe accidents (based on 5 or more deaths, or exceeding certain economic damages) are an accepted measure in risk analysis of possible severe or catastrophic events that may disproportionately affect societal decisions due to risk aversion and public perception. While it is rare to have traffic accidents that exceed this threshold, there is a statistically expected mortality from severe accidents associated with the energy supply chains, which is provided by this indicator.

   Severe accident mortality is measured in [deaths/km] for each vehicle, and in total [deaths] for the fleet.

10. Maximum fatalities from a severe accident

    Public perception of risk and public risk aversion are also based on the maximum credible fatalities per accident (e.g. from a nuclear accident or from a major dam break). This indicator represents an energy-weighted average of the maximum credible fatalities per accident from the different primary energy chains associated with the transportation sector.

    Maximum fatalities from a severe accident are measured in [fatalities/km] for each vehicle, and in [fatalities] for the fleet.

11. Security of energy supply

    This indicator is based on expert-judgment estimation of the security of supply for each primary energy resource, based on market concentration, estimated resources, or geopolitical concerns

that could lead to interruptions of supply or increases in market prices. This is combined with the primary energy mix to calculate an energy-weighted average indicator for each fleet scenario.

The security of energy supply is estimated on a fleet basis for each scenario, using a unitless scale from 0 (worst) to 10 (best).

12. Vehicle driving range

    Driving range is a relatively minor concern for Internal Combustion Engine Vehicles (ICEVs), but it is a major concern for Battery Electric Vehicles (BEVs) and an intermediate concern for Plug-in Hybrid Electric Vehicles (PHEVs), Fuel Cell Electric Vehicles (FCEVs) and some ICEVs fueled by compressed gaseous fuels. The Electric Vehicle (EV) driving range here is not based on complete battery discharge, but rather on a partial discharge based on the economic costs related to battery life, etc.

    Vehicle driving range is measured in [kilometers] for each vehicle.

13. Charging/fueling time

    This indicator gives the necessary time for the vehicle to refuel or recharge. Refueling times for fossil and renewable fuels (including H_2 and CH_4 gases) are generally not a problem for individual customers, but the time required to recharge an EV battery may be a significant drawback that along with range may reduce buyer acceptance. The rate is based on battery size and the ordinary charging rate. Faster charging rates are also possible, but this can result in reduced battery lifetime.

    Charging/fueling time is measured in [minutes] for each vehicle.

Table 6-1 to Table 6-4 provide the summary of performance indicators used in this work for sustainability evaluation on the technology level (this sub-chapter) and on the fleet level (sub-chapter 6.4). This includes summary description of methods employed for the quantification of these indicators. The details of the estimation of simulated indicators are provided in section 6.3.2.

Table 6-1 Environmental indicators

Vehicle	Unit	Fleet	Unit	Quantification method	Indicator description
Primary energy use, non-renewable	MJ-eq/vkm	Primary energy use, non-renewable	MJ-eq	CED, fossil + nuclear	The indicator provides cumulative life cycle non-renewable primary energy use, i.e. the demand for fossil and nuclear primary energy carriers (mainly oil, coal, natural gas and uranium). Primary energy content is used for quantification.
Use of metal and mineral resources	kg Fe-eq/vkm	Use of metal and mineral resources	kg Fe-eq	CML v3, abiotic resource depletion excl. energy resources	The indicator provides cumulative life cycle demand of metal and mineral resources. It's quantified according to the LCIA method "CML, abiotic depletion" (without fossil fuels and uranium in order to avoid double counting with the primary energy indicator). It takes into account the scarcity of the single metals and minerals relative to the reference substance iron ore.
GHG emissions	kg CO_2-eq/vkm	GHG emissions	kg CO_2-eq	IPCC 2007 100a	The indicator provides cumulative life cycle GHG emissions according to IPCC 2007 (100a time horizon) methodology. The single GHG's are weighted with their GWP and summed up to the total. The indicator represents potential impacts of global warming on human health, ecosystems, and the society, as a result of anthropogenic GHG emissions (e.g. rise of sea level, spread of diseases, extreme weather events, etc.)
Impacts on ecosystems	species-year/vkm	Impacts on ecosystems	species-year	ReCiPe (H,A) ecosystem quality w/o climate change impacts	The indicator provides cumulative life cycle impacts on ecosystem quality. It's quantified according to the LCIA method "ReCiPe (H, A)" (without impacts of climate change in order to avoid double counting with the GHG emission indicator) and considers impacts of land use, acidification and eutrophication, and ecotoxicity.

Table 6-2 Economic indicators

Vehicle	Unit	Fleet	Unit	Quantification method	Indicator description
Purchase cost	CHF/ vehicle			Calculated in WP2	The indicator is estimated based on vehicle class, size and type of drivetrain, assuming full production economies of scale for emerging technologies. If the batteries are not expected to last the full life of the vehicle, their replacement cost is also included. This indicator is levelised per km and added to the other costs to obtain the total average cost per km for each vehicle.
Operating cost	CHF/vkm			Calculated in WP2	This indicator is the fuel and/or charging cost to operate the vehicle; based on vehicle type, energy use, and forecast fuel and electricity prices. The operating cost is an internal cost, paid by the owner, and does not include any external costs due to environmental or health damages. Other operating costs, including maintenance, insurance, taxes, etc., are omitted as less significant for THELMA's purposes in vehicle comparison.
		Total cost	CHF	Total fleet cost based on individual vehicle data.	This indicator includes the total fleet purchase cost and energy (fuel and electricity) cost based on the sum of the individual fleet vehicles. It also includes any additional grid costs quantified in WP3. Total cost is used here, but the average cost per km is also of interest to policy stakeholders.

Table 6-3 Social indicators.

Vehicle	Unit	Fleet	Unit	Quantification method	Indicator description
Average mortality (normal operation)	YOLL/ km	Average mortality (normal operation)	YOLL	Impact pathway approach.	This indicator measures the normal mortality associated with vehicle operation and its entire life cycle. Because supply chain deaths are often premature mortality associated with chronic illnesses, this indicator is measured in years of life lost (YOLL), indicating the reduction in years of life from the otherwise normal lifespan. Mortality and morbidity are strongly correlated, and the mortality indicator generally dominates so only mortality is used in this case.
Expected severe accident mortality	Deaths/ km	Expected severe accident mortality	deaths	ENSAD database and probabilistic risk assessment.	Severe accidents (based on 5 or more deaths, or exceeding certain economic damages) are an accepted measure in risk analysis of possible severe or catastrophic events that may disproportionately affect societal decisions due to risk aversion and public perception. While it is rare to have traffic accidents that exceed this threshold, there is a statistically expected mortality from severe accidents associated with the energy supply chains, which is provided by this indicator.
Severe accident - max. fatalities	Fatalities /km	Severe accident - max. fatalities	fatalities	ENSAD database and probabilistic risk assessment.	Public perception of risk and public risk aversion are also based on the maximum credible fatalities per accident (e.g. from a nuclear accident or from a major dam break). This indicator represents an energy-weighted average of the maximum credible fatalities per accident from the different primary energy chains associated with the transportation sector.

Table 6-4 Security of supply and vehicle utility indicators.

Vehicle	Unit	Fleet	Unit	Quantification method	Indicator description
		Security of energy supply	Composite index	Calculated in WP5	This indicator is based on expert-based estimation of the security of supply for each energy resource, based on market concentration, estimated resources, or geopolitical concerns that could lead to interruptions of supply or increases in market prices. This is combined with the primary energy mix to calculate an energy-weighted average indicator for each fleet scenario.
Range	km			Calculated in WP2	Driving range is a relatively minor concern for ICE vehicles, but it is a major concern for EVs and an intermediate concern for PHEVs and some ICEVs fueled by compressed gaseous fuels. The \EV driving range here is not based on complete battery discharge, but rather on a partial discharge based on the economic costs related to battery life, etc.
Charging /fueling time	minutes			Calculated in WP2	This indicator gives the necessary time for the vehicle to refuel or recharge. Refueling times for fossil and renewable fuels (including H_2 and CH_4 gases) are generally not a problem for individual customers, but the time required to recharge an EV battery may be a significant drawback that along with range may reduce buyer acceptance.

In most cases the indicators for the evaluation of individual technologies and fleet options overlap. There is a difference between the economic indicators, i.e. for car buyers there is a separation between purchase and operating costs since the earlier are often decisive for them while on the national level the total life cycle cost of fleet options is the core aggregated economic indicator. Furthermore, the security of supply of energy is not a major concern when buying a car but is again of critical importance on the national level. Finally, the vehicle utility may be decisive for car buyers.

6.3.2. Estimation of technology performance indicators

This section is divided into three parts. First the approach to simulation of indicators is described. This is followed by the short description of the approach applied to the estimation of location-dependent indicators and the resulting environmental external costs. Finally the estimates of indicator values are provided for a variety of current and future technologies of interest.

6.3.2.1. Simulation of performance indicators

The following description is adopted from Bauer et al. (2015), which in turn builds on Hofer (2014b). Both papers were produced in the THELMA project.

A novel integrated vehicle simulation and modeling framework to quantitatively assess technical, environmental and economic criteria of a wide range of conventional and electric powertrains, consistently taking into account future technology development, was developed. Its implementation extensively uses a wide range of inputs from WP1 and WP2.

The simulation starts by assessing the mechanical energy demand for a specific type of vehicle and driving cycle. In this context a vehicle can be defined by weight, frontal area, aerodynamic drag and rolling resistance coefficient. A driving cycle prescribes a speed versus time profile. It is usually employed on a chassis dynamometer for vehicle homologation, but can also be used for the simulation of vehicle performance and energy use. The Worldwide harmonized Light vehicles Test Procedure (WLTP) is the reference driving cycle for the calculation of vehicle configuration and energy use. The WLTP is based on statistical analysis of driving conditions from EU, India, Japan, Korea, Switzerland, and USA and is expected to replace the New European Driving Cycle (NEDC) for emission certification in Europe (UN, 2014). In contrast to the NEDC, the WLTP is a transient driving cycle which involves many continuous changes of velocity representing a more realistic driving pattern, i.e. it is more representative for “real-world” driving than the NEDC, which is systematically and substantially underestimating fuel consumption of passenger vehicles in daily driving (P. Mock et al., 2013).

Based on the parametric calculation of mechanical energy demand, an analytic simulation method is used to calculate conventional and electric vehicle configuration and energy use (Hofer, 2014b, Hofer et al., 2012). In this approach mechanical energy demand is converted to vehicle energy consumption using driving cycle averaged powertrain efficiencies which are determined for traction and regeneration modes using Advisor, an open source, numeric vehicle simulation software (Wipke et al., 1999). In addition to propulsive energy use, auxiliary loads for interior climate control and electronic appliances are considered. An analytic expression is used to evaluate vehicle component sizes and energy use as a function of configuration parameters such as range, technical parameters such as battery specific energy, and scenario parameters such as future weight reduction. The high level of integration between technical assessment and powertrain simulation enables a consistent comparison of the different vehicle technologies and the development of future scenarios. Table 6-5

and Figure 6.1 show key results of the simulation for a selected set of current and near future vehicles; the comparative LCA and cost assessment is carried out according to these specifications.

Table 6-5 Vehicle simulation results: vehicle specification used for technology performance assessment

				Power (kW)					Energy Storage	
		Electric range (km)	Fuel range (km)	Engine	Motor and controller	Power battery	Fuel cell	Transmission	Fuel tank (MJ)	Energy battery (kWh)
ICEV-g	2012	0	700	117	0	0	0	117	1956	0
	2030	0	700	103	0	0	0	103	1518	0
ICEV-d	2012	0	700	118	0	0	0	118	1702	0
	2030	0	700	104	0	0	0	104	1353	0
ICEV-cng	2012	0	500	121	0	0	0	121	1373	0
	2030	0	700	108	0	0	0	108	1499	0
HEV-g	2012	0	700	94	69	69	0	126	1531	0
	2030	0	700	81	59	59	0	108	1130	0
HEV-d	2012	0	700	95	70	70	0	127	1363	0
	2030	0	700	82	60	60	0	109	1060	0
HEV-cng	2012	0	500	97	71	71	0	130	1079	0
	2030	0	700	84	62	62	0	112	1152	0
BEV	2012	200	0	0	147	0	0	147	0	50
	2030	350	0	0	122	0	0	122	0	73
FCEV	2012	0	500	0	145	79	145	145	814	0
	2030	0	700	0	120	66	120	120	919	0

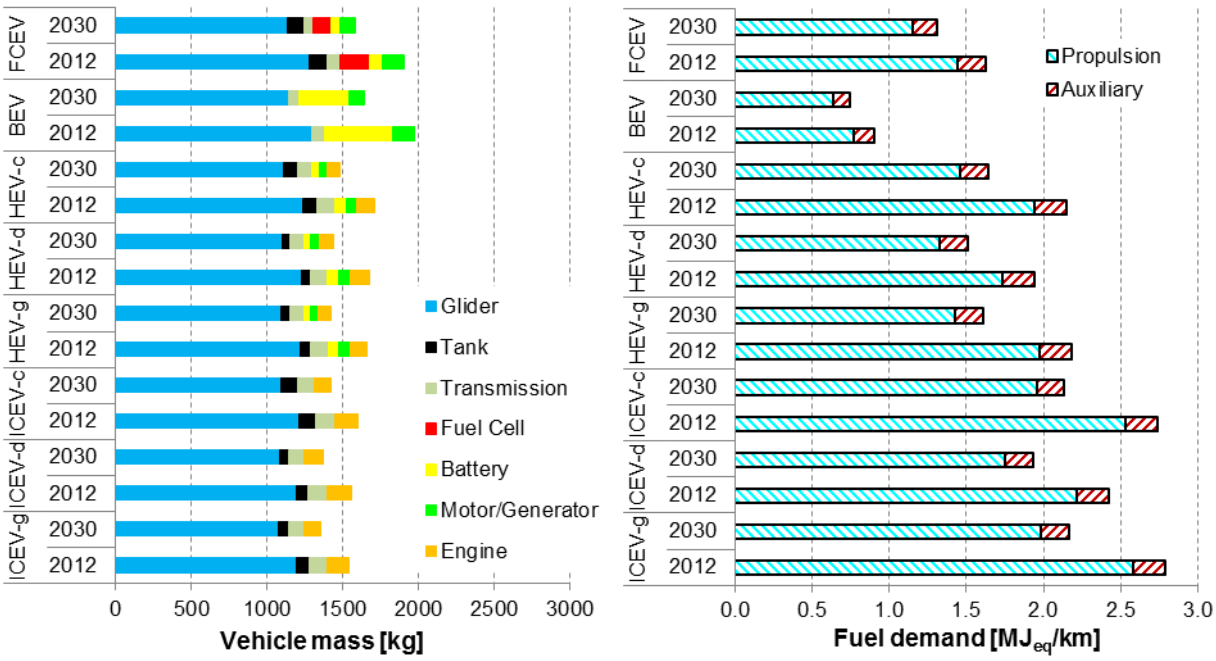

Figure 6.1 Vehicle simulation results: vehicle mass per component (left) and energy (i.e. fuel) demand for vehicle operation (right).

The current and future passenger car options are analyzed with regard to several criteria of interest. As illustrated in Figure 6.2, the modeling framework considers exogenous and endogenous criteria. Exogenous criteria are vehicle performance related aspects such as size, range, and acceleration. Those exogenous criteria are necessary input parameters to specify a car, execute the vehicle simulation, and perform the LCA. Endogenous criteria are the simulation results, such as vehicle mass and energy use.

The technology options are chosen to be independent, i.e. they can be combined in every possible way to study the range of resulting criteria and to better understand the interdependencies between technology and fuel options, future developments, and environmental impacts. The technology options set is split into powertrain and fuel type, vehicle size, range and performance, primary energy source, and vehicle model year. The latter influences the inputs passed on to the powertrain and LCA sub-models in various ways as the following parameters are a function of time:

- Vehicle glider mass, aerodynamic drag, and tire rolling resistance are expected to be reduced by manufacturers in order to lower vehicle energy use and to fulfill new emission standards. Similarly powertrain component efficiencies are increased over time to account for technical progress (Figure 6.1).
- Specific energy and power of powertrain components that are not yet fully developed (such as batteries) are expected to increase over time. This mass-related data is also used in the vehicle simulation to calculate vehicle weight and energy consumption.
- Life cycle inventories and LCIA results by component and energy source change over time as technologies develop. This data is used together with component sizes and vehicle energy consumption to calculate aggregated LCIA results for the complete vehicle life cycle.

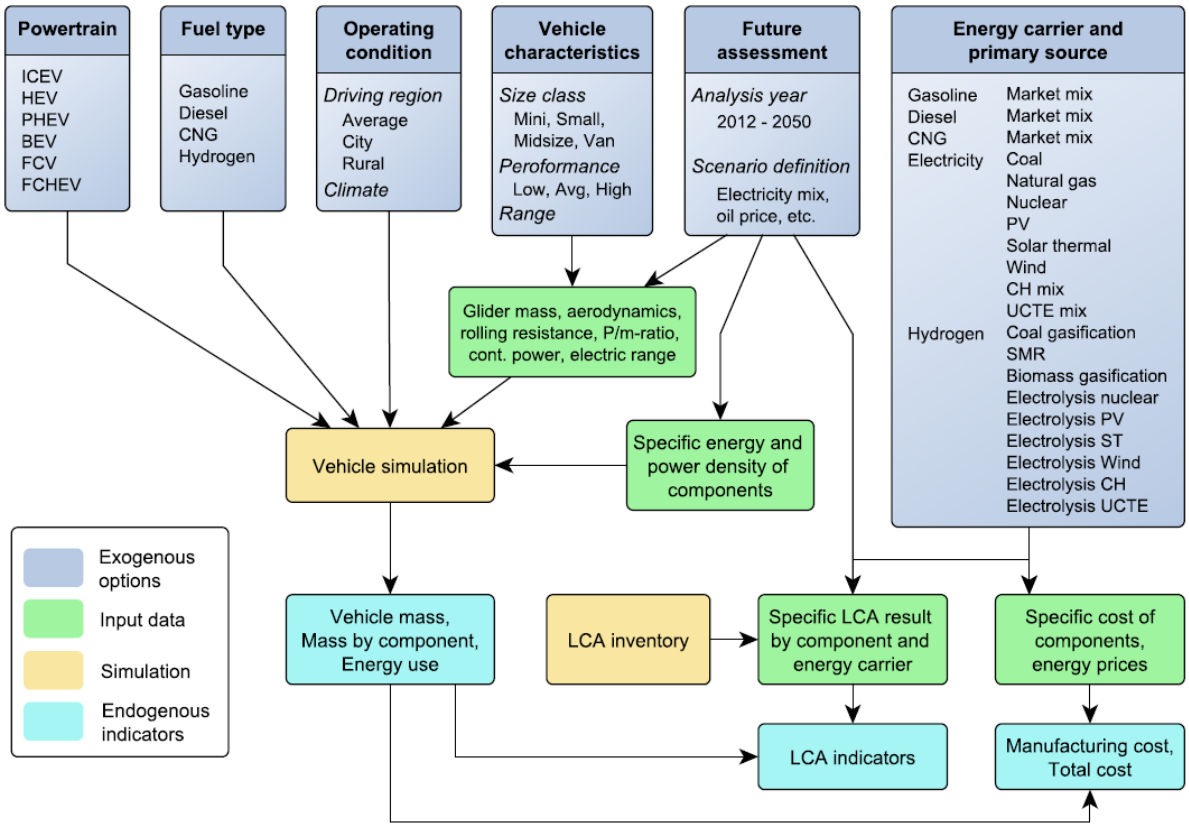

Figure 6.2 Analysis framework: technical, cost, and environmental indicators for current and future passenger cars are calculated using an integrated model based on a set of exogenous boundary conditions.

In the reference scenario, glider mass, aerodynamic drag, and rolling resistance coefficient are reduced by 0.5% per year, which equates to a total reduction of almost 10% by 2030. This rate of reduction seems to be realistic considering historic developments for these parameters and projections used in other studies (Kasseris and Heywood, 2007).

The simulation framework allows for the simulation of a wide range of different vehicle size and performance classes. The full simulation using the approach presented here is implemented in an interactive online tool in which the user can modify scenario assumptions and access the full set of results (Hofer, 2014a).

6.3.2.2. Simulation of location-dependent environmental impacts and estimation of external costs

Scope

A part of WP5 is the assessment of environmental impacts and external costs of electric mobility. The focus is on transport systems in Switzerland. To a certain extent, also European transport is investigated.

Goals and methodology

Major goals are the assessment of environmental impacts and external costs of electric mobility and the comparison of electric vehicles and conventional cars based on fossil fuels. The environmental impact and external cost assessment employs the impact pathway methodology in combination with life cycle assessment.

The principle of the impact pathway approach is outlined in Figure 6.3.

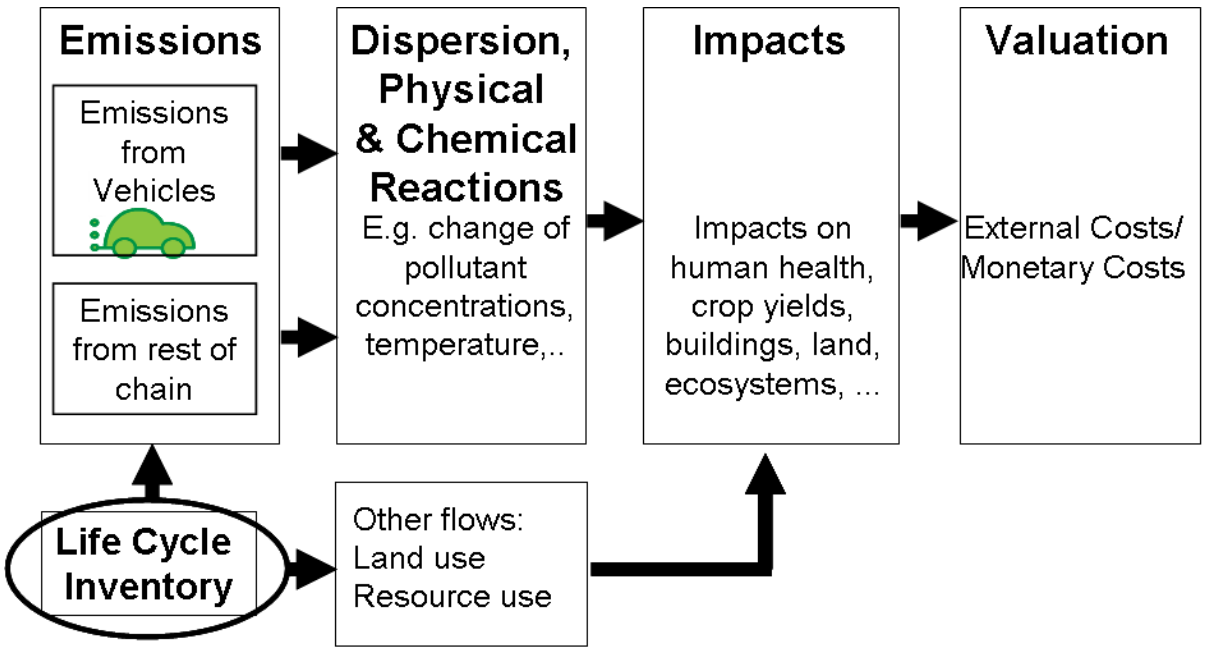

Figure 6.3 Impact pathway approach, including LCI.

The basic approach is the bottom-up environmental impact and external costs assessment in combination with life cycle inventory (LCI) data. In order to consider approximately the spatial resolution, a semi-regionalized approach was applied. Conventional life cycle impact assessment (LCIA) does not consider the locations of emissions. In the semi-regionalized approach the contributions to environmental burdens are split into two parts: Most important emission sources with known locations are modeled with site-specific impact assessment methods. Less important emissions sources or sources where locations are unknown are treated with constant impact factors (like in traditional life cycle impact assessment).

The semi-regionalized approach is a compromise between detailed modeling and simplification due to limited data availability. Data from the rest of the chain are taken from the life cycle inventory (WP1).

For more details on the environmental impact pathway and external costs approach we refer to the literature (Droste-Franke et al., 2005, Watkiss et al., 1999, NEEDS, 2009). The semi-regionalized approach is described in (Heck and Meyer, 2012).

Tasks

The following tasks have been performed:

- Emission modeling for all major vehicle classes (necessary for fleet modeling)
- Improvement of spatial modeling ("semi-regionalized approach")
- Connection to LCI data for electricity scenarios from WP1
- Estimates of external costs (incl. LCI contributions) per km
- Estimates of annual external costs (incl. LCI contributions)
- Estimates of Swiss scenarios until 2050 (incl. LCI contributions)
- Partial extension to the European scale: Potential reduction of particle emissions and external costs due to regenerative braking (scenario 2050)
- Assessment of mortality in terms of Years of Life Lost (YOLL) for about 100 technologies until year 2050 (for the purpose of Multi-criteria Decision Analysis (MCDA))

Modeling details

For the fleet emission modeling, the investigation of vehicle classes had to be extended to include all relevant passenger car types differentiated according to their emission classes.

Health damages and other environmental impacts depend often on the locations of the emission sources. Traditionally, LCA and life cycle impact assessments sum over emissions ignoring the locations. An improvement is the "semi-regionalized" approach (Heck and Meyer, 2010, Heck and Meyer, 2012, Heck, 2014).

For the present study, the direct emissions from the vehicles are considered in detail whereas the emissions and other burdens due to contributions from the rest of the chain are treated in a simplified way with constant factors. It is noted that human health impacts from noise are not included in this study.

Within the THELMA project, the transport in Switzerland was simulated in high resolution using the agent model MATSim. Nevertheless, because the results of MATSim in the form needed were The assessment of external costs environmental impact and external cost assessment was developed. The simplified model was checked for consistency with the MATSim model.

The basic observation is that the distribution of car ownership correlates well with the typical driving distances. In Switzerland, the densely populated areas have fewer cars per person and lower car mileages per person compared to the lower populated areas. Figure 6.4 shows both the number of cars per 1000 persons and the driving distances per person on the canton level in Switzerland.

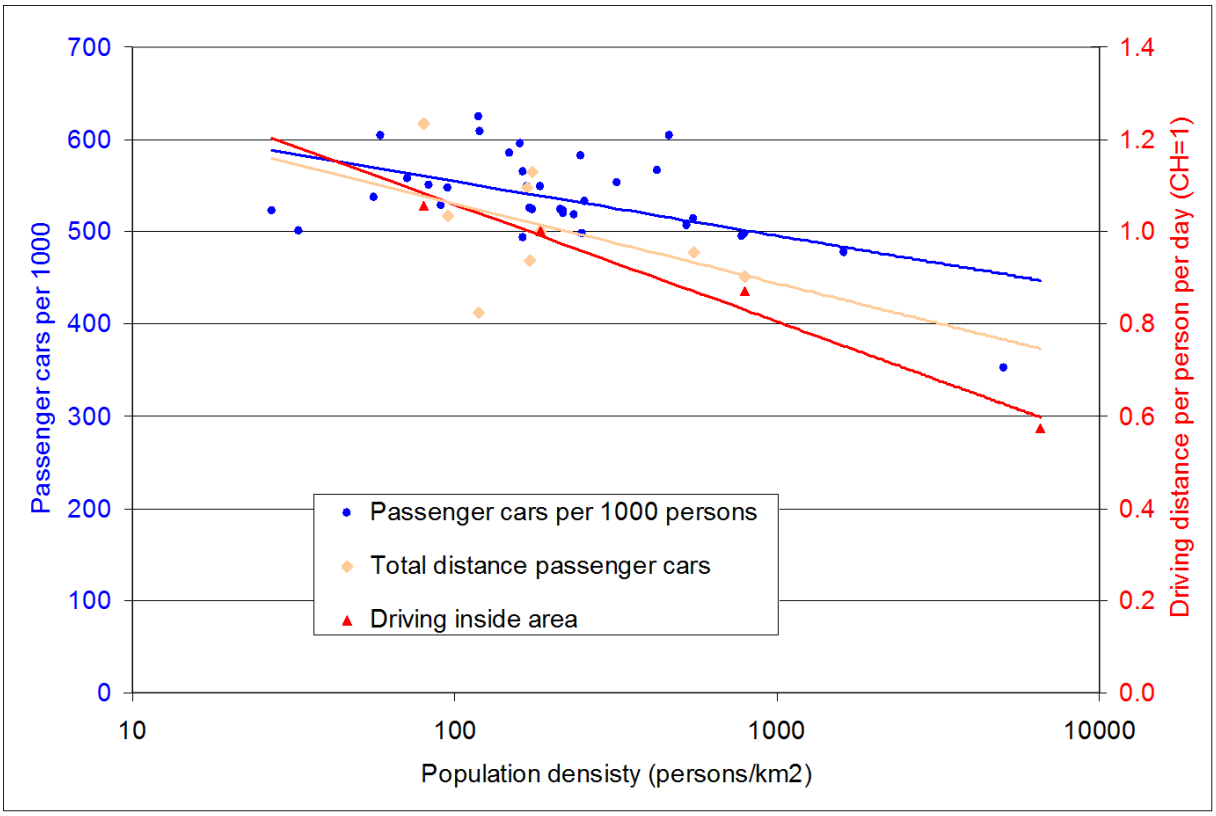

Figure 6.4 Model of spatial distribution – Switzerland. Data sources: (Swiss Federal Office for Spatial Development, 2005, Swiss Federal Statistical Office, 2012, Swiss Federal Statistical Office and Swiss Federal Office for Spatial Development, 2012).

Figure 6.5 shows the number of electric and other cars in cantons of Switzerland for the year 2010. In Figure 6.6 the split of the passenger car fleet into emission classes according to the Swiss Federal Statistical Office (2012) is illustrated. The figure shows that there is still a substantial share of old cars (EURO I and EURO II) in the Swiss fleet as of year 2010 which contribute significantly to the total emissions. The ecoinvent 2.2 (ecoinvent, 2012) database provides emission data only for EURO III, EURO IV, and EURO V emission classes. Therefore the car types EURO I, EURO II, and EURO VI for petrol and diesel had to be newly modelled based on literature and emission regulations (CLRTAP, 2010, EMEP/CORINAIR, 2007, European Environmental Agency, 2011, Swiss Federal Office for the Environment, 2010). The annual mileage depends on the car type and age of the car (Swiss Federal Statistical Office and Swiss Federal Office for Spatial Development, 2012).

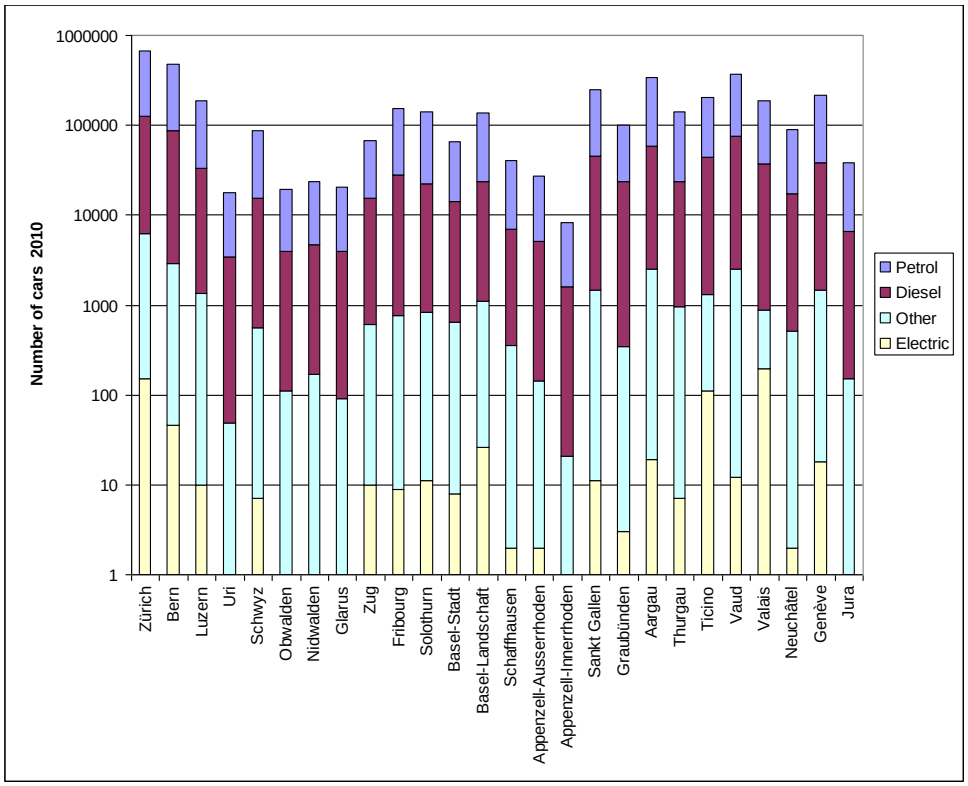

Figure 6.5 Number of registered electric and other cars in Swiss Cantons. Note that the scale is logarithmic. Data source: (Swiss Federal Statistical Office, 2012).

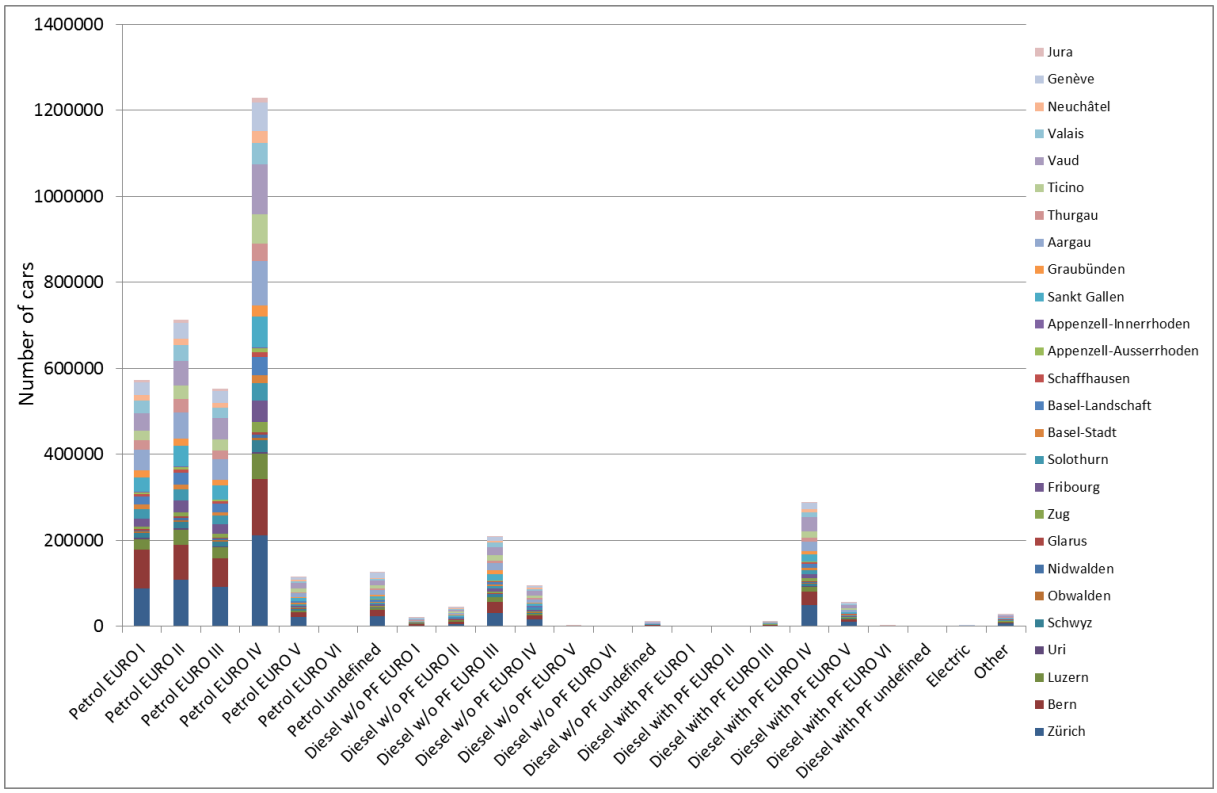

Figure 6.6 Passenger cars in Switzerland 2010 split into emission classes. Data source: (Swiss Federal Statistical Office, 2012).

In order to check the consistency with the more detailed MATSim model, the relative distributions were compared (Figure 6.7).

The MATSim model as applied in THELMA provided results for a single working day during the week. The Environmental Impact Assessment (EIA) model yields annual data according to the requirements of environmental impact assessment. The EIA estimates of annual total km based on annual average mileages of the different vehicle classes agree well with the figures provided by the Swiss Federal Statistical Office (2012). By contrast, a simple multiplication of the single-day estimate of the MATSim model by 365 days yields significantly higher results. This is explained at least partially by the fact that no weekend or seasonal traffic was considered in the MATSim simulation. Therefore, only the relative distribution could be compared. The comparison (Figure 6.7) shows that both models agree well for most cantons in Switzerland.

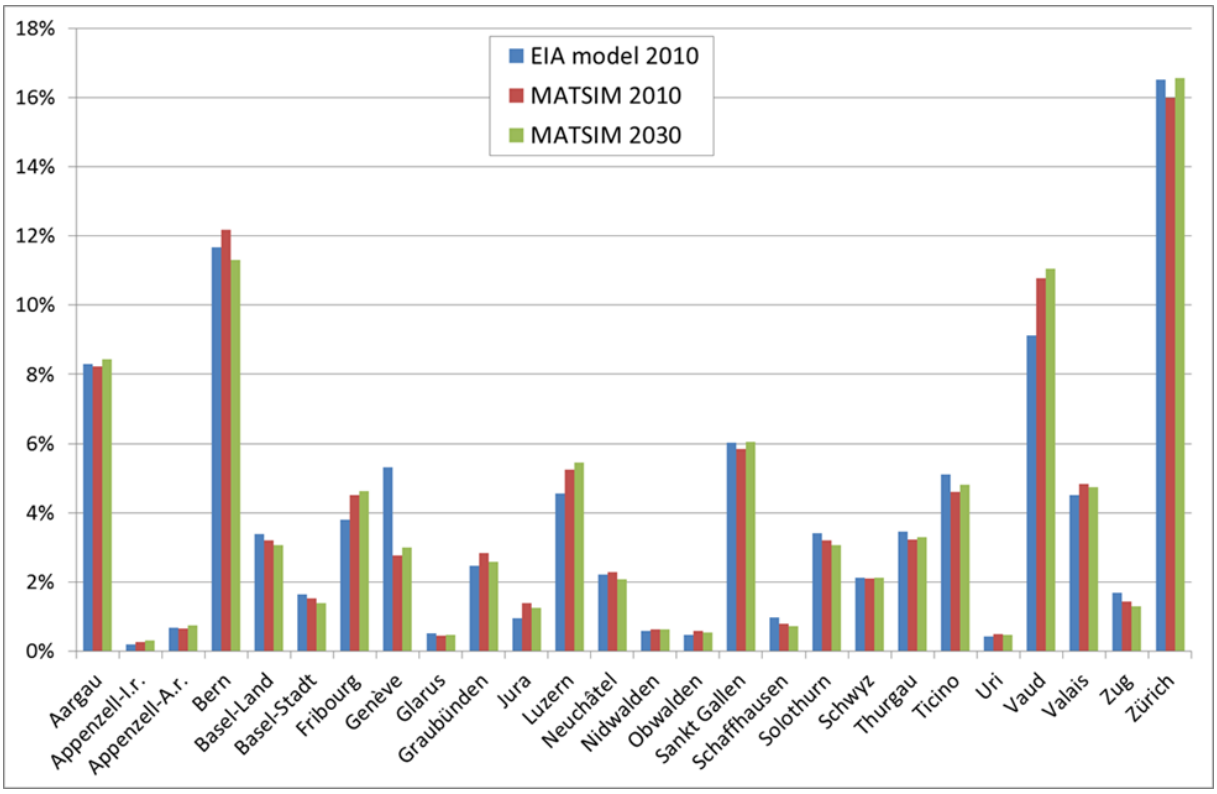

Figure 6.7 Relative spatial distribution of Swiss passenger car km driven based on the simplified EIA model and on the agent model MATSim.

The good agreement with the detailed agent model suggests that an extrapolation of the spatial EIA modeling makes sense. On a larger (e.g. European) scale, detailed traffic and emission data would be much more difficult to model than within Switzerland so that a simplified modelling of the emission distribution is necessary.

The assessment of external costs is based on the ExternE methodology (Watkiss et al., 1999, Friedrich and Bickel, 2001, Krewitt et al., 2001, Droste-Franke et al., 2005, NEEDS, 2009) using the single-source EcoSense model (Droste-Franke et al., 2004, Heck et al., 1999)) weighted and adjusted to the emission distributions and to Swiss conditions. The basic calculations in the EcoSense model are made on a spatial modeling grid. The grid has a resolution of 50km x 50km per grid cell covering the whole of Europe. The cantonal spatial distribution of emissions is transformed to the Swiss part of the spatial modeling grid. The impacts of the emissions of Swiss cars on Switzerland and on the whole of Europe are calculated.

Figure 6.8 shows the estimated distribution of nitrogen oxide emissions for the current passenger cars in Switzerland. Nitrogen oxides and sulfur dioxide emissions are precursors for the formation of secondary particulates in the air. Emission factors for vehicle classes for which no information was available in the ecoinvent database have been collected from different sources (CLRTAP, 2010, EMEP/CORINAIR, 2007, Swiss Federal Office for the Environment, 2010, European Environmental Agency, 2011). Information about the fleet composition and annual kilometers traveled were derived from data from the Swiss Federal Statistical Office (2012).

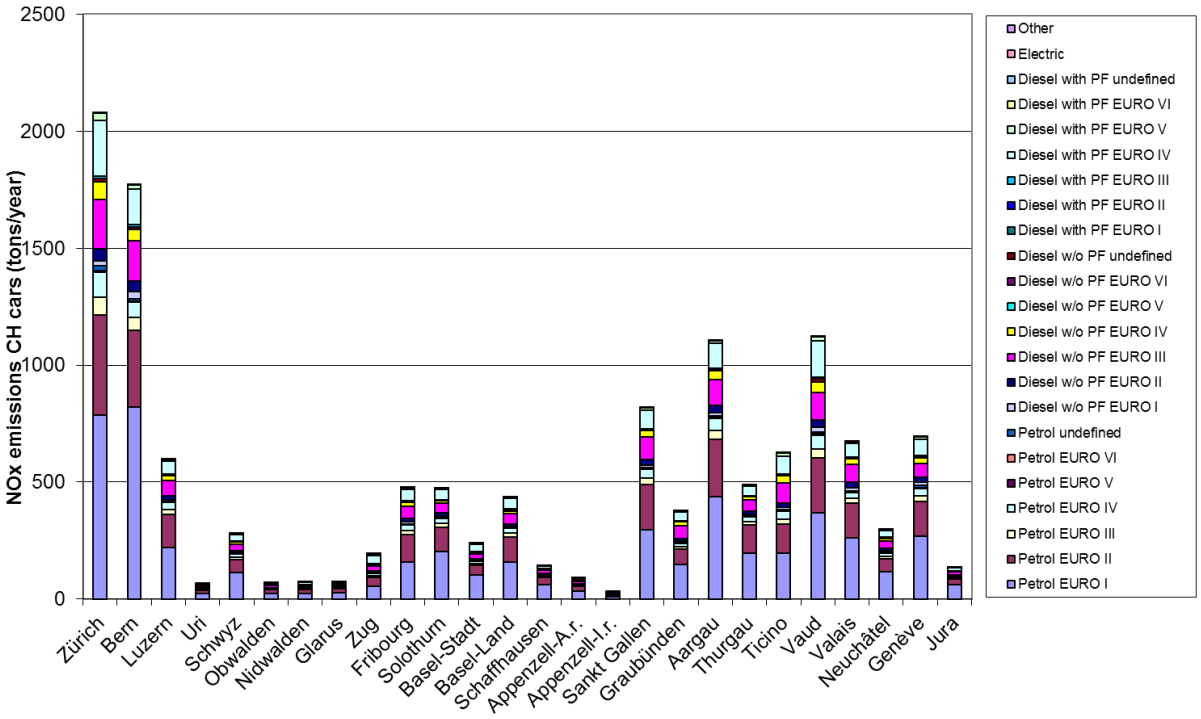

Figure 6.8 Modeled distribution of annual nitrogen oxide (NOx) emissions from the current fleet of passenger cars in Switzerland

Figure 6.9 shows the corresponding distribution for primary particulate non-exhaust emissions from tires, brakes, and road abrasion split into size classes. The smaller the particulates in the air the deeper they can penetrate into the lung. Therefore the fine particulate fraction (PM2.5, i.e. particles with size ≤ 2.5 micrometer) is assumed to cause more severe human health damages per unit emission than the coarse fraction of respirable particulates (PM2.5-10), i.e. particle size between 2.5 and 10 micrometer).

PM10 emissions have been also estimated in a corresponding way according to the size distribution in EMEP/CORINAIR (2007). The health impacts of the fraction between 2.5 and 10 µm was assessed with lower damage factors compared to PM2.5 using the same spatial distribution scaled with the ratio provided in ExternE (Droste-Franke et al., 2005, NEEDS, 2009). Health impacts of the fraction larger than 10 µm are considered negligible.

The distribution of primary particulate exhaust emissions from the vehicles is shown in Figure 6.10.

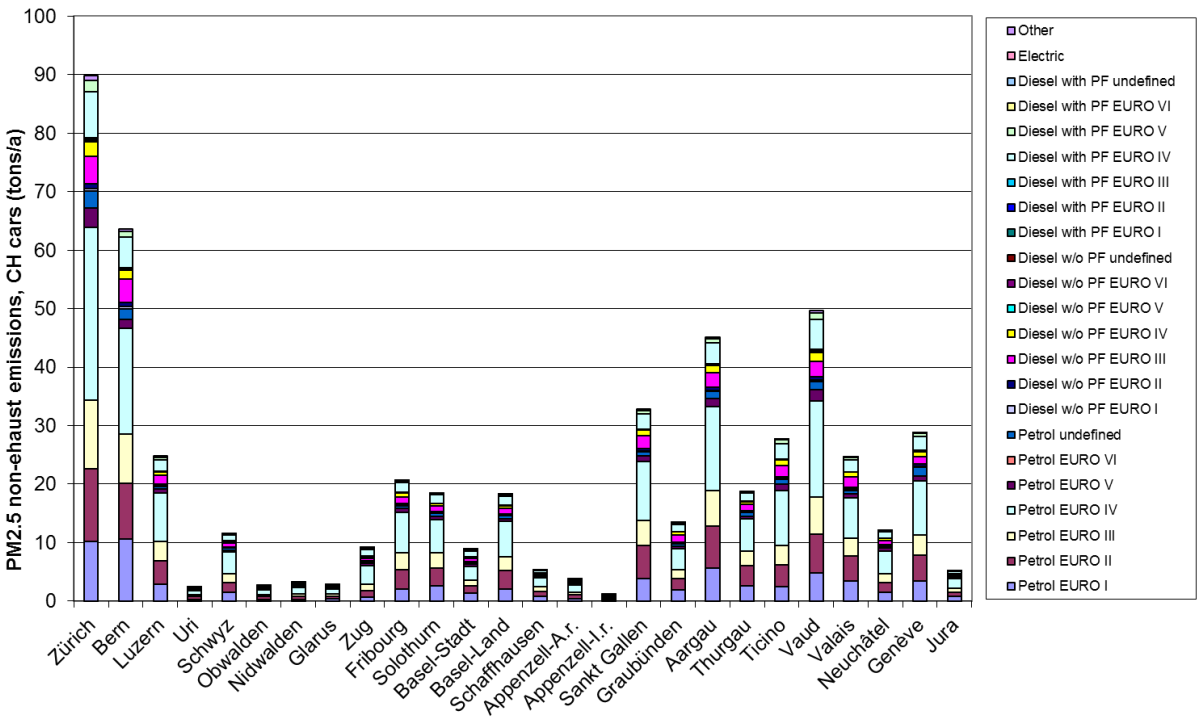

Figure 6.9 Modeled distribution of annual primary particulate matter (PM) non-exhaust emissions from the current fleet of passenger cars in Switzerland.

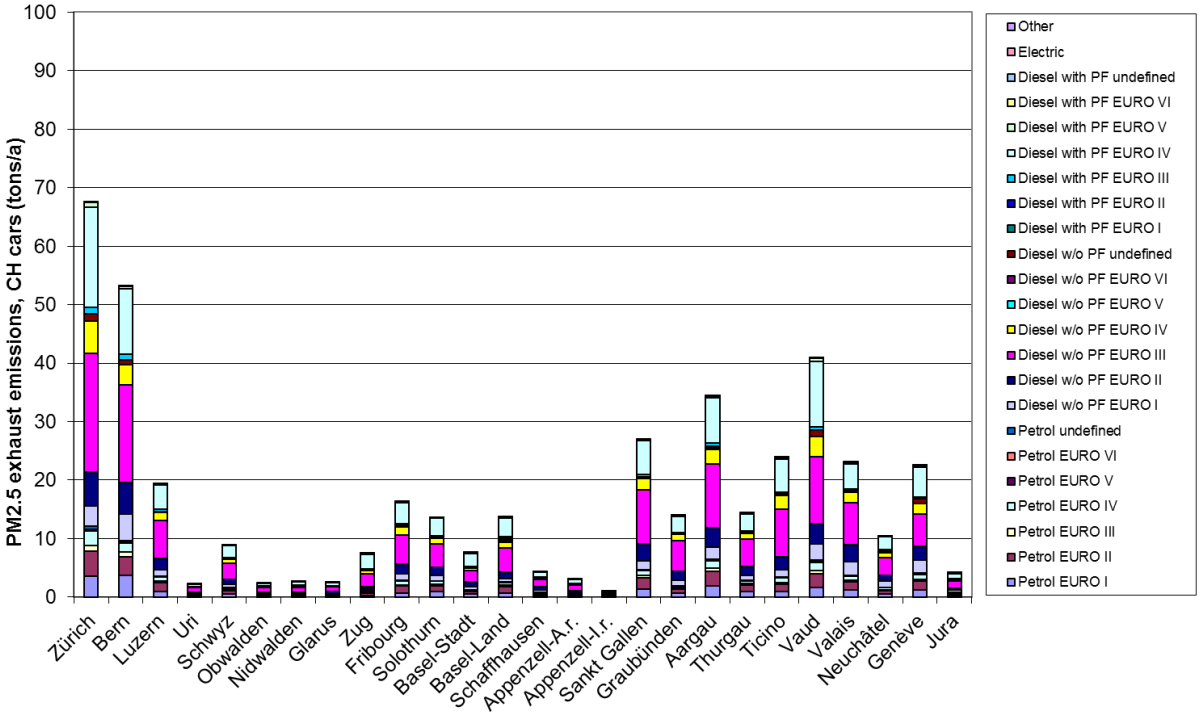

Figure 6.10 Modeled distribution of annual primary particulate (PM) exhaust emissions from the current fleet on passenger cars in Switzerland.

External cost results for Switzerland

Figure 6.11 shows results for the external costs of the major classes of passenger cars in Switzerland. The external costs results include contributions from the life cycle inventory (LCI). The LCI contributions to emissions and land use are derived from the ecoinvent database.

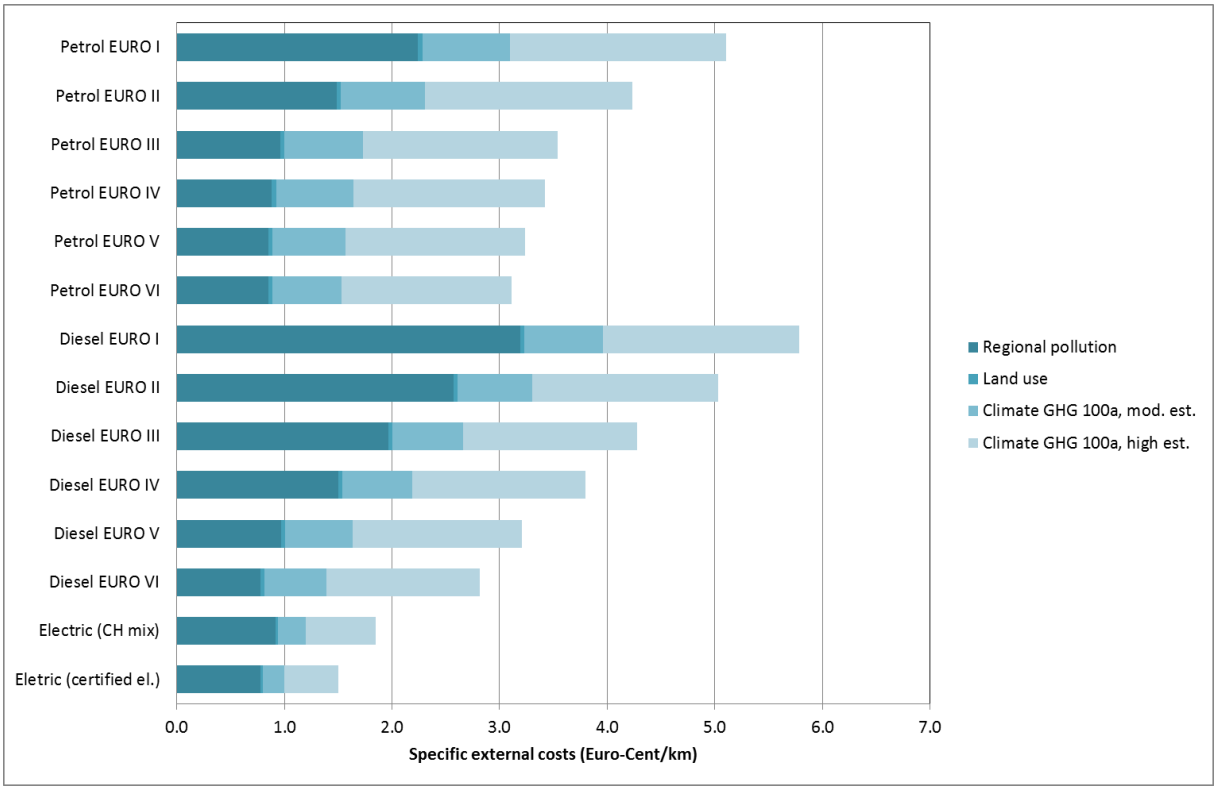

Figure 6.11 Specific environmental external costs for passenger vehicles in Switzerland (including LCI contributions).

External costs have been assessed based on ExternE methodology. The major direct and indirect (i.e. life cycle) emissions and land use have been considered. The vehicles have been assumed to be operating in Switzerland. The rest of the chain was not further spatially resolved but treated uniformly with regional damage factors. The impacts include human mortality and morbidity, crop yield changes, biodiversity losses, material damages, and climate change due to greenhouse gas emissions. The major contributions to the regional impacts are due to health damages. For greenhouse gas emissions, two estimates of the associated external costs, a moderate and a high estimate, are shown separately because of the high uncertainties of external costs of climate change impacts.

In Figure 6.12 the total external costs are further split into specific contributions.

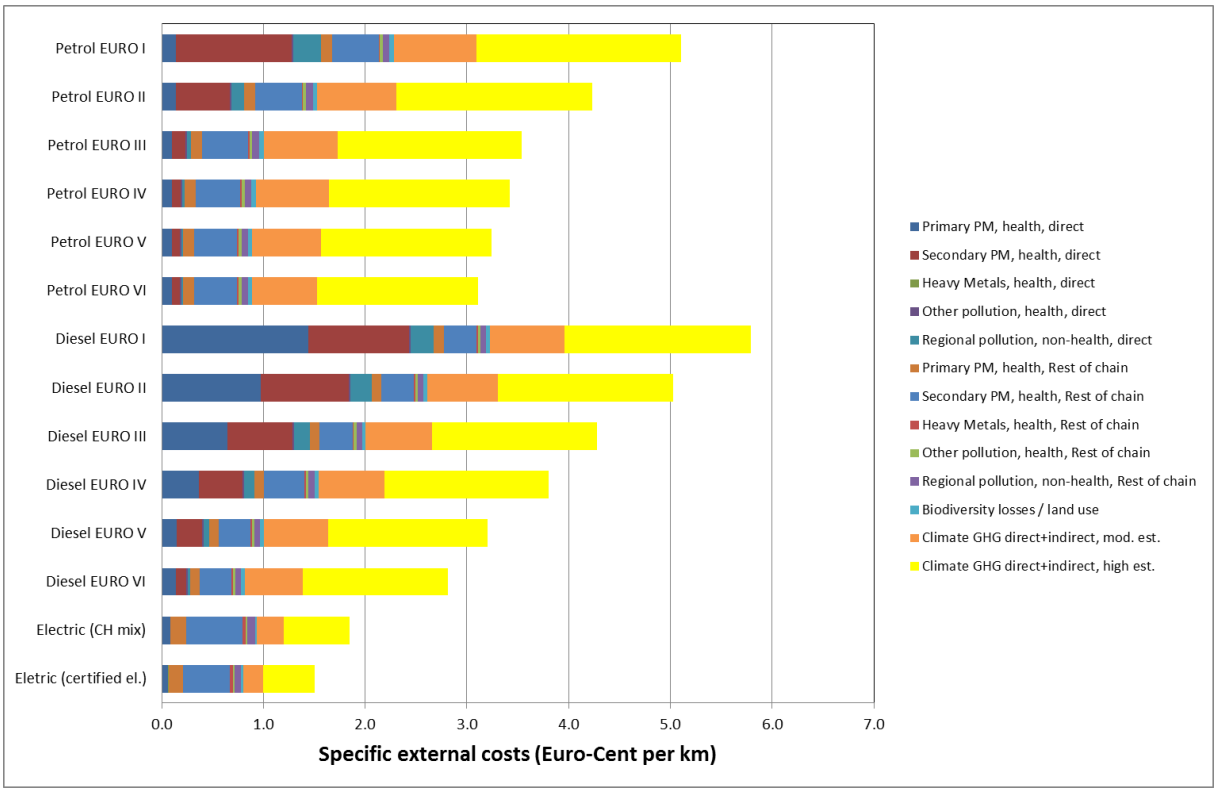

Figure 6.12 Contributions to specific environmental external costs for passenger vehicles in Switzerland (including LCI).

From EURO I to EURO VI emission norms, the external costs per km have been significantly reduced. An important contribution to external costs for old petrol and diesel cars is due to health impacts of secondary particulates. The reduction of nitrogen oxide (NO_x) emissions due to stricter emission limits from EURO I to EURO VI norm have reduced this contribution both for petrol and diesel cars. The model considers also the formation of secondary particulates from sulfur oxide emissions. Due to the low sulfur content of petrol and diesel in Switzerland, these contributions are low for the direct emissions from the vehicles. Nevertheless, secondary particulates both from nitrogen and sulfur oxides play a role in the life cycle contribution for the rest of the chain. Old diesel cars are burdened with high emissions of primary particulates. The strict emissions limits for EURO VI diesel cars lead to a significant reduction of these impacts too. For EURO VI, diesel cars have slightly lower external costs according to the present model than petrol cars due to the assumed better efficiency and lower CO_2 emissions per km. Nevertheless, in view of the uncertainties, small differences in external costs should not be overestimated.

The electric cars are supplied with the Swiss electricity supply mix which included imports from foreign countries. This implies that also emissions from e.g. coal power plants occur in the contribution from the rest of the chain. The restriction to certified electricity leads to a further decrease of external costs. Nevertheless, the externalities of electric vehicles are never zero because, besides non-exhaust emissions from tires, brakes and road abrasion, the indirect contributions from the production of the battery and the other vehicle parts as well as the electricity production are significant.

Figure 6.13 shows the estimated annual external costs from the current fleet of passenger cars in Switzerland.

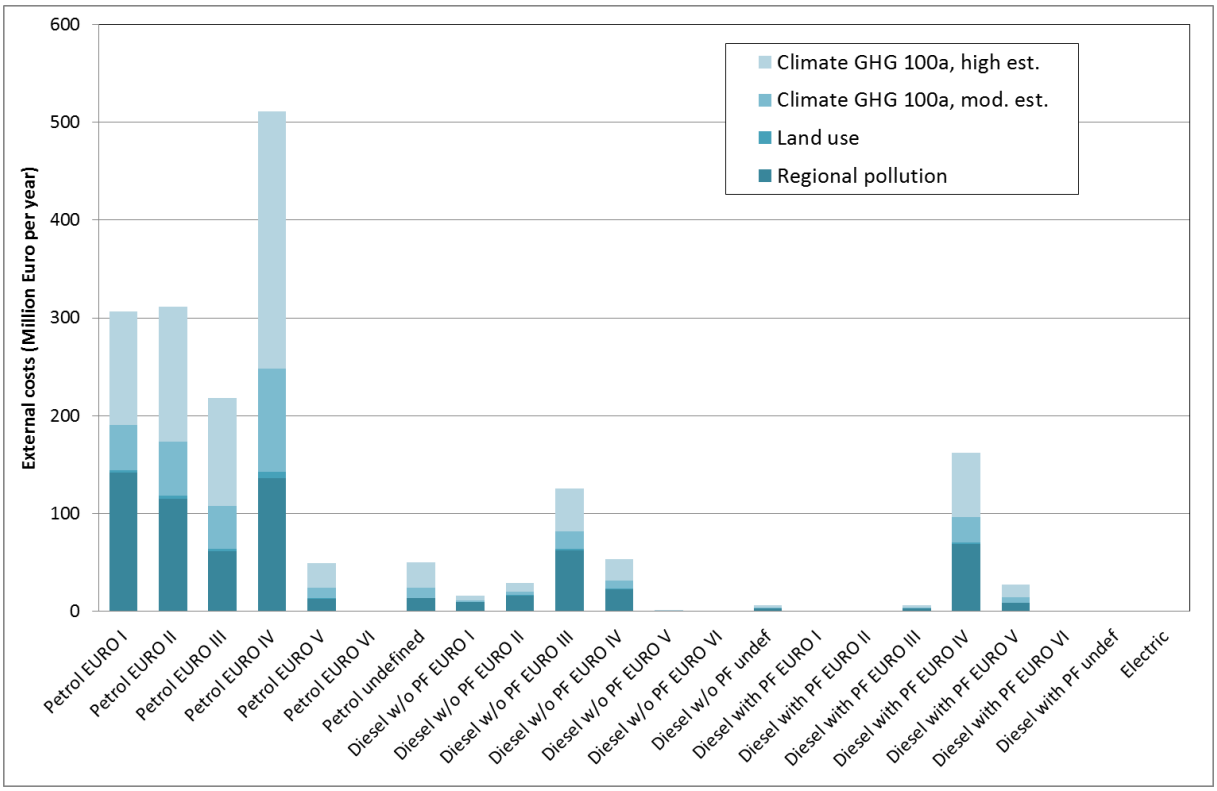

Figure 6.13 Annual environmental external costs for the current car fleet in Switzerland (including LCI contributions).

Figure 6.14 shows external cost results for a scenario until 2050 based on fossil fuel vehicles i.e. without electric vehicles. For the scenario it was assumed based on MATSIM scenario results that the passenger car transport demand will increase only slightly in the future.

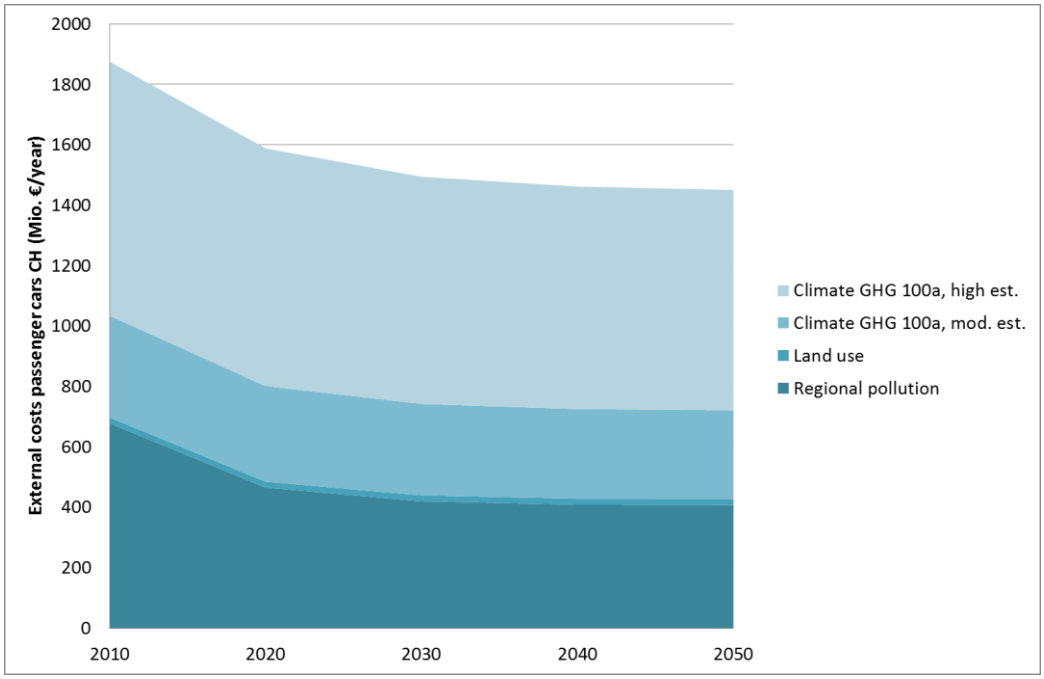

Figure 6.14 Future external cost scenario based on conventional cars (no electric vehicles).

Figure 6.15 shows the external costs development for a scenario with strong penetration of electric vehicles into the Swiss market. It was assumed here that in year 2050 80% of cars are electric. The assumptions including those on the demand are the same as before.

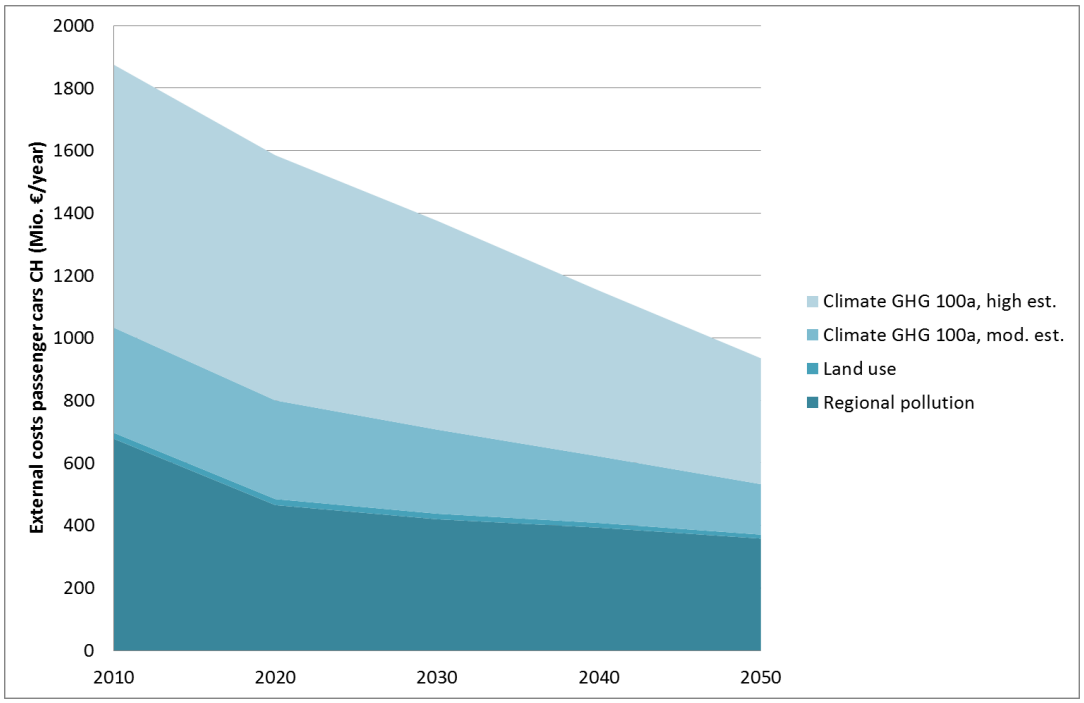

Figure 6.15 Future external costs scenario with strong penetration of electric vehicles into the market.

Towards an extension to European scale

The focus of the THELMA project was on mobility in Switzerland. The perspective was extended to the European scale although only within a limited scope.

Figure 6.16 below shows the results of a future transport scenario for primary particulate emissions up to the year 2050, assuming no EV market penetration. The demand of passenger car transport is expected to grow significantly in Europe, in particular in those countries which currently still have fewer cars per 1000 inhabitants than the average within EU. A medium demand scenario (Skinner, 2010) for European transport was assumed.

It was assumed that the strict exhaust emission limits (Euro-6 norm) will become effective for practically the whole fleet of diesel and petrol cars until year 2050. Due to the reduction of exhaust gas emissions, the non-exhaust emissions from brakes, tires and road abrasion are expected to dominate direct primary particulate (PM10) emissions in future.

One question of interest is how the penetration of electric vehicles into the market until 2050 could reduce the non-exhaust emissions and the associated external costs due to the reduction of mechanical braking. A simple modeling approach based on driving cycles was developed. The balances of power and forces for electric vehicles with regenerative braking and for conventional ICE vehicles were compared in order to estimate the differences in brake wear emissions.

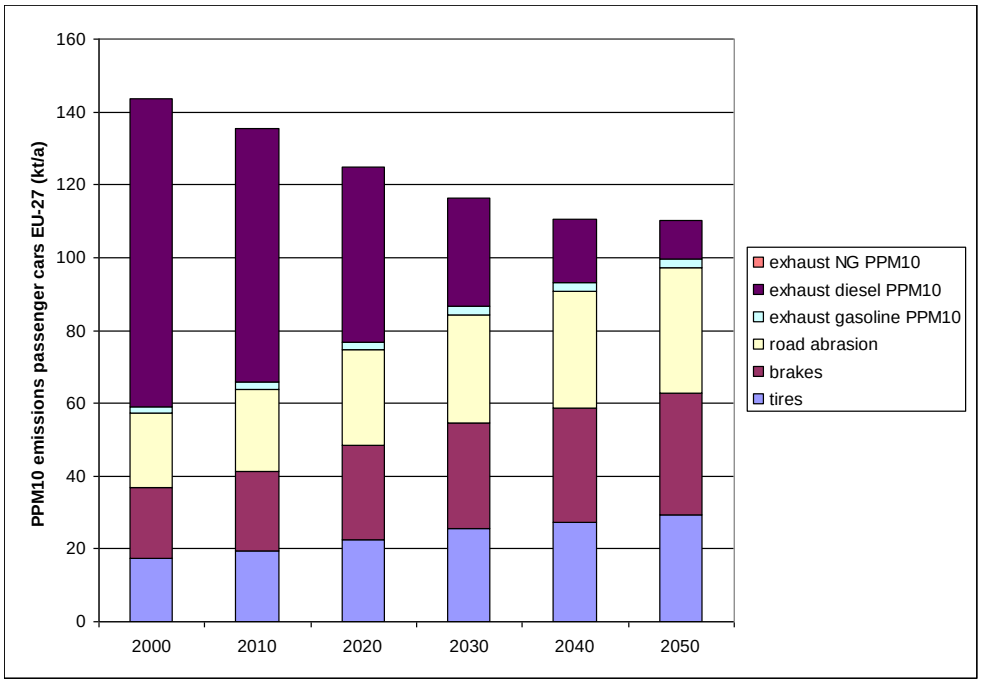

Figure 6.16 Reference scenario for primary PM10 emissions of passenger cars in Europe, 2000 – 2050 (no EV's, direct emissions only).

Figure 6.17 shows the emission results for a scenario with a high share (80%) of electric vehicles in year 2050 in comparison with the "no-EV" reference scenario. The reduction of non-exhaust PM10 emissions until year 2050 is expected to be in the same order as the additional reduction of exhaust emissions due to electric vehicles.

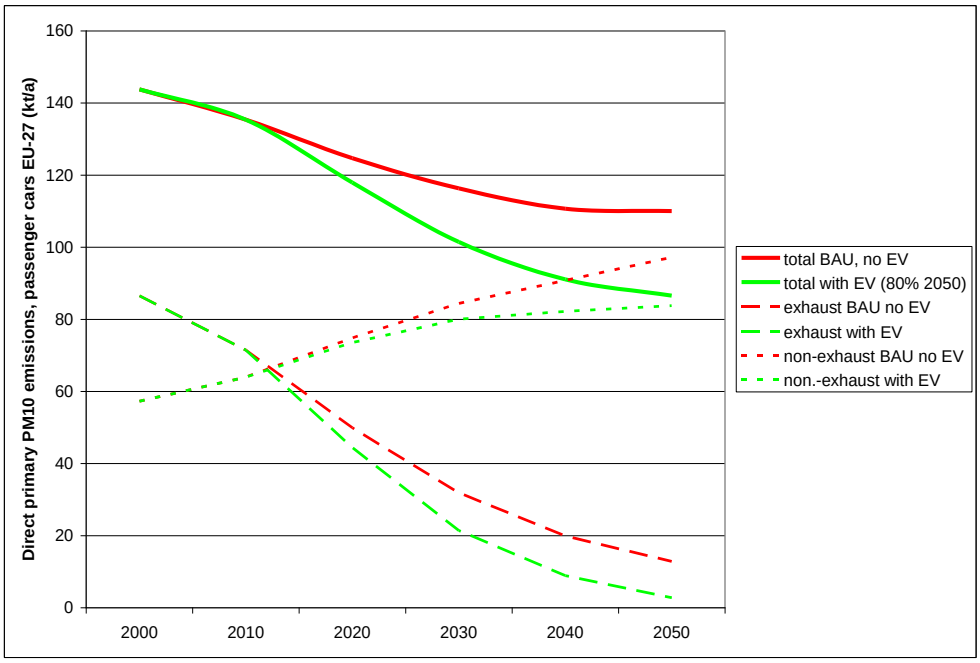

Figure 6.17 Direct exhaust and non-exhaust primary PM10 emissions for a future scenario of conventional cars (BAU, no EV) and a scenario with high penetration of electric vehicles until year 2050 in Europe.

Figure 6.18 shows the associated external costs comparing the electric vehicle scenario with the conventional vehicle reference scenario. The potential reduction of external costs of direct primary particulate emissions due to electric vehicles is estimated at about 600 Million Euro per year in

Europe around year 2050. Within this amount, the possible reduction of external costs due to electric braking compared to conventional mechanical braking is estimated to be of the order of 180 Million Euro per year in Europe around 2050. The external cost estimates are based on constant damage factors for Europe developed in European projects (Droste-Franke et al., 2005, NEEDS, 2009).

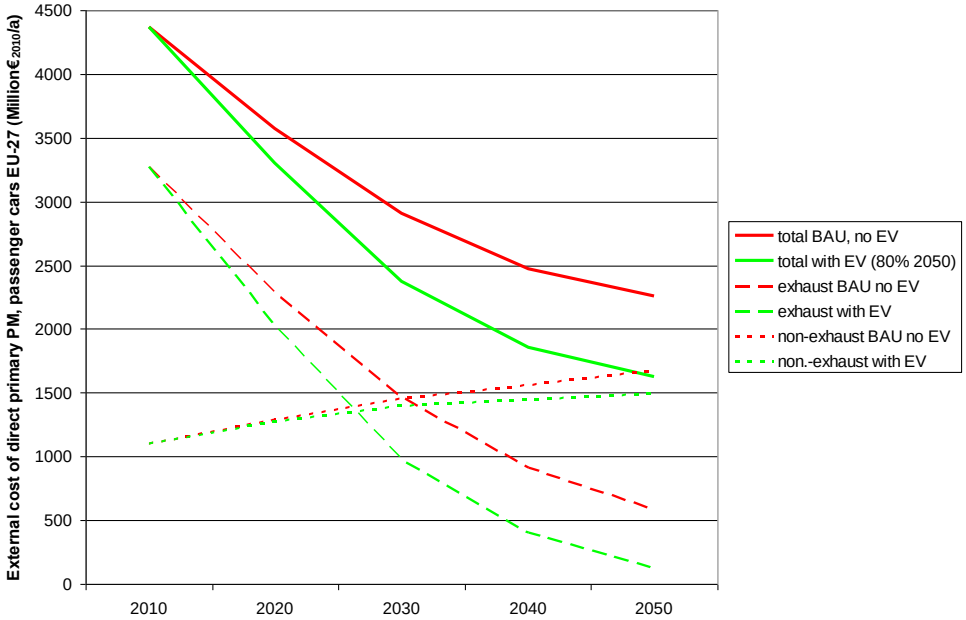

Figure 6.18 External costs of direct primary particulate emissions for a future scenario of conventional cars (BAU, no EV) and a scenario with high penetration of electric vehicles until year 2050 in Europe.

Contrary to the Swiss results, the European scenario results 2010-2050 are covering only the direct PM emissions from cars. In particular, the LCA contributions are not included in this case. The total environmental performance of electric vehicles will depend significantly on the assumed future mix of electricity production in Europe as shown in the case of Switzerland. Nevertheless, the figures indicate that even a special issue like the emissions from brakes has significant influence on external costs on the European scale.

Environmental impact assessment for MCDA

In Multi-criteria Decision Analysis (MCDA), climate change is considered as a separate indicator in terms of CO_2-equivalents. Therefore, contrary to the external costs estimates shown above, the health impact indicator shown in this section does not include climate change impacts.

Figure 6.19 below shows the results for mortality impacts of some selected current technologies in terms of Years of Life Lost (YOLL). The YOLL estimates are based on location-dependent environmental impact assessment as described above. For comparison, the location-independent results derived from the ecoinvent LCIA indicator in terms of DALY (disability adjusted life years) are shown as well.

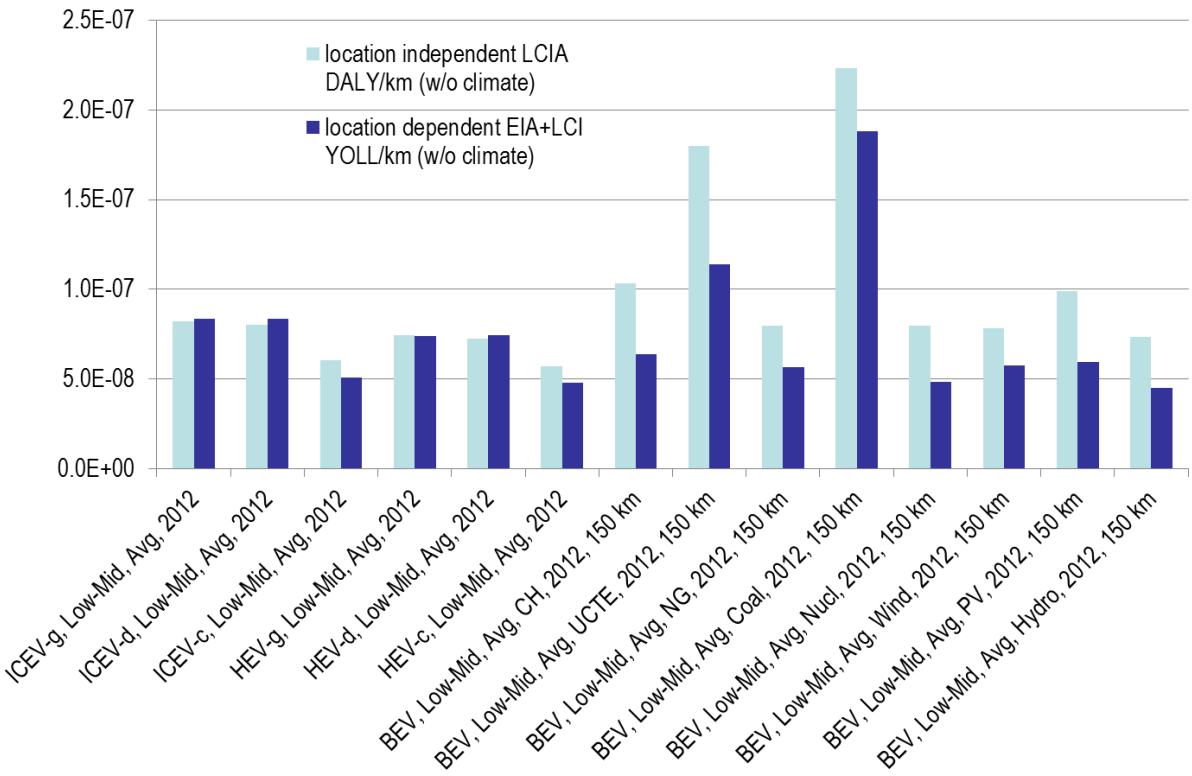

Figure 6.19 Health impact indicators for current technologies. Lower midsize car is used as reference and different electricity supply is assumed for electric battery cars. Avg = average driving conditions. Electricity: CH = Swiss consumption mix, UCTE = European average, NG = natural gas power plant, Coal= coal power plant, Nucl = nuclear power, Wind = wind power, PV= solar photovoltaic, Hydro = hydropower. 2012 refers for construction year of the vehicle. 150 km is the range of the electric vehicle.

Formally, the unit in both cases (YOLL and DALY) is "years per km" but YOLL represents mortality without further valuation whereas DALY combines mortality and morbidity based on expert weighting (i.e. DALY necessarily include a valuation).

The relationship is

$$DALY = YOLL + YLD,$$

where YOLL refers to mortality and YLD (Years Lived with Disability) summarizes the non-fatal diseases.

The comparison shows that the location-dependent EIA+LCI method can change the ranking in some cases compared to the location-independent LCIA DALY indicator.

Figure 6.20 compares a variety of technologies and their expected changes from the present until year 2050 in terms of YOLL based on the EIA+LCI methodology. For such a long-term perspective, improvements in terms of health impacts per driving distance are expected for all technologies. In particular, improvements of battery and fuel cell technologies are expected to reduce impacts significantly. Nevertheless, also fossil technologies are expected to show certain improvements e.g. higher efficiency and lower particle, sulfur and nitrogen dioxide emissions from future coal power plants. (It has to be pointed out again that the YOLL estimates presented in this section do not include effects that are treated separately in MCDA like climate change or accident risks.)

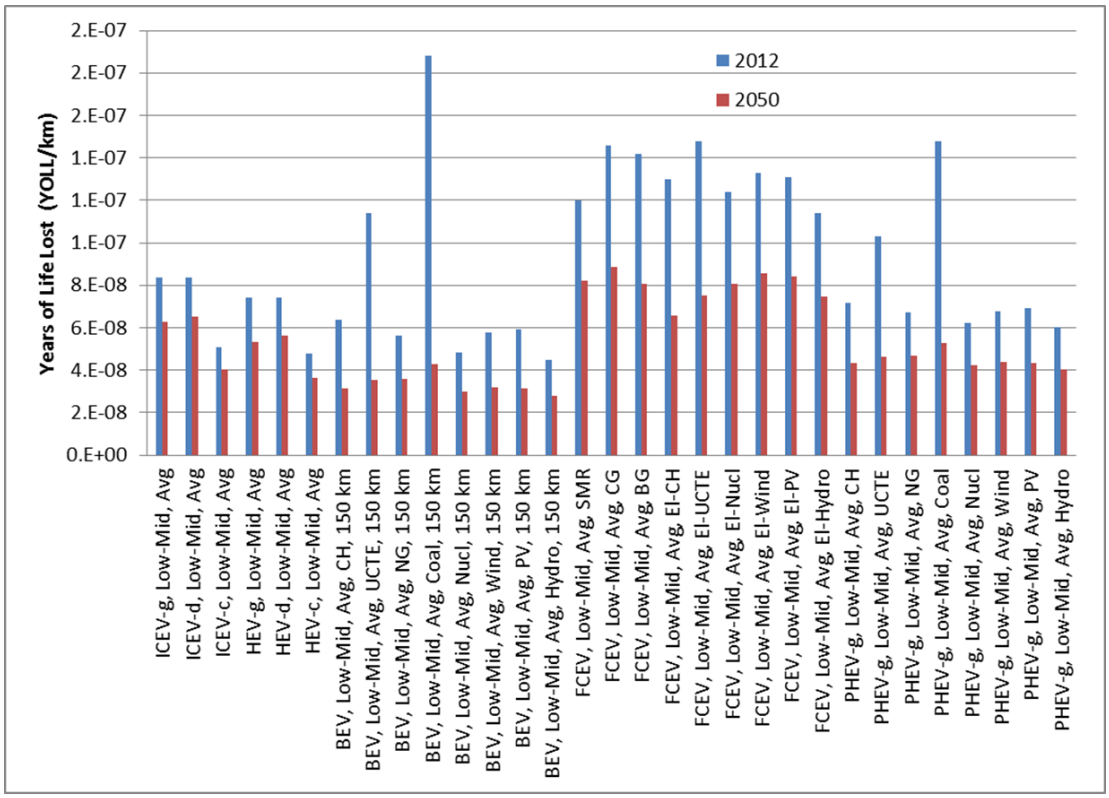

Figure 6.20 Health impacts of different technologies (2012 vs. 2050) without climate change (LCI data from (ecoinvent, 2012, Hofer, 2014b, Bauer et al., 2015)).

Some insights on location-dependent assessment of environmental impacts and external costs:

- An approach for approximate spatial distribution with respect to environmental impact and external cost calculations was developed.
- The introduction of stricter emission norms (from Euro I to Euro VI) leads to a strong reduction of air pollution per distance for conventional cars.
- The environmental performance of electric vehicles depends strongly on the electricity supply.
- Non-exhaust emissions will probably become the major part of direct PM emissions from passenger cars in the future independently of the car fleet (i.e. even with fossil-based cars under EURO-VI+ norm). Replacement of mechanical braking by electric braking can contribute to a substantial additional reduction of health impacts and external costs.
- More detailed environmental impact assessment including the consideration of emission locations can have significant influence on ranking for MCDA (compared to LCIA indicators).

6.3.2.3. Estimated performance indicators for current and future technologies

Following Bauer et al. (2015), Hofer (2014b) for the purpose of this report we present the results for a midsize passenger car of average performance as described in chapters 2 and 3.

All of the future developments taken into account are uncertain and depend on interlinked parameters such as technical developments, policy measures, consumer acceptance, and production volumes. The aim of this work has been to provide a clear framework for the consideration of potential future developments within vehicle analysis and to apply it using transparent input data. For details we refer to (Hofer, 2014b); this includes in applicable cases the basis for extrapolations to

year 2050 since some of the indicators (e.g. LCA-based) were established with a shorter time horizon, i.e. until year 2030. Figure 6.21 illustrates the impacts of prospective technological advancements on costs and LCA-based GHG-emissions.

Figure 6.22 to Figure 6.29 show examples of estimated performance indicators for lower mid class cars for years 2012 and 2050 for a variety of drives, fuels, electricity inputs for battery cars and different means of hydrogen production. Here one indicator for each dimension of sustainability is shown. The complete set of absolute and normalized indicators is provided in Appendix C: Vehicle Indicators for 2012 and 2050.

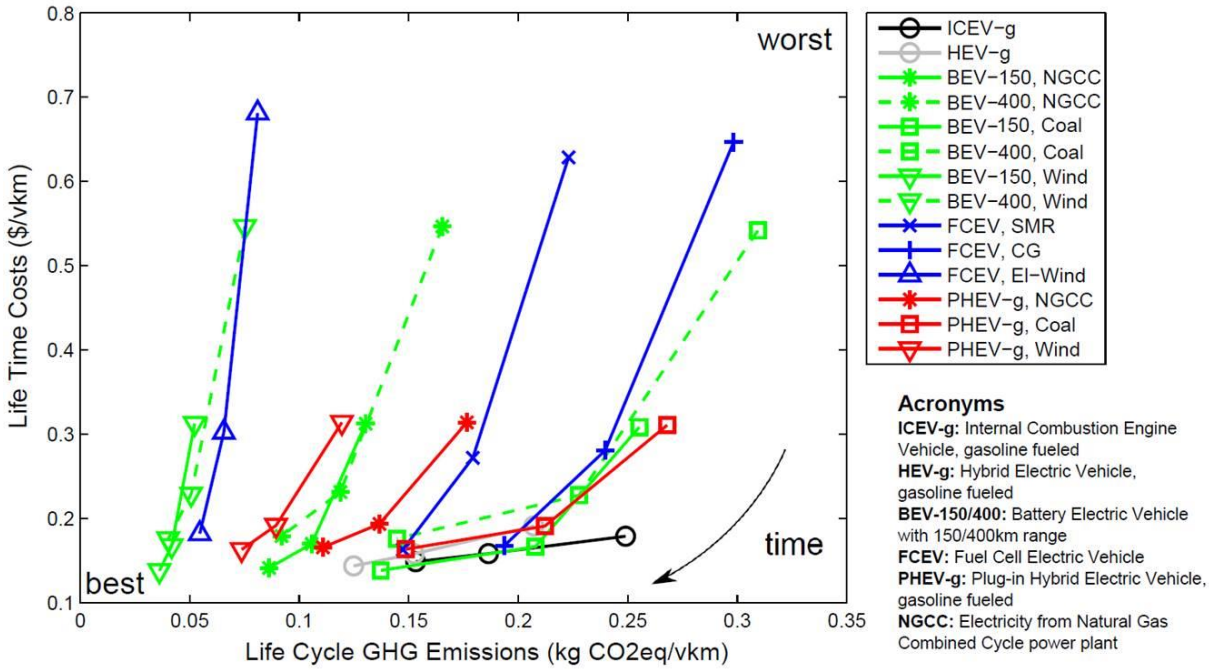

Figure 6.21 Impact of prospective technological advancements between 2012 and 20150 on life time costs and life cycle GHG emissions for different drives and supplies of energy for a midsize car.

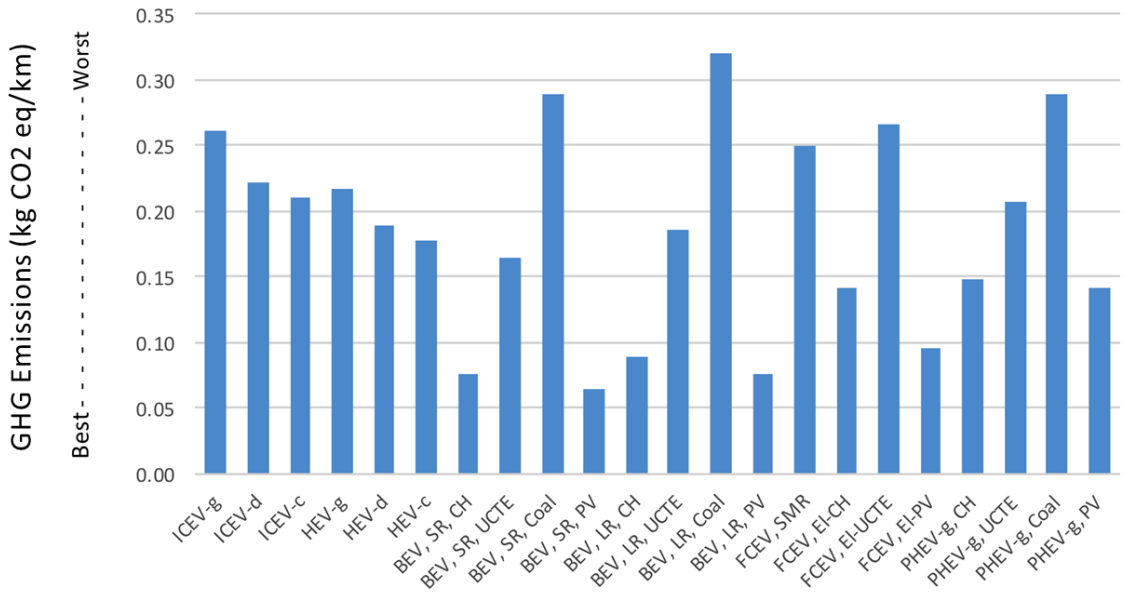

Figure 6.22 2012 Greenhouse Gas Emissions (absolute)

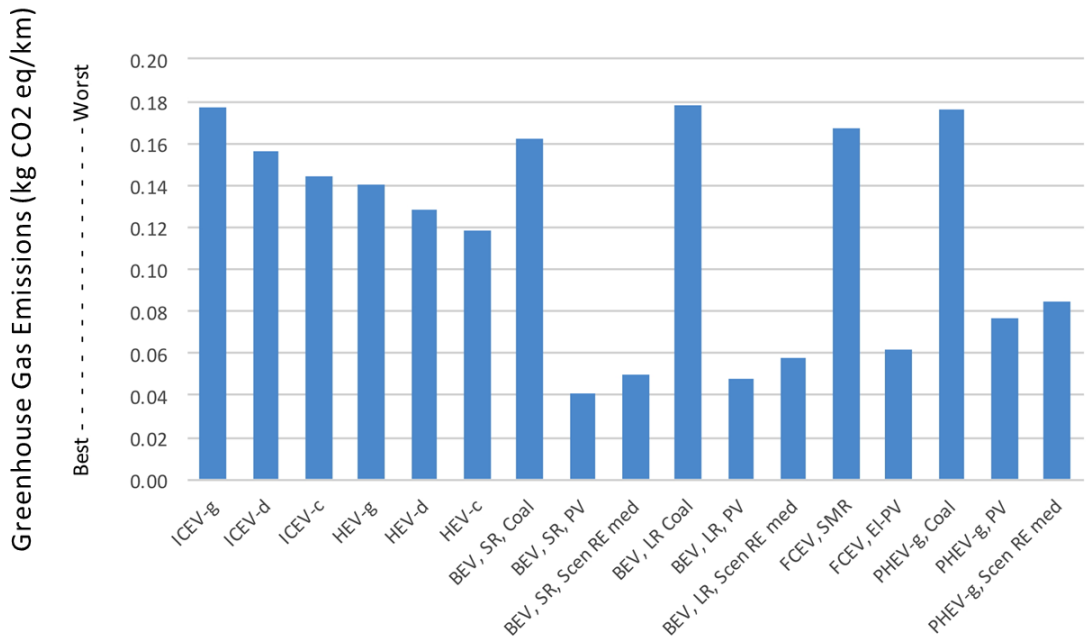

Figure 6.23 2050 Greenhouse Gas Emissions (absolute)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power
Scen RE med - SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

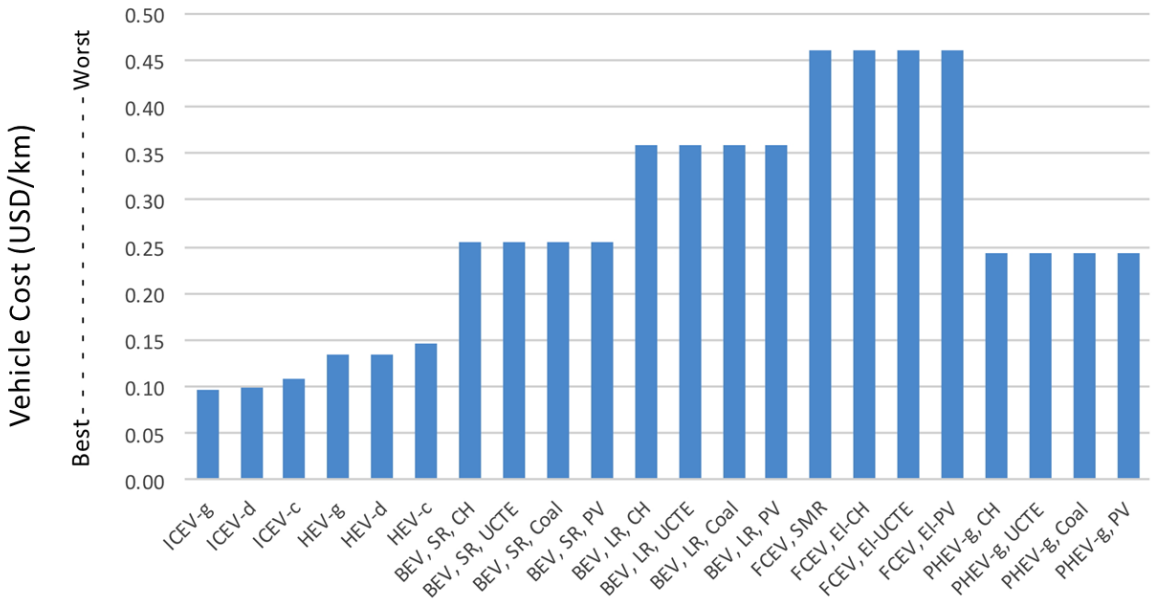

Figure 6.24 2012 Vehicle Cost (absolute)

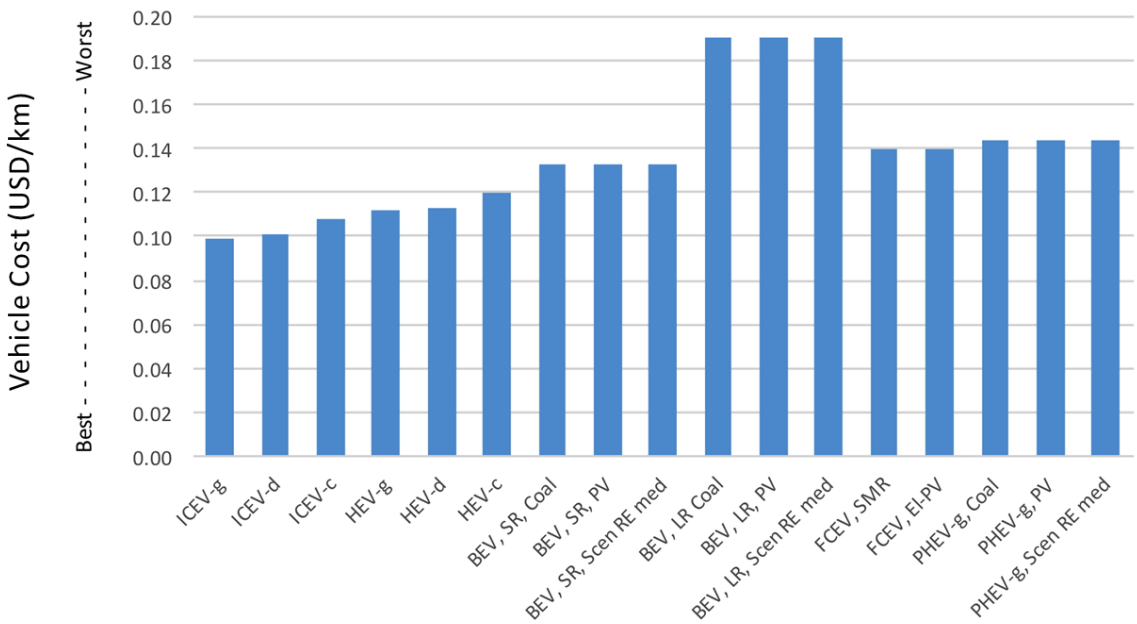

Figure 6.25 2050 Vehicle Cost (absolute)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power
Scen RE med - SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

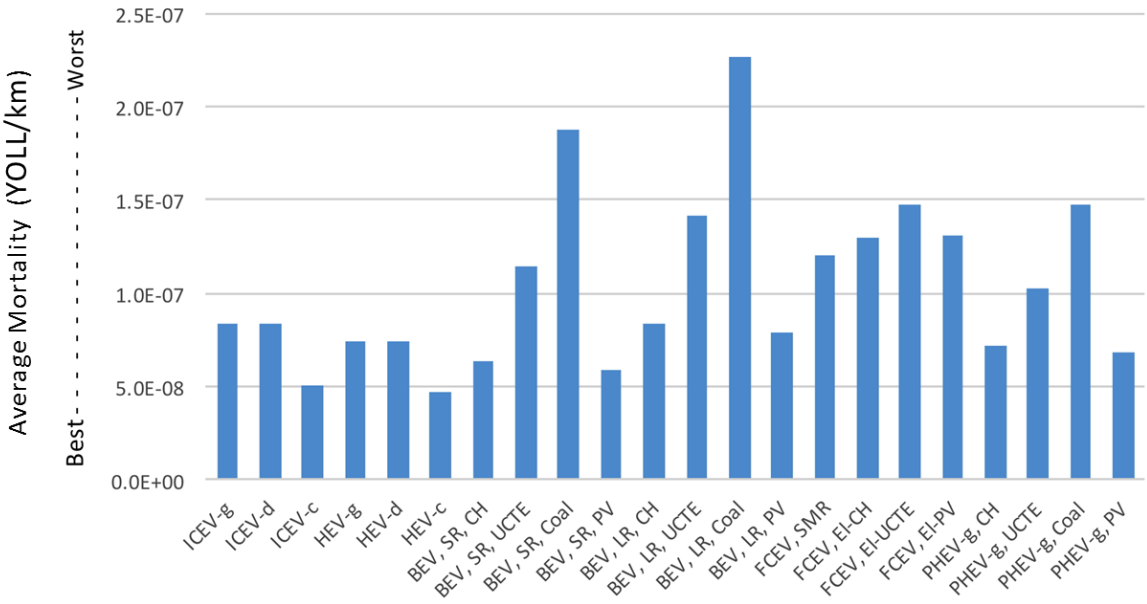

Figure 6.26 2012 Average Mortality (absolute)

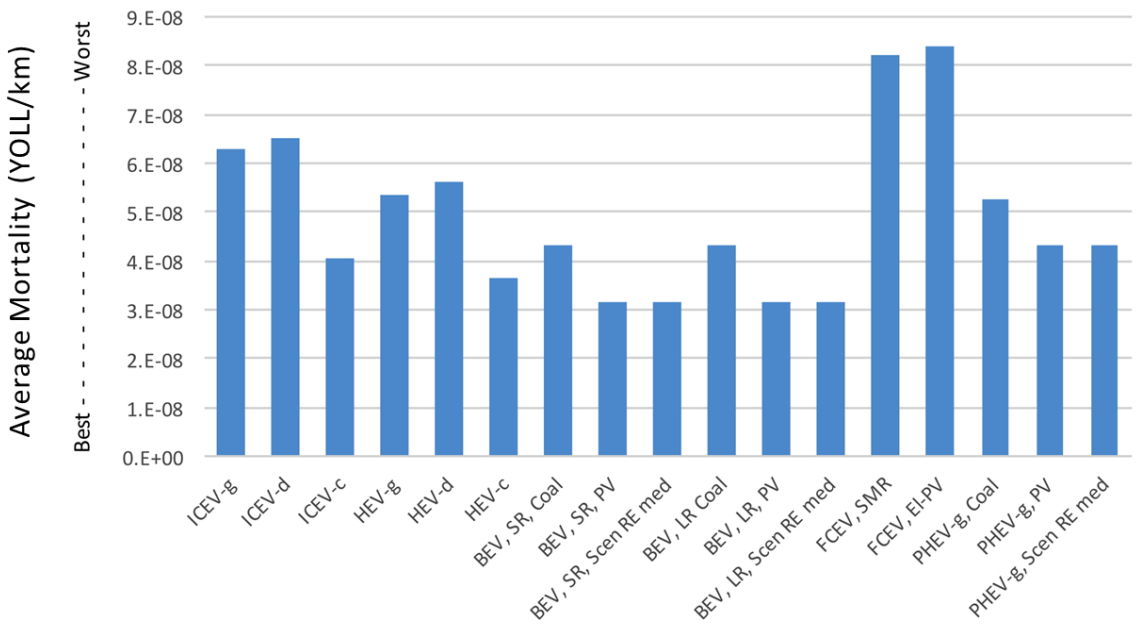

Figure 6.27 2050 Average Mortality (absolute)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
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CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
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Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

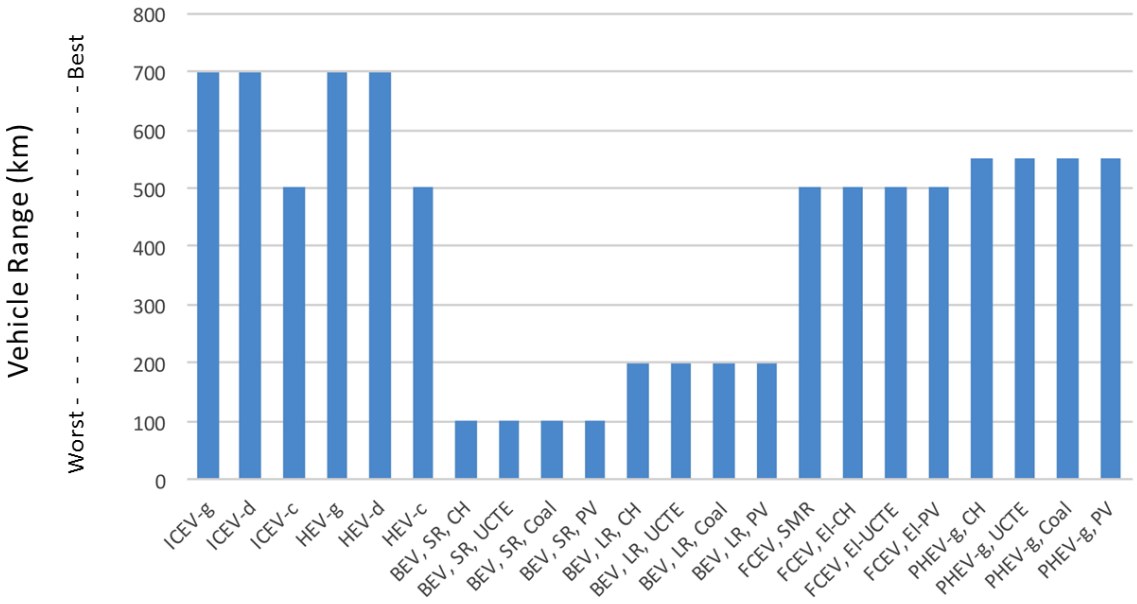


Figure 6.28 2012 Vehicle Range (absolute)

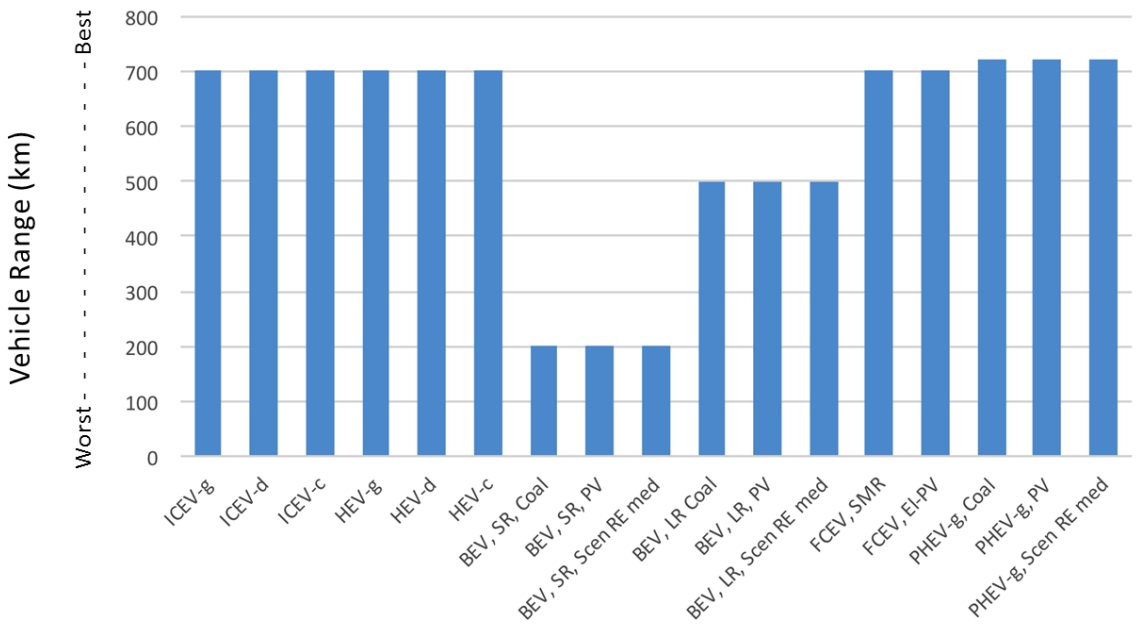


Figure 6.29 2050 Vehicle Range (absolute)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power
Scen RE med - SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

There is a clear tendency towards improving performance parameters with time. This applies in particular to electric cars. There are remarkable cost reductions within the time horizon considered, with costs of battery vehicles being reduced by a factor of two and fuel cell cars by a factor of three.

6.3.3. Total costs of technologies

For the THELMA project, 13 different classes of vehicles (sub-compact, mid-range, luxury, sports cars, etc.) were analyzed. Each vehicle in the design fleet is characterized by its class (weight and power), drivetrain and energy source. The manufacturing cost for each vehicle is the sum of the costs for the vehicle drivetrain (BEV, fuel cell, internal combustion, etc.), energy storage (battery or fuel tank), and the glider (the chassis, plus all other components). There are fixed and variable costs for each type of drivetrain and also for each energy storage system. The base weight and cost for the glider is fixed, except that there is some positive feedback based on the weight of the other two systems. For example, if BEV range is increased, then the glider size and cost increase to handle the bigger battery. As battery technology improves there is a virtuous cycle where for fixed range the lighter battery also allows a decrease in glider size and weight. Once manufacturing cost is given, a 40% margin for overhead and profit is assumed to get the final purchase price. For each car design the energy use is known, so the energy cost per km (fuel and tax) is calculated based on the assumed energy price forecast, see Figure 6.30 (Chang et al., 2012, DOE, 2014, ElCom, 2014, Hirschberg et al., 2010, IEA, 2012, Simbeck and Chang, 2002). VAT is calculated as 8% of the energy price. The same energy tax as presently levied on Swiss gasoline sales was added to all energy carriers.

The assumed vehicle life (in years and total km) and interest rate are used to calculate the average fixed vehicle cost/km, and the energy cost/km is added. Maintenance, insurance and any other costs have been neglected.

Environmental external costs were elaborated in section 6.3.2.2. Figure 6.31 and Figure 6.32 show the results estimated for lower mid class cars with average power for year 2012 and 2050, respectively. A wide range of options was considered both in terms of technologies as well as electricity inputs and means of hydrogen production.

The external environmental costs are significant with the tendency towards reduction in the future. Battery cars have in relative terms the lowest external costs if electricity is provided from sources with low carbon content. The GHG contributions to external costs are subject to large uncertainties.

Figure 6.33 and Figure 6.34 show the total costs, i.e. internal plus environmental external, for lower mid class cars with average power for years 2012 and 2050, respectively.

Internal costs dominate the total costs of both the current and future cars though the environmental external costs are significant. Currently the total costs per km of electric vehicles clearly exceed those of conventional cars. The difference is particularly high for long range battery cars and even more so for fuel cell cars. Due to the expected advancements of electric technologies their total costs are projected in the long-term to come down to the level of further improved conventional technologies.

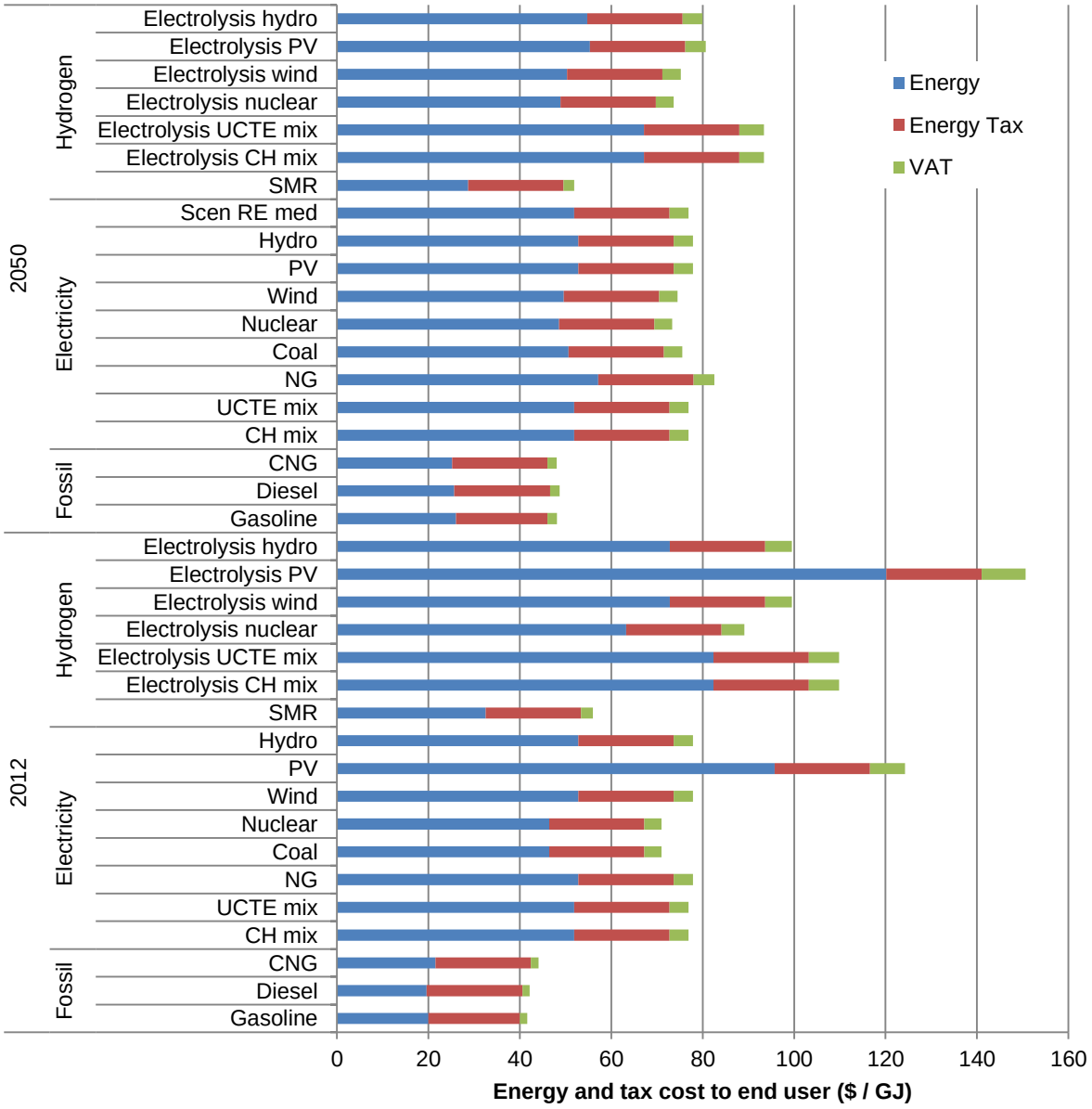


Figure 6.30 Energy and tax costs for 2012 and projected costs for 2050 per GJ. Based on: (Chang et al., 2012, DOE, 2014, ElCom, 2014, Hirschberg et al., 2010, IEA, 2012, Simbeck and Chang, 2002).

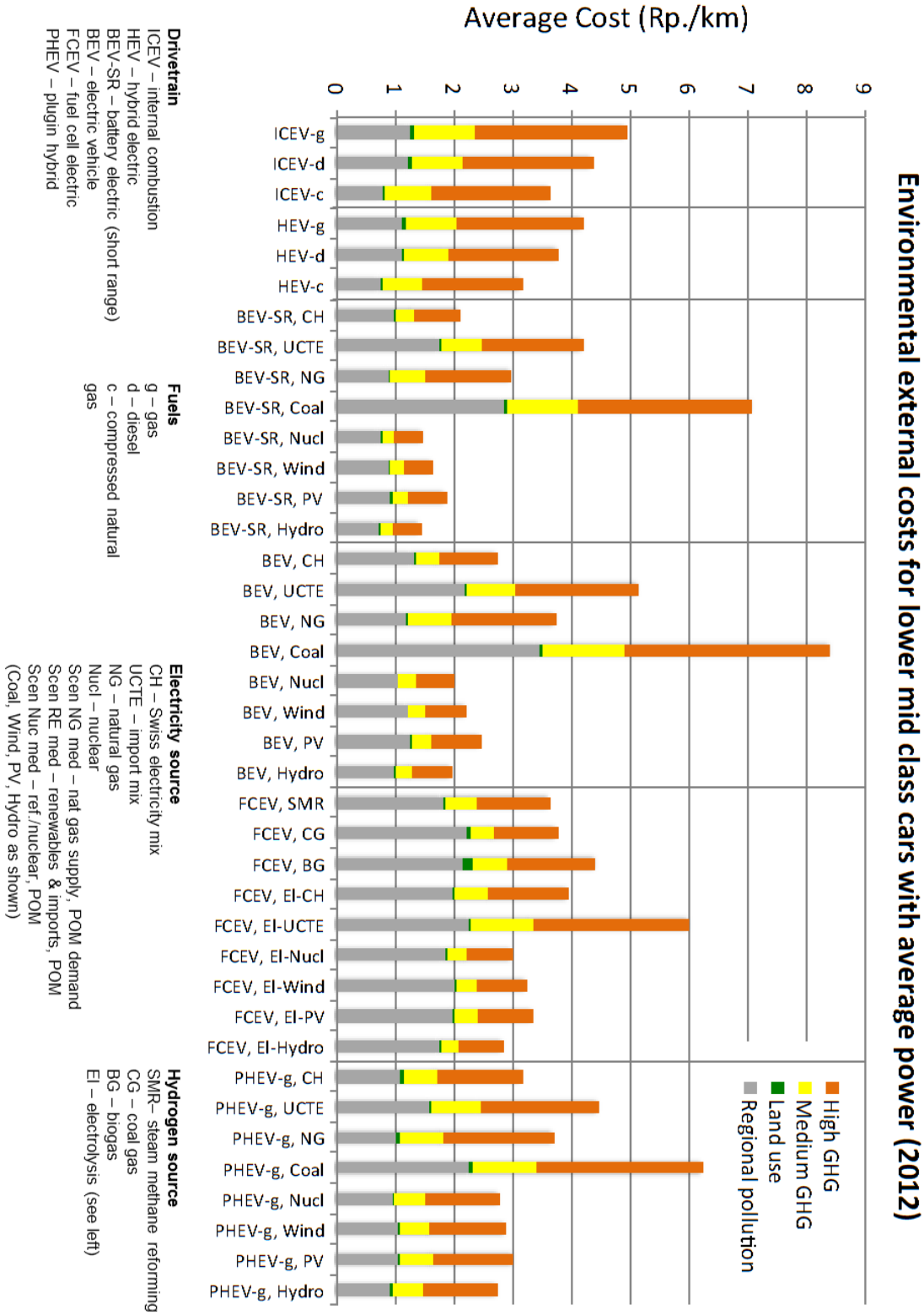


Figure 6.31 External environmental costs in Swiss cents (Rp.) per km for lower mid class cars with average power in year 2012.

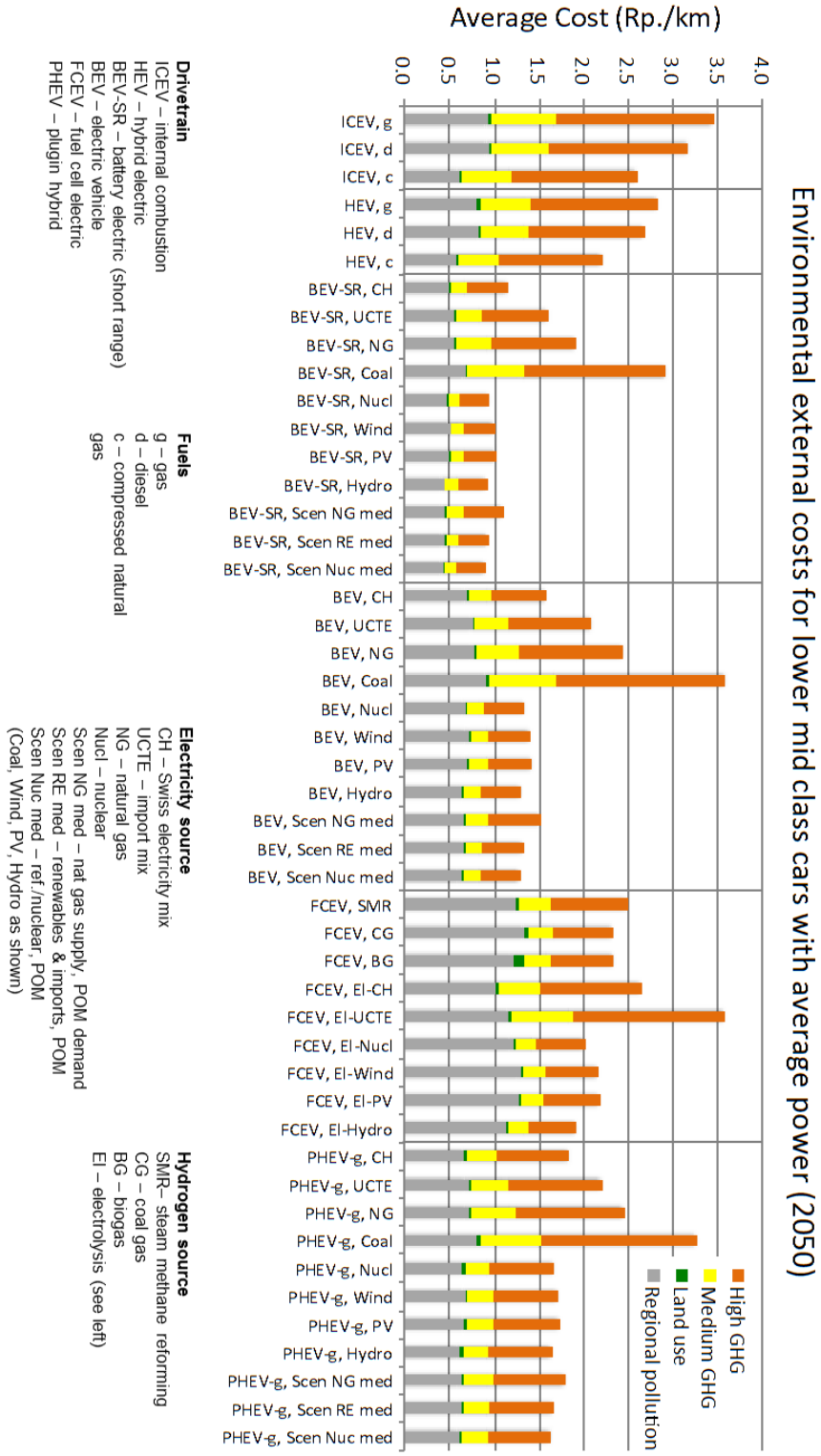


Figure 6.32 External environmental costs in Swiss cents (Rp.) per km for lower mid class cars with average power in year 2050.As electricity source for battery cars apart from specific technologies also future supply mixes are considered based on the medium case for electricity demand (POM) according to the Swiss Energy Strategy (2012) and PSI's scenarios for supply options. More details are provided in sub-chapter 6.4.

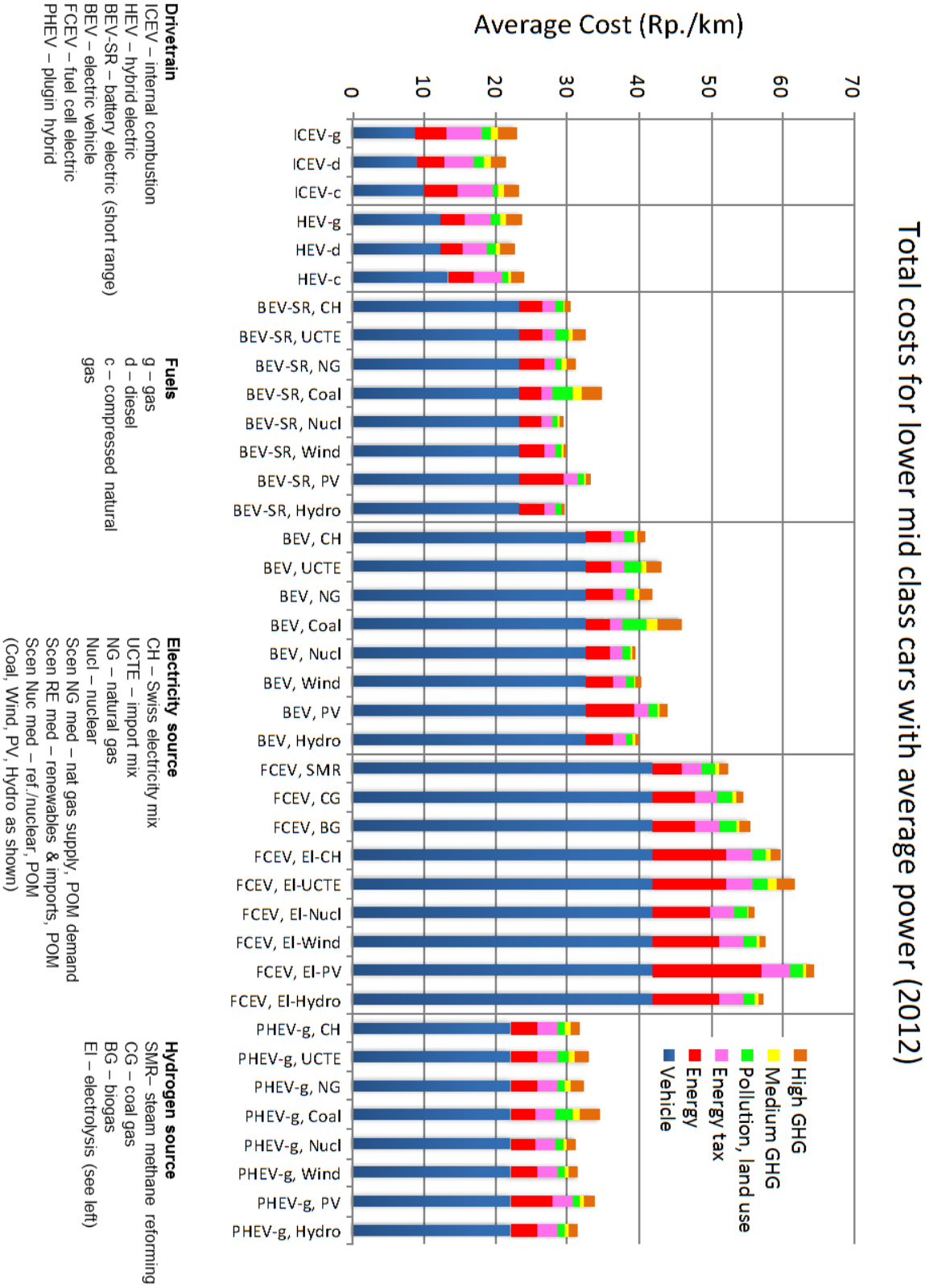


Figure 6.33 Total costs in Swiss cents (Rp.) per km for lower mid class cars with average power in year 2012.

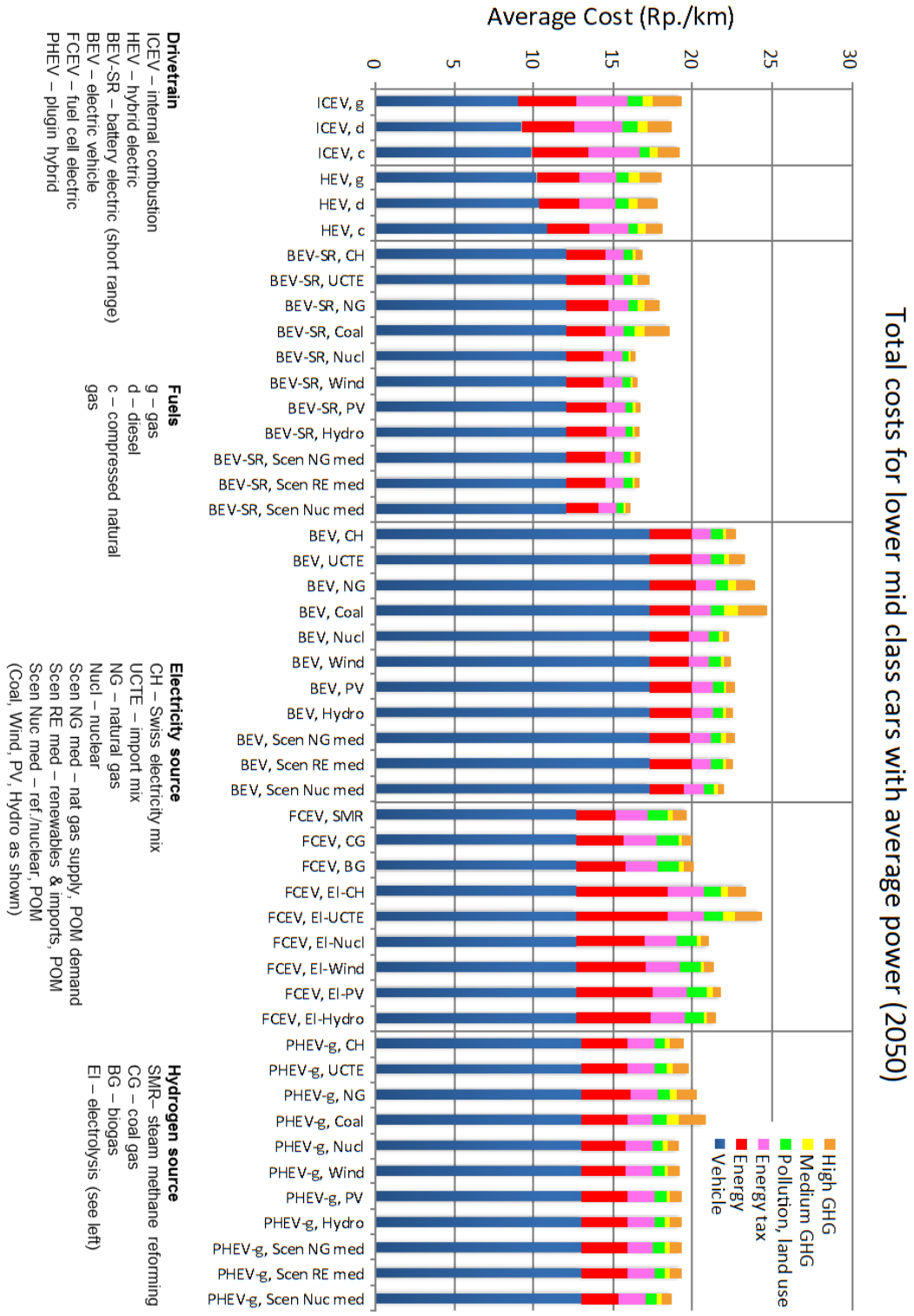


Figure 6.34 Total costs in Swiss cents (Rp.) per km for lower mid class cars with average power in year 2050. As electricity source for battery cars apart from specific technologies also future supply mixes are considered based on the medium case for electricity demand (POM) according to the Swiss Energy Strategy (2012) and PSI's scenarios for supply options. More details are provided in sub-chapter 6.4.

6.3.4. Multi-criteria decision analysis for technologies

6.3.4.1. Introduction

The Laboratory for Energy Systems Analysis at PSI has been applying MCDA to a broad variety of sustainability assessments in the energy sector, including the China Energy Technology Program (Eliasson and Lee, 2003), the EU project NEEDS comparing the sustainability of current and future electricity supply options (Hirschberg et al., 2008, Schenler et al., 2009b), evaluation of the sustainability of the current and future portfolio of electricity generation technologies of a major Swiss electric utility (Roth et al., 2009), the EU project SECURE exploring the impact of CO_2 policy options on energy security (Eckle et al., 2011), sustainability analysis of future vehicle technologies (Wilhelm, 2011b), and interdisciplinary assessment of renewable, nuclear and fossil power generation with and without carbon capture and storage in view of the new Swiss energy policy (Volkart et al., 2016). Several other studies have investigated the use of MCDA in transportation, e.g. to rank advanced passenger vehicle technologies and fuel options (Tzeng et al., 2005, Zhou et al., 2007, Mohamadabadi et al., 2009, Wilhelm, 2011a, Wilhelm and Wokaun, 2011, Wilhelm et al., 2011).

The basic steps in Multi-criteria Decision Analysis (MCDA) include selection of technologies to be considered, establishing the set of indicators covering the chosen/agreed on dimensions of sustainability that can be measured for each individual technology, normalizing the indicators, eliciting stakeholder preferences or selecting a set of preference profiles to be used for sensitivity mapping, and calculating aggregated sustainability index for each technology. In this way technology ranking is established though it may vary depending on the various preference profiles.

MCDA approach facilitates understanding of complex, multi-dimensional problems and assists rational decision-making (Eisenführ et al., 2010).The MCDA approach enables to account for a variety of environmental, economic and social aspects in a transparent manner. It can thus provide an invaluable support to informed decision-making, and to guiding a public debate as well as participative processes. However, the MCDA does not provide a definite ranking of technologies but rather illustrates the sensitivity of the ranking to subjective preferences. Possibly robust alternatives may be identified, i.e. options whose ranking is remains relatively high independently of preference profiles.

6.3.4.2. Implementation

The MCDA was implemented for current (2012) and future (2050) technologies using PSI's web-based tool Mighty MCDA (www.mightymcda.net), developed in connection with a number of major technology assessment projects.

The technology options chosen for the evaluation represent different relevant combinations of various drives, fuels and alternative means to supply electricity and produce hydrogen. There are 22 cases for the current technologies and 17 cases for the future ones.

The indicators used are those provided in Appendix C: Vehicle Indicators for 2012 and 2050. This includes normalized values based on the use of MINIMAX method. Thus, for each performance indicator the best option receives the value 1 and the worst the value 0; the values assigned to the other options are then based on linear interpolation.

We apply the simplest MCDA algorithm, i.e. the Weighted Sum (WS) approach. Other, more advanced approaches, could be used as elaborated within the NEEDS project by (Makowski et al., 2009). However our choice was motivated by the transparency and simplicity of WS.

A screenshot of the hierarchy of criteria and indicators used for technology assessment is shown in Figure 6.35. As the starting point the four top criteria are equally weighted, which corresponds to the spirit of sustainability.

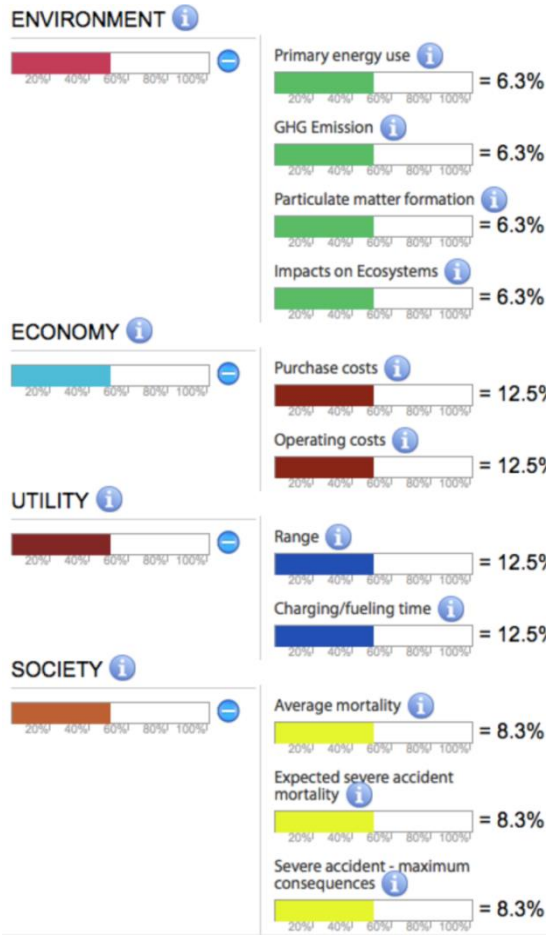
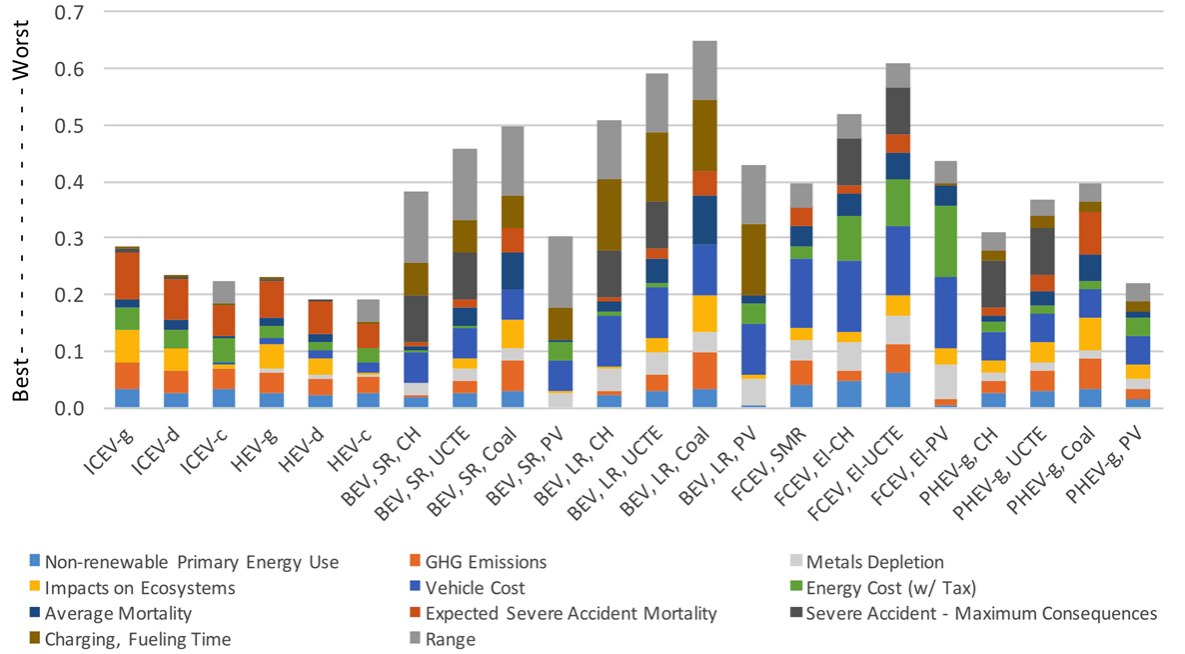


Figure 6.35 Hierarchy of criteria and indicators with equal weighting on the highest level. Primary energy use considers only non-renewable energy.

6.3.4.3. Sensitivity mapping of sustainability index for current and future technologies based on various preference profiles

Figure 6.36-Figure 6.41 show the various cases for the current (2012) technologies. This is followed by Figure 6.42- Figure 6.47 showing the corresponding cases for the future (2050) technologies. The sensitivity cases emphasize one at a time specific dimension of sustainability as used in this analysis; in each of these cases the weights on the second level of hierarchy remain equal. The last cases shown, both for current and future technologies, cover only two criteria, i.e. use of primary non-renewable energy and GHG emissions. The reason for using this sub-set of criteria is that the Swiss energy strategy emphasizes energy efficiency and climate protection as its central goals.



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

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UCTE - UCTE Elec. Mix
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PV - Photovoltaic power

Hydrogen

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El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

Figure 6.36 2012 Vehicle MCDA – EQUAL Weights (Environment, Economy, Society and Driver Utility equally weighted)

With equal weighting of the criteria the conventional technologies (in particular ICEV-diesels and ICEV-gas), and even more so hybrids, perform mostly better than the advanced ones. The exception is PHEV-g, PV, which belongs to top performers. Not surprisingly short range BEV are better than long range BEV. This applies also to FCEV. Range and charging time are the main obstacles for BEV while for FCEV it's vehicle cost and energy cost (if hydrogen is produced by electrolysis).

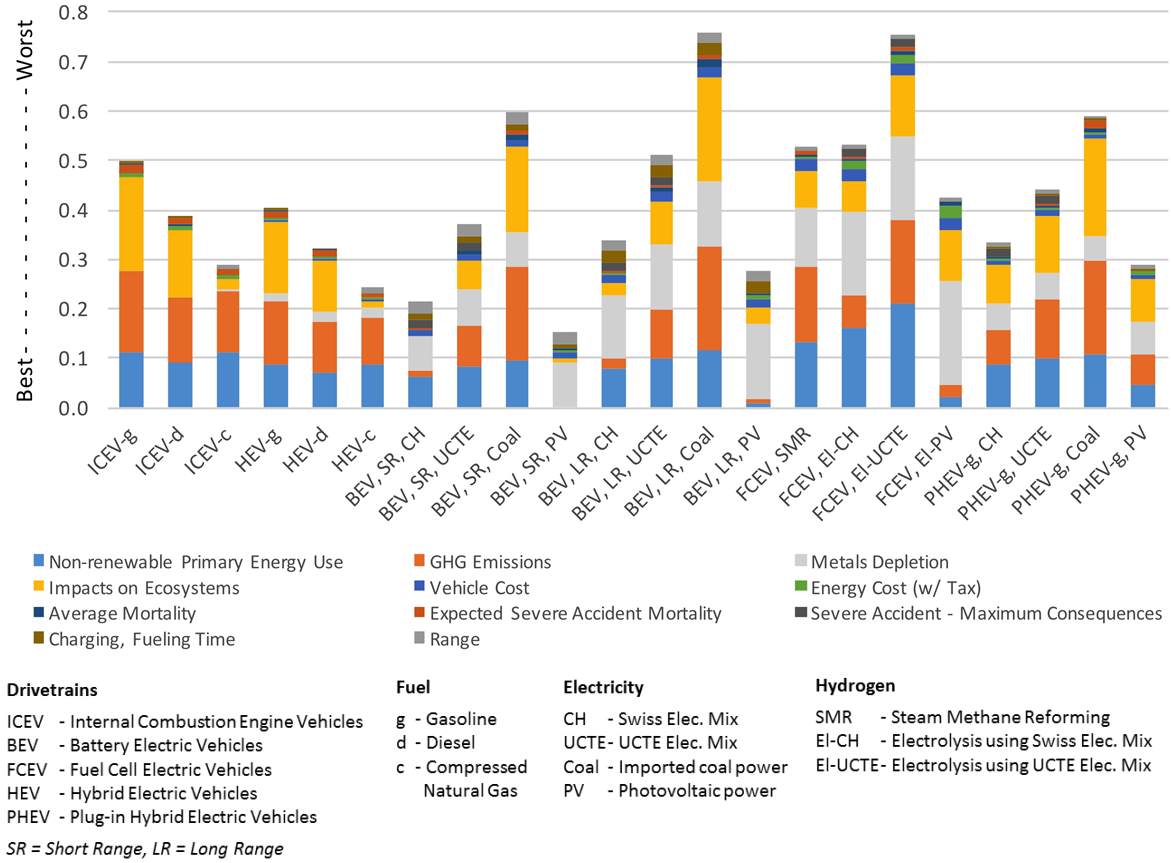
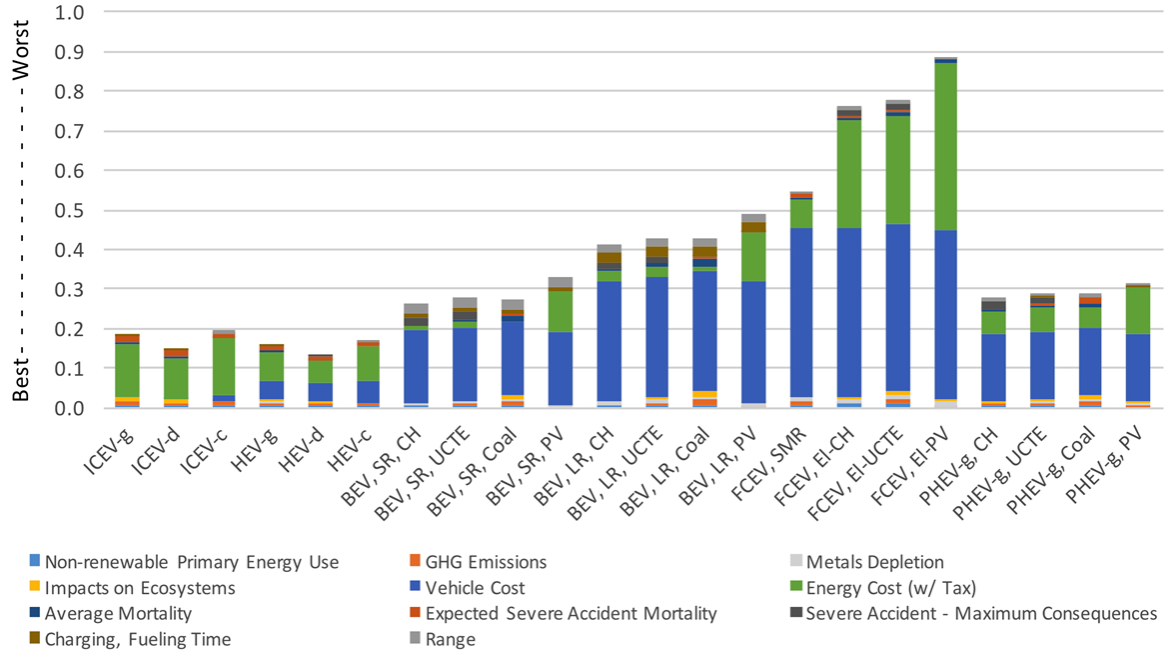


Figure 6.37 2012 Vehicle MCDA – ENV85 Weights (Environment 85%, Economy, Society and Driver Utility 5% each)

Emphasis on environment favors short range BEV if electricity supply is provided by PV or Swiss electricity mix. Metal depletion is an issue for both BEV (particularly long range) and FCEV. GHG have a negative influence on the ranking in cases with substantial share of fossil energy supply; the same mostly applies to impacts on ecosystems.



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PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

Figure 6.38 2012 Vehicle MCDA – ECO85 Weights (Economy 85%, Environment, Society and Driver Utility 5% each)

Emphasis on economy clearly favors conventional cars and hybrids. Ranking of short range BEV is comparable to PHEV. FCEV rank worst due to both highest vehicle costs and energy costs (except for the SMR case).

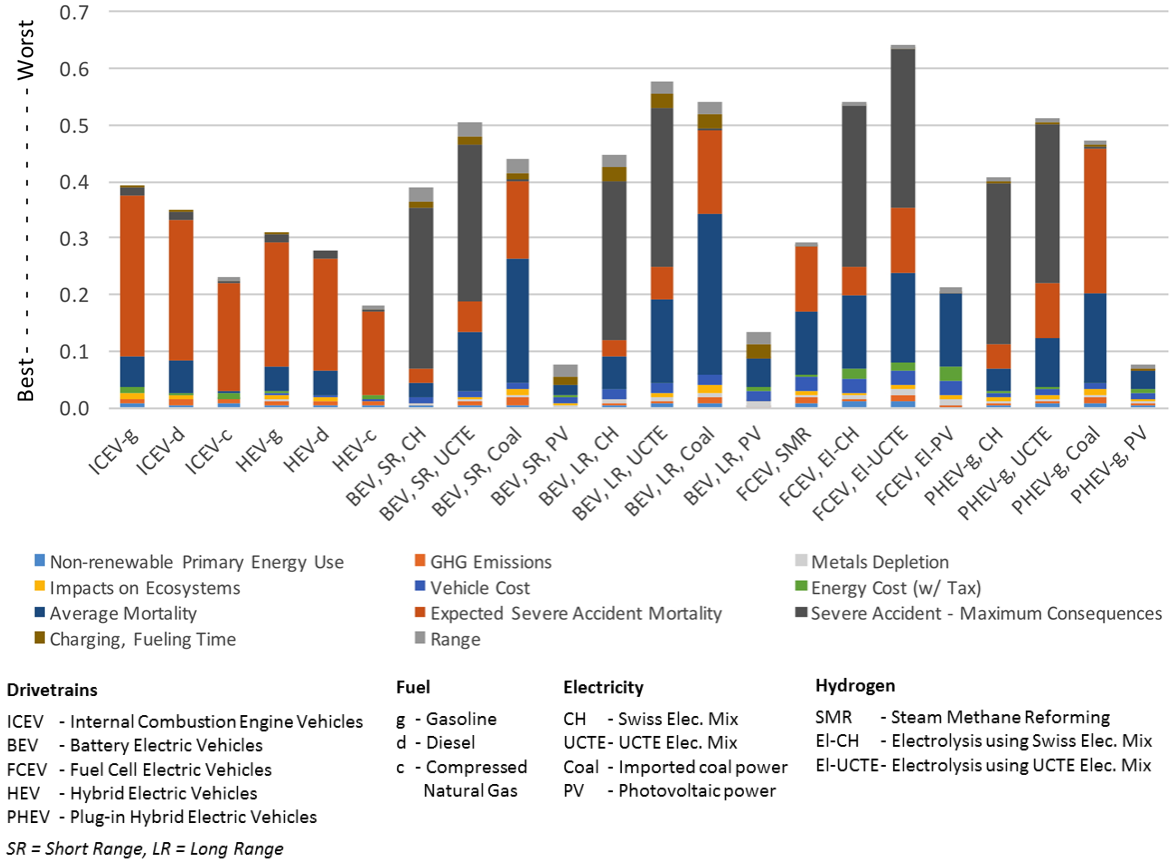


Figure 6.39 2012 Vehicle MCDA – SOC85 Weights (Society 85%, Environment, Economy, and Driver Utility 5% each)

Emphasis on social aspects, here focused on the normal operation and accident-related risks of energy supply, clearly favors BEV and PHEV if electricity is supplied by solar PV. For the conventional cars and hybrids expected severe accident mortality in relative terms contributes most on the side of poor performance. For advanced technologies the most significant negative contributions origin either from mortality in the normal operation of supply energy chain or from expected severe accident mortality in the energy supply chain or from risk aversion (represented by maximum consequences of severe accidents in the supply chain).

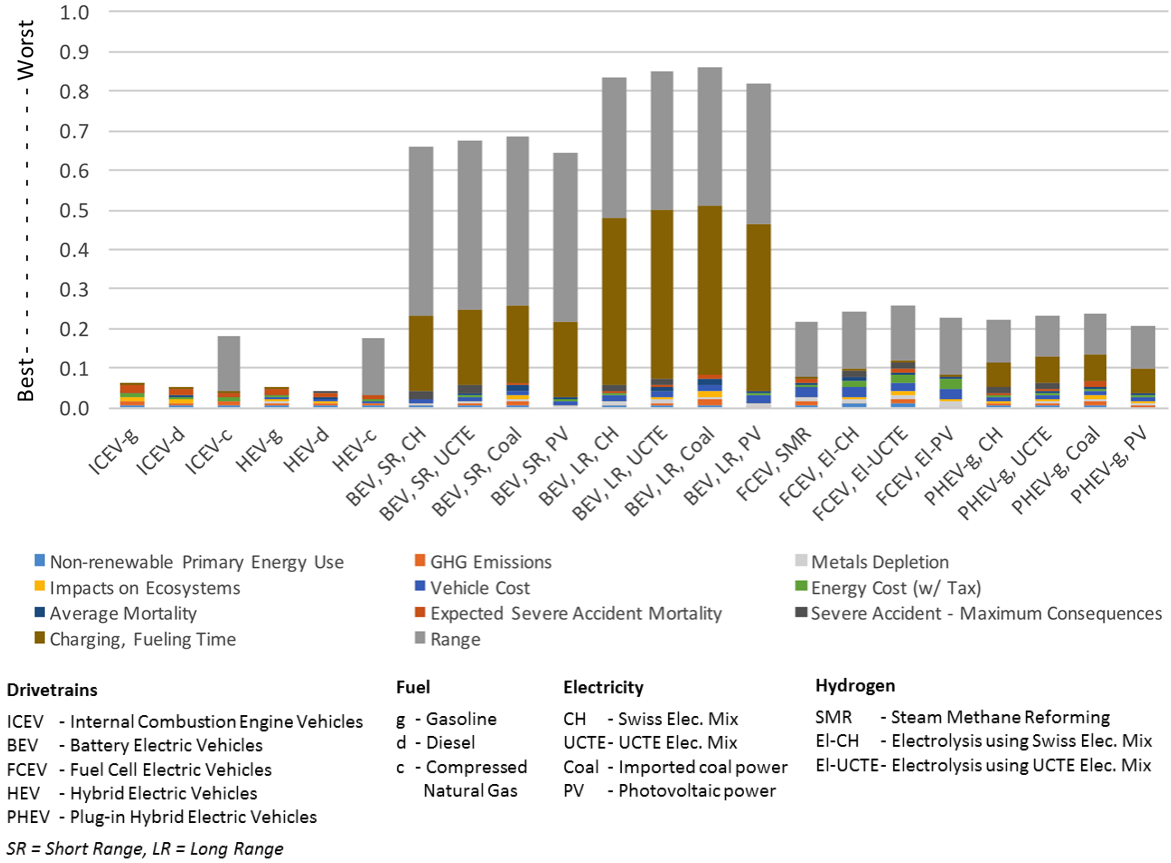


Figure 6.40 2012 Vehicle MCDA – UTI85 Weights (Driver Utility 85%, Environment, Economy, and Society 5% each)

Emphasis on driver utility clearly favors conventional cars closely followed by hybrids, PHEV and FCEV. BEV are penalized with relative disadvantage for short range cars. As expected charging time has the highest negative influence on the low ranking of long range BEV while range is the weakest feature of short range BEV.

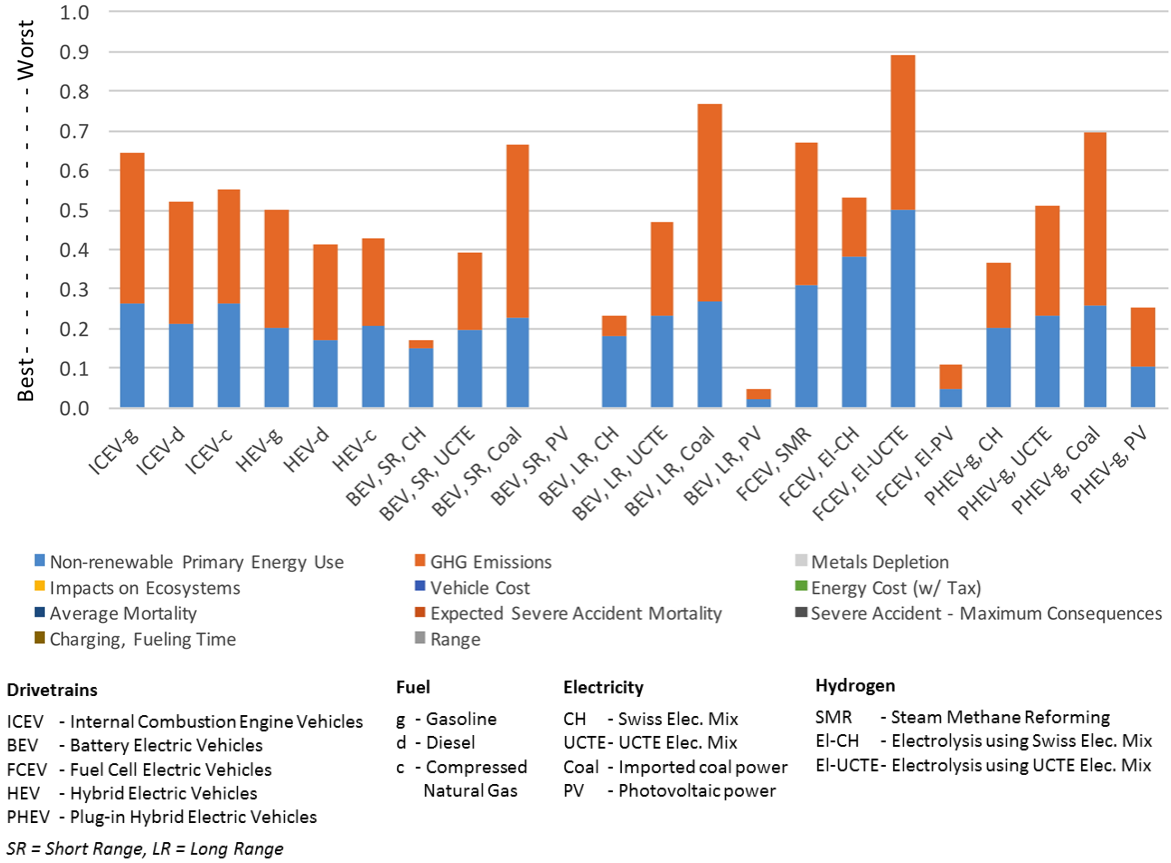


Figure 6.41 2012 Vehicle MCDA – CO_2, Primary Energy 50/50 Weights (CO_2 Emissions and Non-renewable Primary Energy Use 50% each)

Clearly BEV are attractive if use of primary non-renewable energy and GHG emissions are to be minimized, provided that electricity supply is by nearly carbon free sources, preferably solar PV or other renewable sources. The same applies to PHEV. Also FCEV is performing very well in such a setting if hydrogen is produced by using renewable electricity for electrolysis.

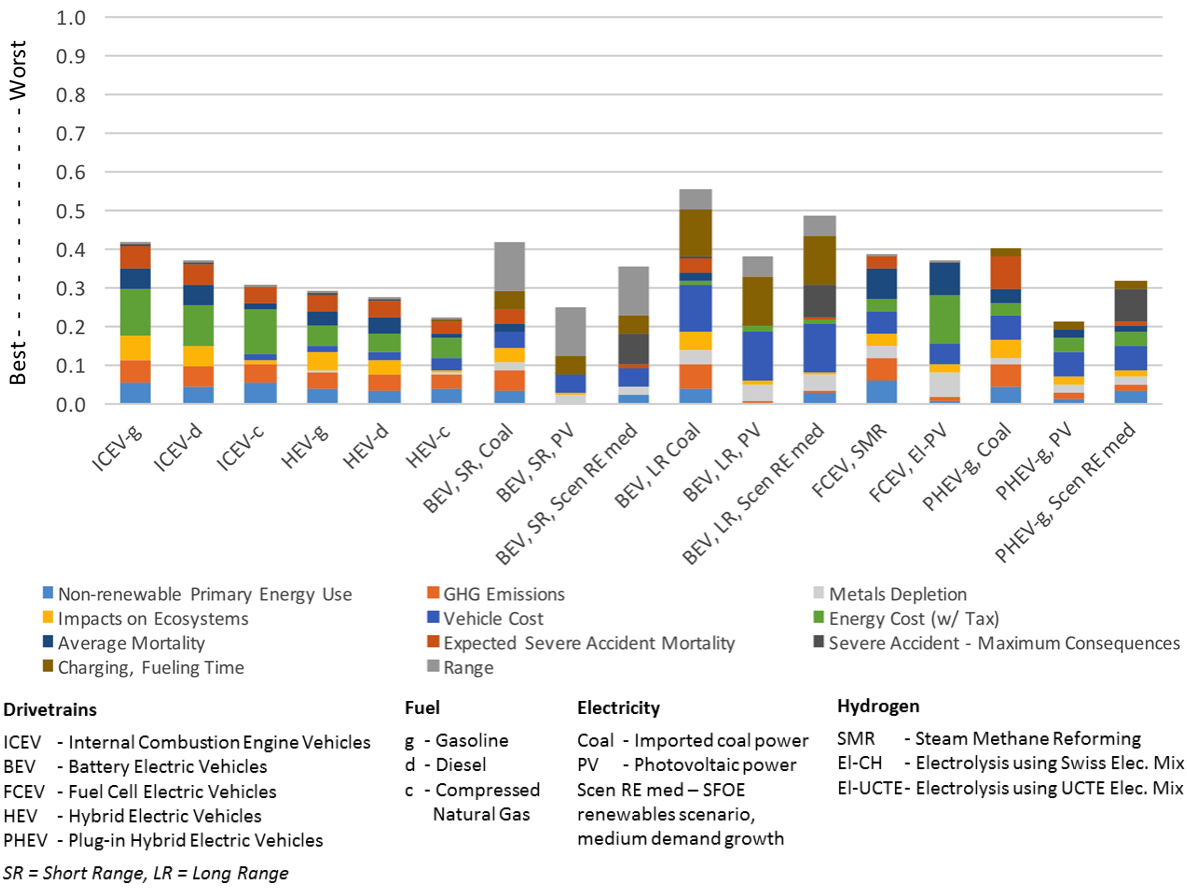
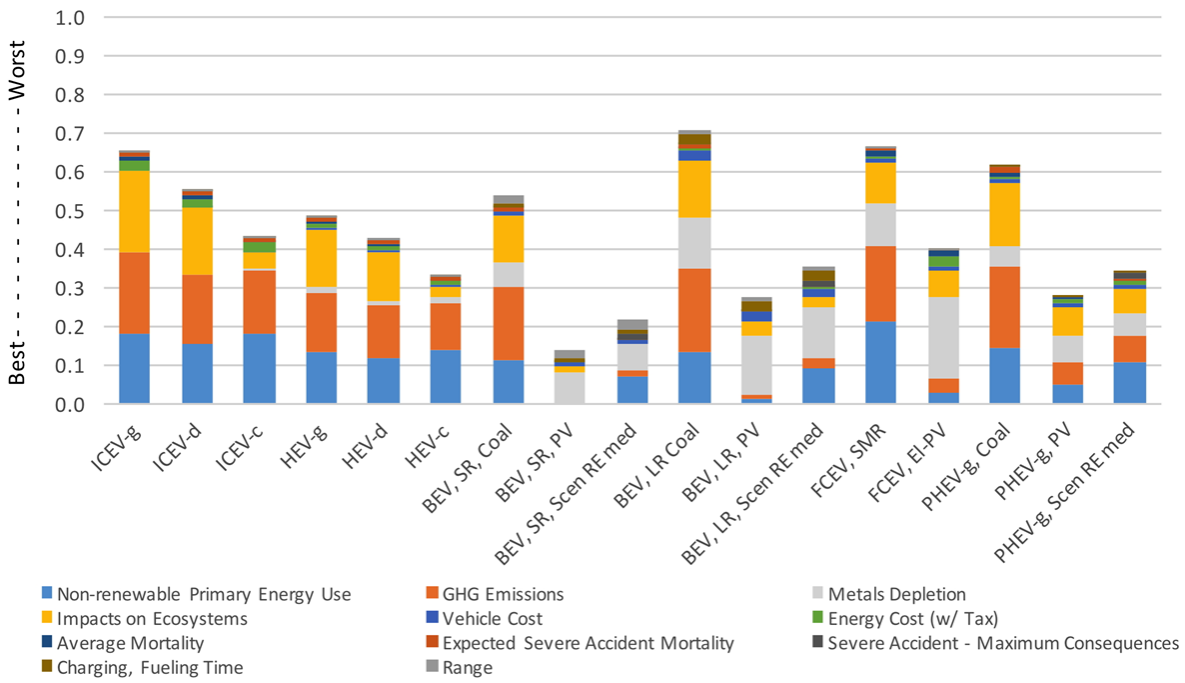


Figure 6.42 2050 Vehicle MCDA – EQUAL Weights (Environment, Economy, Society and Driver Utility equally weighted)

Due to remarkable improvements of electric vehicles their aggregated sustainability performance is overall comparable to that of also much improved ICEV and hybrids. PHEV and short range BEV with PV providing electricity input belong to top performers overall along HEV using gas. In relative terms BEV are still burdened in relative terms by charging time and range issues and by vehicle costs for long range options, and FCEV with low total GHG emissions by energy costs.



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

Coal - Imported coal power
PV - Photovoltaic power
Scen RE med – SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

Figure 6.43 2050 Vehicle MCDA – ENV85 Weights (Environment 85%, Economy, Society and Driver Utility 5% each)

Strong emphasis on environmental performance mostly favors electric cars, particularly short range BEV with renewable electricity supply. Metal depletion is still an issue. Among ICEV those fueled by gas are best performers. The same applies to HEV.

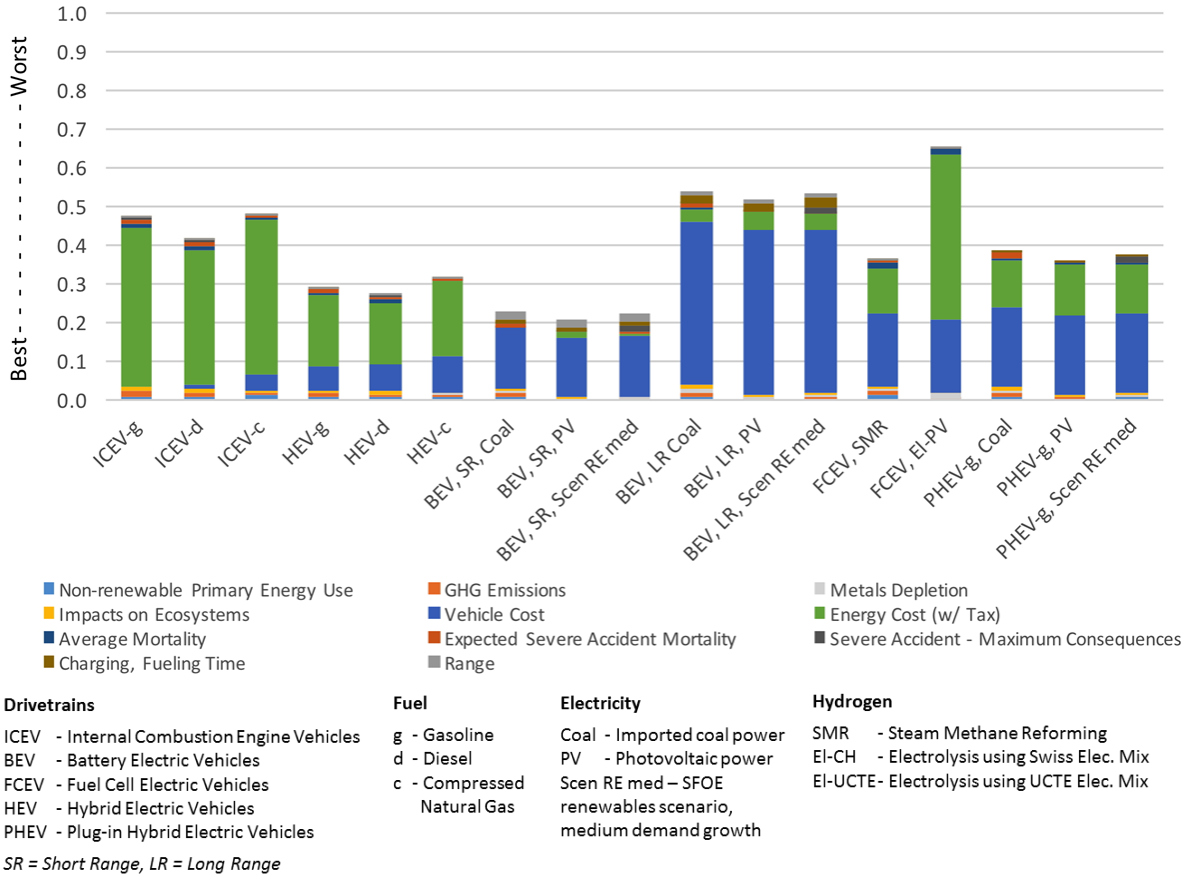


Figure 6.44 2050 Vehicle MCDA – ECO85 Weights (Economy 85%, Environment, Society and Driver Utility 5% each)

Emphasis on economy results in the best ranks for short range BEV. In relative terms ICEV and HEV are burdened by energy costs, long range BEV by vehicle costs, and FCEV by vehicle and energy costs.

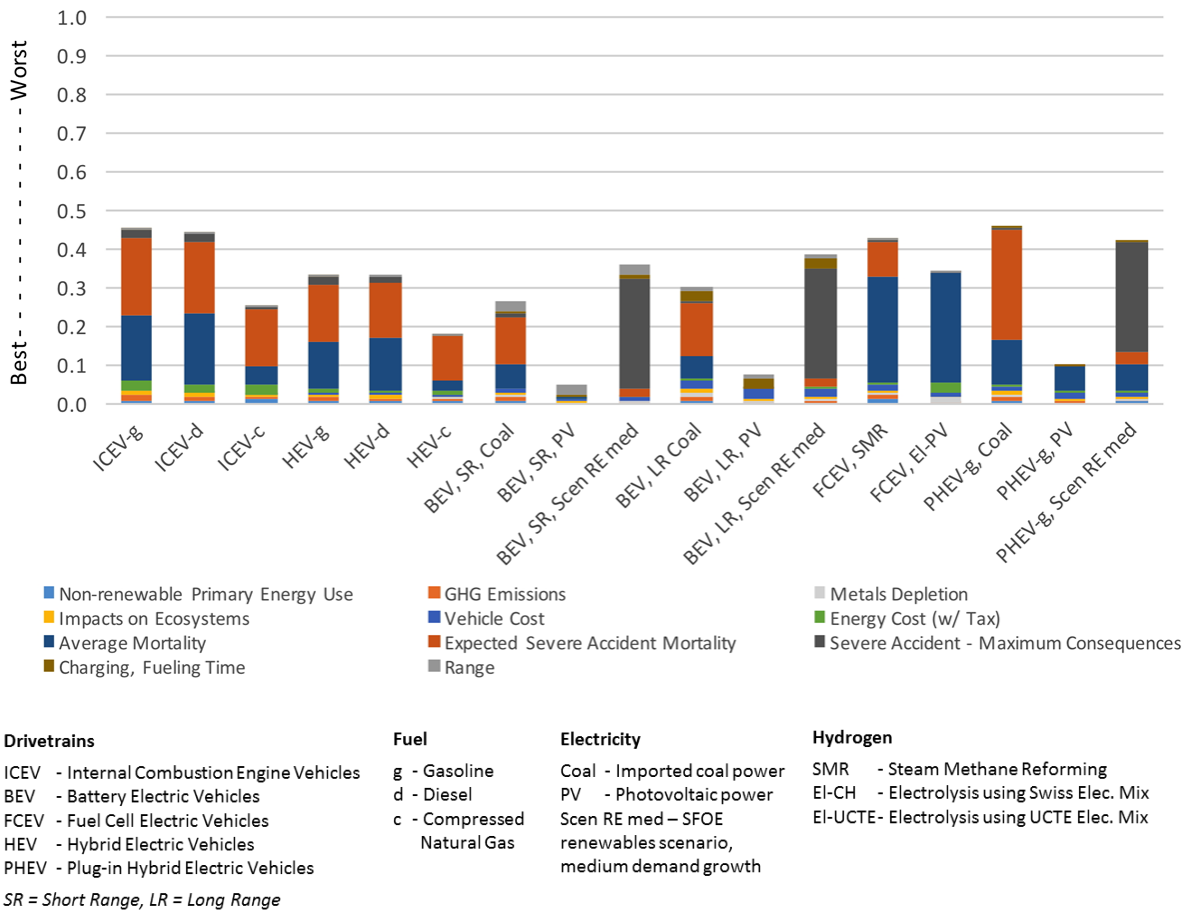
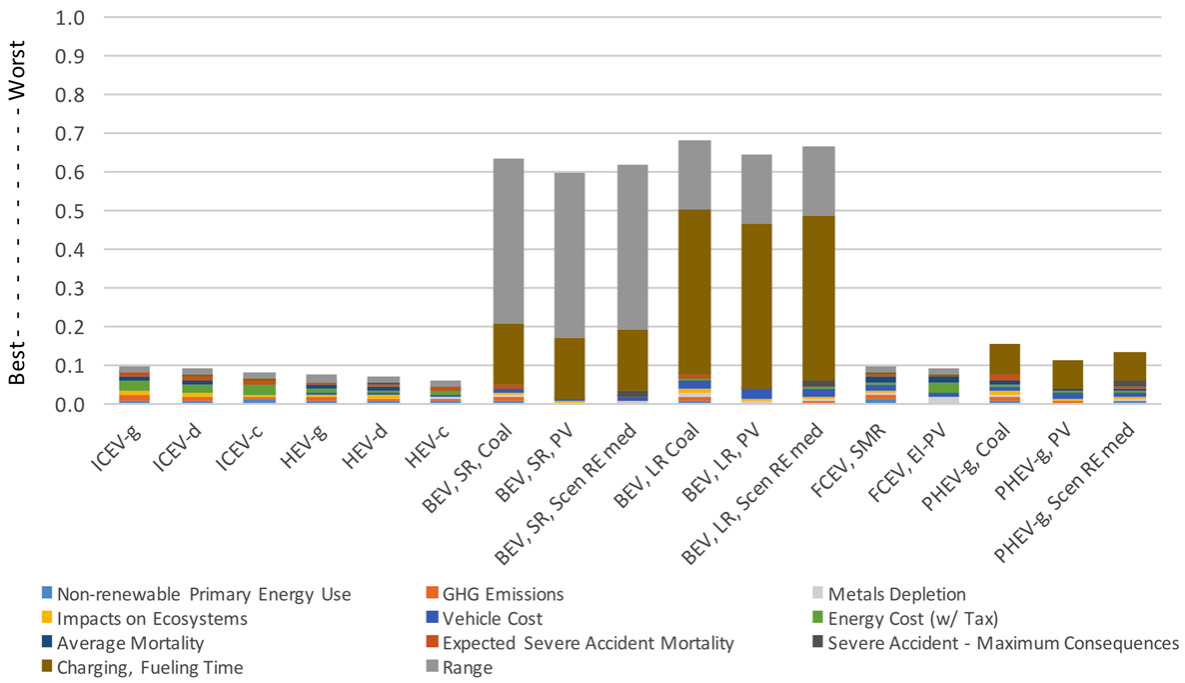


Figure 6.45 2050 Vehicle MCDA – SOC85 Weights (Society 85%, Environment, Economy, and Driver Utility 5% each)

The performance patterns in this case are similar to those in the corresponding case for the current technologies. In fact, in relative terms the "bad" cases among electric cars become better. Thus, emphasis on social aspects, here focused on the normal operation and accident-related risks of energy supply, again clearly favors BEV and PHEV if electricity is supplied by solar PV. For the conventional cars and hybrids expected severe accident mortality in relative terms contributes most on the side of poor performance. For advanced technologies the most significant negative contributions origin either from mortality in the normal operation of supply energy chain or from expected severe accident mortality in the energy supply chain or from risk aversion (represented by maximum consequences of severe accidents in the supply chain).



Drivetrains

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Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

Figure 6.46 2050 Vehicle MCDA – UTI85 Weights (Driver Utility 85%, Environment, Economy, and Society 5% each)

While both a decisive improvement for the future range and charging time of BEV has been credited emphasis on driver utility remains clearly unfavorable for their ranking. As expected charging time has the highest negative influence on the low ranking of long range BEV while range is the weakest feature of short range BEV.

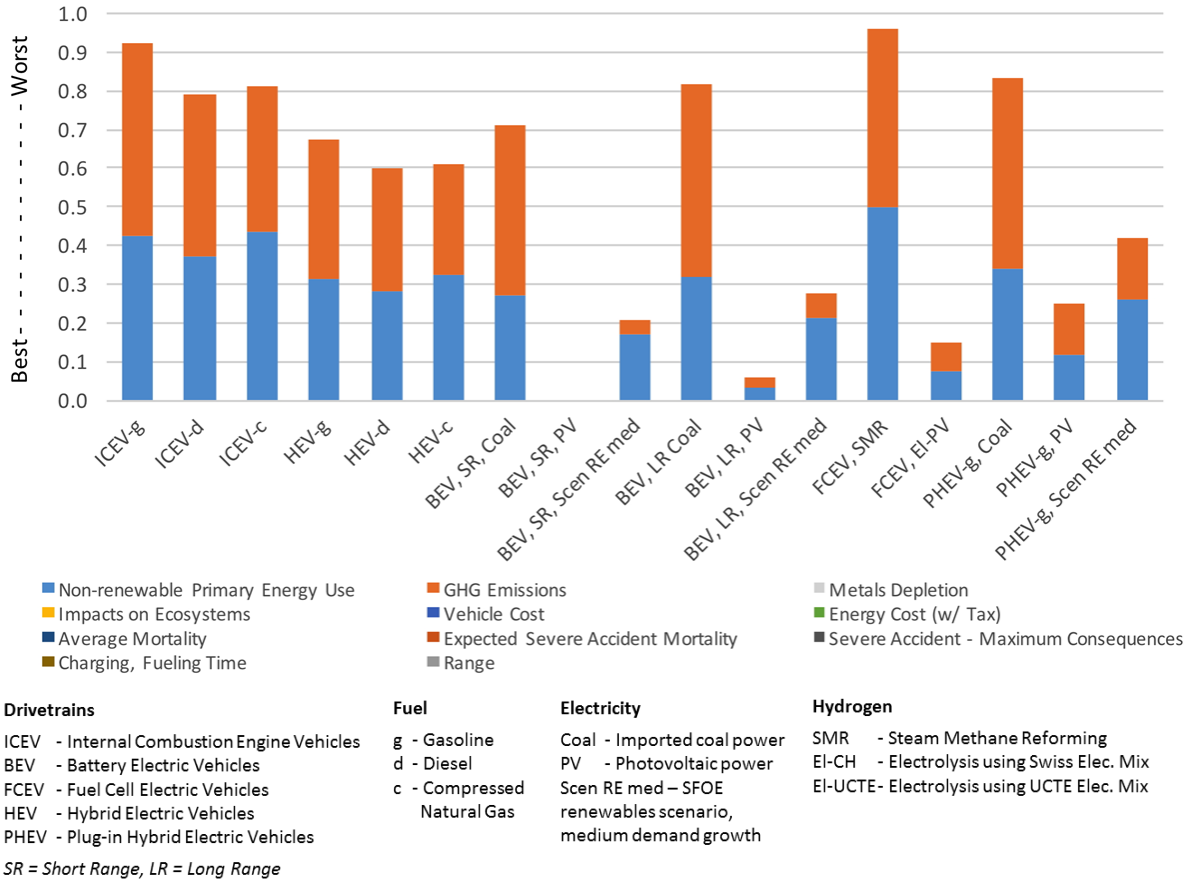


Figure 6.47 2050 Vehicle MCDA – CO_2, Primary Energy 50/50 Weights (CO_2 Emissions and Non-renewable Primary Energy Use 50% each)

Also in this case the results have strong parallels to those for current technologies. BEV are attractive if use of primary non-renewable energy and GHG emissions are to be minimized, provided that electricity supply is by nearly carbon free sources, preferably solar PV or other renewable sources. The same applies to PHEV. Also FCEV is performing very well in such a setting if hydrogen is produced by using renewable electricity for electrolysis.

6.4. Assessment of sustainability of car fleet options

Assessing sustainability of car fleet options calls for very high level of integration of the analytical approaches used and the data flows between the various Work Packages. In this section the overall integration framework is outlined, the data flows are described, the fleet model is elaborated, implementation of MCDA on the fleet level is depicted, and the quantitative indicators for fleet performance as well as of MCDA are provided.

6.4.1. Integrated framework and data flows

Figure 6.48 shows both the model and database components employed in the integrated framework as well as the most essential data flows between the various Work Packages of THELMA.

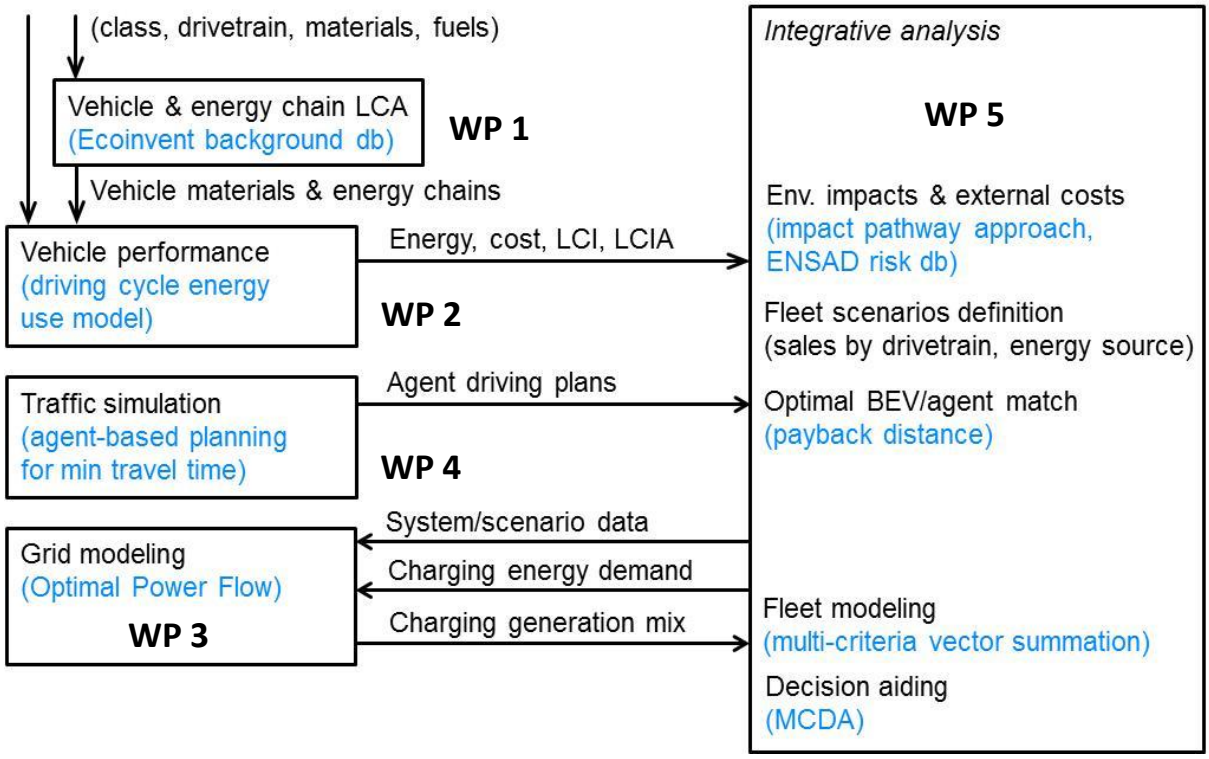


Figure 6.48 Integrated framework for sustainability assessment of car fleet options with emphasis on battery cars. The modeling and database components are in blue color.

The figure above shows the main data flows between the various Work Packages within the THELMA project. WP1 calculated material and energy chain data that were provided as inputs to WP2. WP2 defined a 'virtual fleet' of vehicles combining different classes, drivetrains, energy sources and driving cycles to produce a vector of impact indicators for each vehicle, including energy costs, life cycle inventories and life cycle impacts. Location-dependent environmental impacts and environmental external costs were analyzed in WP5. In parallel, WP5 defined scenarios for the penetration of electric vehicles, and also assumptions for electricity supply and demand that were then passed to WP3. Based on the scenario definitions for the penetration of electric vehicles, WP5 created a fleet model. WP4 supplied WP5 with traffic data from the MATSim model for future traffic scenarios. Based on this, WP5 analyzed individuals' driving plans and combined them with vehicle data to allocate specific vehicle types to drivers. WP5 then supplied WP 3 with the charging demand (both amount and location) so that WP3 could model the grid-constrained dispatch to calculate the marginal charging generation (Optimal Power Flow). Finally, WP5 used the fleet model to combine

the fleet technology penetration scenarios, the traffic pattern data, the BEV charging results, and the individual vehicle impacts to generate the total fleet results for all scenarios.

6.4.2. Approach to fleet modeling

6.4.2.1. Penetration of electric vehicles

The fleet scenarios basically are composed of two different sets of elements. The first set is what combinations of different technologies make up the future vehicle fleet, e.g. how many BEVs, how many FCEVs, how many ICEVs using which fuels, etc. For the vehicle technology mix the goals are to have enough market penetration for each vehicle technology by 2050 to have a significant impact, while recognizing that full market penetration is unlikely, and also keeping the number of scenarios small enough that it is easy to compare them and understand the results. For example, the range of BEV penetrations is 0, 30, 60 and 90 percent of the fleet in 2050. The zero option allows for comparison with the base case and other single technology strategies. The 30% is enough to have a significant impact and small enough to combine with other choices. The 90% fleet penetration recognizes that a full takeover of the marketplace is unlikely. And having 60% penetration as the only mid-point keeps the total number of scenarios in bound. Similar choices have been made for the FCEV, HEV and PHEV technologies. Any remaining vehicles are assumed to be ICEVs, with the possibility of CNG penetrating into the normal mix of gasoline and diesel vehicles.

The second set is related to the environment in which this fleet operates, e.g. what is the source of the electricity or hydrogen. The choice may be to analyze the electricity or hydrogen from a single source (e.g. electricity from solar PV, of hydrogen from steam methane reforming). But the electricity can also come from a future electricity mix that is influenced by both uncertain demand growth and government policies that affect the future generation technologies.

The focus in the present analysis has been on the impact of BEVs in the Swiss transportation sector, and how this interacts with the electric sector in terms of additional demand, shifts in the supply mix, and effects on and due to the power grid. While the other drivetrain mentioned above are very important for technology comparison, pure BEVs (versus PHEVs) obviously have the greatest impact on the electric sector. For these reasons there is more emphasis on BEVs, with scenario options related not only to BEV market penetration, but also the electricity source, demand growth, government policy, and average v. marginal future electricity supply. Pure BEVs are compared against several technologies using chemical energy carriers, with drivetrains that are either electric (hydrogen FCEVs), mechanical (ICEVs), or mixed (HEVs).

However, no scenarios were composed that included the PHEV technology. PHEVs were analyzed and included in the technology comparison, and they are also currently relatively popular compared to BEVs and other emerging technologies, primarily due to their elimination of range limitations. However, from a fleet scenario perspective the PHEV represents an intermediate case between BEV and HEV dominant strategies. A scenario with dominant PHEV penetration would therefore be relatively similar to a mixed BEV and HEV scenario. So given the need to limit the fleet scenario set, this option was not included.

6.4.2.2. Fleet model

The purpose of any fleet model is to track fleet composition by vehicle age and type as new cars are purchased and enter the fleet, and as old cars retire and exit the fleet. For the purposes of THELMA, the fleet model has several main characteristics that are now discussed below.

Fleet registration data - The starting fleet of the model is based on the official existing Swiss vehicle registration data for the years 2001 through 2011, which includes information about vehicle class and geographic location.

Although the geographic fleet distribution by Swiss canton is interesting, this has mainly been used to confirm that purchasing patterns by class do not vary much across cantons. Originally it was expected that the cantonal data would be used as part of the allocation process used for matching BEV sales to geographic locations for estimated charging loads to the transmission grid. However, the WP3 analysis already used MATSim results, so it was only necessary to match the BEV sales to individual MATSim agent identification numbers.

However the registration data by class was used to establish the relative existing market shares for the different vehicle classes. It was assumed the class market shares remained constant over the period covered by the fleet model. This is not a very strong assumption, but there is not much good data for assuming how these vehicle class market shares might otherwise evolve.

The database only goes from 2001 to 2011 and the current fleet still contains vehicles from before 2001. It was therefore assumed that purchase patterns from 1985 to 2000 followed the same average class distribution and cantonal distribution as for the succeeding years with registration data. Any possible inaccuracies from this assumption are reduced by the increasing retirements for vehicles from the earlier years.

Fleet Evolution - The fleet must evolve over time to meet the MATSim model fleet results for the year 2030. The MATSim model is a 10% scale model, i.e. it contains 10% of the people, vehicles, activities and km traveled compared to the real world. This is done of course to reduce computational hardware and time requirements, with little or no loss of insight on the resulting traffic patterns. This does mean that the registration data (see above) were reduced by a factor of 10, and that the final THELMA fleet results for km traveled and energy used must also be increased by a factor of 10.

The MATSim results contain a wide range of assumptions that drive transportation demand and distribution, including population growth and shifts, economic forecasts, etc. (please see chapter 5 of this report on WP4). The geographic distribution (based on the location of agents' homes) of cars by canton is different in the MATSim results for 2010 and 2030 than the cantonal distribution based on the registration data. This difference in geographic distribution was smoothly adjusted from the registration distribution to the MATSim distribution over the period from 2012 to 2030. The growth in the overall fleet size from the 2010 MATSim reference year to the 2030 MATSim case is quite modest, with the result that the shifts between cantons can cause actual drops in the number of vehicles in some cantons, while causing increases in others. As the BEV sales are matched to individual MATSim agents regardless of their location, this effect could safely be ignored.

Retirements and Sales - The retirements of vehicles leaving the fleet and the purchases of vehicles penetrating the fleet are assumed to follow an s-shaped logistic curve. The formula for a generic logistic curve is:

$$P(t) = \frac{1}{1 + e^{-t}} \tag{1}$$

which gives the s-shaped curve that can be seen in Figure 6.49 below:

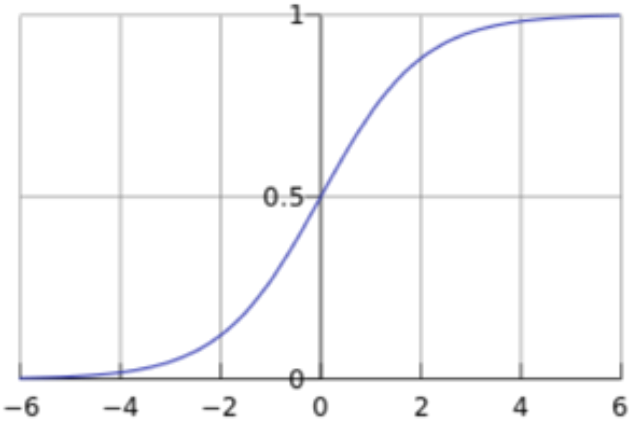


Figure 6.49 Generic logistic curve used to model vehicle retirement and fleet penetration.

This curve reflects how people are influenced by the way that information penetrates society and by the example of their peers and neighbors. In other words the curve embodies the old saying: "Be not the first by whom the new is tried, nor yet the last to set the old aside."

There are three parameters that can be used to adjust this generic curve for specific vehicle survival or penetration cases. First, the whole curve can be 'shifted sideways' by adjusting the year at which t = 0. Second, the steepness of the curve can be adjusted, and third, the vertical scale can be adjusted or inverted.

The historic vehicle registration data described above must be combined with some description of how many have already retired in order to determine how large the fleet is in total. This description of retirement behavior is normally given in the form of a retirement curve, as shown below in Figure 6.50. As can be seen, the red line shows a generic survival curve (Lu, 2006), i.e. what fraction of vehicles remains in the fleet after a given number of years. Retirements increase over time to a peak rate (maximum slope) at an age of about 12 years, and essentially all vehicles are retired by the age of 25 years. If this generic curve was used, then the resulting total fleet size would be smaller than the actual fleet size used for the MATSim 2010 base case. The curve was therefore adjusted as described above by making the retirements occur later and fall off more rapidly. This agrees with conventional experience that modern cars have longer lives, but still very few are around after 25 years. The coefficients for the adjusted curve were set so that the MATSim fleet size was met, and the resulting survival curve is shown in Figure 6.50 with a blue line. It should be noted that the same survival curve was used for all vehicle classes, which may not be entirely realistic. Experience says that the vehicles that survive the longest are disproportionately from the sport and/or luxury classes, but these are also numerically the smallest classes, so it does not change the results much to use the same curve for all classes.

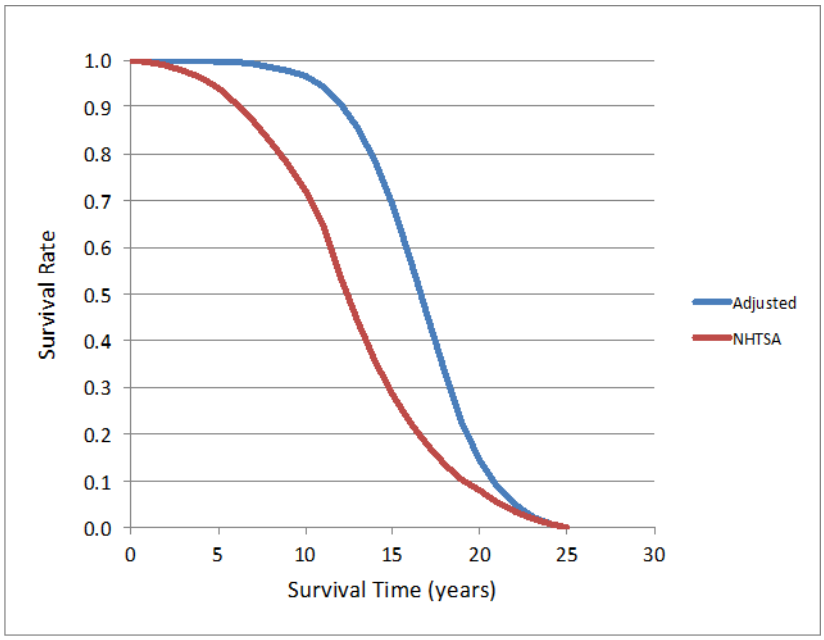


Figure 6.50 Generic and adjusted vehicle survival curves fit to match MATSim fleet size.

<u>THELMA Penetration Curves</u> – The market penetration curves for the THELMA analysis of BEVs are also based on logistic curves, except that now the curves are explicitly different for the different vehicle classes. As we know from the penetration of many innovations into the car market, changes are normally made in the market classes with the highest prestige and profit margins, i.e. the luxury and sport markets. As costs decline, the technology then progressively penetrates lower margin market segments as profitability permits. This has been the case with innovations like electric starters, power steering, air conditioning, anti-lock brakes, etc. Safety-related innovations (seat belts, airbags, etc.) may penetrate somewhat more evenly due to government regulation. The initial penetration of hybrid vehicles agrees with this progress in the number of hybrid models released, even though the single model with the largest sales (the Honda Prius) is a midsize sedan. There is a strong argument that Toyota has made a strategic decision to sell this model with an internal subsidy (or even possibly at a loss to actual cost) in order to advance the technology and establish market dominance in this segment.

Even though it is impossible to know from past innovations how fast the BEV technology will progress through this same sequence of market classes, it still seemed important to model this process rather than impose some more arbitrary penetration targets. As a result, a separate logistic penetration curve was modeled for each vehicle class and their parameters were adjusted so that the total BEV market penetration achieved the target levels of 30%, 60% and 90% in 2050. Table 6-6 below shows the vehicle classes, their relative market share, the relative delay between classes, the total delay from the starting year of 2010 , and a 'stretch factor' to delay market penetration over a longer period

Table 6-6 Logistic curve parameters for market penetration.

Class	Class name	Class share	Fraction	Class Delay	Total Delay	Stretch Factor
1	Mini	0.060	0.330	10	20	1.5
2	Small	0.200	0.330	10	20	1.5
3	Medium	0.379	0.330	8	18	1.5
4	Upper Med	0.048	0.330	8	18	1.5
5	Luxury	0.005	0.330	0	10	1.5
6	MPV	0.124	0.330	6	16	1.5
7	SUV	0.132	0.330	6	16	1.5
8	Sport	0.027	0.330	2	12	1.5
9	Van	0.025	0.330	8	18	1.5
Total		1.000				

The market penetration model starts in 2010, and there is an initial delay of 10 years so that even for the luxury class BEV penetration does not even start until 2020. The successive classes then start in order as given by their relative delay in the table above. As can be seen from the original, generic logistic curve in Figure 6.50 above, about 90% of the penetration takes place in about 6 to 7 years. The stretch factor increases this so that the penetration for each model class is complete in about 10 years.

Figure 6.51 below shows the individual market penetration curves for each market segment, in order to reach a total 90% fleet share by 2050.

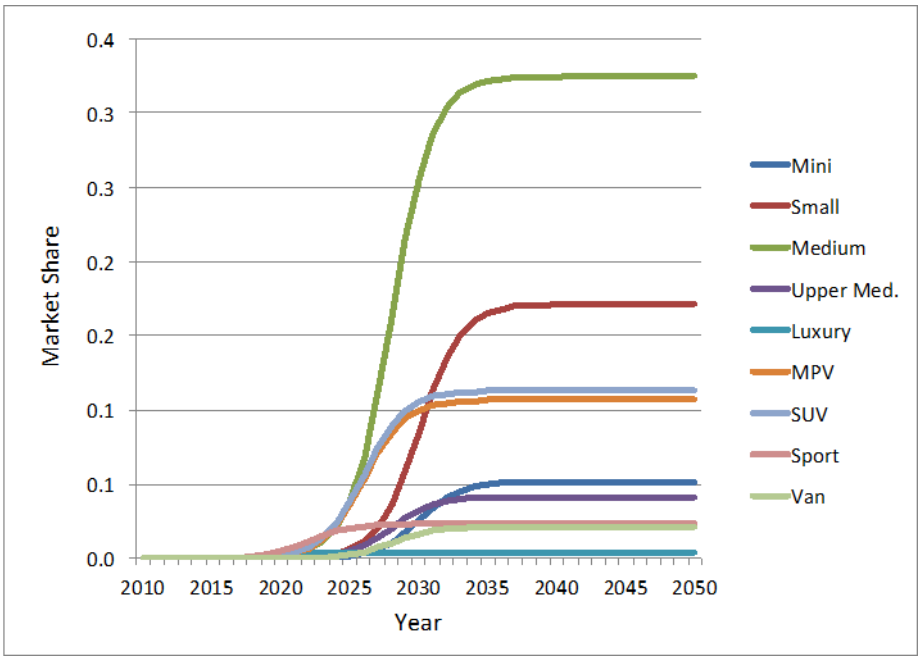


Figure 6.51 Vehicle market penetration curves by vehicle class.

The relative size of the different classes' market shares and the delays between the different classes can be clearly seen. In order to see the total market penetration, the individual curves were stacked in order of their market penetration delay (from first to last), as shown in Figure 6.52 below.

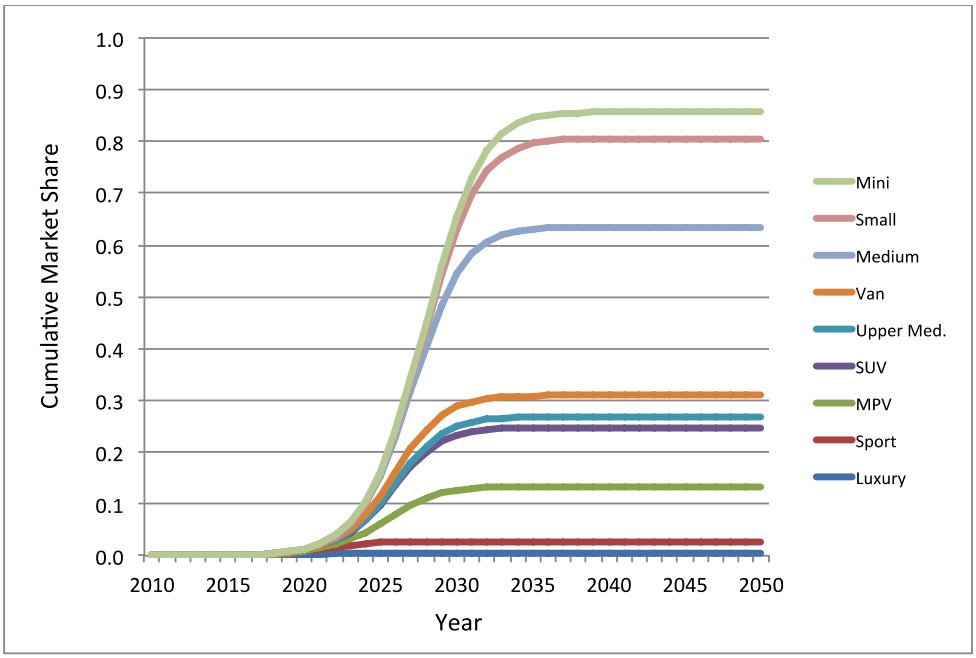


Figure 6.52 Cumulative market penetration curves, stacked by vehicle class penetration order.

These two figures clearly show that several factors that make it difficult to achieve a significant overall BEV market share even over the medium term. First, the absolute and relative delays show that the maximum sales rates for the latter classes with the biggest market shares cannot be reached until about 2035 to 2040. Second, these are *sales* penetration curves, and not *fleet share* penetration curves, so even after BEV sales reach a relatively high level it still takes quite some time to build up the BEV fleet share. Even for the highest BEV penetration scenario where the fleet share is 90% by 2050, the fleet share in 2030 is only about 17%.

6.4.2.3. Vehicle allocation algorithm

Once the basic scenario definitions and data assumptions were supplied to WP3, and the market penetration sales trajectories were determined by class, the remaining key information that was needed was to allocate the vehicles of the projected fleet for 2030 to specific drivers (or agents) in the MATSim model output, so that their vehicle energy demands and the available charging times could be determined.

The original idea for the vehicle allocation algorithm was to find a minimum driving distance that would make the EV's economic to buy, and then to allocate BEVs to a fraction of the qualifying drivers that would meet the target penetration goals in 2050.

The minimum daily driving distance that would make a BEV economic is called the payback distance. This is based on the fact that BEVs cost more than ICE vehicles and the cost of electricity to operate them is less than the cost of gasoline (or diesel fuel). So by taking the difference in the original purchase cost (manufacturing cost plus a 40% retail markup) and balancing this against the present value of the future stream of fuel costs minus electricity costs, it is possible to calculate the daily payback distance required to break even. Obviously this distance depends upon not just the estimated manufacturing costs, but also on the projection of future fuel and electricity prices, energy taxes and the interest rate. For the purposes of the WP5 analysis, the payback for each class of BEV was calculated using the data for the corresponding class of gasoline-fueled ICE vehicle.

Once this was done, there was a range of payback distances for the different classes and model years of BEVs. This led to the concept that the payback distance should not be used to just find a daily km threshold for the MATSim agents, but rather that the payback distances could serve as a figure-of-merit to calculate the relative attractiveness of different BEVs, compared to their gasoline counterparts, with the lowest payback distances being the most attractive.

This led to seeing the possibility of optimizing the assignment or allocation of BEVs to the available agents or drivers in a way that would optimize the total societal benefit. The daily driving distance of the individual agents could be ranked from highest to lowest, and the BEVs could also be ranked from lowest payback distance to highest. If the highest distance drivers are matched with the lowest payback distance BEVs, this maximizes the driver's savings, and if the two ranked lists are matched against each other sequentially this maximizes the savings to society.

To illustrate this, consider two drivers with daily driving distances of a and a+b km per day. For this purpose is it also easiest to consider the inverse of the payback distance, i.e. to use the payback/km, for two BEVs of c and c+d. If the best car is matched to the longest distance (the best match), the total savings will be (a+b)*(c+d) + a*c, whereas if they are inversely matched (higher distance to lower payback, and lower distance to higher payback) the total cost savings will by (a+b)*c + a*(c+d). The difference between best match and inverse match is therefore the cross product term b*d. By extension, it is clear that this calculation can be done for any two pairs of agents and BEVs, and any inverse match should be swapped for the best match, so that the optimum societal benefit (minimum overall cost) will be to match the agents in descending order of daily km (or energy demand) against the BEVs in ascending order of their daily payback distance.

This optimization would be similar to the familiar "knapsack problem" in operations research (i.e., to maximize the value of a fixed-volume knapsack packed with individual packages of different sizes and values), except that size of the total value contributed by each agent-vehicle match is relatively very small compared to the total, so any optimization problems related to granularity were deemed negligible.

Of course, there are also some practical constraints as well for allocating the BEV vehicle fleet existing in 2030, as it is composed of BEVs of different classes and model years that have been purchased over the preceding years. The allocation algorithm of matching agents ranked by decreasing distance and BEVs ranked by increasing payback distance was constrained to meet the BEV fleet purchase requirements. So each MATSim agent was allowed to "purchase" a BEV as long as:

- there were still cars needed in the BEV's class and year,
- the vehicle's model year is available in the current purchase year
- the vehicle's model year has not been replaced by a later model year,
- the daily driving distance was less than the vehicle range,
- the daily driving distance was more than the payback distance, and
- the present agent had not already purchased a car

This methodology thus matches the best agents to each car needed (in order of increasing payback distance) for each successive year. It would be possible to further optimize the 2030 fleet if the vehicle allocation for all purchase years could be done all at once. But the present method is more

realistic in the sense that (by stepping through successive years) the best BEV purchase candidates buy a car in the early years, rather than waiting for a later model year BEV than has a lower payback.

The problem of ranking the 90 BEVs (9 classes times 5 model years times 2 range classes) by their payback distances was of course quite trivial. In contrast the problem of ranking the MATSim agents by their driving distances was much less so. The results of the 10% scale MATSim model contain data for 467 800 different agents, who drive a total of about 1.4 million different plan legs. (Each plan leg has a starting and ending time and location, and is composed of different road network segments or links that include different road types, as indicated by their speed limits. Each link is followed by an activity (e.g. work, shopping, recreation or home) that gives the available charging time.) There were several different problems with ranking the agents by their overall driving distances.

First, the number of legs for each agent's plan are not constant, so it was not possible to simply swap two plans in the computer's memory during the sorting algorithm. In the end, the distance sort problem was solved by creating an index with one line for each agent, sorting this index, and then using the index to find the leg data for each agent during the final output. A relatively inefficient sort algorithm was used, resulting in sort time requirements of 22 and 38 minutes for different cases using a modern laptop. However, the sorting process was not done often, and the index was stored and used repeatedly during the code development process, so the time to implement a more efficient sort was not judged to be necessary.

Second, the MATSim model output data contains some plans that did not fit well with the data needed for WP3. Some of the plans had agents that left their homes in the morning, but then left their cars somewhere (e.g. at work) during the day and returned home by public transport and/or walking. Other agents had the reverse problem of leaving their homes by public transport and/or walking, picking their car up during the day, and then driving home at night. And some agents drove at some times during the day, but never left from or returned to their homes. In such cases, it was not possible to repeat the day over and over (as an assumed "typical" day for the electricity dispatch modeling), and it was not possible to establish what was the available overnight charging time at home. The end result was that all such agent plans were flagged as errors and not considered as possible purchasers of a BEV.

The other main problem was that some plans extended beyond 24 hours in duration (i.e., both past midnight (24:00), and more than 24 hours past the first leg's starting time the previous day. Such plans were also flagged and rejected by the vehicle allocation algorithm.

Both of these "problems" (from the THELMA point of view) are valid model results from the MATSim algorithm's method of generating and comparing alternate agent plans or routes, and they are a very small minority of all plans. From the MATSim point of view (as we understand it), they are simply accepted as outliers that basically disappear in the average or total results for overall traffic patterns.

Third, and as mentioned above, each leg of an agent's plan has a total distance that is made up of different road links that each have a maximum speed limit. These road links were sorted into 3 'bins': from 0 – 6 m/s (0 – 22 km/h), 6 – 16 m/s (22 – 58 km/h), and greater than 16 m/s (58 km/h), which corresponded to urban, suburban (or rural) and highway road types. It is possible to see from the MATSim output what the average road speed for a *whole* leg is (based on the modeled traffic congestion), but not to know what the average speed is for *each* road type. However, a BEV has a different energy use, based on its average driving cycle on each road type. Therefore, instead of

simply summing the total km for each plan for the overall plan ranking, it is desirable to calculate an energy-weighted distance for each plan. This was implemented by using weighting factors of 0.607, 0.750 and 1.104 for the urban, suburban and highway distances, based on a 2011 fleet class-weighted average of BEV energy use. Thus, all the agents were ranked by their adjusted daily distance, based on the average BEV energy use for different driving cycles. This daily distance for an *average* BEV was then matched to a payback distance for a *specific* BEV (by class and model year), but this is of course unavoidable since it is impossible to know in advance which car will be matched to which agent.

In the preliminary data set of vehicle characteristics from WP2, the BEVs spanned a range of payback distances from 12 to 114 km/day. Using these payback distances, the ranked daily agent driving distances, and the algorithm briefly outlined above showed that it was feasible to match all the planned vehicle purchases to specific MATSim agents, and to fully achieve the planned market penetration trajectory.

Unfortunately, in the final data received from WP2 the range of the payback distances had increased significantly to a range from 10.5 to 285 km/day, due to a range of factors. Using this new data showed that not all the desired BEV 'sales' could be accomplished to meet the planned market penetration trajectory. This was especially due to the fact that the payback distances for the 2012 and 2020 model years were too high to find enough matches in the relative small fraction of Swiss drivers that drive longer average daily travel distances. The payback distance performance of the BEVs is significantly improved in the later model years, primarily by improved batteries, so that achieving the needed 'sales' in later years is not the binding constraint. Three methods were tried to solve this problem.

First, the vehicle driving range constraint was relaxed by 10%. The original matching constraint was that the agent's daily driving distance should be less than the BEV's driving range, i.e. the vehicle should be able to be driven all day and charged at night, without necessarily having to be charged during the day. This constraint was relaxed, but it did not sufficiently improve the vehicle allocation so that all projected BEV sales could be achieved.

Second, the battery ranges for all BEV classes and model years were reduced. All the BEV classes have both short-range and long-range versions, i.e. they have model versions with smaller and larger battery sizes. Reducing the battery sizes for both the short and long range models reduces the initial difference in purchase cost between the BEV and ICE gas cars, and hence reduces the daily breakeven distance necessary to make up this difference, based on the difference in the future energy costs. The WP2 team therefore reduced the battery sizes, and all the related results, including vehicle mass, energy use, and costs. The lower payback distances were reduced to a range from 23 to 238 km/day (the list of BEVs ranked by their final payback distance is shown below in Table 6-7.

Table 6-7 BEVs with class and battery range, ranked by payback distance (2nd table continues ranking).

Vehicle Class	Vehicle Range Category	Model Year	Battery Range (km)	Payback Distance (km)		Vehicle Class	Vehicle Range Category	Model Year	Battery Range (km)	Payback Distance (km)
Mini	BEV-SR	2050	200	23.1		Small	BEV	2040	425	99.5
Sport	BEV-SR	2050	200	24.3		Midsize	BEV	2040	425	100.2
Small	BEV-SR	2050	200	24.5		SUV	BEV	2040	425	100.3
Midsize	BEV-SR	2050	200	26.1		Luxury	BEV	2040	425	101.2
Upper_midsize	BEV-SR	2050	200	27.3		Upper_midsize	BEV	2040	425	101.7
Luxury	BEV-SR	2050	200	27.6		MPV	BEV	2040	425	101.8
MPV	BEV-SR	2050	200	27.9		Small	BEV-SR	2020	122	104
SUV	BEV-SR	2050	200	27.9		Mini	BEV-SR	2020	122	104
Van	BEV-SR	2050	200	29.3		Van	BEV	2040	425	104.4
Mini	BEV-SR	2040	175	34.6		Sport	BEV	2030	350	105.1
Sport	BEV-SR	2040	175	34.6		Mini	BEV	2030	350	106.1
Small	BEV-SR	2040	175	35.8		SUV	BEV	2030	350	106.8
SUV	BEV-SR	2040	175	36.3		MPV	BEV	2030	350	108.3
Midsize	BEV-SR	2040	175	36.4		Midsize	BEV	2030	350	108.3
MPV	BEV-SR	2040	175	36.6		Small	BEV	2030	350	108.5
Upper_midsize	BEV-SR	2040	175	37.1		Luxury	BEV	2030	350	109.7
Van	BEV-SR	2040	175	37.2		Van	BEV	2030	350	109.9
Luxury	BEV-SR	2040	175	37.3		Upper_midsize	BEV	2030	350	109.9
SUV	BEV-SR	2030	150	43.9		SUV	BEV-SR	2012	100	119.7
Sport	BEV-SR	2030	150	44.1		Van	BEV-SR	2012	100	121.3
Van	BEV-SR	2030	150	44.3		MPV	BEV-SR	2012	100	124.3
MPV	BEV-SR	2030	150	44.5		Luxury	BEV-SR	2012	100	125
Mini	BEV-SR	2030	150	45.1		Sport	BEV-SR	2012	100	126.5
Midsize	BEV-SR	2030	150	45.7		Upper_midsize	BEV-SR	2012	100	128.7
Upper_midsize	BEV-SR	2030	150	46.1		Midsize	BEV-SR	2012	100	133.2
Small	BEV-SR	2030	150	46.1		Small	BEV-SR	2012	100	142.4
Luxury	BEV-SR	2030	150	46.2		Mini	BEV-SR	2012	100	143.2
Sport	BEV	2050	500	85.5		SUV	BEV	2020	267	172.1
Mini	BEV	2050	500	87.1		Van	BEV	2020	267	176
SUV	BEV-SR	2020	122	89.6		Sport	BEV	2020	267	176
Small	BEV	2050	500	89.8		MPV	BEV	2020	267	176.1
Van	BEV-SR	2020	122	90.7		Luxury	BEV	2020	267	178.9
Midsize	BEV	2050	500	91.3		Upper_midsize	BEV	2020	267	180.7
Luxury	BEV	2050	500	91.9		Midsize	BEV	2020	267	180.8
MPV	BEV-SR	2020	122	92.5		Mini	BEV	2020	267	184
Upper_midsize	BEV	2050	500	92.7		Small	BEV	2020	267	185.9
SUV	BEV	2050	500	93.3		SUV	BEV	2012	200	215.5
Sport	BEV-SR	2020	122	93.6		Van	BEV	2012	200	219.9
Luxury	BEV-SR	2020	122	93.6		MPV	BEV	2012	200	221
MPV	BEV	2050	500	94.7		Sport	BEV	2012	200	223.7
Sport	BEV	2040	425	95.6		Luxury	BEV	2012	200	225
Upper_midsize	BEV-SR	2020	122	95.8		Upper_midsize	BEV	2012	200	227.9
Mini	BEV	2040	425	97		Midsize	BEV	2012	200	229
Midsize	BEV-SR	2020	122	98.3		Mini	BEV	2012	200	236
Van	BEV	2050	500	98.4		Small	BEV	2012	200	237.6

As can be seen, the late model year cars with shorter range batteries have the lowest payback distances, while the earliest model years with the higher range batteries have the highest payback distances. This reduction in BEV battery size and range did improve the 'sales' achieved in the vehicle allocation process, but it did not entirely solve the problem of achieving the full market penetration trajectory

Third, the economic breakeven distance constraint was relaxed. This solution was of course successful, but it did mean that some BEVs were 'purchased' where the initial increase in the

purchase cost would never be repaid by later 'fuel' savings, based on the assumed recharging costs. Although this was not the original goal, several factors were considered, i.e.:

- Many (perhaps most) people do not act with strict, economic rationality when they are purchasing a car.
- Although some individual purchasers have increased their personal costs by purchasing a BEV, the algorithm still ensures that the vehicle allocation is optimized by achieving the target market penetration trajectory at the least overall societal cost.
- In the end it was decided that meeting the BEV penetration targets was more important than meeting the payback criterion.

In the process of trying these different changes to ensure that all the BEV penetration targets were met, some other changes were also made to improve the data supplied to WP3. The main change was that the allocation constraint tests were changed from using a km basis to an energy basis. That is, instead of comparing the agent's adjusted daily driving distance to the BEV's driving range, the comparison is now made between the BEV's daily energy requirement and the BEV's battery energy capacity. This is more accurate, because the vehicle's daily energy requirement is calculated based on the distance driven (on all three road types) *and* also on the driving time that is multiplied times the auxiliary load (e.g. heating or air conditioning) which is in MJ/hour, instead of MJ/km. The agent plans are now still ranked or sorted in the same order based on the adjusted daily km, based on a fleet average BEV, *but* now the energy comparison for daily energy used and vehicle battery capacity are both specific to the particular BEV that is being checked for a match against the agent. The vehicle allocation algorithm has thus kept the same matching of agents' daily distances (high to low) to BEV payback distances (low to high), but the matching constraints listed above have now been changed to:

- there were still cars needed in the BEV's class and year,
- the vehicle's model year is available in the current purchase year,
- the vehicle's model year has not been replaced by a later model year,
- *the daily energy requirement was less than the vehicle's battery capacity,* (changed)
- ~~the daily driving distance was more than the payback distance, and~~ (eliminated)
- the present agent had not already purchased a car.

Plus the allocation algorithm, was thus changed to provide the total energy per leg directly to WP3 instead of supplying the km by road type, in addition to the previous information on agent id, location, travel times and distances and potential charging times.

Although the focus in the THELMA analysis has been on the effects of BEV market penetration rather than on analyzing PHEV impacts (as explained earlier in this chapter), it is still possible to possible to use the daily travel information contained in the MATSim model results to estimate the fossil versus electrical energy split for PHEVs. Obviously, after some of the drivers or agents have been selected to purchase BEVs, the remaining drivers do not have the same patterns of vehicle energy use. It is assumed that any single (non-BEV) driver will not choose a PHEV versus an ICE vehicle based on his (or her) daily driving pattern, since with a PHEV they are not limited by the vehicle's battery range due to the backup engine. Therefore, the distribution of daily driving distances was examined for all the non-BEV drivers (remaining after the BEV allocation). This driving distance distribution was used to determine the number of km driven by PHEVs below the PHEV's battery range. All this energy is

assumed to be charged overnight, and supplied by the power system's marginal electricity mix. All the km that are driven beyond the PHEV's battery range are assumed to be supplied by the gasoline supply chain, based on the same vehicle energy use but using the ICE conversion efficiency.

ICE's are assumed to share the same, remaining (non-BEV) driving distance distribution, but obviously all their driving and auxiliary energy is supplied by whatever chemical energy source (fuel) is selected.

6.4.3. Electricity supply scenarios

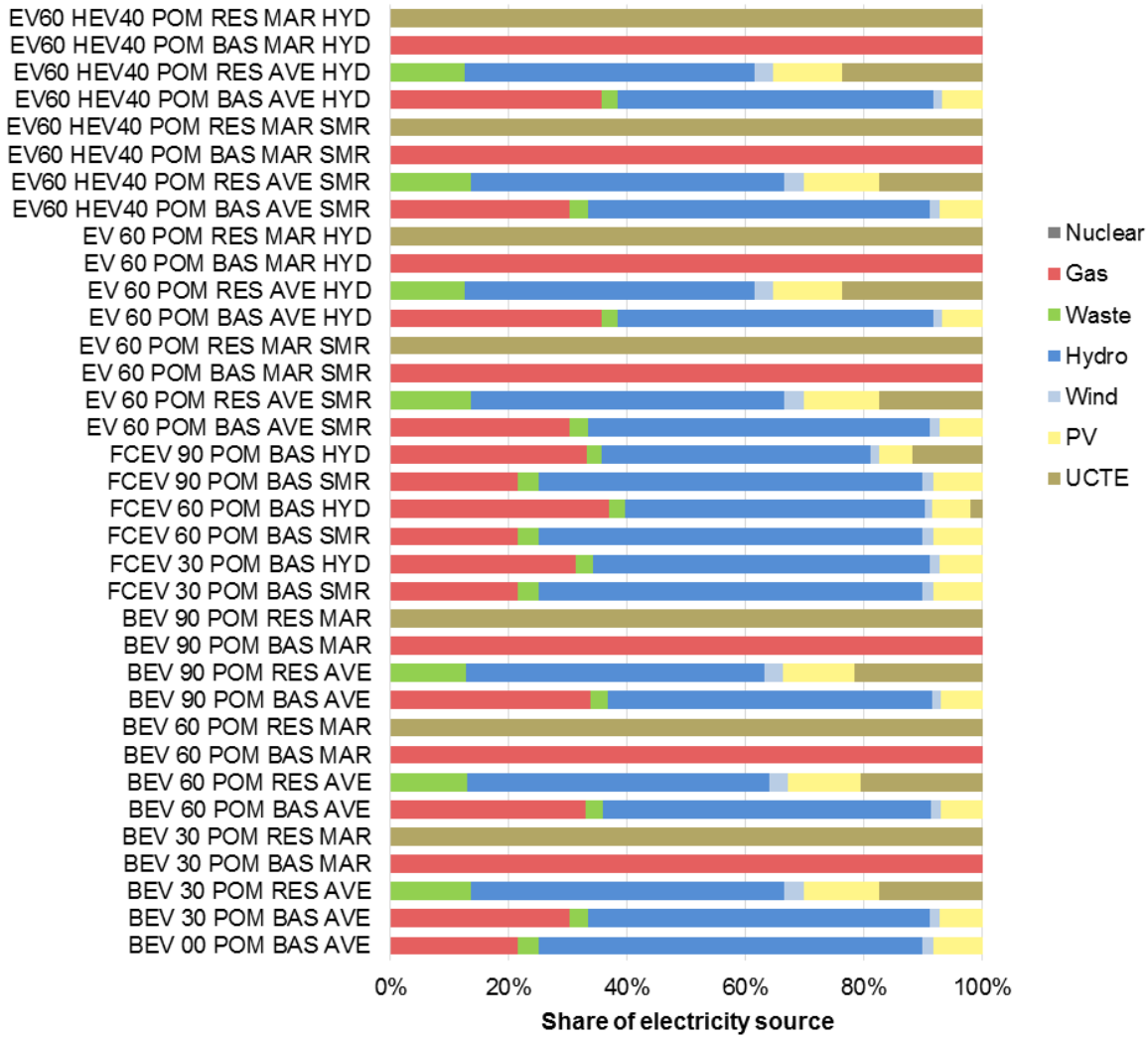
The electricity supply scenarios for the year 2050 are an essential input to the assessment since the composition of the supply has a decisive impact on the performance of electric vehicles as already indicated by technology assessment. In the current work PSI's electricity supply scenarios were used based on the Swiss TIMES Electricity Model developed by PSI, e.g. (Ramachandran and Turton, 2011, Ramachandran and Turton, 2012b). The model has high time resolution and thus allows appropriate modeling of the intermittent renewables (solar photovoltaic and wind). The model has been extensively applied e.g. (Ramachandran and Turton, 2013). Choosing PSI's scenarios enabled full access to the data used in quantification. For the description of the scenarios we refer to Appendix D, which contains excerpts from PSI's Energy-Mirror (PSI, 2012). Further details are provided in Ramachandran and Turton (2012a).

Three types of electricity supply strategies were considered, i.e. primarily renewable generation with remaining needs covered by domestic gas power plants or by imports, primarily hydro- and gas-fired generation, and as a reference primarily hydro- and nuclear-based. The last mentioned scenario was not further used in the present work due to the Swiss energy policy decision to phase out nuclear.

Adding EV charging demand to the forecast baseline demand requires additional, marginal generation that differs from the baseline generation mix. Hydro power is limited by rainfall and site-availability, nuclear power is limited by expected retirement schedules and no new plants, and renewable generation from planned capacity is limited by the solar and wind resources. This means that any significant marginal generation must come from gas-fired generation based on gas imports, or directly upon electricity imports. However, whether the environmental effects of this marginal generation should be allocated only to BEVs is debatable – in the present work indicator and MCDA scenario results are reported using both the marginal and average electricity mixes.

The electricity mix for each fleet scenario was calculated by adding the EV charging and hydrogen electrolysis electricity to the electricity mix of the Political Measures (PoM) demand scenario from Ramachandran and Turton (2012a). See Figure 6.53. The electricity demand assumed by Ramachandran and Turton (2012a) for electric vehicles (4.64 TWh) was first subtracted out. The BEV charging electricity added was 8.1, 11.0 and 12.1 TWh TWh for the fleet penetration levels of 30%, 60% and 90%, respectively. FCEV electricity (for scenarios with hydrogen from electrolysis) was 9.2, 18.3, and 27.5 TWh for the same fleet penetration levels. See Figure 6.54 for a comparison with the PoM electricity demand in 2050. It is noted that the BEV charging energy is not linear with the BEV fleet penetration because the EVs are first allocated to those drivers who drive the longest daily distances (but still below the battery range) to maximize their payback due to lower variable cost per km. This means that the next two increments of 30% fleet penetration allocate cars to drivers who travel progressively shorter distances each day. The FCEV electricity demand is linear as the vehicles are not preferentially allocated to any drivers. For both BEV and FCEV scenarios charging and

electrolysis energy from the grid is also increased for transmission and distribution losses and charging losses.



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure 6.53 Electricity supply mix for fleet scenarios.

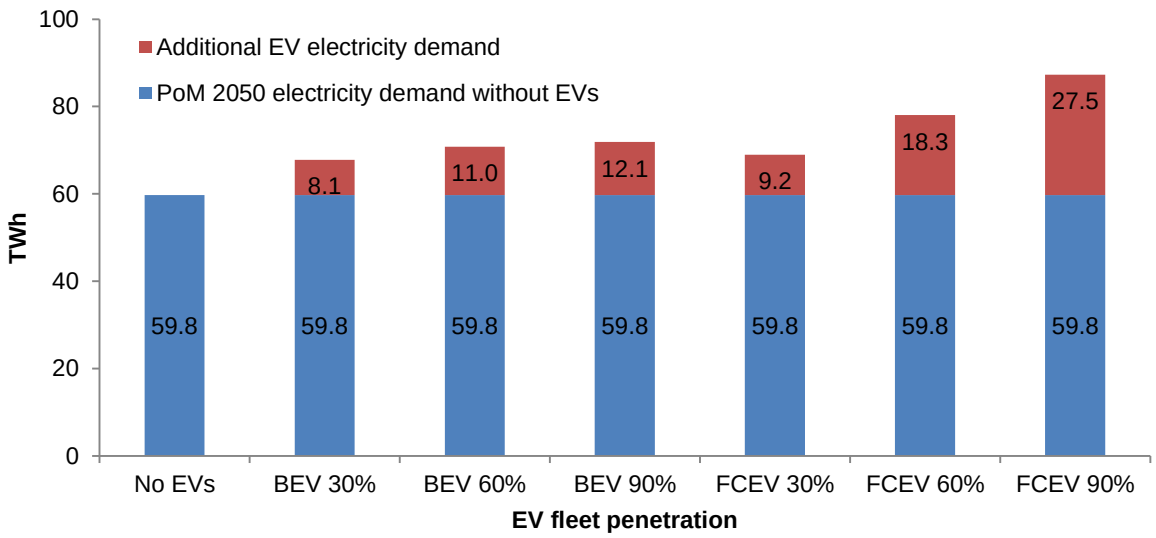


Figure 6.54 Additional electricity demand due to BEVs and FCEVs when charged with hydrogen from electrolysis.

6.4.4. Multi-criteria decision analysis for fleet scenarios

6.4.4.1. Implementation

The implementation exhibits parallels to MCDA for technologies described in 6.3.4.2, i.e. PSI's web-based tool Mighty MCDA (www.mightymcda.net), was used.

Also for fleet options the simplest MCDA algorithm was selected, i.e. the weighted sum (WS) approach and again our choice was motivated by the transparency and simplicity of WS.

A screenshot of the hierarchy of criteria and indicators used for fleet assessment is shown in Figure 6.55. For the definitions of criteria and indicators we refer to Table 6-1 to Table 6-4. As the starting point the four top criteria are equally weighted, which corresponds to the spirit of sustainability; also the indicators on the second level of the hierarchy are equally weighted.

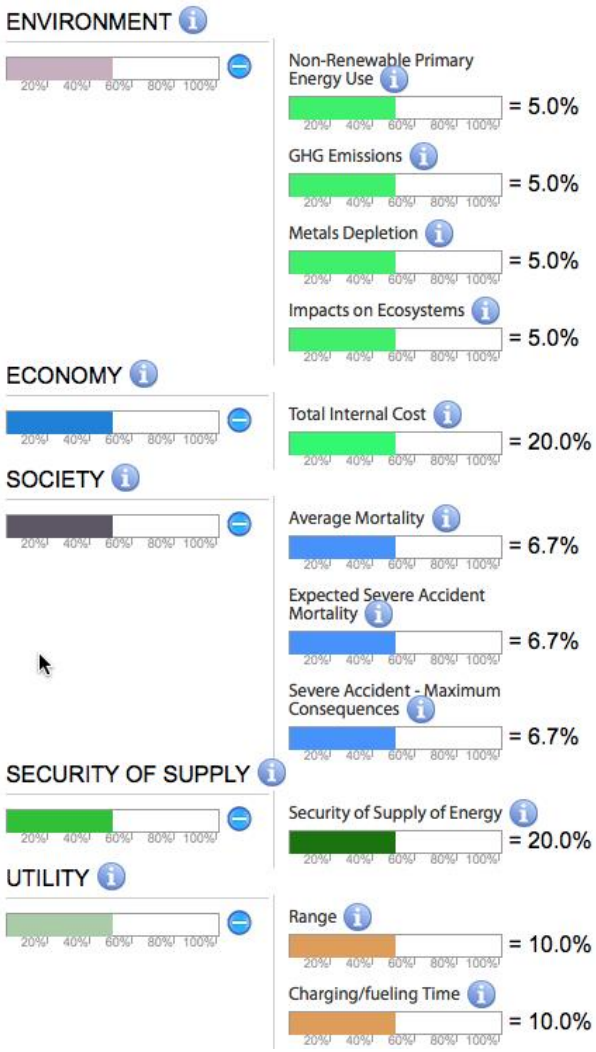


Figure 6.55 Hierarchy of criteria and indicators with equal weighting on all levels.

6.4.4.2. Estimated performance indicators for future fleet options

In total 11 indicators shown above were quantified for 35 future (2050) fleet options based on the process illustrated in Figure 6.48 and using as the input technology-specific indicators described in sub-chapter 6.3. The fleet options represent combinations of different levels of penetration of electric vehicle (differentiating between battery and fuel cell cars) with various scenarios for electricity supply and various means for producing hydrogen. In addition, for the purpose of comparison the corresponding indicators were quantified for the current (2012) fleet.

We also quantified fleet scenarios with different charging strategies analyzed in Chapter 4. These scenarios are not shown here since a somewhat surprising outcome was that the strategies do not result in significant differences in the quantified performance of the scenarios with regard to the various criteria. The overall result that charging strategy doesn't matter is *not* general, but appears to be true in the present specific case for Switzerland because Switzerland has enough hydro storage (both pumped storage, and more importantly "virtual" storage by properly scheduling the regular dams). Furthermore, the grid is adequate so that system dispatch is not constrained by transmission limitations.

The combination of these two factors basically means that no matter what time of day the EVs charge, there is enough hydropower to keep the overall electricity mix the same. The charging mix is of course still not the average overall generation mix, but rather the marginal generation mix of EV charging that has been added to the normal hourly demand. The reason that this is fairly simple for Switzerland (and the basis for the projected charging mix in 2050 without optimized power flow modeling) is based on known dispatch order (marginal cost ranking) and the total energy from many of the technologies is limited. Specifically:

- Hydro generation is fixed for the year (rainfall is unchanged)
- Renewables are fixed by installed capacity and resource capacity factor (these are always used as available due to low/zero dispatch cost)
- Waste incineration is fixed (by "resource" limit)
- Nuclear can decrease, but the maximum is fixed by the max capacity factor
- Only gas combined cycle generation and imports can increase to cover the charging load

The charging strategy matters however to the *car owner/driver*, because:

- Charging during the day allows marginal drivers to go further and get home
- Time-of-day electricity pricing (or site-dependent or fast premium charging costs) will alter the cost to the driver and hence also revenue to the utilities

The charging strategy does not matter on the *societal/fleet level*, because:

- Time of charging does not affect total charging energy demand
- Total system *generation* costs remain unchanged, because
- Total system generation mix remains fixed.

If *all* generation were priced and/or valued at the spot price (i.e., no long term contracts), then the total revenue to the whole utility/generation sector would change, but this is a transfer from drivers to generators that nets to zero for the society as a whole. At the most simple:

- Anytime/daytime charging will cause more hydro generation during the day
- Nighttime tariffs (both off-peak (at 22.00) and optimized) will cause hydro generation to shift from day to night
- The off-peak tariff will cause a sudden demand pattern shift at 22.00, but according to grid analysis the system is adequate (peak load is still daytime in summer and early evening in winter).

Only inadequate hydro storage or transmission capacity could cause a change in dispatch that would alter the total generation costs, based on the charging strategy. This result confirms that the overall storage and grid capacities do not impose constraint costs.

Appendix E: THELMA Fleet Indicators for 2012 and 2050, Full Scenario Set provides absolute and normalized values for the 36 cases outlined above. Since the differences between indicators for several scenarios showed to be rather small and it is difficult to identify specific patterns when confronted with such an abundance of results, we also provide a reduced set of indicators in Appendix F: THELMA Fleet Indicators for 2012 and 2050, Scenario Subset.

In the following we provide examples for selected indicators from the reduced set, i.e. one indicator for each dimension of sustainability (Figure 6.56 to Figure 6.61).

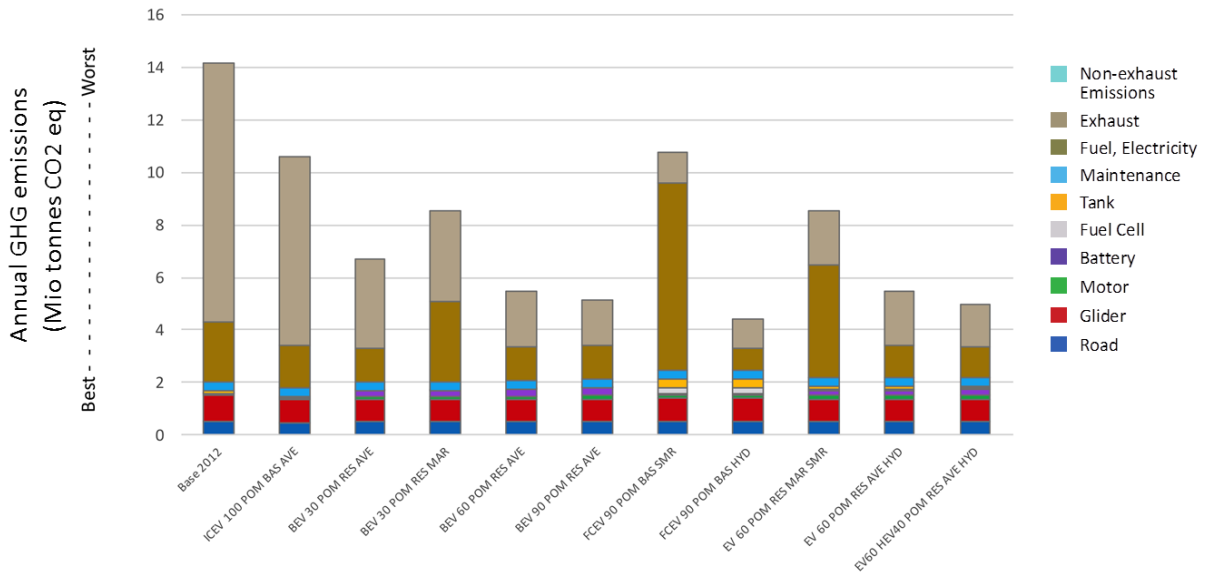


Figure 6.56 Fleet 2050 Greenhouse Gas Emissions (absolute), by component

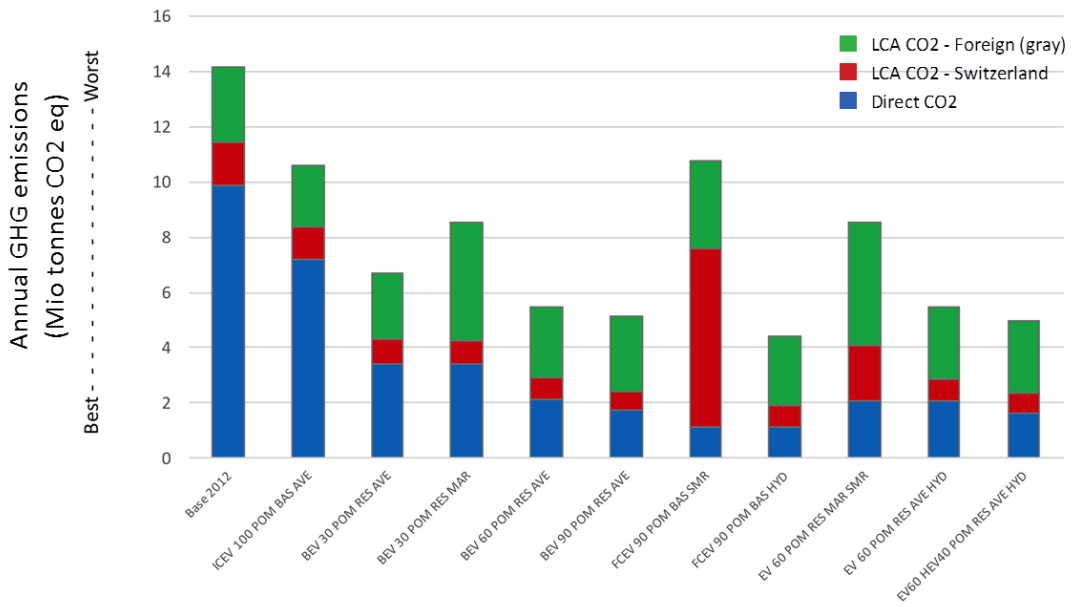


Figure 6.57 Fleet 2050 Greenhouse Gas Emissions (absolute), by location

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

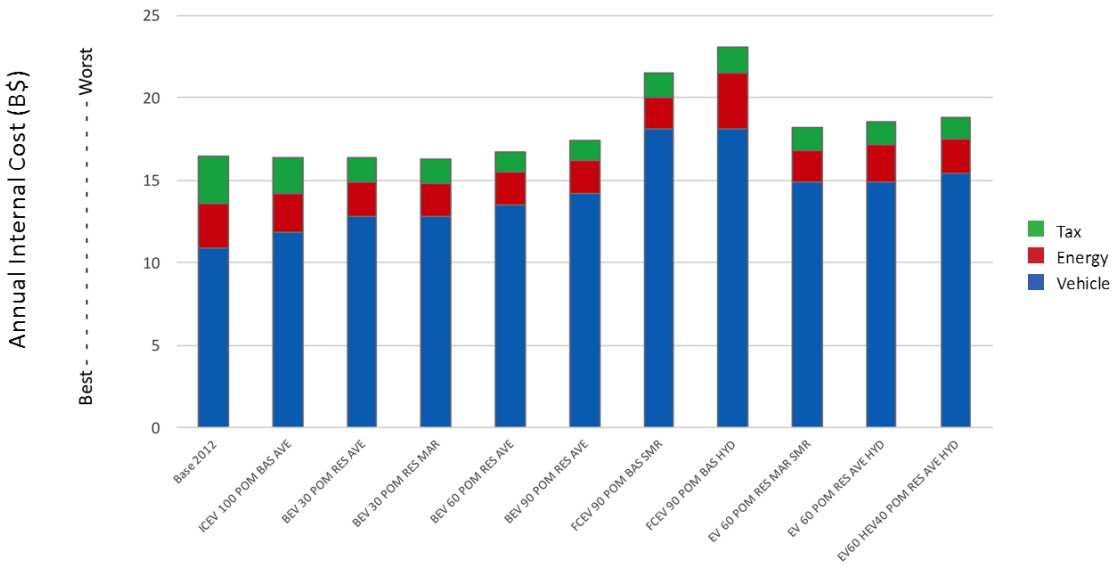


Figure 6.58 Fleet 2050 Annual Internal Fleet Cost (absolute), by component

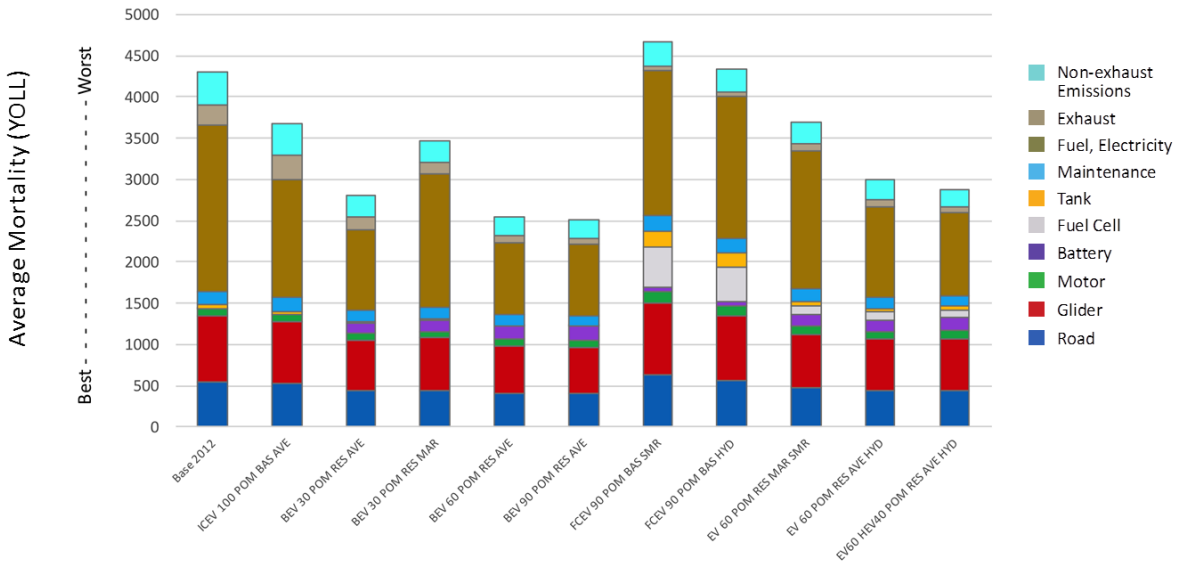


Figure 6.59 Fleet 2050 Average Mortality due to Normal Operation (YOLL = Years of Life Lost)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
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EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

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Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

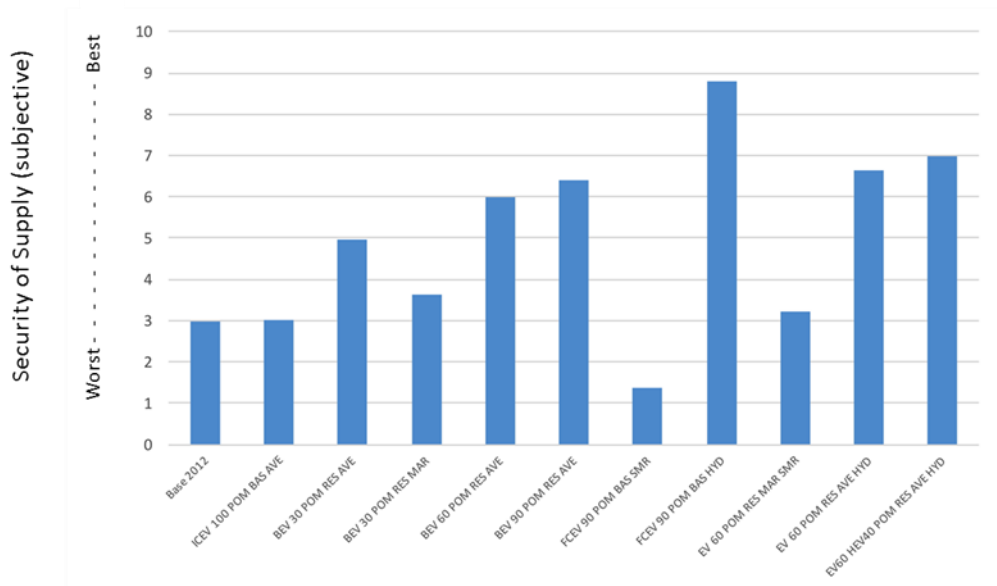

Figure 6.60 Fleet 2050 Security of Fuel Supply (absolute)

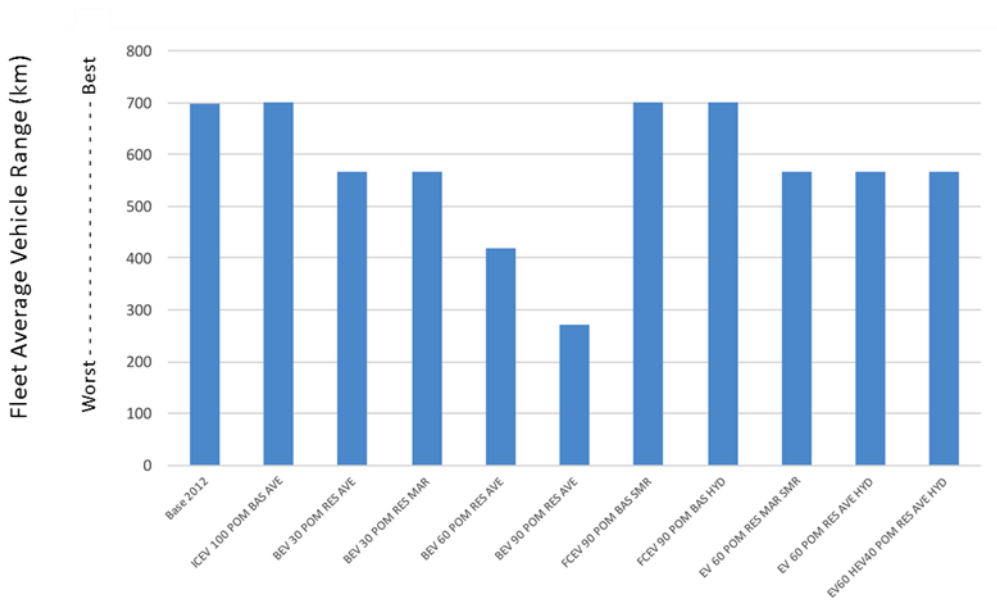

Figure 6.61 Fleet 2050 Average Vehicle Range (absolute)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
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Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

For the indicators shown above the fleet option with 100% ICEV is either substantially better (e.g. when considering emissions of GHG) or at least as good as the current fleet. Compared to the base year 2012, the total life cycle GHG emissions caused by Swiss passenger cars in 2050 are estimated to be reduced by 25%-65%, depending on the penetration rate of advanced powertrain vehicles and the development of the energy system. One factor strongly affecting the GHG-performance of electrified

car fleet is whether the electricity for BEV and/or FCEV will be provided by average or marginal mix. In the latter case the emissions are expected to be higher due to higher carbon content. Also, the LCA-perspective leads to lower reductions of GHG emissions due to extended scope of the analysis both in terms of accounting for the associated domestic as well as foreign energy chain emissions.

Annual internal costs of future fleet options are relatively close to the current ones due to much reduced costs of future technologies though costs of FCEV-dominated scenarios remain higher in spite of large improvements. It should be noted that the costs of infrastructure needed for advanced technologies have not been extensively analyzed and are underestimated in the present analysis.

Mortality caused by normal operation is reduced in fleet options with strong expansion of BEV. Most future fleet options perform better in security of supply than the current fleet. The best option is the fleet dominated by FCEV with hydrogen produced using renewable electricity; the worst is the same fleet but with hydrogen from SMR. In the context of vehicle range, fleet scenarios with high share of FCEV perform as well as scenarios dominated by ICEV while much improved BEV are still more limited in this respect.

6.4.4.3. Sensitivity mapping of sustainability index for future fleet options based on various preference profiles

Figure 6.62 to Figure 6.68 show the various MCDA cases for the reduced set of ten fleet options for 2050. In addition, the current (2012) fleet is included. Analog to MCDA for technologies the sensitivity cases emphasize one at a time specific dimension of sustainability as used in this analysis; in each of these cases the weights on the second level of hierarchy remain unchanged. The last case shown covers only two criteria, i.e. use of primary non-renewable energy and GHG emissions. The reason for using this sub-set of criteria is that the Swiss energy strategy emphasizes energy efficiency and climate protection as its central goals.

Figure 6.62 shows that, except for scenarios with SMR, fleets with various shares of electric vehicles rank at the same level as the future fleet fully dominated by ICEV. Also, excluding scenarios with SMR the sustainability performance is clearly better than that of the current fleet. The factors affecting negatively the sustainability of electric mobility are range and charging time of BEV, and internal costs for FCEV (along with security of supply if SMR is used).

In Figure 6.63 the focus on environmental performance exhibits major improvements of ICEV and hybrids in this respect. However, the best performers are the fleet options with high share of BEV. FCEV-dominated fleet with SMR rank worse than future ICEV-dominated fleet. Generally, metal depletion is a negative factor for electric vehicles.

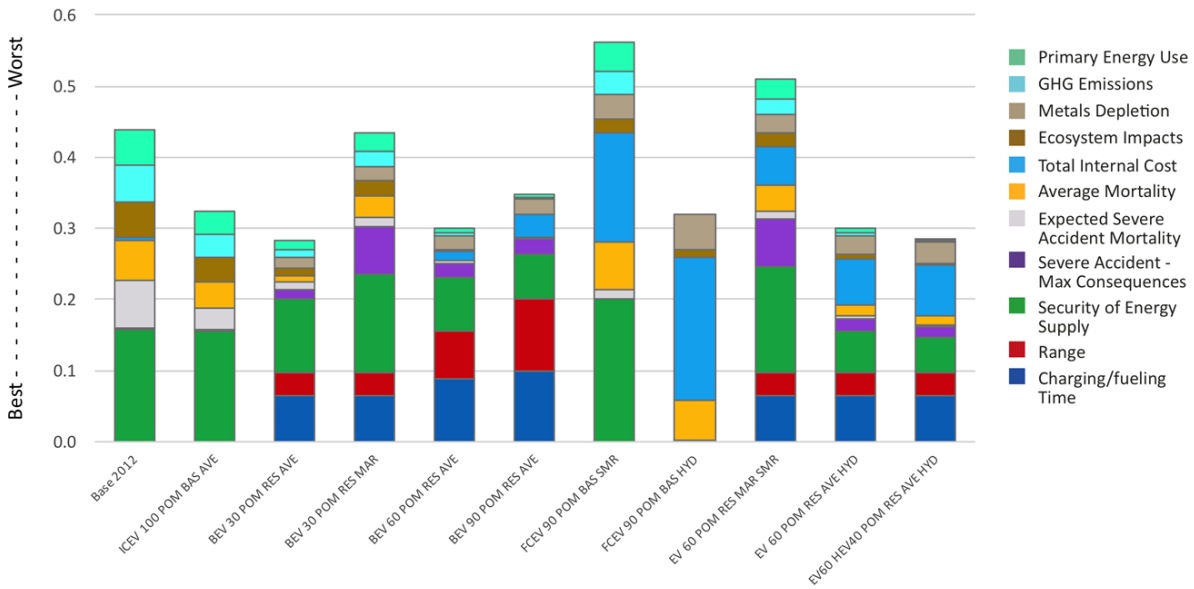
Figure 6.64 shows that if economy is the focal point, conventional vehicles are on the winning side but fleet options with moderate share of BEV are competitive. FCEV remain disadvantaged in relative terms.

Figure 6.65 Emphasizes social aspects (represented in this project by risks in the energy supply chain). This weighting favors mostly fleets with substantial share of BEV. Also ICEV and FCEV-dominant fleets perform better than the current fleet.

Figure 6.66 shows results with weighting focus on security of energy supply. This mostly favors fleets with high share of electric vehicles except when SMR is involved. The best case is FCEV-dominated fleet with hydro providing electricity for electrolysis.

Figure 6.67 shows that if emphasis is placed on driver utility, ICEV- and FCEV-dominated fleets are ranked highest. Cases with BEV are disadvantaged.

Figure 6.68 shows weighting split equally between non- renewable primary energy and CO_2 emissions. All fleet scenarios shown in the figure perform clearly better than the current fleet if only the two evaluation criteria emphasized in the new Swiss energy strategy are used. The best performing scenarios are those with high share of electric cars (BEV and/or FCEV) provided that the average or practically carbon-free electricity can be used for charging and hydrogen production.



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure 6.62 Fleet 2050 MCDA – EQUAL Weights (Environment, Economy, Society, Security of Energy Supply and Driver Utility equally weighted)

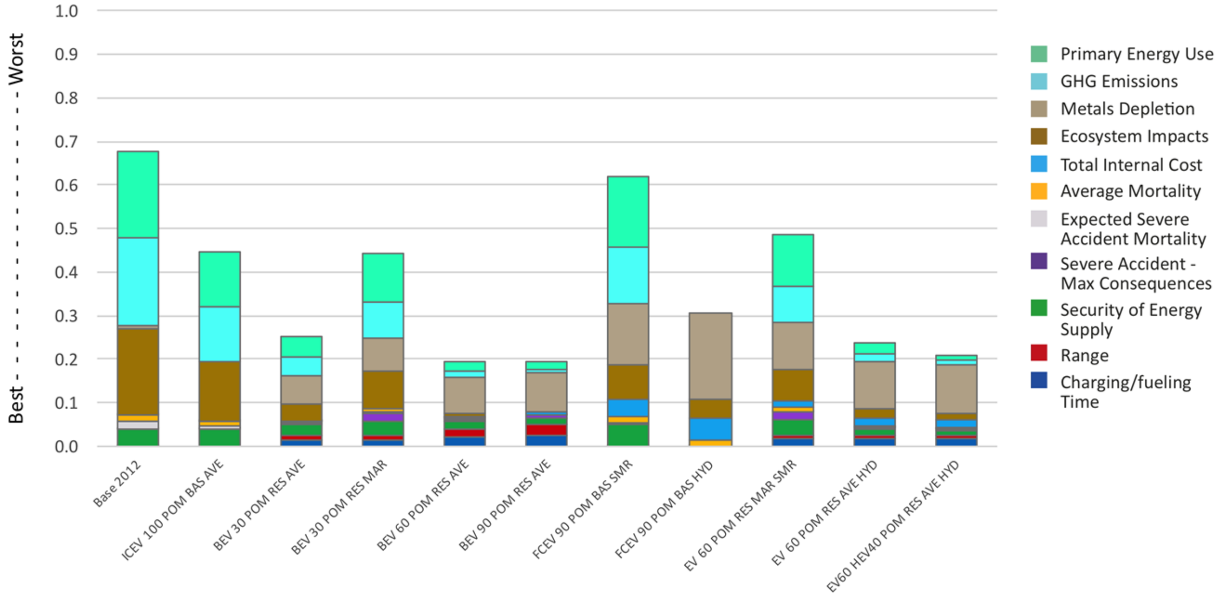


Figure 6.63 Fleet 2050 MCDA – ENV80 Weights (Environment 80%, Economy, Society, Security of Energy Supply and Driver Utility 5% each)

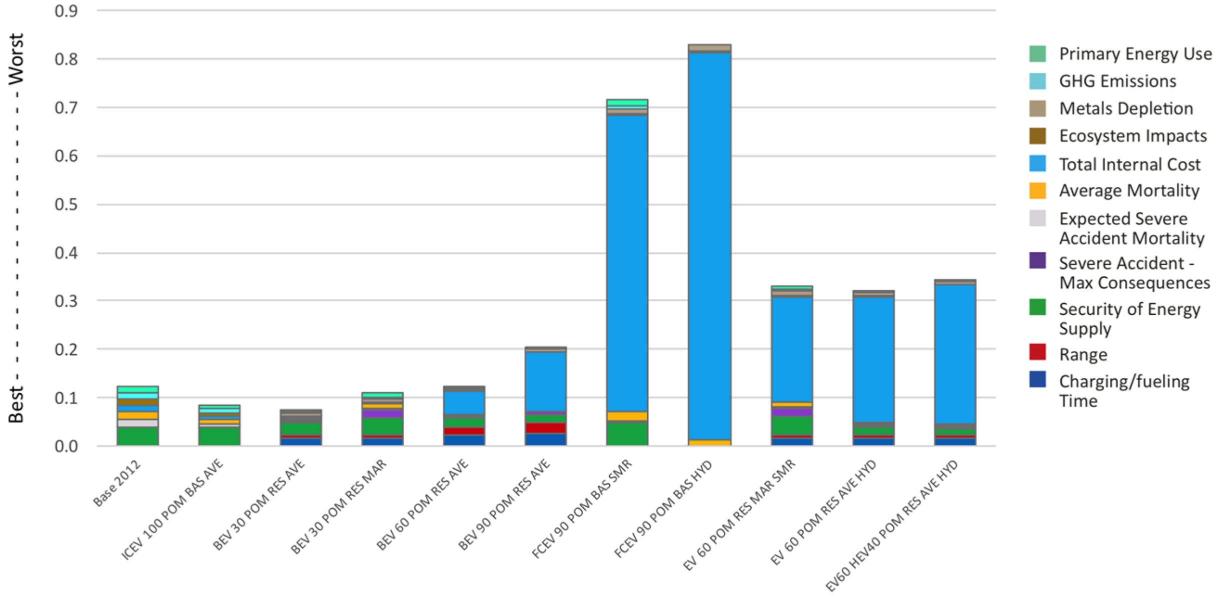


Figure 6.64 Fleet 2050 MCDA – ECO80 Weights (Economy 80%, Environment, Society, Security of Energy Supply and Driver Utility 5% each)

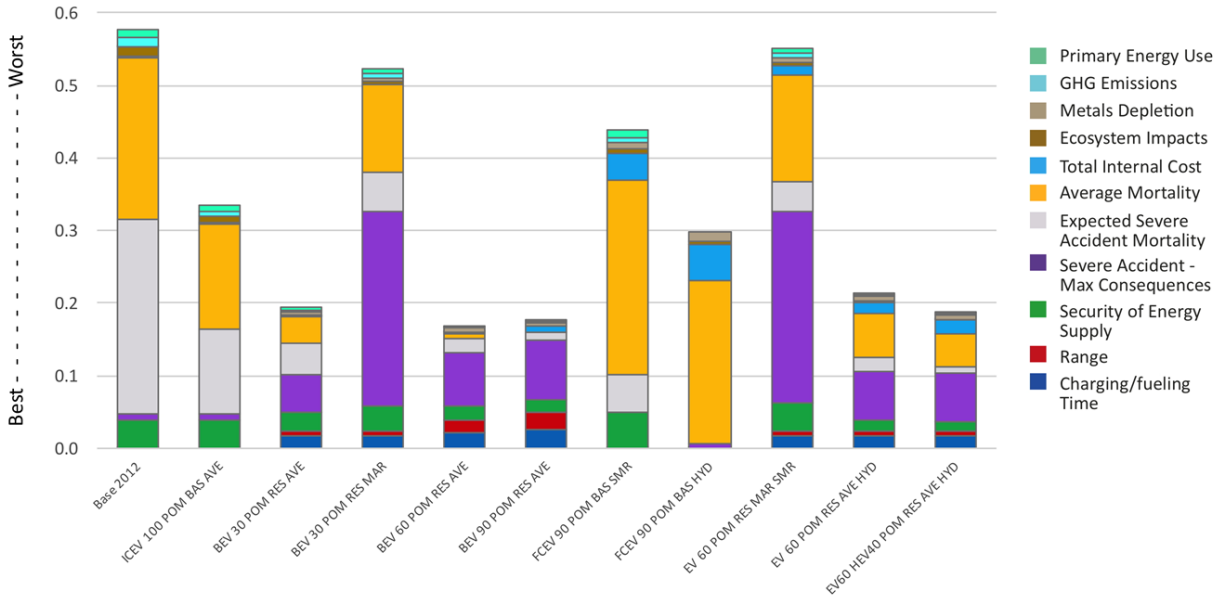


Figure 6.65 Fleet 2050 MCDA – SOC80 Weights (Society 80%, Environment, Economy, Security of Energy Supply and Driver Utility 5% each)

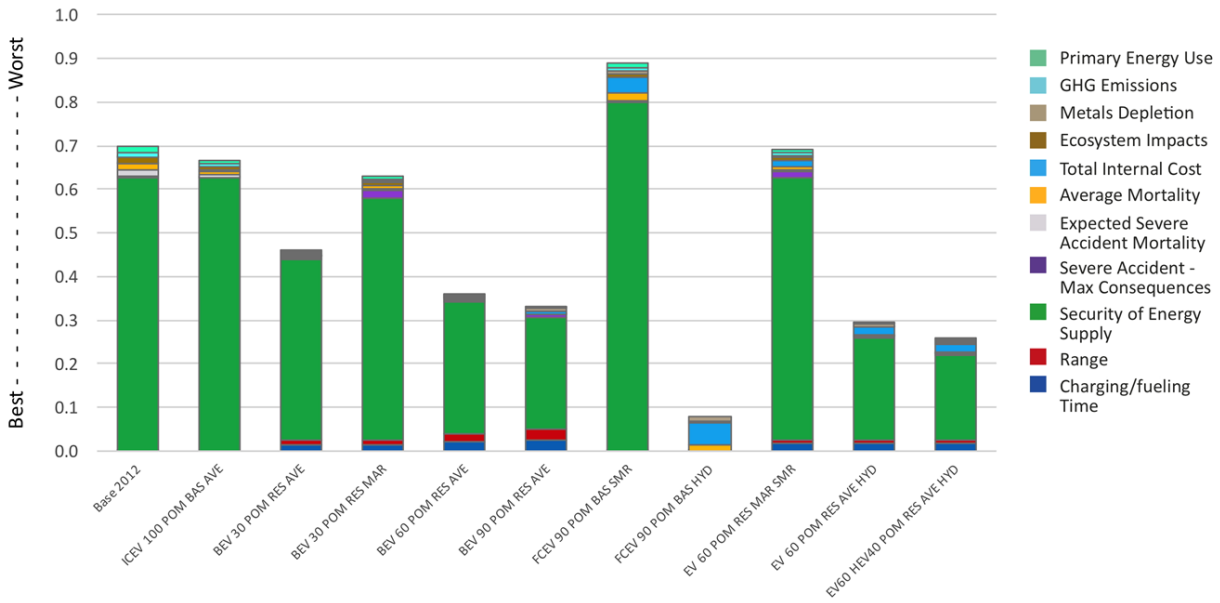


Figure 6.66 Fleet 2050 MCDA – SEC80 Weights (Security of Energy Supply 80%, Environment, Economy, Society, and Driver Utility 5% each)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
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AVE - Charging is average generation mix
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Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

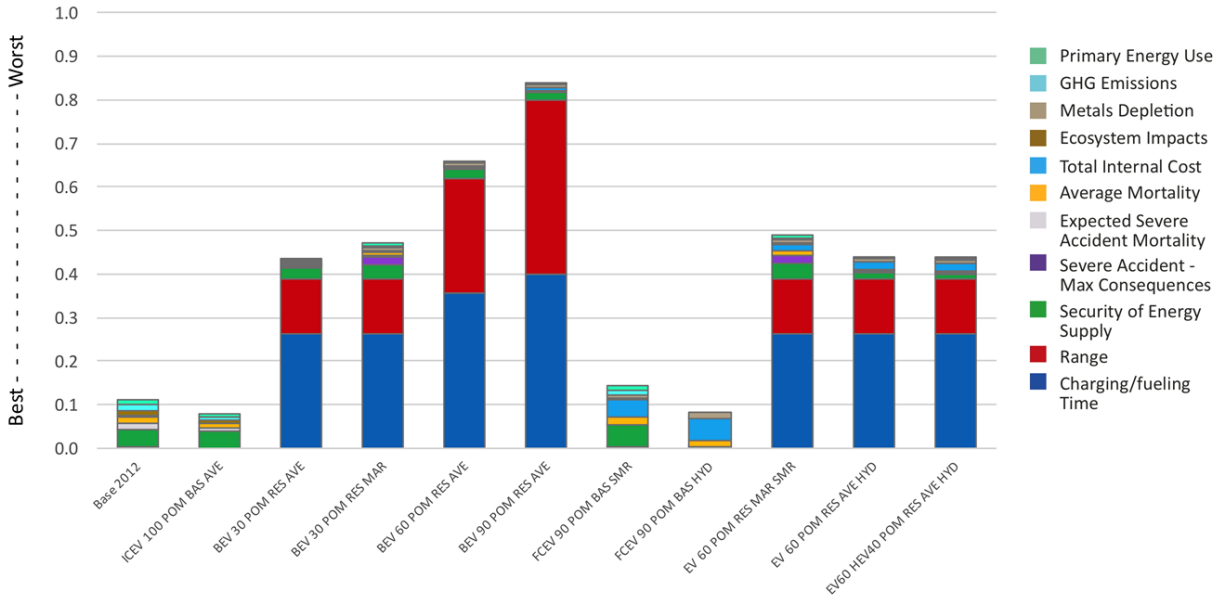

Figure 6.67 Fleet 2050 MCDA – UTI80 Weights (Driver Utility 80%, Environment, Economy, Society, and Security of Energy Supply 5% each)

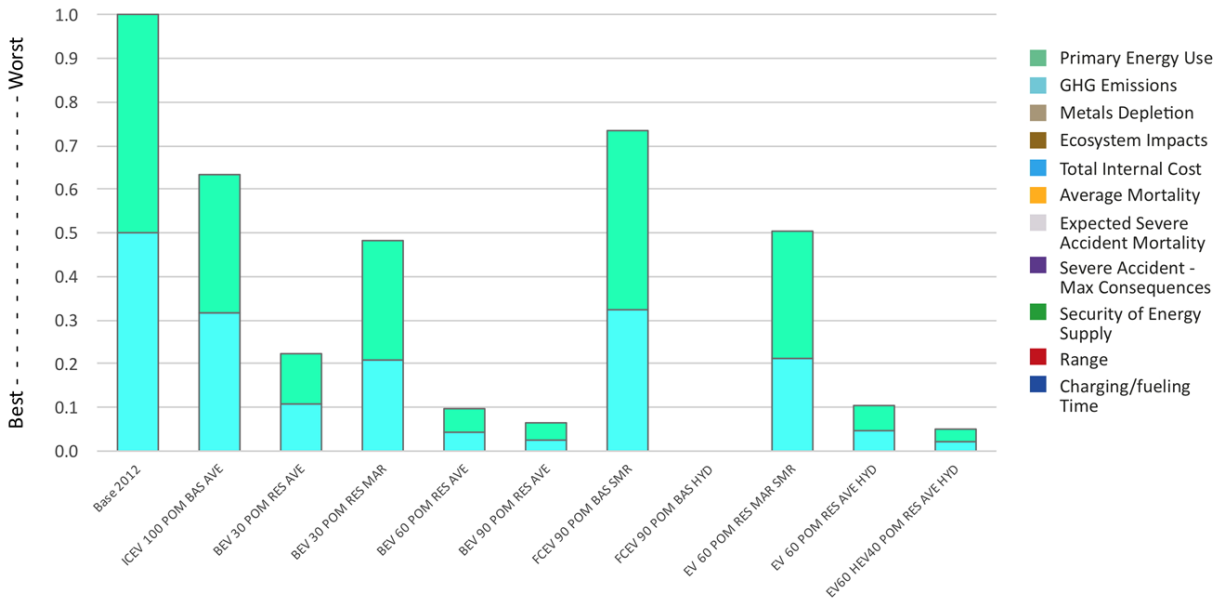

Figure 6.68 Fleet 2050 MCDA – CO2, Primary Energy 50/50 Weights (CO2 Emissions and Non-renewable Primary Energy Use 50% each)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Acronyms

BEV	Battery Electric Vehicle
CNG	Compressed Natural Gas
DALY	Disability Adjusted Life Years
EIA	Environmental Impact Assessment
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
Fleet 2050 MCDA – CO2, Primary Energy 50/50 Weights	CO2 Emissions and Non-renewable Primary Energy Use 50% each
Fleet 2050 MCDA – ECO80 Weights	Economy 80%, Environment, Society, Security of Energy Supply and Driver Utility 5% each
Fleet 2050 MCDA – ENV80 Weights	Environment 80%, Economy, Society, Security of Energy Supply and Driver Utility 5% each
Fleet 2050 MCDA – EQUAL Weights	Environment, Economy, Society, Security of Energy Supply and Driver Utility equally weighted
Fleet 2050 MCDA – SEC80 Weights	Security of Energy Supply 80%, Environment, Economy, Society, and Driver Utility 5% each
Fleet 2050 MCDA – SOC80 Weights	Society 80%, Environment, Economy, Security of Energy Supply and Driver Utility 5% each
Fleet 2050 MCDA – UTI80 Weights	Driver Utility 80%, Environment, Economy, Society, and Security of Energy Supply 5% each
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventories
LCIA	Life Cycle Impact Assessment
MCDA	Multi-Criteria Decision Analysis
NEDC	New European Driving Cycle
NGCC	Natural Gas Combined Cycle
PHEV	Plug-in Hybrid Electric Vehicle
PSI	Paul Scherrer Institute
PV	Photovoltaic
SFOE	Swiss Federal Office for Energy
SMR	Steam Methane Reforming
UCTE	Union for the Coordination of the Transmission of Electricity (continental Europe)
Vehicle MCDA – CO_2, Primary Energy 50/50 Weights	CO_2 Emissions and Non-renewable Primary Energy Use 50% each
Vehicle MCDA – ECO85 Vehicle Weights	Economy 85%, Environment, Society and Driver Utility 5% each
Vehicle MCDA – ENV85 Weights	Environment 85%, Economy, Society and Driver Utility 5% each
Vehicle MCDA – EQUAL Weights	Environment, Economy, Society and Driver Utility equally weighted
Vehicle MCDA – SOC85 Weights	Society 85%, Environment, Economy, and Driver Utility 5% each
Vehicle MCDA – UTI85 Weights	Driver Utility 85%, Environment, Economy, and Society 5% each
WLTP	Worldwide harmonized Light vehicles Test Procedure
WP	Work Package
WS	Weighted Sum
YLD	Years Lived with Disability
YOLL	Years Of Life Lost

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7. Conclusions and Recommendations

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This chapter summarizes the main insights from the project and provides an outlook in terms of recommendations for the future work.

7.1. Conclusions

7.1.1. Life Cycle Assessment

The Life Cycle Assessment (LCA) carried out in the present study represents a "complete LCA", i.e. as opposed to the usually performed well-to-wheel (WTW) studies which consider vehicle and fuel chain efficiencies, this study also covers the equipment life cycle (i.e. vehicle and road infrastructure). This aspect is important since the various powertrain technologies such as Internal Combustion Engine Vehicles (ICEV), Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV) differ particularly in terms of environmental burdens associated with manufacturing of vehicles.

This work explicitly addressed prospective technical advancements within the time horizon until year 2030 and with extrapolations until 2050. These prospective improvements have high impacts on the results for all considered technologies, though they are most significant for today's less mature electric vehicles compared to conventional ones. However, results are naturally subject to major uncertainties.

BEV and FCEV exhibit lower life cycle Greenhouse Gas (GHG) emissions than ICEV provided that electricity supply for batteries and for production of hydrogen is based on sources with low carbon content. In such cases, the carbon footprint of electric vehicles may be reduced by up to almost 80% in relation to current conventional vehicles. The reductions are higher for BEV than for FCEV. At the same time, use of fossil energy for this purpose can even lead to an increase of GHG emissions and in the case of coal electricity or natural gas Steam Methane Reforming (SMR) is in fact counter-productive. Among the ICEV evaluated, natural gas vehicles clearly generate the lowest life cycle environmental burdens.

Concerning the other environmental burdens analyzed, BEV and FCEV provide limited benefits. While BEV charged with ''clean electricity'' cause slightly lower burdens than fossil fueled ICEV, FCEV tend to generate higher burdens for all considered hydrogen generation pathways. In fact, conventional natural gas vehicles even cause lower burdens than gasoline and diesel hybrid vehicles for most of the Life Cycle Impact Assessment (LCIA) indicators (this does not generally apply to plug-in hybrids). This less beneficial performance of BEV and FCEV is mainly a consequence of emissions along the fuel supply chains and vehicle (component) manufacturing; often, resource extraction and processing as well as combustion of fossil fuels in the production chains generate comparatively high burdens. Since FCEV are less mature than other types of vehicles we expect that there is potential for further reductions of environmental burdens beyond the credit taken in this study.

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[44] Since this chapter builds on the results generated in all Work Packages of the THELMA Project, the author thanks all contributors to this report for their inputs.

7.1.2. Vehicle simulation and powertrain assessment

The time horizon of nearly 40 years as applied in this work incurs high uncertainty concerning the developments of technologies. The technical and economic performance of batteries and fuels cells is paramount to the commercial success of electric mobility, though they are still rather immature technologies in the mobility context. Historically, most other core automotive components and aspects such as aerodynamics and tire rolling resistance have exhibited rather steady improvement curves.

Furthermore, improvements in specific energy storage density result in reduced weight and energy penalties for high autonomy ranges (through battery mass reduction). However, the primary concern may not be so much on the technology development itself, but rather with the ensuing customer expectations.

Indeed a central assumption of the WP2 methodology is that of stable vehicle classes and time-invariant attributes (at least with respect to performance). This allows sizing powertrain components such that the final vehicle assembly achieves the average performance criteria of its glider's market segment. Break-through innovation, resource scarcity or perhaps changes in the social significance of the car as a transportation mode are just a few examples of what could lead to fundamentally altered customer expectations, perhaps even a complete redefinition of the market segmentation itself – with far reaching consequences for the validity of the results at hand.

In general, ICEVs have an edge both in terms of costs and performance over all considered alternative technologies, as long as energy prices and all the involved sustainability implications do not play the core role. Electric mobility directly compromises performance and comfort with energy usage. The fact that it was possible to apply all powertrain options to all vehicle classes without sacrificing the corresponding class performance targets indicates that fleet-wide electrification is indeed technically feasible, even with today's technology. Economically on the larger scale this may not be the case though, since especially the "higher-end" segments exhibit up to twice the production cost over their respective ICEV variant in the model year 2012.

It has been shown that the electrification premium in "lower-end" segments is over-proportionally lower due to the lower glider weight. It is therefore likely that, contrary to the usual dynamics of automotive technology markets, full electrification (via BEV and/or FCEV solutions) may diffuse in through low price segments – while the heavier, expensive variants may still rely on ICEV technology (which includes HEVs).

Interestingly, with regard to the range FCEV and BEV offer mutually exclusive benefits here: boosting the range of an FCEV is rather cheap, as is increasing the power of a BEV; doing the opposite may be exorbitantly expensive in both cases. A future, electrified individual mobility system may thus depart from the "one-fits-all" general purpose car solution the ICEV is today, and instead feature a wide variety of powertrains, tailored to cover a very specific driving situation. This could have deep repercussions to the way cars are operated and sold.

7.1.3. Power System Modeling

Power system modeling addressed the effects of electric mobility on the power system. In particular it aimed at evaluating the influence of higher penetration rates of electric vehicles on transmission and distribution grids as well as on the generation portfolio(González Vayá, 2015)(González Vayá,

2015)(González Vayá, 2015)(González Vayá, 2015). In doing so, WP3 studies whether electric mobility will increase congestion in the grid, eventually leading to a need for investments on the transmission and/or on the distribution level. Moreover, different electric vehicle charging concepts were considered in order to assess if intelligent control strategies can be used to minimize possible adverse effects on transmission and distribution grids, as well as on the generation portfolio. Complementary research targeted questions concerning the aging of transmission and distribution assets, the aging of the cars' batteries as well as the potential to provide ancillary services with electric vehicles.

It should be noted that the time horizon of this work was limited to year 2030 and thus a substantially lower penetration of electric vehicles was assumed compared to the penetration assumptions in fleet scenarios for 2050. Under the conditions assumed with regard to the demand, supply and electric vehicle (EV) penetration scenarios the results suggest that EVs could be integrated into power systems without any major impact for the electricity supply side, as well as the transmission and distribution networks.

EV demand would represent a small share of total demand and does therefore not affect the supply mix significantly nor does it have a major impact on the power flows at the transmission system level. Distribution networks have different characteristics (e.g. rural vs. urban networks) and loading situations. Moreover, the penetration of EVs could be higher in specific areas than in others. Therefore, for distribution networks, the impact assessment should be done on a case by case basis. Moreover, EV charging is a very flexible load that can be shaped to reduce the costs of generation, to avoid congestions and even to provide network ancillary services. EVs could, for example, contribute significantly to the provision of frequency regulation. EVs could also potentially play a role in system restoration after a blackout.

In fact, given that the currently required capacity for secondary frequency control is 400 MW a substantial portion of this service could be potentially provided by EV fleets, especially if vehicle-to-grid (V2G) is used.

7.1.4. Case studies

The results of the case studies revealed that housing and mobility are comparably important areas in the context of household consumption and responsible for a large share of the environmental impacts induced by household demand. In terms of GHG emissions and for the situations in Wattwil and Zernez, low impacts for housing can only be achieved by a combination of low demand and almost carbon-free supply. Therefore, buildings should be refurbished. Furthermore, the living area per capita has a strong impact and it is advantageous to keep it at moderate levels. Wood heating and heat pump systems have a favorable impact on GHG emissions. The disadvantage of the former is the relatively high emission load of particulate matter and that of the latter is the augmented use of electricity. The presented optimization approach is able to assist in such trade-off-situations. The results of the optimization model can help policy makers to identify the most effective measures for improvement at the decision making level, e.g. at the building level for refurbishment and selection of heating systems or at the municipal level for designing district heating networks.

For today's land-based mobility, the benefits of the future introduction of electric mobility could be demonstrated by the application of mobility scenarios to the municipality of Zernez. However, immediate switch to a low-carbon supply is not realistic. In the short-term, impacts from mobility can

only be significantly reduced by a change in mobility behavior and particularly by a reduction of motorized private transportation and an increased use of public transport.

The analysis showed that every household has its own lifestyle and makes decision based on personal preferences that can be interdependent from each other and different from other, apparently similar, households. In other words, the relationship between different household expenditure categories does not seem perfectly rational (or its rationality is not captured by the model used) but travel demand generation seems fairly rational as clear dependency on the supply and possibilities of a given transportation network could be observed.

Useful enhancements of the MATSim model were made in order to generate a scenario for year 2030 later used in the modeling of future fleet options. This included the fleet choice model, the parking model, the ability to account for energy consumption and the electric charging of vehicles. Examination of mobility trends was performed to support scenario implementation.

Travel behavior did not change substantially in Switzerland in the span of time analyzed (1994 to 2010). The number of out-of-home activities and home-to-home journeys for the same age groups across cohorts is fairly stable, although the time spent at activities is slightly decreasing. Some change has been observed, however, in license ownership, car ownership, and public transport subscriptions. There is also the impressive growth of the number of public transport subscriptions which more than doubled in the last 20 years. This trend is particularly strong among younger generations and more affluent people.

The peak analysis did not show substantial changes either. The only noticeable difference through the years is a tendency of the peaks to flatten out. The peaks are still there and at similar time of the day but are not as high as they used to be. The literature research on teleworking and teleshopping showed that a much larger diffusion in the next 10 to 20 years is expected for both activities. It was not possible, though, to answer the question to which extent this will influence individuals' mobility behavior in the future. If the trends emerged in this study will go on in the next years, mobility patterns in 2030 will probably not depart substantially from current patterns, which corresponds to "business as usual" scenario. Nevertheless, there are some hints that the society is, slowly but steadily, moving from a car centered mobility to a more varied and possibly complex mobility style and also to different ways to carry out activities. The generated "combined" scenario reflects this trend.

7.1.5. Integrated analysis

The integrated analysis has been carried out on two levels, i.e. technologic and systemic.

<u>Technology level</u>

11 performance indicators for lower mid class cars were estimated for the current (reference year 2012) and future (reference year 2050) cars for a variety of drivetrains, fuels, electricity inputs for battery cars and different means of hydrogen production for fuel cell cars. The indicators correspond to four groups of criteria representing the three pillars of sustainability (environment, economy and social) complemented by the driver utility (important for individual drivers). The specific indicators used are: GHG emissions, use of primary non-renewable energy, use of metal and mineral resources, impact on ecosystems, purchase cost, operation cost, average mortality associated with normal operation of the vehicle and its entire life cycle, expected severe accident mortality associated with

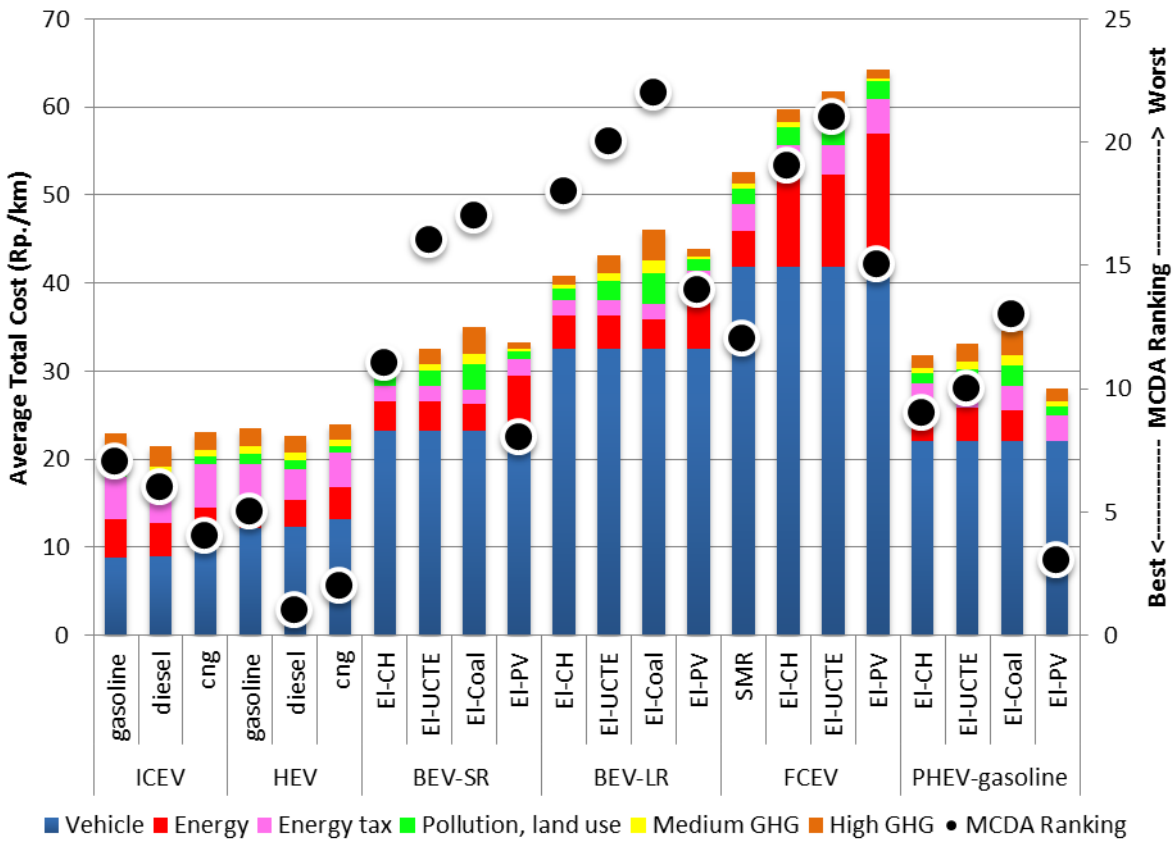
accidents within the applicable energy supply chain(s), maximum number of fatalities per accident within the applicable energy supply chain(s), vehicle driving range and charging/fueling time. Quantification methods supported by major databases included among others: Life Cycle Assessment, Impact Pathway Approach (enabling location-dependent quantification of health impacts caused by pollution) and Risk Assessment. The simulation tool developed by PSI allows in principle to quantify the corresponding indicators for many combinations of vehicle characteristics (size classes, performance levels such as, ranges), powertrains, fuel types, operating conditions, time points, fuel prices, and options for electricity supply and hydrogen production.

The estimated indicators exhibit a clear tendency towards improving performance parameters with time. This applies in particular to electric cars. There are remarkable cost reductions within the time horizon considered, with costs of battery vehicles being reduced by a factor of two and fuel cell cars by a factor of three. Additionally, other indicators such as GHG-emissions, use of non-renewable primary energy, average mortality or ranges for BEV are also expected to improve decisively.

Apart from the individual indicators, aggregation was carried out using two approaches, i.e. total costs (internal plus environmental external) and Multi-criteria Decision Analysis (MCDA) utilizing the above criteria. Figure 7.1 shows the ranking for current (2012) and Figure 7.2 for future technologies (2050), based on these two approaches; in the MCDA-case shown in the figure equal weighting was used for the four criteria. Other cases analyzed provide sensitivity mapping with one at a time emphasis on each criterion thus reflecting positions (preferences) taken (expressed) by some stakeholders in the debate on mobility.

It should be noted that for the BEV electricity prices, the same energy tax as presently levied on Swiss gasoline sales was added. There is also the 8% VAT added. However the BEVs have lower per km energy use than the ICEVs, so the net road taxes per kilometer travelled are still lower by a factor of 2.5 to 3. It is therefore arguable that for high BEV penetration scenarios there might need to be a tax/km traveled (this is already being discussed in the US, e.g. in Oregon).

As can be seen in the figure for current technologies, ICEV and HEV rank best together with PHEV when it is charged using solar PV. The MCDA-ranking is for these technologies roughly consistent with ranking based on total costs. Other PHEV, short-range BEV charged by solar PV, and FCEV with hydrogen produced by SMR or electrolysis with solar PV electricity, belong to the middle group in MCDA ranking while long range BEV as well as the remaining cases of short range BEV and FCEV get the worst ranking.

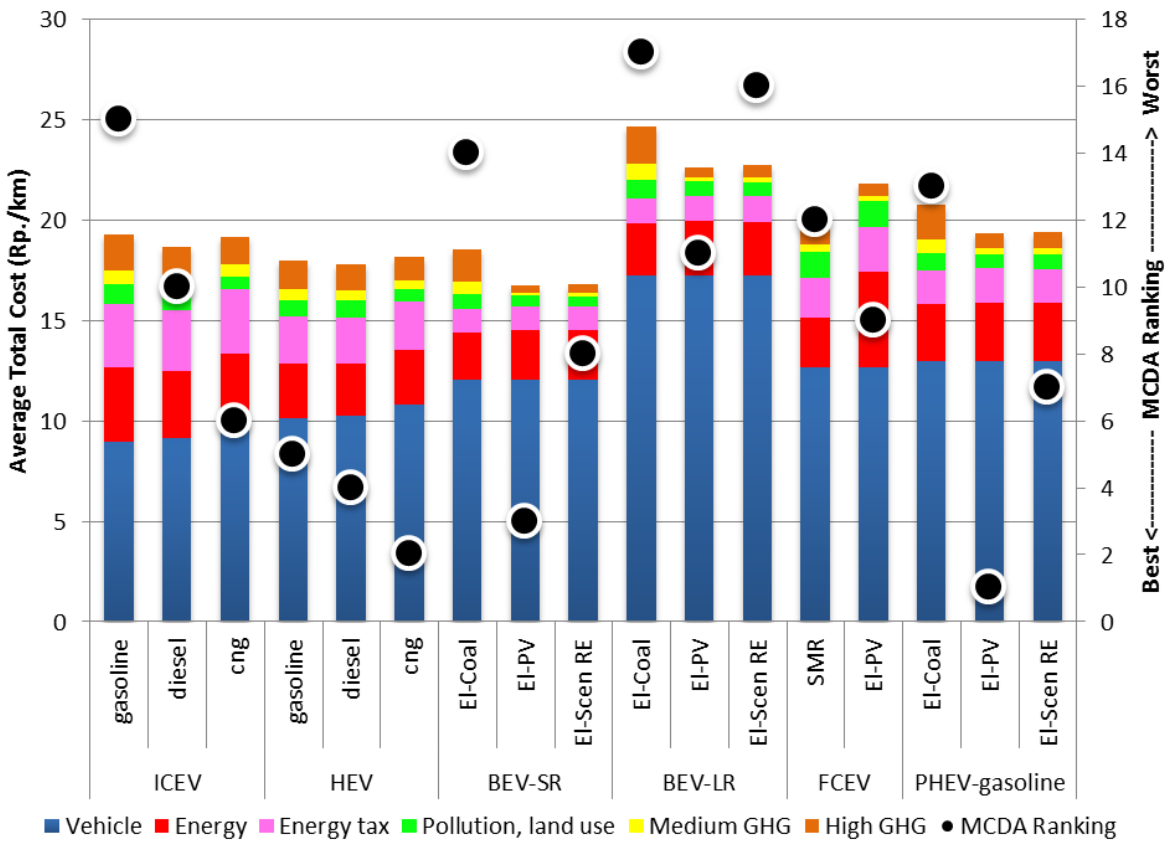


Drivetrain
ICEV – internal combustion
HEV – hybrid electric
BEV-SR – battery electric (short range)
BEV -LR– electric vehicle (long range)
FCEV – fuel cell electric
PHEV – plug in hybrid

Electricity source
CH – Swiss electricity mix
UCTE – import mix
Coal – coal fired power plant
PV - photovoltaic

Hydrogen source
SMR– steam methane reforming
EI – electrolysis (see left)

Figure 7.1 Total cost and MCDA ranking of selected lower mid class cars in 2012. MCDA ranking is represented by black dots (the lower the number the better); equal weights were used for all criteria. (1 Rp. = 1 Swiss cent = 1.01 US cent as of 31.10.2016).



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ICEV – internal combustion
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PHEV – plug in hybrid

Electricity source
Coal – coal fired power plant
PV – photovoltaic
El-Scen RE- SFOE renewables scenario, medium demand growth

Hydrogen source
SMR– steam methane reforming
El – electrolysis (see left)

Figure 7.2 Total cost and MCDA ranking of selected lower mid class cars in 2050. MCDA ranking is represented by black dots (the lower the number the better); equal weights were used for all criteria. (1 Rp. = 1 Swiss cent = 1.01 US cent as of 31.10.2016).

The internal ranking of these cases is not necessarily consistent with total costs, which disfavor FCEV. Generally, in relative terms, use of fossil electricity in relative terms affects the MCDA ranking of BEV more negatively than use of SMR in connection with FCEV.

For future technologies there are extensive changes in the rankings based on the two approaches. First, in terms of total costs electric vehicles come much closer to the conventional ones with short range BEV being fully competitive. BEV and FCEV have comparably higher total costs but the gap is much reduced compared with 2012. Second, in the MCDA-ranking ICEV no longer belong to the top. Rather PHEV and short range BEV charged by solar PV, followed remarkably by HEV with natural gas as fuel take the top places. Other HEV perform also well along with PHEV charged by the future Swiss electricity mix (average) primarily based on renewables. In relative terms FCEV perform somewhat better than long range BEV having still a substantial advantage with regard to driver utility and in terms of lifetime internal costs. The latter depends on the assumption of very high reduction of purchase cost of FCEV, which is highly uncertain and may be questioned.

For current technologies MCDA sensitivity mapping shows that:

- Emphasis on environment favors short range BEV if electricity supply is provided by solar PV or Swiss electricity mix.
- Emphasis on economy favors conventional cars and hybrids.
- Emphasis on social aspects, here focused on the normal operation and accident-related risks of energy supply, favors BEV and PHEV if electricity is supplied by solar PV.
- Emphasis on driver utility clearly favors conventional cars closely followed by hybrids, PHEV and FCEV. BEV are penalized with relative disadvantage for short range cars.

For future technologies MCDA sensitivity mapping shows that:

- Emphasis on environmental performance mostly favors electric cars, particularly short range BEV with renewable electricity supply.
- Emphasis on economy results in the best ranks for short range BEV.
- Emphasis on social aspects results in performance patterns similar to those in the corresponding case for the current technologies. However, in relative terms the "bad" cases among electric cars become better.
- While both a decisive improvement for the future range and charging time of BEV has been credited emphasis on driver utility remains clearly unfavorable for their ranking.

System level

The highest level of integration was needed when assessing sustainability of future car fleet options. This involved integration of the various analytical approaches used in the project by means of organizing the data flows between the various Work Packages to enable the integration.

The fleet model used in this work assumes different levels of penetration of electric vehicles until year 2050, from no penetration at all to dominance of such technologies. The most complex part of the implementation of the assessment concerned BEV as this required the interplay between the fleet model, simulation of traffic for a future scenario (carried out using the MATSim model), future scenarios for electricity supply and electric grid modeling on top of using the results from LCA and vehicle simulation. Ultimately, the quantitative indicators for the performance of the various fleet options were generated and MCDA was carried out for these options.

Total electricity demand increases for different penetration levels are shown in Figure 7.3. The additional annual electricity demand due to BEV charging was found to be 8.1, 11.0 and 12.1 TWh for fleet penetration levels of 30%, 60% and 90%, respectively. For the same fleet penetration levels the increase in electricity demand from charging FCEVs with hydrogen produced by electrolysis was found to be 9.2, 18.3, and 27.5 TWh.

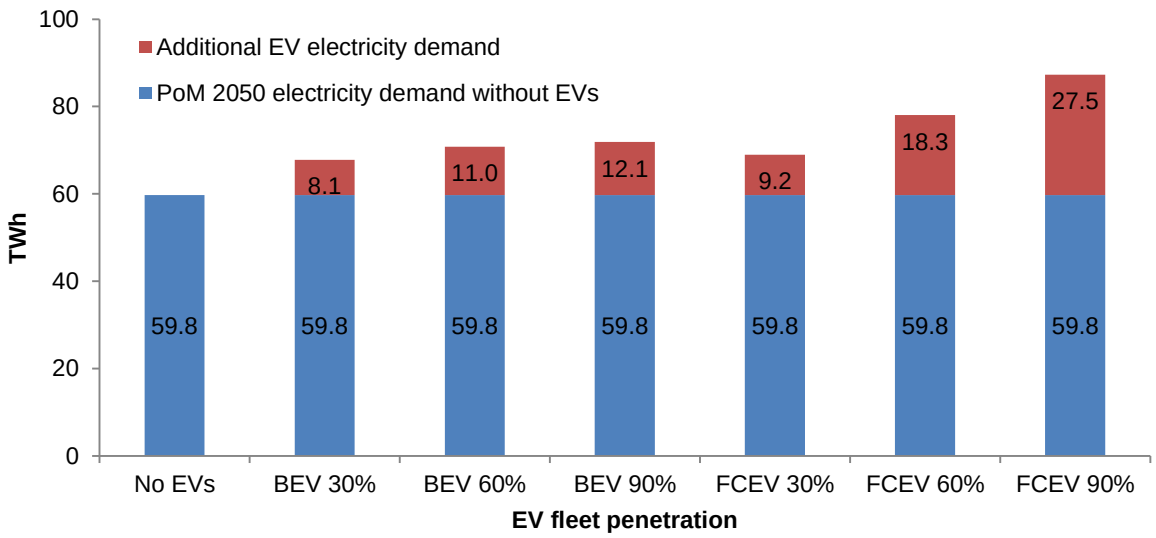
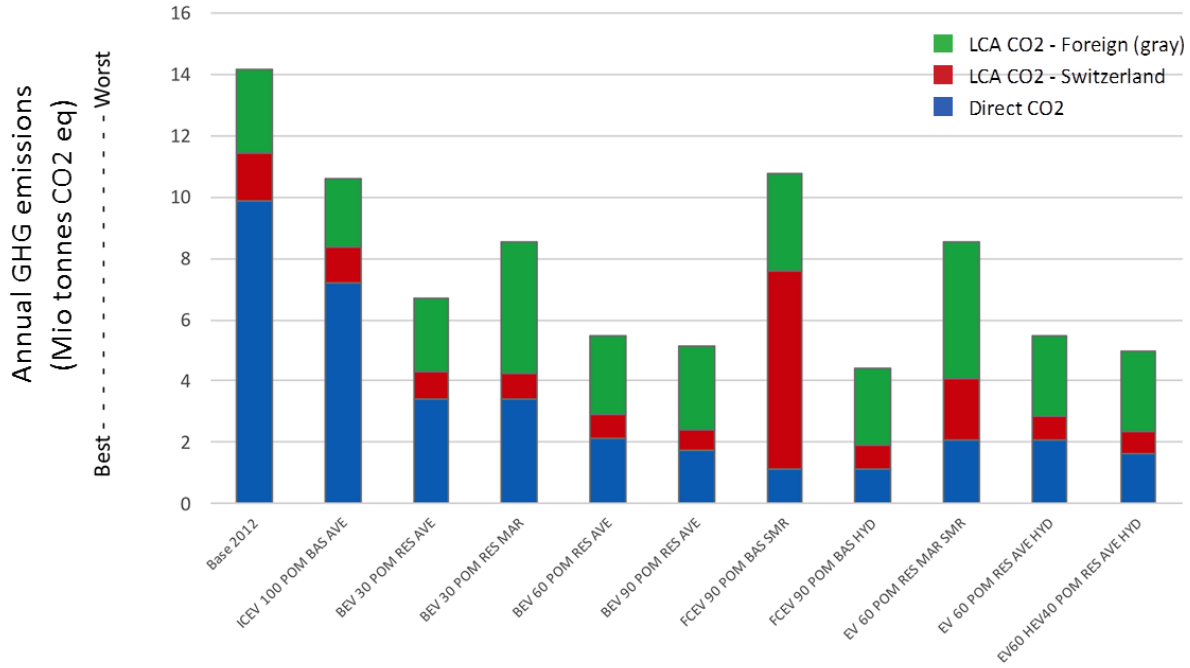


Figure 7.3 Total electricity demand increases for different electric vehicle fleet penetrations.

In total 11 indicators were quantified for 35 future (2050) fleet options. The fleet options represent combinations of different levels of penetration of electric vehicle (differentiating between battery and fuel cell cars) with various scenarios for electricity supply and various means for producing hydrogen. In addition, for the purpose of comparison, the corresponding indicators were also quantified for the current (2012) fleet.

In most cases the indicators for the evaluation of individual technologies and fleet options overlap. There is a difference between the economic indicators, i.e. for car buyers there is a separation between purchase and operating costs since the earlier are often decisive for them while on the national level the total life cycle cost of fleet options is the core aggregated economic indicator. Furthermore, the security of supply of energy is not a major concern when buying a car but is again of critical importance on the national level. Finally, the vehicle utility may be decisive for car buyers.

As shown in Figure 7.4 compared to the base year 2012, the total life cycle GHG emissions caused by Swiss passenger cars in 2050 are estimated to be reduced by 25%-65%, depending on the penetration rate of advanced powertrain vehicles and the development of the energy system.



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure 7.4 2050 fleet Greenhouse Gas Emissions by location for a reduced set of options.

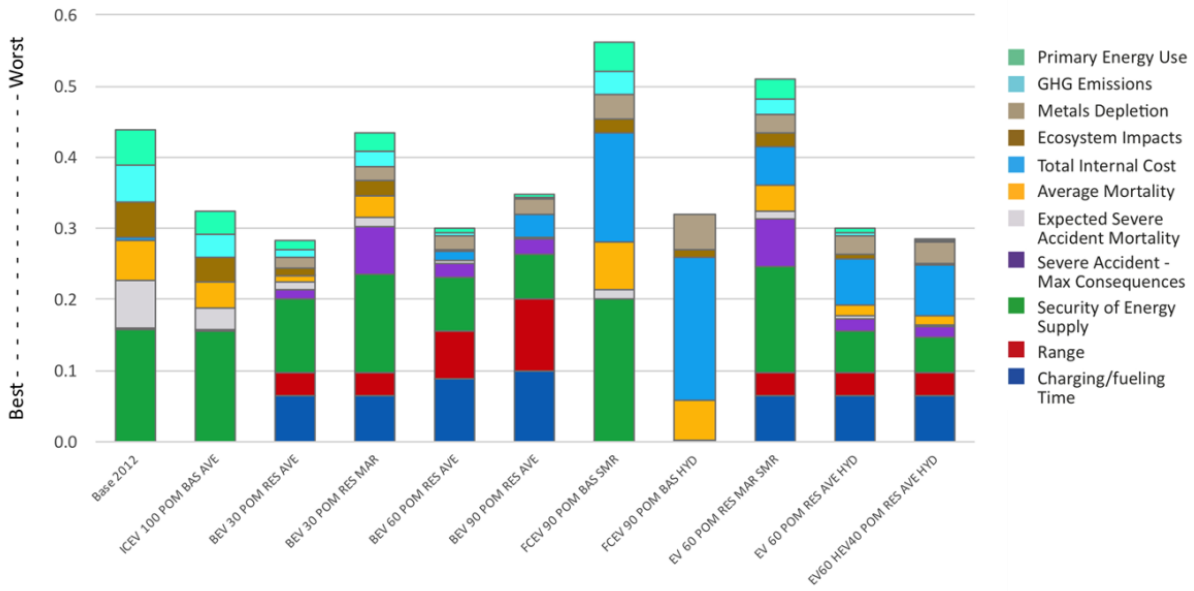
One factor strongly affecting the GHG-performance of electrified car fleet is whether the electricity for BEV and/or FCEV will be provided by average or marginal mix. In the latter case the emissions are expected to be higher due to higher carbon content.

For most indicators the fleet option with 100% ICEV is either substantially better (e.g. for emissions of GHG shown above) or at least as good as the current fleet. The exceptions in this respect are metal depletion, maximum number of fatalities per accident and driver utility.

Annual internal costs of future fleet options are relatively close to the current ones due to much reduced costs of future technologies, though costs of FCEV-dominated scenarios remain higher in spite of large improvements. It should be noted that the costs of infrastructure needed for advanced technologies have not been extensively analyzed and are underestimated in the present analysis. Mortality caused by normal operation is reduced in fleet options with strong expansion of BEV. Most future fleet options perform better in security of supply than the current fleet. The best option is the fleet dominated by FCEV with hydrogen produced using renewable electricity; the worst is the same fleet but with hydrogen from SMR. In the context of vehicle range, fleet scenarios with high shares of FCEV perform as well as scenarios dominated by ICEV. The much improved BEV are still more limited in this respect.

Multi-criteria Decision Analysis (MCDA) was also performed on the level of fleet options. Figure 7.5 shows the ranking for the current (2012) and future (2050) fleets, based on equal weighting for the five high level criteria. Other cases analyzed provide sensitivity mapping with one at a time emphasis

on each criterion thus reflecting positions (preferences) taken (expressed) by some stakeholders in the debate on mobility.



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Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure 7.5 Fleet 2050 MCDA for reduced set of fleet options – EQUAL Weights (Environment, Economy, Society, Security of Energy Supply and Driver Utility equally weighted)

Except for scenarios with SMR, fleets with various shares of electric vehicles rank at the same level as the future fleet fully dominated by ICEV. Also, excluding scenarios with SMR, the sustainability performance is clearly better than that of the current fleet. The factors negatively affecting the sustainability of electric mobility are range and charging time of BEV, and internal costs for FCEV (along with security of supply if SMR is used).

Focus on environmental performance exhibits major improvements of ICEV and hybrids in this respect. However, the best performers are the fleet options with high shares of BEV. FCEV-dominated fleet with SMR rank worse than future ICEV-dominated fleet. Generally, metal depletion is a negative factor for electric vehicles. If economy is the focal point, conventional vehicles are on the winning side but fleet options with moderate share of BEV are competitive. Emphasis on social aspects (represented in this project by risks in the energy supply chain) favors mostly fleets with substantial share of BEV. Also ICEV and FCEV-dominant fleets perform better than the current fleet. Focus on security of energy supply mostly favors fleets with high share of electric vehicles except when SMR is involved. The best case is FCEV-dominated fleet with hydro providing electricity for electrolysis. If emphasis is placed on driver utility, ICEV- and FCEV-dominated fleets are ranked highest, while cases with BEV are disadvantaged.

7.1.6. Overall conclusions on opportunities and challenges for electric mobility

The following conclusions can be drawn from the present study:

- **Electric mobility can strongly reduce consumption of non-renewable energy and GHG-emissions of future individual car mobility in Switzerland.** The largest reductions result if non-fossil energy resources are used for electricity and hydrogen production. Thus, compared to the base year 2012 and based on the analyzed fleet scenarios for Swiss passenger cars in 2050, the consumption of non-renewable energy could be reduced by 10%-65% and the total life cycle GHG emissions are estimated to be reduced by 25%-65%, depending on the penetration rate of advanced powertrain vehicles and the development of the energy system. This conclusion is essential since efficiency improvements and climate protection are the core goals of the new Swiss energy policy.

- **Environmental external costs of individual technologies with high standards have limited influence on their ranking but cumulative external costs are very substantial.** Current external costs of the car fleet in Switzerland are in the range of about 0.7 – 1.9 billion Euro per year; the broad range of this estimate is associated with large uncertainties of external costs caused by greenhouse gases. The evaluated scenario without electric vehicles but taking into account the advancements of fossil fuel vehicles leads to a reduction of the annual external costs by about 25 % in year 2050; the corresponding reduction in a scenario with 80 % penetration of electric vehicles is close to 50 %. It should be noted that external costs of accidents are not included in these estimates.

- **Future BEVs and FCEVs exhibit strongly improved performance over a range of criteria and stakeholder profiles.** The evaluations of fleet options by and large reflect the behavior of technologies in accordance with the shares of the various types of vehicles. The estimated indicators exhibit a clear tendency towards improving performance parameters with time. This applies in particular to electric cars. Apart from the above mentioned reductions in consumption of non-renewable energy consumption and GHG emissions there are, for example, remarkable cost reductions within the time horizon considered, with costs of battery vehicles being reduced by a factor of two and fuel cell cars by a factor of three. But also other indicators such as average mortality or ranges and charging times for BEV are expected to improve decisively. In the balanced multi-criteria perspective (i.e. with equal preference given to the high level criteria), with the exception for scenarios with SMR, fleets with various shares of electric vehicles rank at the same level as the hypothetical future fleet fully dominated by (much improved) ICEV. Also, excluding scenarios with SMR the sustainability performance of fleet scenarios is clearly better than that of the current fleet.

- **Electric mobility faces challenges with regard to a number of factors.** These include costs, range and charging performance for BEV, environmental performance for example with regard to metal depletion, dependence of future availability of nearly carbon-free electricity for charging BEV and production of hydrogen (use of average electricity mix versus marginal mix with possibly substantial carbon content), deployment of the necessary infrastructure and last but not least the continued trend towards remarkable improvements of conventional technologies.

7.2. Recommendations for Future Work

Life Cycle Assessment

The following issues have not been extensively analyzed within THELMA and call for further attention:

- Primary industry data from manufacturers of batteries and fuel cells would substantially reduce uncertainties in these Life Cycle Inventory (LCI) data.
- Establishment of LCI data for specific future battery technologies not considered in this work, such as Li-air or Li-sulfur.
- Establishment of LCI data for future fuel cells explicitly taking into account new materials and manufacturing technologies.
- Establishment of LCI data for unconventional and future fossil fuel production, such as oil sands, shale oil and gas, and deep sea reservoirs, which are supposed to increase their market shares in the future.
- Analysis of biofuels. This task has a high priority.
- Metal resource scarcity was identified as one of relative weaknesses of electric vehicles. For technologies which, due to lifetime and market size, do not yet have commercially available End of Life (EoL) services, the detailed analysis of potential future recycling options remains to be an area of particular uncertainty for LCA and needs to be analyzed in detail.
- Human health impacts related to noise should be included in future analyses.
- Consideration of systemic aspects in addition to the current technology centered perspective and integration of economic interactions. For example, potential consequences of the implementation of a large-scale hydrogen production and distribution network as well as all kinds of rebound effects need to be explored, based on consequential LCA.

Vehicle simulation and powertrain assessment

A very challenging but highly desirable endeavor is pursuing for road-freight transportation similar type of analysis as carried out here for individual mobility. The demand for freight transportation (in terms of ton kilometers per year) increased by 50% over the last 30 years. Both the operation patterns and machinery are more complex, due to the commercial and much more energy intensive nature of heavy-duty transportation.

Power system modeling

Topics of primary interest include:

- Extension of grid analysis to address a substantially higher penetration of BEV and PHEV with time horizon of year 2050, i.e. beyond year 2030 as implemented in the present study.
- Integration of the needs of the distribution network in the controlled charging approach. This could be done by introducing additional control loops within a hierarchical control framework.
- Modeling of imports and exports as endogenous parameters within the model, e.g. by assuming electricity prices for the neighboring countries.
- Development of a more detailed battery degradation model. Within the project it was only possible to use a model available in the literature.

Case studies including traffic simulation

The following issues worth future consideration were identified:

- Extension of the household demand model to include for example food and clothing. This is not of primary interest in the mobility context but would lead to a more complete LCA-based picture of household environmental impacts.
- More Swiss municipalities should be investigated in the way we demonstrated for Wattwil and Zernez. Low-impacting communities could be identified and factors like short commuting distances could be derived from the analysis of their community structure. The results should be used to establish long-term roadmaps that focus on promoting these factors. Also, the investigation of future mobility scenarios should also be considered for further municipalities in order to gain a better grasp of the large scale implications of electric mobility. The scenario work should also address a broader spectrum of electricity mixes and environmental indicators beyond GHG emissions (as done in other Work Packages of this project).
- The presented optimization approach remains to be limited in the sense that neither economic aspects nor the willingness of households to take action regarding the installation of new technologies and the refurbishment of their homes were taken into consideration. Further research is therefore necessary to take these factors into account and investigate, e.g., cost-optimal options to reduce environmental impacts. Further model improvements could comprise the consideration of future technology development, implementing mobility-related optimizers, taking into account building park renewal rates and changes in population number, and changed demand in e.g. living space. Even though the presented optimization model was tailored for the case study of Wattwil, it is conceivable to adapt this model to other regions and constraints, given the availability of data.
- Future work in the field of household expenditure as related to travel demand, next to the search of better model specifications of the given methodology, would have to consist of designing and implementing surveys that explicitly relate income and expenditure for certain categories and transportation with reported trips and travel demand generation.
- On the MATSim side, in the near future, it will be attempted to consolidate the improvements that this project brought to the software. An important factor will be to apply the simulation to other similar problems (i.e. involving energy consumption calculation, use of electric vehicles, etc.) in order to get more experience with these new tools. This is a crucial aspect when such complex modeling systems are used. At the same time, some of the enhancements were based on ad-hoc solutions because of the unavailability of some household characteristics in the current MATSim population specification. Therefore work will be pursued on the generation of a population where all the necessary attributes would be available as a standard. Finally, it is desirable to have week-days and week-end scenarios.

Integration analysis and desirable scope extensions

The following issues are of primary interest to be pursued as the extension of the THELMA project:

- The integration analysis as carried out in this work can be further refined. A certain component of improvisation in the implementation was necessary including extrapolations of some results to year 2050 as the analysis only stretched to 2030.

- Some of the essential developments within the various tasks listed above could be implemented in the integration analysis.
- Generally, perspectives on the future performance of technologies change with time as more knowledge is available and specific technologies successfully enter the market, which boosts their performance. Thus, updates and extensions of technology assessment are necessary particularly having in mind that the reference year for current technologies as defined in the THELMA project is 2012.
- While a wide spectrum of options was covered, biofuels were not included. Interdisciplinary assessment of biofuels and their implementation in the fleet model is considered to be a high priority.
- Autonomous vehicles were not addressed in this work. Given the potentially revolutionary impact they could have on the future mobility they need to be included and subjected to detailed analysis.
- The infrastructure necessary for the expansion of electric mobility has been addressed to a very limited extent in this work. The development of the infrastructure and the associated impacts on economy, environment, risks etc. as well as social acceptance issues should be investigated in order to achieve a more realistic assessment of future mobility.
- Mobility demand and associated social aspects have been included to very a limited extent and call for much extended attention. This includes consideration of rebound effects.
- Tools for multi-indicator and multi-criteria analysis were partially developed within this project. Further developments of such tools would be beneficial for support of decision-making.
- The fleet analysis builds on rather arbitrary assumptions about future composition of the future fleet. Furthermore, though electricity supply scenarios and energy supply chains constituted part of the analysis, no energy-economic model with mobility as one of the end use sectors was used in the present work. Such a model allows representation of the complex and dynamic interplay of the mobility sector with the overall energy system and is capable to endogenously generate cost-optimal solutions also under climate protection constraints.
- The current analysis needs to be extended to cover the whole mobility sector, i.e. other modes of passenger mobility such as motorcycles, buses, railway and airplanes as well as transport of goods.

During the last two years the THELMA project was coordinated with the Swiss Coordination Centre for Energy Research (SCCER) "Efficient technologies and systems for mobility" http://www.sccer-mobility.ch/ to the mutual benefit. Some of the developments mentioned above are already pursued within this SCCER.

Acronyms

BEV	Battery Electric Vehicle
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MCDA	Multi-Criteria Decision Analysis
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
SMR	Steam Methane Reforming
V2G	Vehicle to Grid
WP	Work Package
WTW	Well to Wheel

Appendix A: Selected vehicle indicators by powertrain, class, and year

Authors: Gil Georges (ETHZ)[45], Johannes Hofer (PSI)[46]

Powertrain	Class	Year	Electric range (km)	Vehicle mass (kg)	Energy use (MJ/km)	Manufacturing cost ($)
ICEV-gasoline	Mini	2012	0	918	1.88	9681
ICEV-gasoline	Small	2012	0	1095	2.05	12185
ICEV-gasoline	Low-Mid	2012	0	1323	2.35	16490
ICEV-gasoline	Midsize	2012	0	1528	2.73	22204
ICEV-gasoline	MPV	2012	0	1711	3.24	21216
ICEV-gasoline	SUV	2012	0	1998	3.75	27413
ICEV-diesel	Mini	2012	0	932	1.67	9902
ICEV-diesel	Small	2012	0	1110	1.82	12422
ICEV-diesel	Low-Mid	2012	0	1340	2.07	16753
ICEV-diesel	Midsize	2012	0	1548	2.37	22501
ICEV-diesel	MPV	2012	0	1728	2.84	21491
ICEV-diesel	SUV	2012	0	2020	3.22	27760
ICEV-cng	Mini	2012	0	961	1.86	11328
ICEV-cng	Small	2012	0	1140	2.03	13924
ICEV-cng	Low-Mid	2012	0	1372	2.32	18398
ICEV-cng	Midsize	2012	0	1582	2.67	24328
ICEV-cng	MPV	2012	0	1768	3.18	23601
ICEV-cng	SUV	2012	0	2062	3.64	30101
HEV-gasoline	Mini	2012	0	961	1.48	12540
HEV-gasoline	Small	2012	0	1152	1.60	15655
HEV-gasoline	Low-Mid	2012	0	1406	1.82	21039
HEV-gasoline	Midsize	2012	0	1648	2.10	28175
HEV-gasoline	MPV	2012	0	1817	2.52	26828
HEV-gasoline	SUV	2012	0	2181	2.89	35980
HEV-diesel	Mini	2012	0	972	1.32	12734
HEV-diesel	Small	2012	0	1164	1.43	15867
HEV-diesel	Low-Mid	2012	0	1421	1.62	21288
HEV-diesel	Midsize	2012	0	1666	1.88	28476
HEV-diesel	MPV	2012	0	1832	2.24	27086
HEV-diesel	SUV	2012	0	2204	2.58	36361
HEV-cng	Mini	2012	0	1002	1.47	14053
HEV-cng	Small	2012	0	1194	1.59	17246
HEV-cng	Low-Mid	2012	0	1453	1.80	22785
HEV-cng	Midsize	2012	0	1700	2.08	30138
HEV-cng	MPV	2012	0	1870	2.49	28970
HEV-cng	SUV	2012	0	2244	2.86	38460
BEV-SR	Mini	2012	100	958	0.52	23497
BEV-SR	Small	2012	100	1141	0.56	26752
BEV-SR	Low-Mid	2012	100	1379	0.63	32269
BEV-SR	Midsize	2012	100	1602	0.73	39687

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Powertrain	Class	Year	Electric range (km)	Vehicle mass (kg)	Energy use (MJ/km)	Manufacturing cost ($)
BEV-SR	MPV	2012	100	1818	0.89	40557
BEV-SR	SUV	2012	100	2119	0.99	49095
BEV-LR	Mini	2012	200	1146	0.56	31215
BEV-LR	Small	2012	200	1347	0.60	35142
BEV-LR	Low-Mid	2012	200	1613	0.68	41757
BEV-LR	Midsize	2012	200	1880	0.79	50914
BEV-LR	MPV	2012	200	2151	0.96	54089
BEV-LR	SUV	2012	200	2508	1.08	64663
FCEV	Mini	2012	0	1080	0.99	49074
FCEV	Small	2012	0	1293	1.08	58750
FCEV	Low-Mid	2012	0	1590	1.23	76033
FCEV	Midsize	2012	0	1892	1.45	99428
FCEV	MPV	2012	0	2042	1.72	93620
FCEV	SUV	2012	0	2537	2.00	137140
PHEV-gasoline	Mini	2012	50	1091	0.97	23784
PHEV-gasoline	Small	2012	50	1289	1.05	27144
PHEV-gasoline	Low-Mid	2012	50	1553	1.18	32895
PHEV-gasoline	Midsize	2012	50	1811	1.37	40646
PHEV-gasoline	MPV	2012	50	1988	1.64	40056
PHEV-gasoline	SUV	2012	50	2372	1.86	49845
PHEV-diesel	Mini	2012	50	1102	0.91	23991
PHEV-diesel	Small	2012	50	1301	0.98	27364
PHEV-diesel	Low-Mid	2012	50	1566	1.10	33138
PHEV-diesel	Midsize	2012	50	1827	1.28	40923
PHEV-diesel	MPV	2012	50	2000	1.53	40293
PHEV-diesel	SUV	2012	50	2390	1.74	50156
PHEV-cng	Mini	2012	50	1150	0.98	25543
PHEV-cng	Small	2012	50	1350	1.06	28993
PHEV-cng	Low-Mid	2012	50	1620	1.19	34918
PHEV-cng	Midsize	2012	50	1887	1.38	42928
PHEV-cng	MPV	2012	50	2070	1.65	42586
PHEV-cng	SUV	2012	50	2467	1.87	52735
ICEV-gasoline	Mini	2030	0	814	1.47	9945
ICEV-gasoline	Small	2030	0	970	1.60	12431
ICEV-gasoline	Low-Mid	2030	0	1169	1.83	16703
ICEV-gasoline	Midsize	2030	0	1344	2.11	22369
ICEV-gasoline	MPV	2030	0	1512	2.51	21373
ICEV-gasoline	SUV	2030	0	1750	2.90	27479
ICEV-diesel	Mini	2030	0	826	1.34	10223
ICEV-diesel	Small	2030	0	983	1.46	12726
ICEV-diesel	Low-Mid	2030	0	1183	1.65	17026
ICEV-diesel	Midsize	2030	0	1360	1.88	22727
ICEV-diesel	MPV	2030	0	1526	2.26	21717
ICEV-diesel	SUV	2030	0	1767	2.56	27893
ICEV-cng	Mini	2030	0	862	1.47	11561
ICEV-cng	Small	2030	0	1021	1.60	14142
ICEV-cng	Low-Mid	2030	0	1226	1.82	18590
ICEV-cng	Midsize	2030	0	1408	2.08	24480
ICEV-cng	MPV	2030	0	1583	2.49	23767
ICEV-cng	SUV	2030	0	1831	2.84	30193

Powertrain	Class	Year	Electric range (km)	Vehicle mass (kg)	Energy use (MJ/km)	Manufacturing cost ($)
HEV-gasoline	Mini	2030	0	836	1.12	11438
HEV-gasoline	Small	2030	0	1001	1.21	14265
HEV-gasoline	Low-Mid	2030	0	1217	1.36	19132
HEV-gasoline	Midsize	2030	0	1414	1.55	25568
HEV-gasoline	MPV	2030	0	1573	1.88	24391
HEV-gasoline	SUV	2030	0	1858	2.13	32081
HEV-diesel	Mini	2030	0	846	1.05	11669
HEV-diesel	Small	2030	0	1013	1.13	14514
HEV-diesel	Low-Mid	2030	0	1230	1.27	19413
HEV-diesel	Midsize	2030	0	1430	1.46	25894
HEV-diesel	MPV	2030	0	1587	1.76	24692
HEV-diesel	SUV	2030	0	1877	2.00	32478
HEV-cng	Mini	2030	0	880	1.14	12866
HEV-cng	Small	2030	0	1047	1.23	15770
HEV-cng	Low-Mid	2030	0	1268	1.38	20787
HEV-cng	Midsize	2030	0	1472	1.58	27430
HEV-cng	MPV	2030	0	1636	1.91	26465
HEV-cng	SUV	2030	0	1932	2.17	34470
BEV-SR	Mini	2030	150	802	0.44	13567
BEV-SR	Small	2030	150	962	0.47	16349
BEV-SR	Low-Mid	2030	150	1167	0.53	21105
BEV-SR	Midsize	2030	150	1351	0.61	27434
BEV-SR	MPV	2030	150	1538	0.75	27267
BEV-SR	SUV	2030	150	1783	0.83	34270
BEV-LR	Mini	2030	350	958	0.47	18027
BEV-LR	Small	2030	350	1131	0.51	21174
BEV-LR	Low-Mid	2030	350	1357	0.57	26545
BEV-LR	Midsize	2030	350	1575	0.65	33801
BEV-LR	MPV	2030	350	1809	0.80	34993
BEV-LR	SUV	2030	350	2095	0.90	43097
FCEV	Mini	2030	0	919	0.82	23153
FCEV	Small	2030	0	1097	0.89	27308
FCEV	Low-Mid	2030	0	1335	1.00	34537
FCEV	Midsize	2030	0	1565	1.16	44123
FCEV	MPV	2030	0	1723	1.40	42585
FCEV	SUV	2030	0	2072	1.59	56630
PHEV-gasoline	Mini	2030	80	936	0.73	15480
PHEV-gasoline	Small	2030	80	1107	0.78	18427
PHEV-gasoline	Low-Mid	2030	80	1332	0.87	23481
PHEV-gasoline	Midsize	2030	80	1545	1.00	30236
PHEV-gasoline	MPV	2030	80	1710	1.22	29350
PHEV-gasoline	SUV	2030	80	2017	1.37	37432
PHEV-diesel	Mini	2030	80	946	0.70	15722
PHEV-diesel	Small	2030	80	1118	0.75	18680
PHEV-diesel	Low-Mid	2030	80	1344	0.84	23754
PHEV-diesel	Midsize	2030	80	1558	0.96	30538
PHEV-diesel	MPV	2030	80	1720	1.16	29624
PHEV-diesel	SUV	2030	80	2031	1.31	37767
PHEV-cng	Mini	2030	80	977	0.73	16847
PHEV-cng	Small	2030	80	1150	0.79	19857

Powertrain	Class	Year	Electric range (km)	Vehicle mass (kg)	Energy use (MJ/km)	Manufacturing cost ($)
PHEV-cng	Low-Mid	2030	80	1379	0.88	25034
PHEV-cng	Midsize	2030	80	1597	1.01	31964
PHEV-cng	MPV	2030	80	1766	1.22	31286
PHEV-cng	SUV	2030	80	2081	1.37	39606
ICEV-gasoline	Mini	2050	0	736	1.23	10183
ICEV-gasoline	Small	2050	0	876	1.34	12660
ICEV-gasoline	Low-Mid	2050	0	1052	1.52	16914
ICEV-gasoline	Midsize	2050	0	1207	1.75	22557
ICEV-gasoline	MPV	2050	0	1358	2.08	21552
ICEV-gasoline	SUV	2050	0	1565	2.40	27616
ICEV-diesel	Mini	2050	0	747	1.14	10499
ICEV-diesel	Small	2050	0	887	1.24	12993
ICEV-diesel	Low-Mid	2050	0	1065	1.40	17277
ICEV-diesel	Midsize	2050	0	1220	1.59	22956
ICEV-diesel	MPV	2050	0	1370	1.90	21940
ICEV-diesel	SUV	2050	0	1579	2.14	28075
ICEV-cng	Mini	2050	0	773	1.23	11406
ICEV-cng	Small	2050	0	913	1.33	13950
ICEV-cng	Low-Mid	2050	0	1094	1.51	18331
ICEV-cng	Midsize	2050	0	1252	1.72	24132
ICEV-cng	MPV	2050	0	1407	2.05	23326
ICEV-cng	SUV	2050	0	1621	2.33	29620
HEV-gasoline	Mini	2050	0	744	0.93	11046
HEV-gasoline	Small	2050	0	888	0.99	13746
HEV-gasoline	Low-Mid	2050	0	1075	1.11	18387
HEV-gasoline	Midsize	2050	0	1242	1.26	24525
HEV-gasoline	MPV	2050	0	1388	1.53	23407
HEV-gasoline	SUV	2050	0	1622	1.72	30482
HEV-diesel	Mini	2050	0	753	0.88	11298
HEV-diesel	Small	2050	0	898	0.94	14015
HEV-diesel	Low-Mid	2050	0	1086	1.06	18686
HEV-diesel	Midsize	2050	0	1255	1.20	24862
HEV-diesel	MPV	2050	0	1399	1.45	23727
HEV-diesel	SUV	2050	0	1637	1.64	30884
HEV-cng	Mini	2050	0	776	0.94	12105
HEV-cng	Small	2050	0	922	1.00	14856
HEV-cng	Low-Mid	2050	0	1112	1.12	19597
HEV-cng	Midsize	2050	0	1283	1.28	25869
HEV-cng	MPV	2050	0	1432	1.54	24902
HEV-cng	SUV	2050	0	1672	1.74	32179
BEV-SR	Mini	2050	200	701	0.38	11882
BEV-SR	Small	2050	200	843	0.41	14565
BEV-SR	Low-Mid	2050	200	1022	0.45	19160
BEV-SR	Midsize	2050	200	1182	0.52	25266
BEV-SR	MPV	2050	200	1347	0.64	25042
BEV-SR	SUV	2050	200	1557	0.71	31666
BEV-LR	Mini	2050	500	828	0.40	16317
BEV-LR	Small	2050	500	979	0.43	19337
BEV-LR	Low-Mid	2050	500	1176	0.48	24513
BEV-LR	Midsize	2050	500	1361	0.55	31466

Powertrain	Class	Year	Electric range (km)	Vehicle mass (kg)	Energy use (MJ/km)	Manufacturing cost ($)
BEV-LR	MPV	2050	500	1564	0.68	32612
BEV-LR	SUV	2050	500	1805	0.76	40232
FCEV	Mini	2050	0	785	0.69	14208
FCEV	Small	2050	0	936	0.74	17410
FCEV	Low-Mid	2050	0	1134	0.83	22934
FCEV	Midsize	2050	0	1318	0.95	30227
FCEV	MPV	2050	0	1464	1.16	29153
FCEV	SUV	2050	0	1730	1.30	38473
PHEV-gasoline	Mini	2050	120	829	0.58	14103
PHEV-gasoline	Small	2050	120	979	0.62	16935
PHEV-gasoline	Low-Mid	2050	120	1175	0.69	21796
PHEV-gasoline	Midsize	2050	120	1357	0.79	28284
PHEV-gasoline	MPV	2050	120	1508	0.96	27498
PHEV-gasoline	SUV	2050	120	1766	1.07	35046
PHEV-diesel	Mini	2050	120	839	0.57	14377
PHEV-diesel	Small	2050	120	989	0.60	17221
PHEV-diesel	Low-Mid	2050	120	1186	0.67	22102
PHEV-diesel	Midsize	2050	120	1369	0.77	28619
PHEV-diesel	MPV	2050	120	1518	0.93	27808
PHEV-diesel	SUV	2050	120	1778	1.04	35416
PHEV-cng	Mini	2050	120	860	0.58	15127
PHEV-cng	Small	2050	120	1012	0.62	18001
PHEV-cng	Low-Mid	2050	120	1210	0.69	22946
PHEV-cng	Midsize	2050	120	1395	0.79	29550
PHEV-cng	MPV	2050	120	1549	0.96	28909
PHEV-cng	SUV	2050	120	1811	1.07	36616

Appendix B: MATSim 2030 – Switzerland Scenario

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B.1 Introduction

The MATSim 2030 Switzerland scenario is part of work package 4 of the THELMA project. THELMA stands for TecHnology-centered ELectric Mobility Assessment. The goal of the project is to understand the multi- criteria, sustainability implications of widespread electric vehicle use in Switzerland. The project performs an integrated assessment of a significant penetration of electric vehicles in the Swiss transport sector, analyzing also impacts on the electric grid. It's funded by the Competence Center for Energy & Mobility (CCEM) and Swiss Electric Research. Six different research groups of the Swiss Federal Institute of Technology are involved. Besides the IVT, the Life Cycle Assessment and Modelling (LCAM) Unit of EMPA, the Aerothermochemistry and Combustion Systems Laboratory (ACL), the Power Systems Laboratory (PSL), the Ecological Systems Design (ESD), and the Laboratory for Energy Systems Analysis (LEA) of PSI are participating.

As a part of this project, the IVT carried out the case study "MATSim 2030 Switzerland scenario" that aims at forecasting the transport demand in Switzerland in the year 2030, employing the agent-based micro-simulation toolkit MATSim. Simulation results will then deal as a basis for assessing the impacts of electric car mobility on a local level for whole Switzerland.

The documentation report is organized as follows: Section 2 describes all employed input files. The set-up of the config-file is presented in section 3. Finally, the calibration process is delineated in section 4.

B.2 Input

This section gives an overview of the input files used for MATSim 2030 Switzerland scenario.

B.2.1 Population

The initial demand is described based on two files: The plans file containing the MATSim population and the preferences file detailing minimal and typical activity durations for each agent.

B.2.1.1 Population

The MATSim population is based on the work of Müller and Axhausen (2013). Two major datasets and a classification of communes were used for generating the synthetic population:

- Register survey: This dataset describes the full population of Switzerland at a certain day of 2010. It contains the spatial location at the hectare level in addition to basic sociodemographics available from the civil registry.

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- Microcensus 2010: The latest version of the survey on mobility behavior in Switzerland which includes, among others, extended sociodemographics as well as information on mobility behavior (activities and detailed trips).
- Commune classification: Official classification (22 types) of Swiss communes according to commuter movement, occupation, housing conditions, wealth, tourism, population, and role in the Central Place Theory. A coarser version of this classification with nine levels is used.

For the year 2030, hypotheses for the travel behavior were constructed based on an extended analysis of mobility patterns in Switzerland (Ciari et al., 2013). Four different scenarios were defined:

- Baseline: Original frequency of activities, nothing changes
- Home office: Working from home is encouraged, the number of work trips decreases by 20%
- Delivery: Many people use internet shopping and get items delivered at home. People replace 20% of their shopping trips by leisure trips
- Combined: The combination of the former two scenarios

The population generation process consisted of two stages. In the first stage, survey calibration was used to reweight a person sample with activity schedules to reflect postulated changes in the frequency of certain activity types (according to the scenario). The second stage combined this calibrated dataset with the register survey data by means of statistical matching based on the attributes age, gender, and the nine-level classification of Swiss communes. All in all, 5 different 10% sample populations were generated:

- *population2010baseline.xml.gz*: baseline population of 2010
- *population2030baseline.xml.gz*: baseline population of 2030
- *population2030homeOffice.xml.gz*: population of 2030 assuming 20% less work trips
- *population2030delivery.xml.gz*: population of 2030 assuming that 20% of the shopping trips are replaced by leisure trips
- *population2030combined.xml.gz*: population of 2030 combining the former two hypotheses

Table B. 1 gives an overview of the different 10% sample populations. In general, the MATSim population only contains persons with transport demand. Therefore, people staying the whole day at home or toddlers are excluded and the (up scaled) population size is smaller than the number of inhabitants in Switzerland.

Table B. 1 Overview of population files

Population	Size	Number of Activities			
		Work	Shopping	Leisure	Education
population2010baseline.xml.gz	736’894	496’388	316’447	677’363	150’747
population2030baseline.xml.gz	794’871	486’103	354’472	738’153	156’208
population2030homeOffice.xml.gz	790’916	385’789	354’145	737’735	156’730
population2030delivery.xml.gz	796’667	484’323	284’393	884’913	157’060
population2030combined.xml.gz	793’370	386’270	283’705	884’919	156’594

A comparison to the Microcensus 2010 is presented in Table B. 2.

Table B. 2 Share of activity types of the different populations

Population	Share of activity types [%]			
	Work	Shopping	Leisure	Education
Microcensus 2010 (working day)	30.5	22.2	36.1	11.1
population2010baseline.xml.gz	30.3	19.3	41.3	9.2
population2030baseline.xml.gz	28.0	20.4	42.5	9.0
population2030homeOffice.xml.gz	23.6	21.7	45.1	9.6
population2030delivery.xml.gz	26.7	15.7	48.9	8.7
population2030combined.xml.gz	22.6	16.6	51.7	9.1

It can be seen that the baseline population 2010 matches the Microcensus distribution of activities reasonably. The differences vary between -1.9% (education) and 5.2% (leisure).

B.2.1.2 Preferences

The employed scoring function in MATSim (see chapter 3) penalizes agents that start an activity too late, stop an activity too early, or perform activities with too short durations. In order to calculate these disutilities, the following parameters need to be provided: typical activity duration, minimal activity duration, earliest activity end time, latest activity start time. These parameters can be set in the config-file, but it's also possible to create individual parameters for each agent and load them as object attributes in the simulation. The second approach was chosen for the MATSim 2030 runs. The interface "prefsFile" in the location choice module in the config-file was used to load these parameters. A preferences file was created for each of the 5 populations. A sample of the object attributes created for one agent with a home and a leisure activity is shown below:

```
<object id="1">
        <attribute    name="earliestEndTime_home"    class="java.lang.Double">0.0</attribute>
        <attribute    name="earliestEndTime_leisure"    class="java.lang.Double">0.0</attribute>
        <attribute    name="latestStartTime_home"    class="java.lang.Double">86400.0</attribute>
        <attribute    name="latestStartTime_leisure"    class="java.lang.Double">86400.0</attribute>
        <attribute    name="minimalDuration_home"    class="java.lang.Double">1800.0</attribute>
        <attribute    name="minimalDuration_leisure"    class="java.lang.Double">1800.0</attribute>
        <attribute    name="typicalDuration_home"    class="java.lang.Double">54631.0</attribute>
        <attribute    name="typicalDuration_leisure"    class="java.lang.Double">31769.0</attribute>
</object>
```

The following assumptions were drawn:

- earliestEndTime: always set to 0s (midnight)
- latestStartTime: always set 86400s (midnight)

- minimal duration: 1800s, for further calibration (after delivering output to the project partners) minimal durations for shopping (300s) and for leisure (900s) were reduced, the file name with those assumptions contains the suffix “SHORT”
- typical durations: the sum of the typical activity durations for each agents amounts to 24h, for work: the durations vary between 3 and 12h, for education: between 4-9h, for shopping or leisure: between 0.5- 19h, for home: at least 5-7h (depending on other activities)

The class where the preferences are created can be found under:

playground.staheale.matsim2030.CreatePrefs.java

B.2.2 Network

Within this project, two separate networks for private and public transport were generated and then assembled to one file named multimodalNetwork2010final.xml and multimodalNetwork2030final.xml, respectively. The final network is not multimodal in the sense that private and public transport vehicles interact; it provides a separate network for cars as well as for public transport vehicles. In addition, a thinned transit router network was used in order to fasten up the simulation.

B.2.2.1 Private transport network

Two different states of the private transport network were modelled, one for the condition in 2010 and one for the condition in 2030. For the private transport network of 2010, a detailed navigation network from 2010 was used that had been employed in other projects. A detailed description of the conversion to MATSim can be found in (Balmer et al., 2010). The resulting network includes over 1.3 Mio links and over 600'000 nodes. It is shown in Figure B. 1.

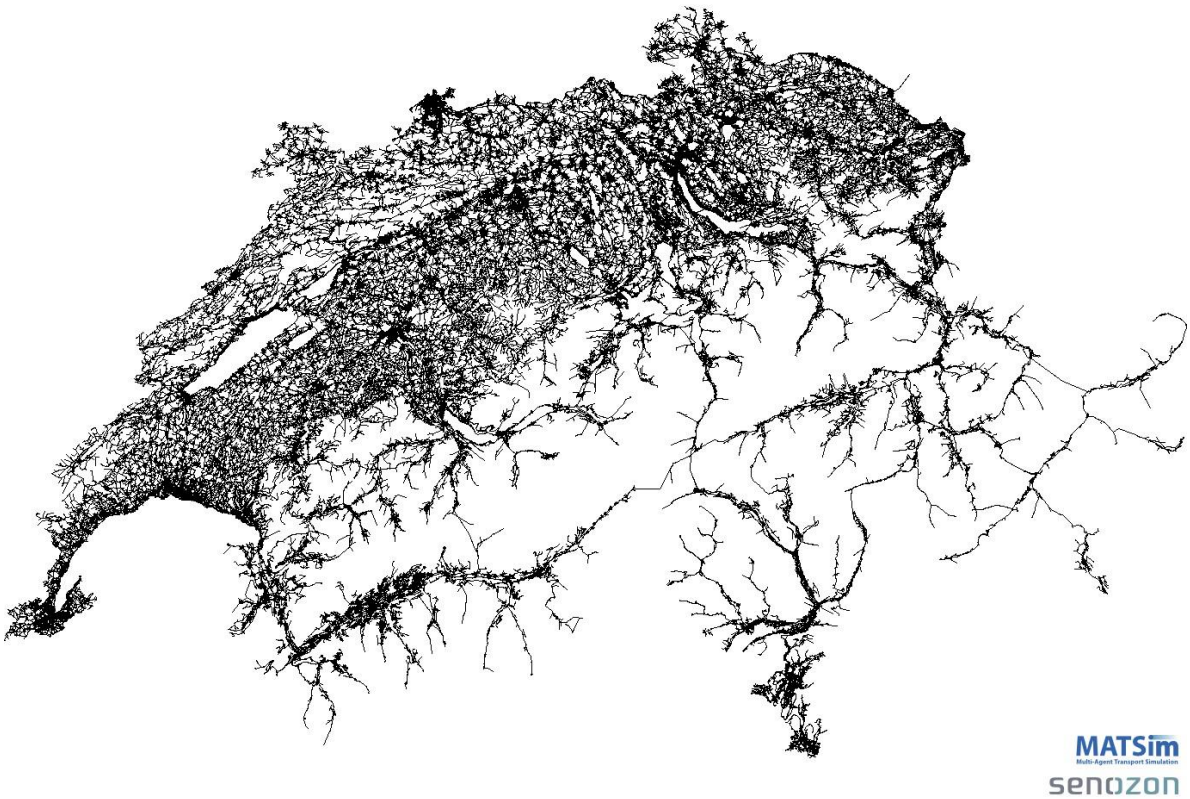

Figure B. 1 Private transport network of 2010

The network is updated to the conditions in 2030 by adding the extension projects for which the federal and cantonal governments have firmly committed themselves. The included projects are listed in Table B.3. The same approach has been applied for modeling the network conditions of 2030 in the National Transport Model (Swiss Federal Office for Spatial Development, 2010). Projects in the context of the completion of the national highway network are extension projects leading to new links and nodes in MATSim. Projects within the framework of the further development of the national highway network were mainly included by adapting the attributes of existing links. The projects were added by hand with the NetworkEditor tool in MATSim (org.matsim.contrib.networkEditor). Newly created links can be identified by the id. Their ids only consist of numbers. TeleAtlas link ids usually end with “FT” or “TF”, indicating the direction of the link.

Table B. 3 List of included road building projects between 2010 and 2030

Description	Code	Extension	Adaption
Zubringer Nidau	BE_N05_01	X	
Biel Süd - Biel West	BE_N05_08	X	
Biel West - Schlössli	BE_N05_08	X	
Biel Ost - Biel Süd	BE_N05_09	X	
Moutier Est - Court	BE_N16_02	X	
Court - Tavannes	BE_N16_03	X	
Bahnhof SBB - Gellertdreieck	BS_N02_07	X	
Frontière France - Porrentruy Ouest	JU_N16_02	X	
Delémont est - Frontière Berne	JU_N16_08	X	
Umfahrung Lungern	OW_N08_52	X	
6-Spur Ausbau Härkingen - Wiggertal	SOAG1		X
Neue Axenstrasse Brunnen - Ktgr. Uri	SZ_N04_09	X	
Neue Axenstrasse Ktgr. Schwyz - Flüelen	UR_N04_09	X	
Goulet d'étranglement de Crissier	VD3		X
Sierre - Gampel	VS_N09_55	X	
Gampel - Brig-Glis	VS_N09_56	X	
6-Spur Ausbau Blegi - Rütihof	ZG4		X
6-Spur Ausbau Fildern - Affoltern a.A.	ZH19		X
6-Spur Ausbau Nordumfahrung Zürich	ZH4		X

As an example, the newly added A16 Transjurane segments are marked red in Figure B. 2.

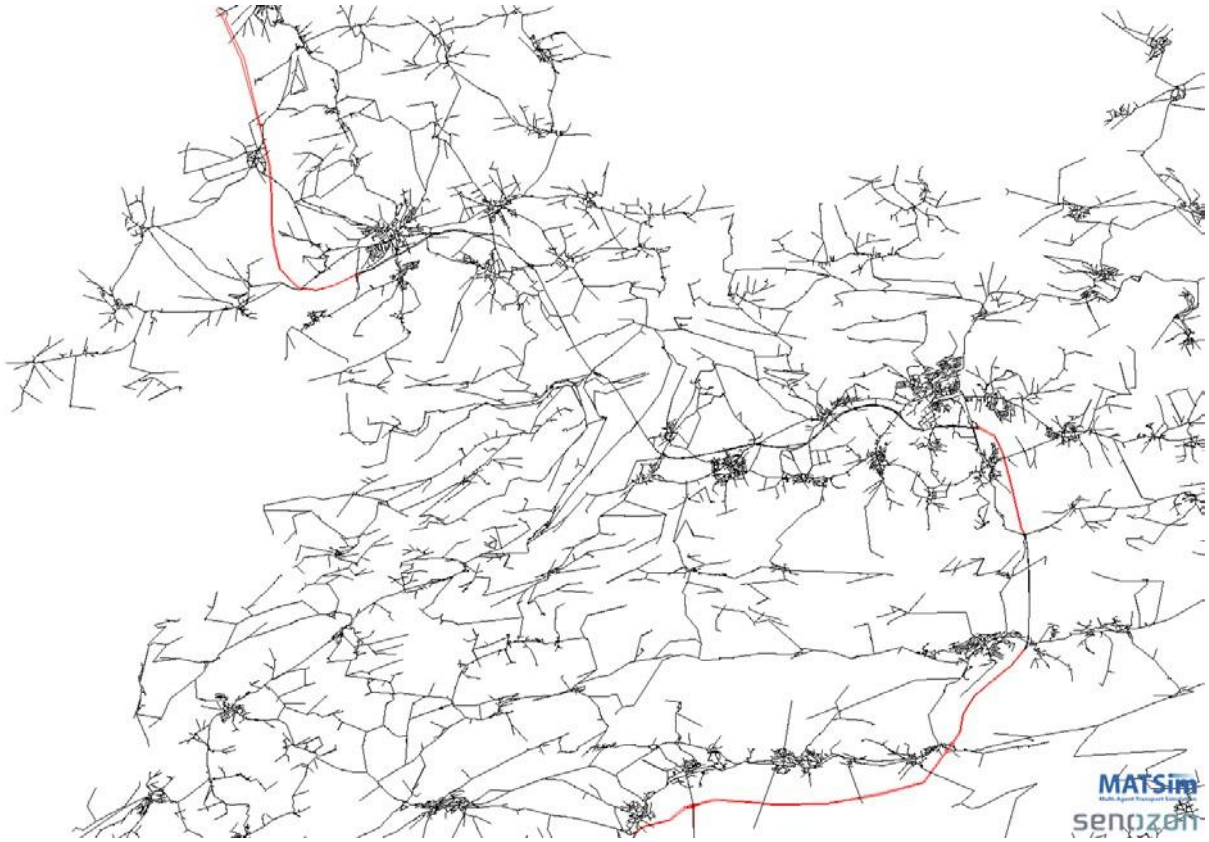

Figure B. 2 Newly added segments of the highway A16 Transjurane

There are different versions of the TeleAtlas network in the repository. Always make sure that the network is cleaned before you use it (no double links, no links which cannot be reached by others, no nodes without incoming or outgoing links etc.). A network cleaner can be found under *org.matsim.core.network.algorithms.NetworkCleaner*.

B.2.2.2 Public transport network

MATSim requires the following input for the simulation of public transport:

- A network consisting of links and nodes available to public transport vehicles
- A schedule describing the public transport lines, their routes, and their departures
- A file defining the public transport vehicles

Similar to the private transport network, two different states are modelled, one for current condition and one for the condition in 2030. The difficulty for the state in 2030 is that there is no complete schedule for that time. There is only a so-called system timetable which describes frequencies of connections between railway stations. Feeder lines are not included in the system timetable. In order to completely model public transport services, the feeder lines of the current state have to be added to the system timetable. This is quite complex because one has to check that the transfer times are reasonable and realistic. In addition, it is necessary to also use the system timetable for the current state in order to ensure consistency. Due to the complexity of timetable construction for 2030, the public transport

networks of the National Transport Model of the UVEK were used which are provided for the base year 2005 and for the year 2030. The National Transport Model constructed the schedules for 2005

The NPVM is modelled within the macroscopic transport simulation VISUM. Therefore, the conversion to MATSim - belonging to the group of microsimulations - posed a challenge. Since VISUM is a zone-based simulation toolkit, the area of Switzerland is divided in zones and intrazonal traffic, including intrazonal public transport services, is not modelled. The level of resolution for the zoning of the NPVM was chosen carefully, allowing for capturing the relevant traffic flows in whole Switzerland. For that reason, not every public transport service is included in the model. This is in particular the case for (intrazonal) urban buses.

Virtual urban transport network

In addition to leaving out intrazonal traffic, only a virtual urban transport network is modelled within the biggest cities in Switzerland. The following nine cities are affected:

- Zurich
- Geneva
- Basel
- Lausanne
- Bern
- Lucerne
- Winterthur
- St. Gallen
- Thun

Within those cities, a virtual urban transport network, connecting the zone centroids, is realized. The number of zones per city corresponds to the number of city districts and varies between 3 and 10. The travel times between the district centroids are assumed to amount to the effective travel time in the time schedule (HAFAS) plus half of the headway (during peak traffic periods). In order to remain consistent with the NPVM, the virtual urban transport network is recreated in MATSim. For that purpose, the district centroid connectors to the network are taken from Visum and the connections between the district centroids are emulated. The following assumptions were made:

District centroid connectors (- network):

- Frequency: every 7 minutes from 05:00 to 24:00
- Speed: 1.38 m/s
- Vehicle capacity: 1’000 persons

District centroid – District centroid:

- Frequency: every 7 minutes from 05:00 to 24:00
- Speed: 5.55 m/s
- Vehicle capacity: 1’000 persons

In Figure B. 3, the converted district centroid connectors of Zurich are shown.

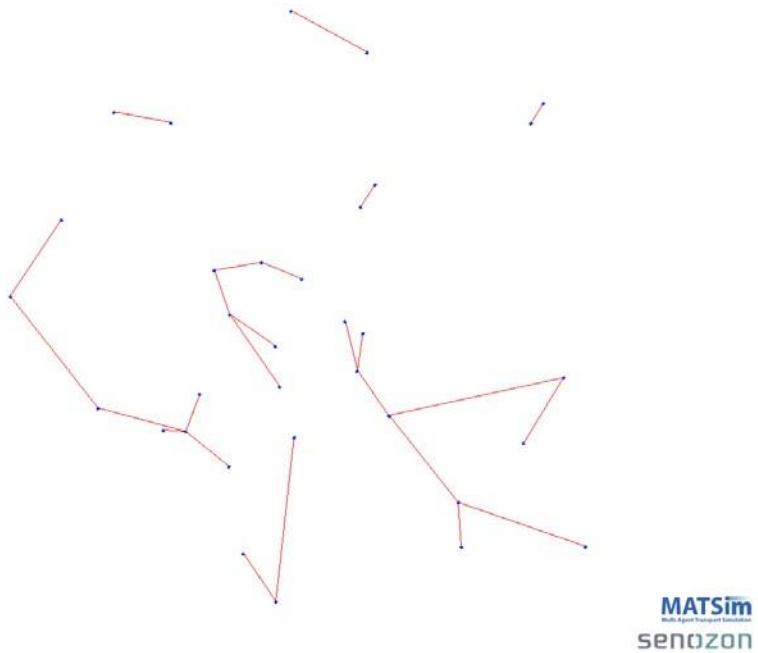

Figure B. 3 District centroid connectors of Zurich

The connections between the district centroids of Zurich are illustrated in Figure B. 4.

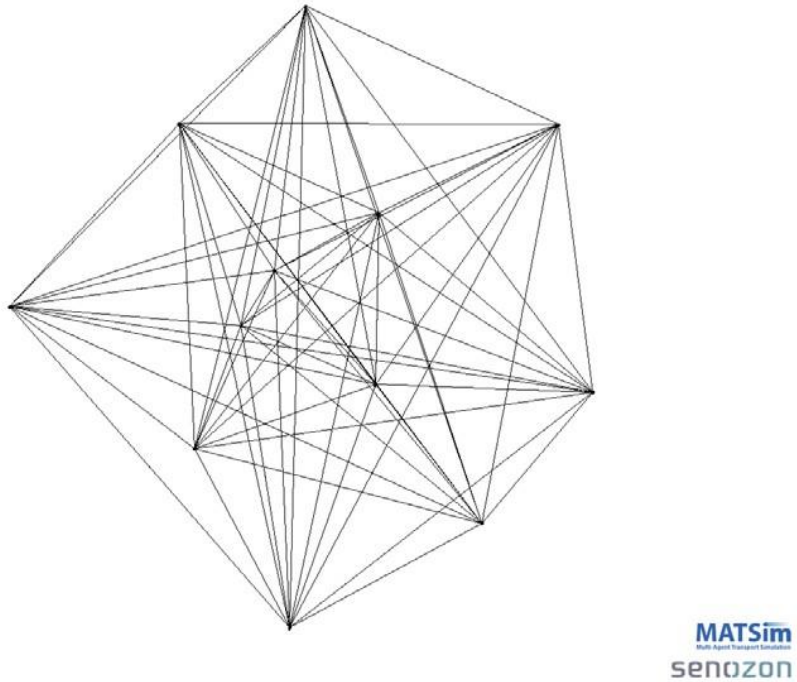

Figure B. 4 The connections between the district centroids of Zurich

These two public transport networks compose the urban transport network in Zurich which can be seen in Figure B. 5.

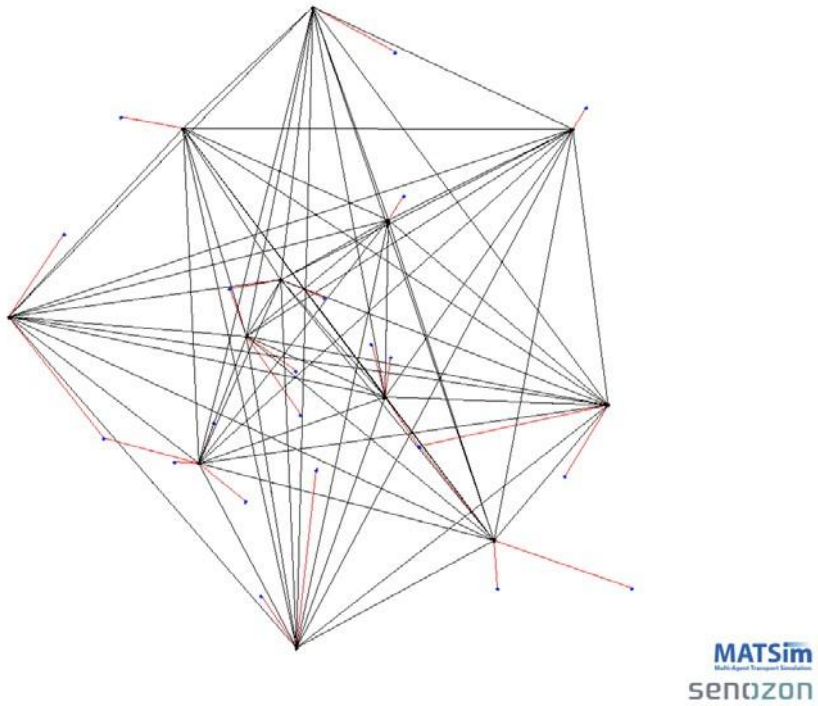

Figure B. 5 Urban transport network of Zurich

Line and vehicle capacities

In Visum, public transport vehicles are modelled through vehicle units (e.g. a wagon) and vehicle combinations

(e.g. an Intercity). Vehicle units can be combined to vehicle combinations. Both types of public transport vehicles entail information on the capacity (the number of seats and the total capacity including the standing capacity.

Unfortunately, not every line is attributed with a public transport vehicle. For instance, only 3.4% of the lines in the national transport model 2030 have specified a vehicle combination. Consequently, the capacity information is not available for those lines. Therefore, the missing information had to be added by hand to the lines. The classification of vehicle types, shown in Table B. 4, was taken as a basis.

Table B. 4 Classification of vehicle types

Vehicle type	Capacity [Number of seats]	Number
Long-distance traffic		100
Small LD train	400	101
TGV	400	102
Min LD train	450	103
Mid LD train	700	104
Max LD train	900	105
Regional traffic		200
Regional train	400	201
City railway		300
Metro Lausanne	300	301
Night train	500	302
City railway	1100	303
Tram		400
Min tram	150	401
Max tram	200	402
Bus		500
Call taxi	4	501
Min bus	15	502
Mid bus	30	503
Bus	80	504
Trolleybus/Low floor bus	120	505
Double-articulated bus	200	506
Ship		600
Min ferry	100	601
Max ferry	200	602
Ship	300	603
Ropeway		700
Aerial cableway	80	701
Funicular	100	702
Gondola cableway	10	703
Urban vehicle		900
Virtual urban vehicle	1000	901

Line routes and departures

Besides the missing capacities, some inconsistencies within the specification of public transport lines were detected. Some lines of the National Transport Model in Visum have no route specified or no departure at all. In addition, there are consecutive stops that have the same coordinates which leads to route links with zero length. In order to solve these issues, lines with no departure information were excluded and consecutive stops with the same coordinates were merged to one stop.

Timetable

A major difference between Visum and MATSim regarding the simulation of public transport is that public transport vehicles in Visum operate according to the timetable, whereas vehicles in MATSim run according to the travel times in the network. This is an issue because the travel times of the route in the network don't match the information in the timetable.

Therefore, the line routes in MATSim were created from scratch. A link between every stop was generated and the speed on that link was set in a way that the free flow travel time on the link matches the travel time according to the timetable.

Also, the timetables of the National Transport Model in Visum include no dwell time and sometimes there's no travel time between stops. This leads to unrealistic delays in MATSim because agents need some time (1s per agent) to get on and off the vehicle. If no dwell time is modelled, the vehicle gets delayed and this delay accumulates over the route. Thus, dwell times had to be added to the schedule. The dwell time was assumed to amount to 60s. If the next stop was closer than 60s, the dwell time was reduced to 30s. In the extreme case of no travel time between two stops, a travel time of 30s was added (meaning that the second stop gets served 60s later than in Visum).

If dwell time is added to the schedule, don't forget to set the parameter "awaitDeparture" for every stop to "true". Otherwise, the vehicle departures as soon as all passengers have entered or left.

Comparison

A final comparison of the public transport networks in Visum and in MATSim is given in Table B. 5.

Table B. 5 Comparison of the public transport networks in Visum and in MATSim

Attribute	2005 Visum	MATSim	2030 Visum	MATSim
Number of nodes	35'988	15'795	26'778	16'846
Number of links	57'348	56'059	60'670	64'050
Number of stops	39'377	56'059	18'202	64'050
Number of lines	19'231	19'136	9'495	10'108
Number of routes	18'919	22'205	9'912	14'426
Number of departures	62'422	155'657	90'305	208'643

B.2.2.3 Thinned transit router network

If public transport is fully simulated, a transit router network is created during the simulation which is required for routing the transit legs. For that purpose, walk links are added to the network allowing agents to walk from one stop to another. If the transit stops have the same coordinates, links with zero length are created. It's possible to remove most of those links while ensuring full connectivity. Thus, the simulation can be fastened up. For instance, over 17.8 million transfer links were added to the transit router network of 2010. All in all, the file contained roughly 18 million links. The employed transit router network thinner allows for a significant reduction. The thinned network in the end contains only 700'000 links.

The thinned transit router network is created prior to the simulation. When starting the simulation, the thinned network is read-in by writing a new transit router implementation factory and calling it in the controller. An example of such a new transit router implementation factory (not very elegant modelling) can be found under:

playground.staheale.matsim2030.NewTransitRouterImplFactory.

The code for writing-out and thinning a transit router network can be found under:

playground.christoph.evacuation.pt.

B.2.3 Facilities

B.2.3.1 Facilities

Facilities are generated for all secondary activities, namely shopping and leisure activities. For those two types of activities, agents are able to change the destination during the simulation. Home, work, and education destinations are fixed during the simulation. In the plans file, no facility is assigned to those activity types, instead coordinates are used. A refined version of the secondary activities facilities data set generated by Meister (2008) is employed where facilities are computed from the Federal Enterprise Census 2001 (Swiss Federal Statistical Office 2001). This survey collects data on all private and public businesses and workplaces in the second and third sector using NOGA-1995-classification. NOGA stands for Nomenclature Générale des Activités économiques and classifies businesses and workplaces according to their economic activity. In this manner, businesses and workplaces can be arranged in coherent groups (Swiss Federal Statistical Office 2011). Approximately 1'000 attributes related to employment (both full-time and part-time) and NOGA commercial types are aggregated on a hectare level or stored as presence-codes. Enterprises from the Federal Enterprise Census 2001 are grouped to shopping or leisure according to Table B. 6.

Table B. 6 Shopping and leisure activity types according to NOGA commercial types

Activity type	NOGA commercial types
Shopping	B015211A-E, B015212A-B, B015221A, B015222A, B015223A, B015224A, B015225A, B015226A, B015227A-B, B015231A, B015232A, B015233A-B, B015241A, B015242A-E, B015243A-B, B015244A-C, B015245A-E, B015246A-B, B015247A-C, B015248A-P, B015250A-B, B015271A, B015272A, B015273A, B015274A, B019301A, B019302A-B, B019305A
Leisure	B015540A, B019233A, B019234A-C, B019261A, B019262A-B, B019271A, B019272A, B019304A-C, B015530A, B015551A, B019213A, B019231A-B, B019234D, B019251A, B019252A, B019253A

In addition, opening times for shopping and leisure facilities are refined. Table B. 7 details the newly specified opening times.

Table B. 7 Opening times for shopping and leisure facilities

Location type	Opening times [day-day, hh:mm-hh:mm]
retail shop	According to the next retail store from sample data set containing opening hours and address of Migros, Coop, Denner, and Pick Pay (source: Meister)
service shop	Monday-Friday, 08:00-18:00
sport facilities	Monday-Friday, 09:00-22:00, Saturday-Sunday, 09:00-20:00
bar, discotheque, casino	Monday-Friday, 09:00-24:00, Saturday-Sunday, 16:00-24:00
restaurant, natural parks	Monday-Sunday, 09:00-24:00
theatre, cinema, orchestra	Monday-Sunday, 14:00-24:00
libraries, file rooms	Monday-Friday, 08:00-18:00, Saturday, 09:00-16:00
zoo, amusement park	Monday-Sunday, 09:00-18:00
museum	Tuesday-Saturday, 10:00-18:00, Sunday, 10:00-16:00

The resulting facility file *facilities2012secondary.xml* contains 105'081 facilities. In order that the simulation runs correctly with the opening times of the secondary facilities, it needs to be ensured that home and pt interaction activity locations are always opened during the simulation. For that purpose, the following code needs to be pasted into the employed scoring function which can be found under *org.matsim.contrib.locationchoice.bestresponse.scoring.DCActivityScoringFunction* (at line 228):

```
//return openInterval;
double homeOpening = 0;
double homeClosing = 30*3600; //corresponds to the end of the simulation (stuckTime)
double[] ot = {homeOpening, homeClosing;
return ot;
```

B.2.3.2 Facilities2Links

Each facility needs to be referenced to a link in the network, so that it's clear from which link agents can access a certain facility. Normally, the closest link is taken, no matter which modes are allowed on the link. This leads to a problem if some links do not allow cars. During the iterations (or already at the start of the simulation), it's possible that the mode of a trip to a facility referring to a link which doesn't allow cars gets changed to "car". The simulation then crashes because the agent isn't able to reach the link. This isn't a problem for public transport because the last stage of the trip can be teleported ("transit_walk") and the agent can also access facilities that refer to a link not allowing public transport.

The problem can be solved by referencing facilities only to links which allow cars. Obviously this isn't the most elegant solution, but bearing in mind that the car network is very dense, it's reasonable to make this assumption without losing substantial precision. For that purpose, a text file is created which entails the link reference of each facility. The code for this project can be found under

playground.staheale.matsim2030.ConnectFacilities2Links.

This file can then be plugged to the simulation by calling the WorldConnectLocations module in the controller:

```
ActivityFacilities facilities = this.getFacilities();
NetworkImpl network = (NetworkImpl) this.getNetwork();
WorldConnectLocations wcl = new WorldConnectLocations(this.getConfig());
wcl.connectFacilitiesWithLinks(facilities, network);
```

In the config-file, the “f2l” module needs to be added:

```
<module name="f2l" >
        <param name="inputF2LFile" value="&INBASE;/facilities2links.txt" />
        <param name="outputF2LFile" value="null" />
</module>
```

B.3 Config-file

This section describes the setting of the config-file. A small paragraph is devoted to the modules where further explanation is given. No description is provided for modules with standard settings.

When starting a simulation, it’s recommended to always check thoroughly the output config-file which is automatically written to the output folder. The output config-file entails all parameters and you can check if also the parameters that you didn’t specify in your config-file are set correctly according to your scenario.

controller module

The simulation is set to run for 150 iterations. Results showed that the average score is fairly stable after 150 iterations, implying that a user equilibrium is approximated. Nevertheless, this value should not be regarded as fixed. 150 iterations are rather few iterations for this kind of scenario, but due to the long computing times, it was decided to abstain from simulating 200-300 iterations. “FastAStarLandmarks” is used as routing algorithm because it showed to be the fastest one. Events and plans are written only every 10th iteration in order to save computing time and memory.

global module

The number of threads was set to 20. It represents an experience value from older scenarios, but no extensive study on the optimal value was conducted within this project.

f2l module

As mentioned in section 2.3, this module was used to reference facilities to links.

planCalcScore module

The setting of these values is described in more detail in section 4.

qsim module

The simulation runs until 30:00:00. A later end time (e.g. 36:00:00) wasn't chosen in order to fasten up the simulation. 8 threads were used for qsim which represents an experience value from older scenarios. The stuck time is 30s and the parameter "removeStuckVehicles" is set to false. Thus, stuck vehicles are pushed into the next link after not moving for 30s.

The flow capacity is scaled to 0.1, whereas the storage capacity remains 1.0. It was tested to scale down the storage capacity to 0.1 as well, but this lead to more unrealistic blockages on short links in the TeleAtlas network. The setting of those two factors should always be tested because it depends on the features of the scenario (resolution of the network, simulated sample of the population, etc.).

scenario module

The parameters "useTransit" and "useVehicles" need to be set to "true" in order to enable the full public transport simulation.

strategy module

The following modules were used within this scenario:

- Selecting a plan: "ChangeExpBeta", an agent changes to another plan if that plan is better. The probability to change depends on score difference.
- Route choice: "ReRoute", the module calculates new least cost routes using the travel times from the previous iteration.
- Time choice: "TimeAllocationMutator", the module mutates the duration of activities randomly.
- Mode choice: "SubtourModeChoice", the module changes the transportation mode of a sub-tour.
- Location choice: "org.matsim.contrib.locationchoice.BestReplyLocationChoicePlanStrategy", the module changes the destination of secondary activities (shopping and leisure).

For the first 15 iterations, it showed to be useful to just perform the route, time, and "select plan" modules in order to make sure that agents find reasonable slots before starting to bring in mode and location choice. The fact that a 10% sample of the population (resulting in a down-scaled network) and a very dense navigation network for cars were used, lead to unrealistic blockages of small links and biases in the simulation. Therefore, it was decided to first "distribute" agents better when starting the simulation. In addition, this scaling problem didn't allow to run smaller population samples (e.g. 1%) because the biases were even higher. Small roads were either not used or congested. These biases also occur in other areas of the simulation where capacities are defined (public transport vehicles, facilities, etc.).

In order to implement that the route, time, and “select plan” modules are run for the first 15 iterations, the module definitions were copied and added to the end of the strategy module. The probabilities of the last three modules were then increased up three digit values and the parameter “ModuleDisableAfterIteration” was set to 15 for those three modules.

The location choice module runs for 30 iterations which is enough according to experiences of previous scenarios. It’s disabled after 45 iteration.

All replanning modules except for the “select plan” module are disabled after 130 iterations. Agents just select their “best” plan out of their portfolio of plans for the last 20 iterations. This results in a characteristic upward shift of the average score after 130 iterations. It’s recommended to always disable replanning for the last iterations.

The setting of the strategy modules is detailed in Table B. 8.

Table B. 8 Overview of the employed strategy modules

Module	Number	Probability	Disabled after iteration
ChangeExpBeta	1	0.6	-
ReRoute	2	0.2	130
TimeAllocationMutator	3	0.1	130
org.matsim.contrib.locationchoice.BestReplyLocationChoicePlanStrategy	4	0.1	45
SubtourModeChoice	5	0.1	130
ChangeExpBeta	6	700	15
ReRoute	7	100	15
TimeAllocationMutator	8	100	15

locationchoice module

In order to enable destination choice, a specific controller, namely org.matsim.contrib.locationchoice.DCControler, has to be used. Therefore, this controller served as a basis for the one that was set up for MATSim 2030. This controller can be found under playground.staheale.matsim2030.RunControlerMATSim2030.

The module contains a number of parameters. For most of them, the standard configuration was used. The search algorithm is set to “bestResponse” and a destination sample of 1% is chosen. For computational reasons, the parameter “tt_approximationLevel” is set to 2 which means that the travel-times are approximated based on the distance (no routing). Nevertheless, it would better to use routing (level 0: complete routing, level 1: local routing).

The parameter “epsilonScaleFactors” is important. This allows for scaling the epsilons and consequently scaling the distance distribution. The lower the values, the lower the distances. For this scenario, a scale factor between 0.1 and 0.7 has been used. Do not set it to 0.0 because the module (up to now) doesn’t work with zero epsilons.

The facility load penalty functionality of the module is not used; the parameters “restraintFcnExp” and “restraintFcnFactor” are set to 0.0. The utility of performing an activity doesn’t depend on the facility load within this scenario.

As mentioned in section 2.1.2, the preferences file is loaded by the parameter “prefsFile”.

Make sure that you use the term for shopping and leisure consistently in the scenario (plans, preferences, facilities, config-file, etc.). For instance, avoid using “shopping” at one point and “shop” at another point.

transit module

Within this module, the paths to the schedule and the vehicles file has to be specified. Also the transportation modes that are handled as transit are defined. For this scenario, there’s only one transit mode named “pt”.

It’s again of high importance to use this term consistently in the scenario. Corresponding terms need to be used in the plans file (leg mode), in the schedule file (mode of the transitRoute), and in the network file (link mode).

parallelEventHandling module

Parallel event handling is turned on for this scenario. The number of threads is set to 5 representing an experience value, but no extensive study on the optimal value was conducted within this project.

timeAllocationMutator module

Here one can set how many seconds a time mutation can maximally shift. The default value is 1800s which is quite low. For this scenario, a mutation range of 7200s is selected.

subtourModeChoice module

Within this scenario, the chain-based modes are car and bike. It’s assumed that these vehicles are parked and need to be picked up again.

The parameter “considerCarAvailability” is set to true (the default is false!). In this manner, an agent only has the car mode available for mode choice if he has a license and access to a car. Whereas license ownership is modelled, car availability is not included in the scenario (agents always have access to a car, this is the default if car availability is not defined in the plans-file). In summary, the car mode can only be chosen by agents owning a license, but the availability of a car is not modelled.

planscalcroute module

Within this module, the parameters for calculating the routes are configured. The values from previous scenarios were taken as a reference. Only the bike speed and walk speed were changed during

the calibration (in combination with other parameters). Please check the next section for more information. In the end, the bike speed was set to 4.167m/s, the walk speed to 1.34m/s.

B.4 Calibration

B.4.1 Introduction

Calibration of a scenario is quite complex and time consuming. Since MATSim delivers a wide range of results in a very disaggregate state, many aspects of the output can be examined and compared to census/survey results. Additionally, numerous input parameters and settings can be adjusted.

Matters were complicated further by the fact that one iteration took more than one hour. This meant that one had to wait at least two days (50 iterations) to see where for instance the modal split was heading to. Also, a great part of the initial calibration was performed without the location choice module because it needed to be updated in order to work with the fully simulated public transport.

Due to the limited time, it was decided to first have a look at the modal split and the distance distribution of car trips because the partners of the THELMA project that needed scenario results were only interested in car traffic. From MATSim, they only required information on all car trips (start time, end time, length of the trip, etc.).

The input parameters that were changed in order to control the modal split and distance distribution of car trips were mainly parameters of the utility function (*planCalcScore*) and the routing module (*planscalcroute*). Also the setting of the strategy modules were adapted during the calibration process. Table B. 9 gives an overview of the parameters that were changed during calibration.

Table B. 9 Overview of the adjusted parameters

Parameter	Range	Remarks
planCalcScore		
earlyDeparture	-180/-18	only changed for further calibration
traveling	-6.0 – 0.0	
travelingPt	-6.0 – 0.0	
travelingWalk	-6.0 – 0.0	
travelingBike	-15.0 – 0.0	
constantCar	-6.0 – 0.0	
constantBike	-8.0 – 0.0	
constantPt	-3.0 – 0.0	
qsim		
storageCapacityFactor	0.1/1.0	
planscalcroute		
bikeSpeed	2.084/4.167	
walkSpeed	0.833/1.34	
strategy		
location choice	on/off	
reroute	-	probability of getting selected for the first 15 iterations was changed
timeAllocationMutator	-	probability of getting selected for the first 15 iterations was changed
controler		
lastIteration	50-200	
location choice		
epsilonScaleFactors	0.0-1.0	
prefsFile	-	minimal durations for shopping and leisure were changed

In general, simulation results were also checked in Via which offers a wide range of analyses. For instance, transit stats can be produced or link volumes can be analyzed. The tool is very helpful for getting an overview of the plausibility of the simulation output.

B.4.2 Initial calibration

Always two calibration runs were set up at the same time. For the initial calibration, the leg distance distribution file, created every tenth iteration, was loaded in Excel and then compared to Microcensus 2010 data. This file is written by the ControlerListener *LegDistanceDistributionWriter* which can be found under *herbie.running.controler.listeners*. In Excel, the overall mode share, the mode share per distance category and the car distance distribution were examined. Figure B. 6 shows exemplary the overall mode share of the delivered 2010 baseline run. It can be seen that the car mode share matches the Microcensus 2010 data quite well, whereas the other modes have higher deviations.

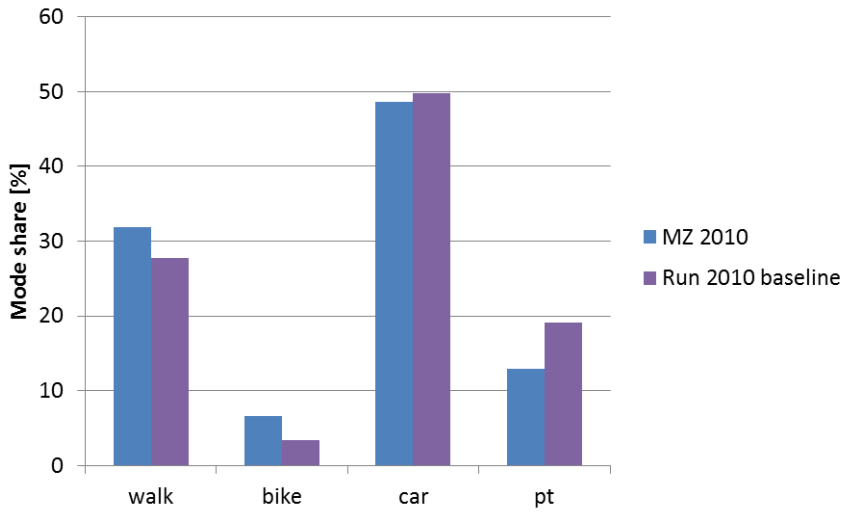

Figure B. 6 Overall mode share of 2010 baseline run

The car distance distribution of the delivered 2010 baseline run is shown in Figure B. 7

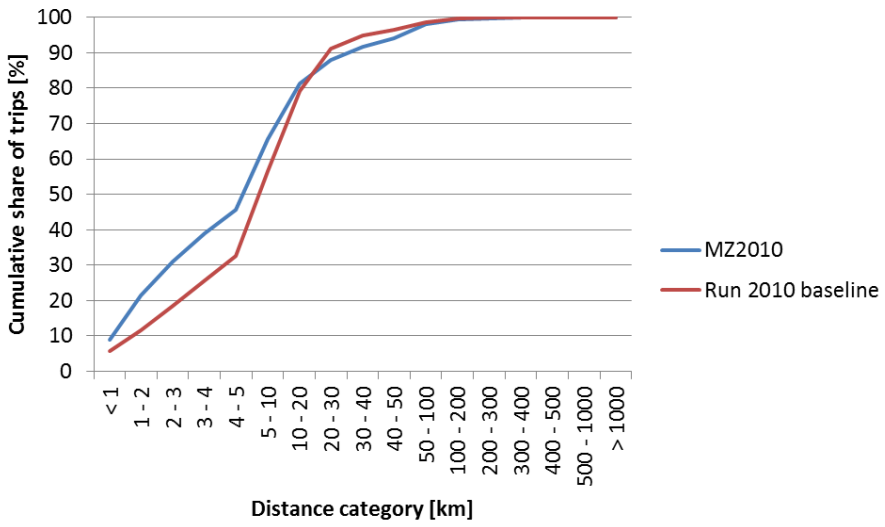

Figure B. 7 Car distance distribution of 2010 baseline run

There are less short car trips than according to the Microcensus. In general, the trip distances for all modes are longer than in the Microcensus data. Therefore, the aim of further calibration efforts is to reduce the distances by setting the location choice module differently (reduce the epsilonScaleFactors).

B.4.3 Further calibration

For further calibration, it was decided to examine the output with R (https://rstudio.ivt.ethz.ch/) rather than with Excel. This has several advantages. It's faster, less error-prone once the code is written and offers more flexibility for analysis. For that purpose, a program was written that creates a trip text file out of an events file. The trip text file entails the following information for every trip: agent Id, trip start time, start link, start link x coordinate, start link y coordinate, end link, end link x coordinate, end link y

coordinate, main mode and trip purpose. The code can be found under *playground.staheale.analysis.Events2Trips*. Analyses in RStudio are then based on this trip text file. Figure B. 8 shows the overall mode share of further calibration runs. The aim is to adjust the mode shares of walk, bike and pt trips in order to match the Microcensus 2010 data better.

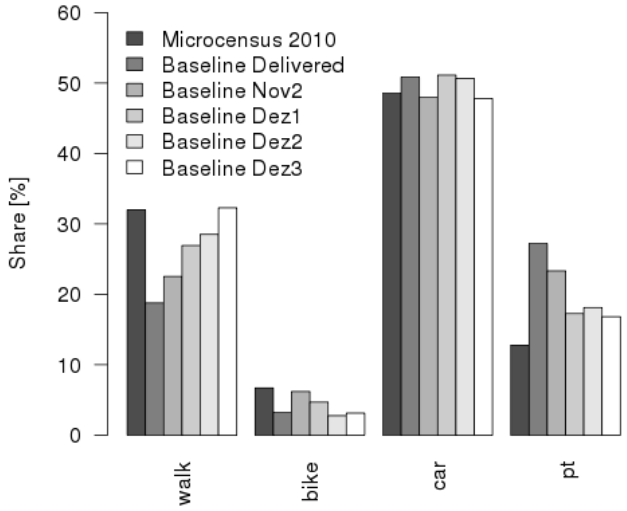

Figure B. 8 Overall mode share of further calibration runs

For the latest run in December (Dez3), dwell times were added to the transit schedule. The results look very promising, but there was an error in the transit schedule (the vehicles didn't wait for the departure time at a stop). Therefore, this run has to be repeated again. The overall trip distance distribution can be seen in Figure B. 9.

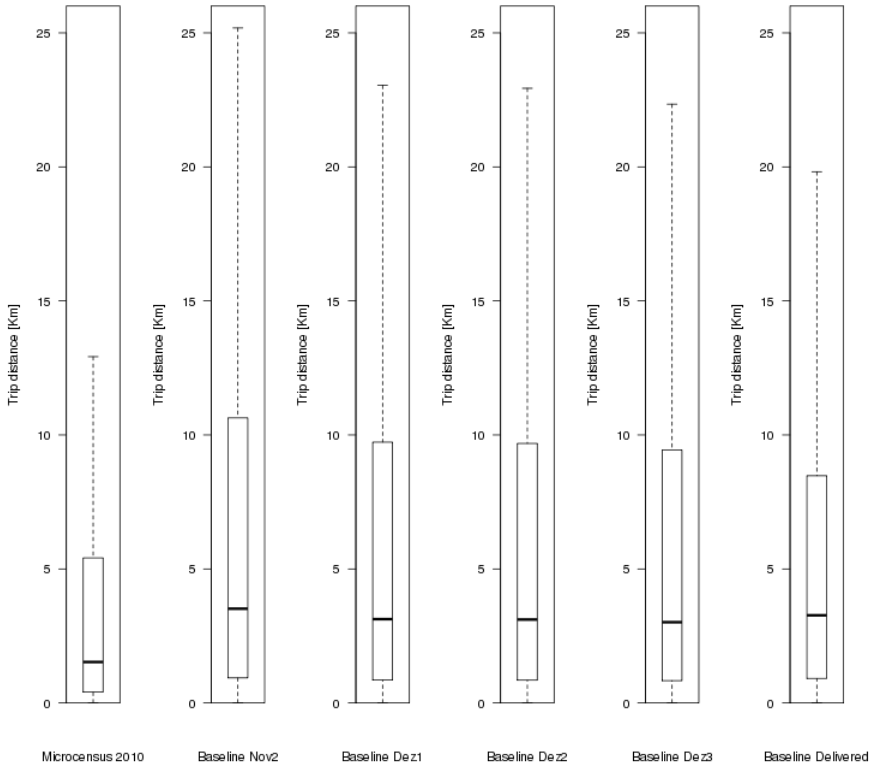

Figure B. 9 Overall trip distance distribution

As mentioned previously, the trip distances are longer than in the Microcensus 2010 data. The changes in the location choice module of the further calibration runs (lower epsilonScaleFactors) didn't lead to expected improvements. Therefore, the module was checked again. Analysis showed that the module works for car trips, but not properly for the other modes. There's a problem with the routing to the evaluated facilities because they are referenced to car links (where the other modes aren't allowed). The code was corrected and the next calibration run should check if location choice is working for all modes. There's R-code already available that plots the overall distances (as in Figure 9), the distances per mode and the distances per purpose.

If the distances are reduced, the mode share will change again. Therefore, changes of the parameters in the *planCalcScore* module are very likely. In addition, the activity durations should be checked as well. Up to now, the durations haven't been compared to Microcensus 2010 information. The trip text file described above can be used for that purpose.

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Appendix C: Vehicle Indicators for 2012 and 2050

Authors: Warren Schenler[48], Stefan Hirschberg[49] (PSI)

List of figures

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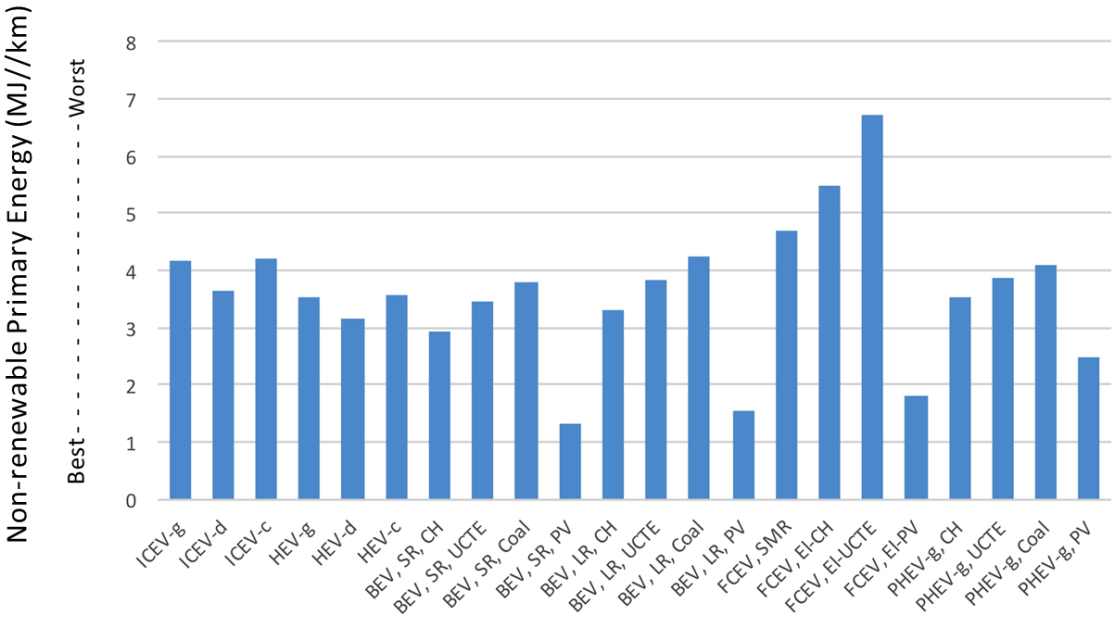

Figure C. 1 2012 Non-renewable Primary Energy (absolute)

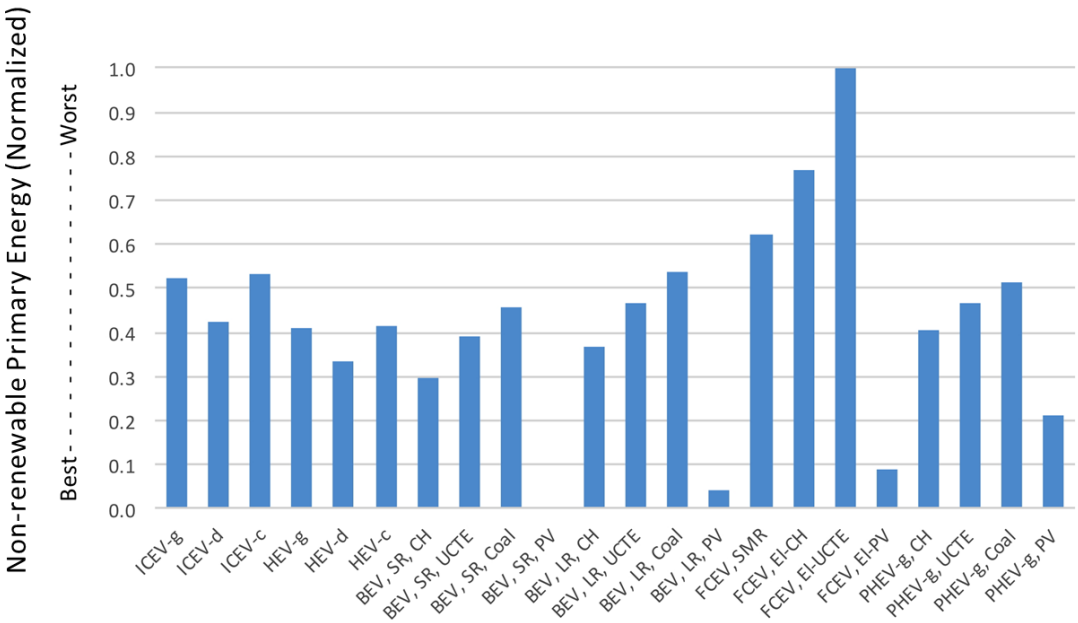

Figure C. 2 2012 Non-renewable Primary Energy (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

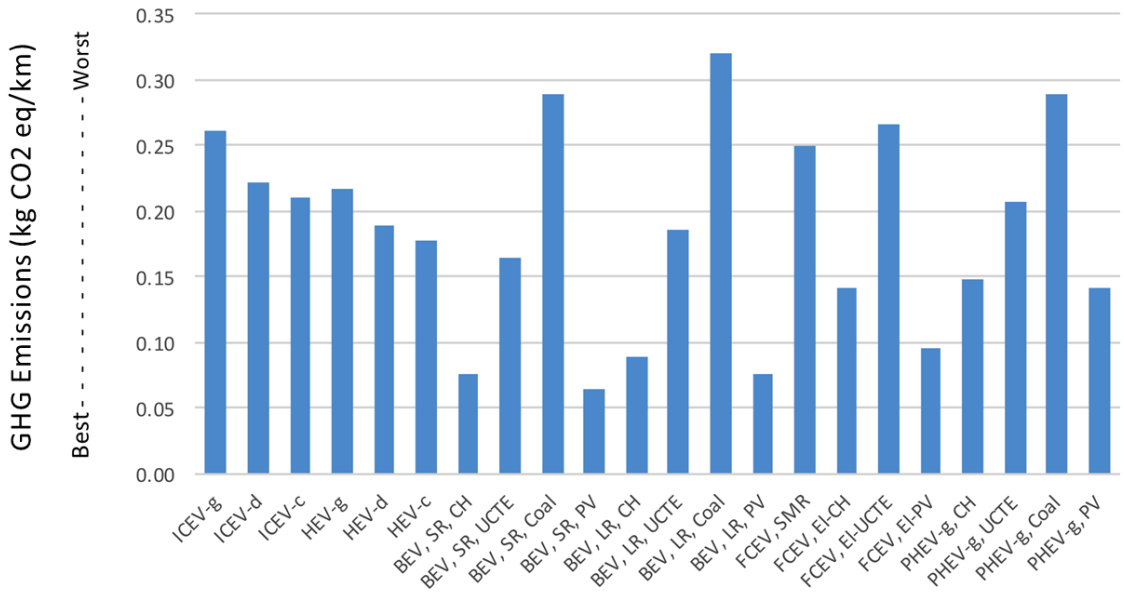

Figure C. 3 2012 Greenhouse Gas Emissions (absolute)

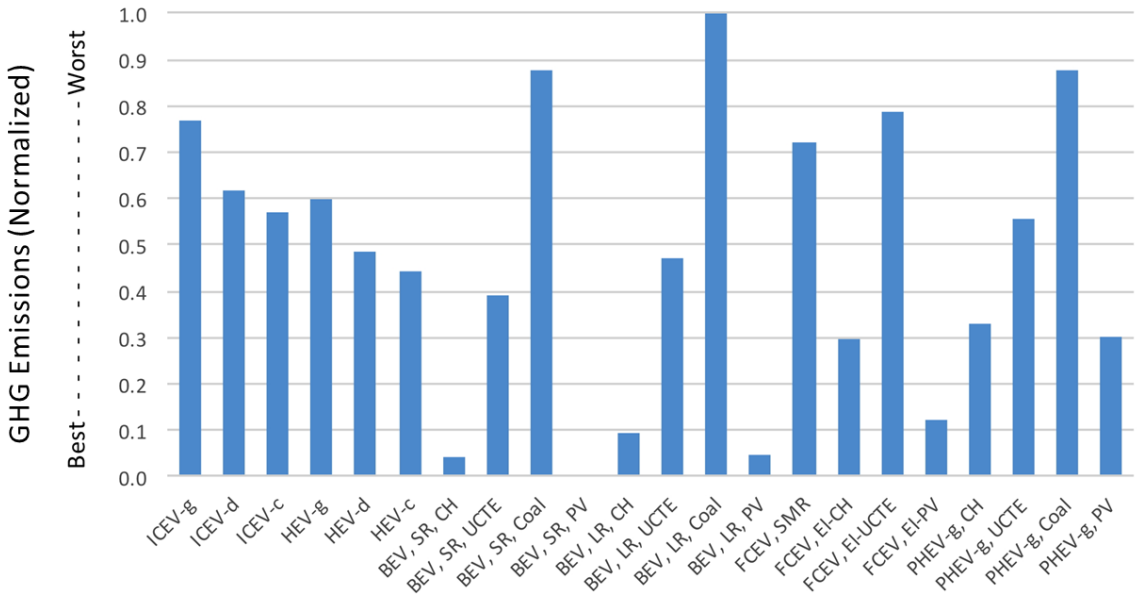

Figure C. 4 2012 Greenhouse Gas Emissions (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

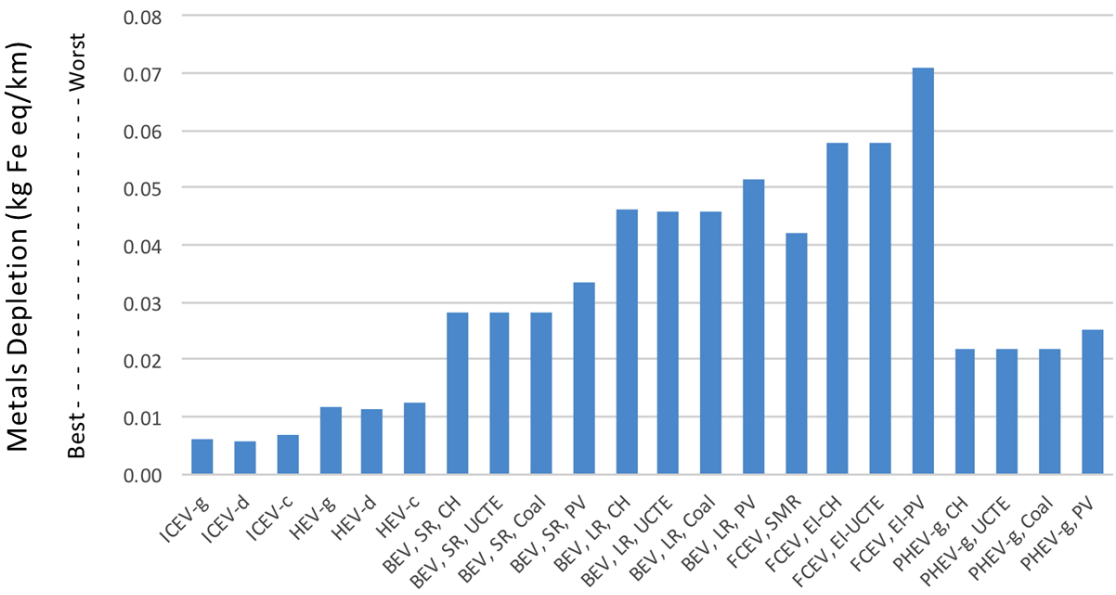

Figure C. 5 2012 Metals Depletion (absolute)

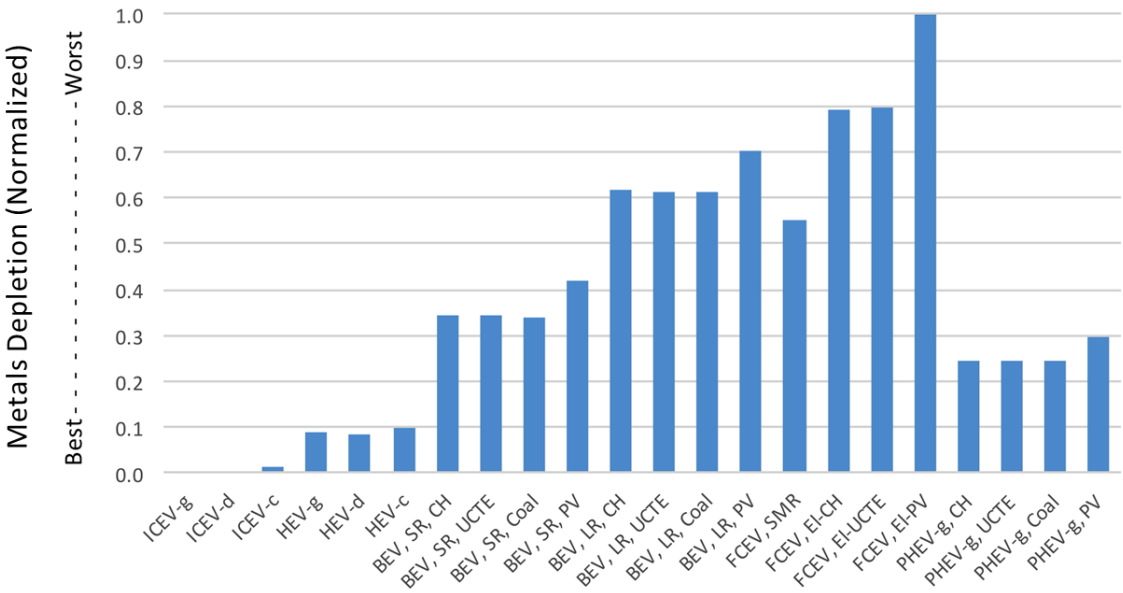

Figure C. 6 2012 Metals Depletion (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

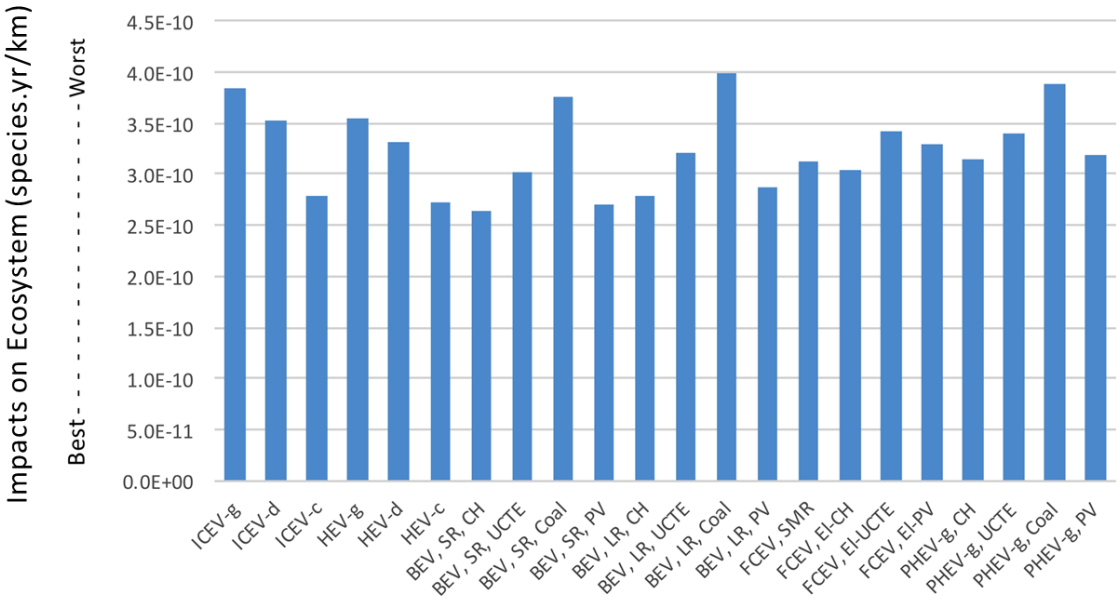

Figure C. 7 2012 Ecosystem Impacts (absolute)

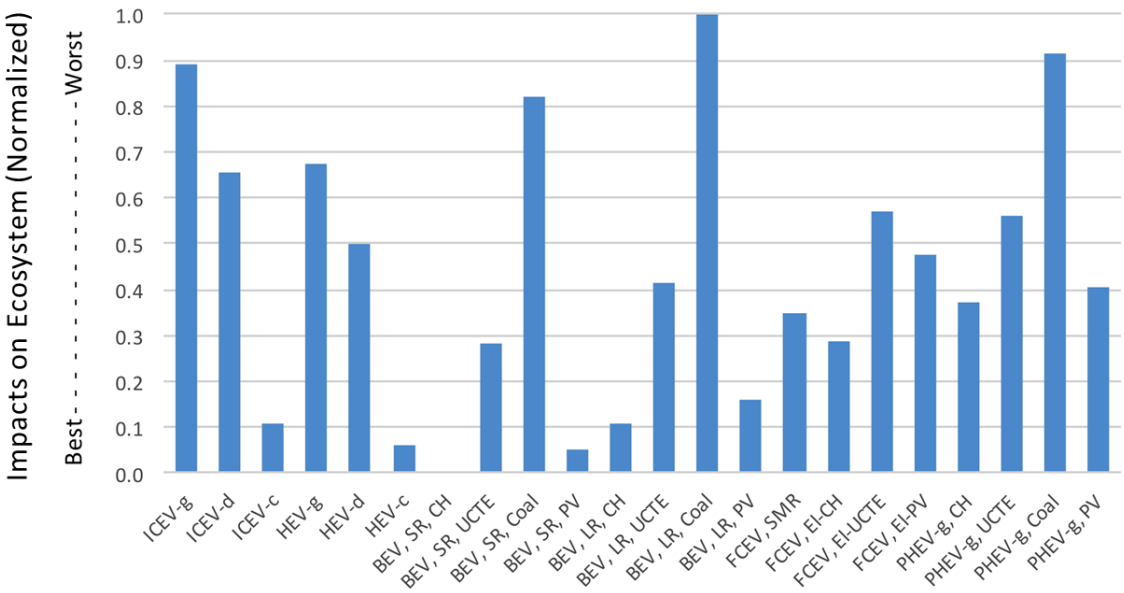

Figure C. 8 2012 Ecosystem Impacts (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

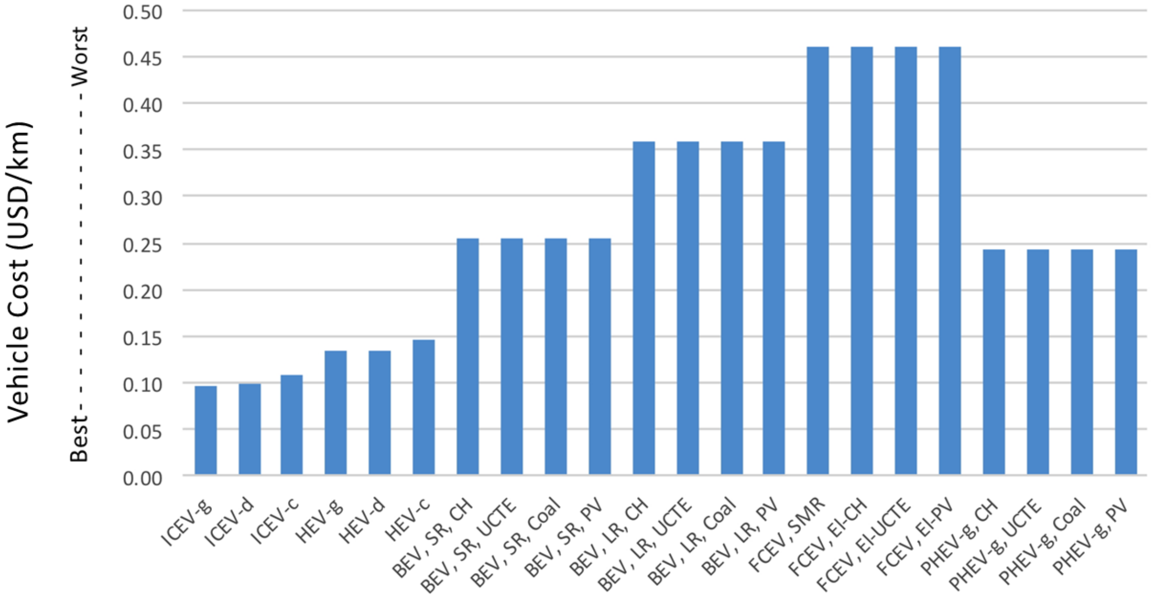

Figure C. 9 2012 Vehicle Cost (absolute)

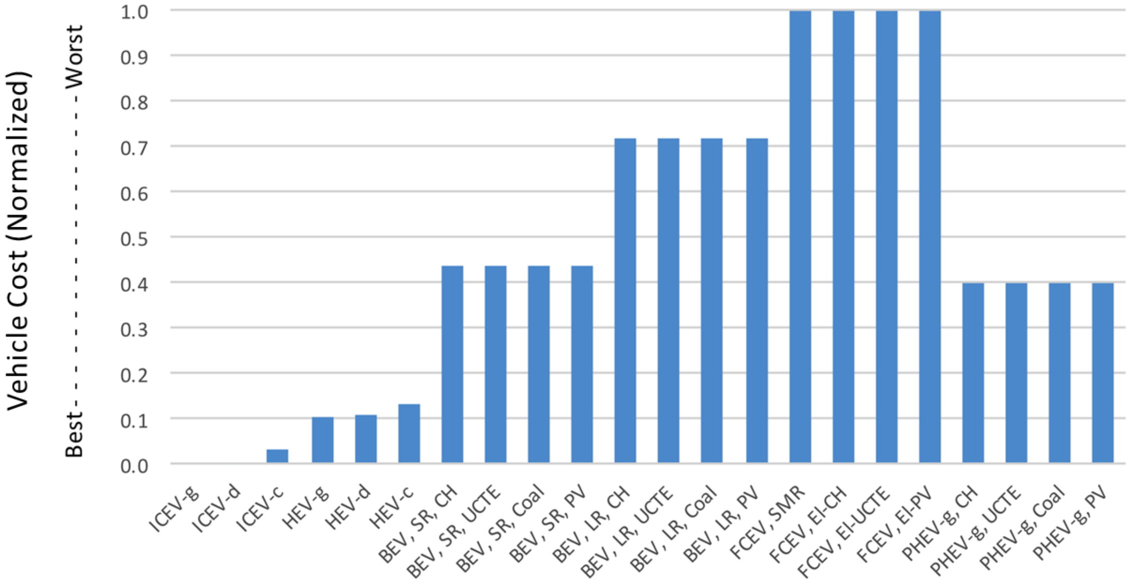

Figure C. 10 2012 Vehicle Cost (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

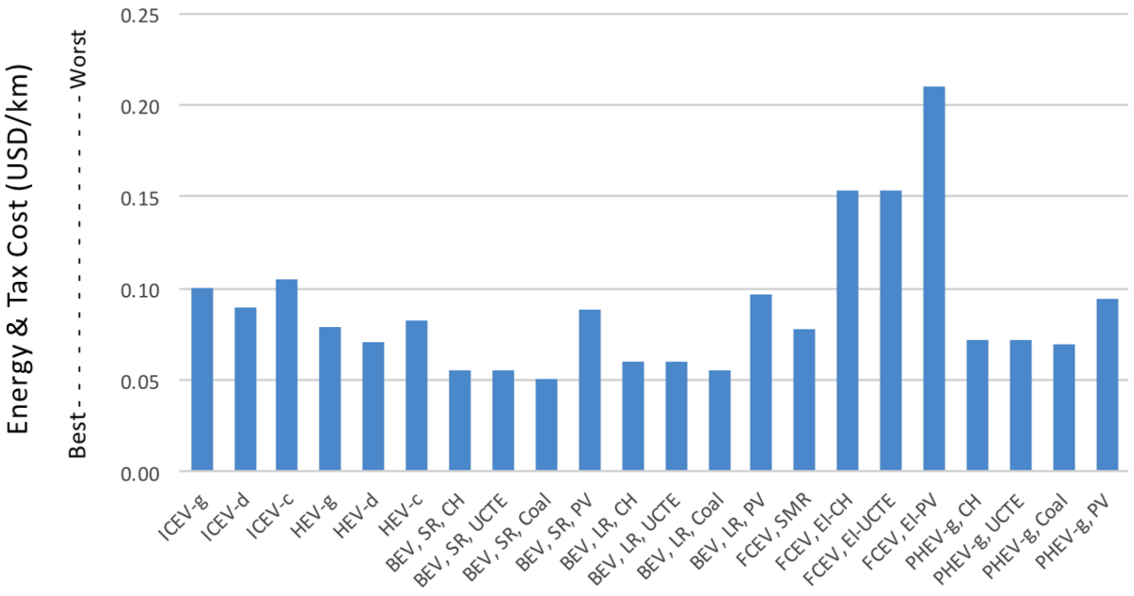

Figure C. 11 2012 Energy & Tax Cost (absolute)

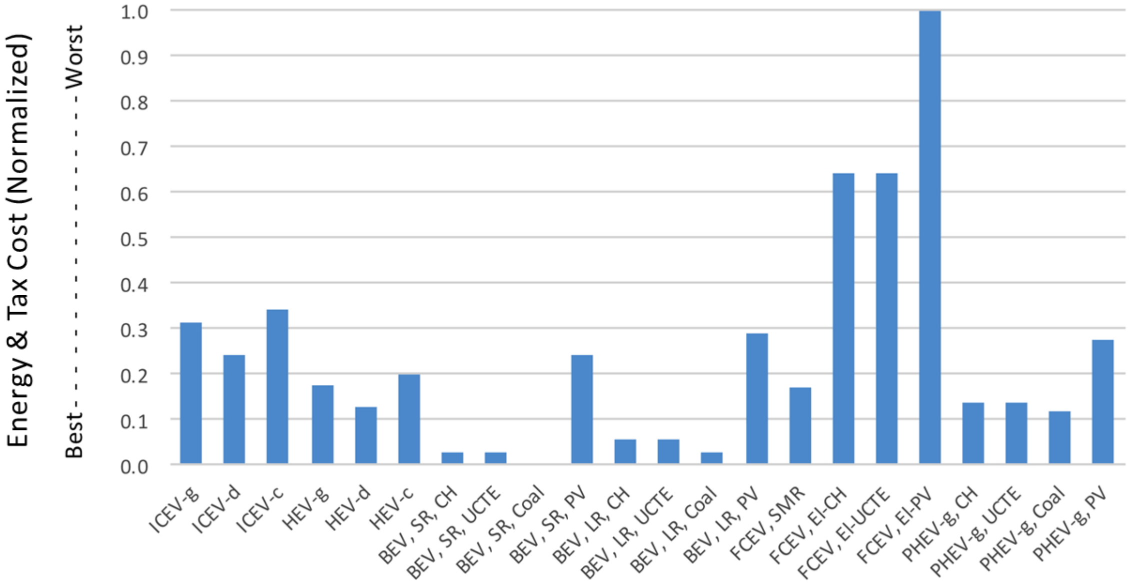

Figure C. 12 2012 Energy & Tax Cost (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

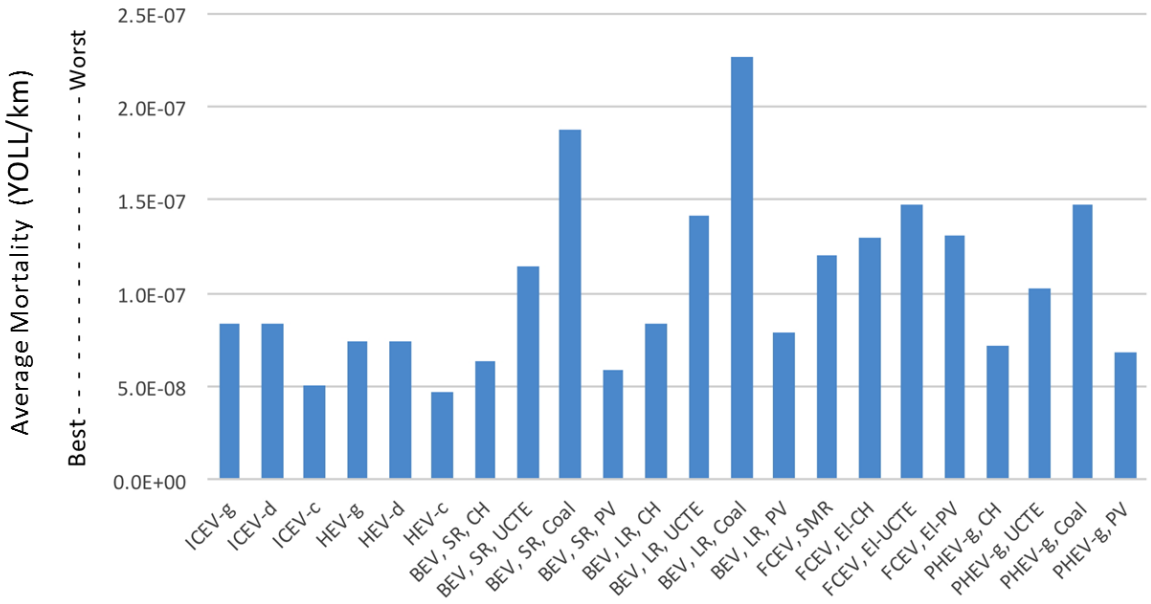

Figure C. 13 2012 Average Mortality (absolute)

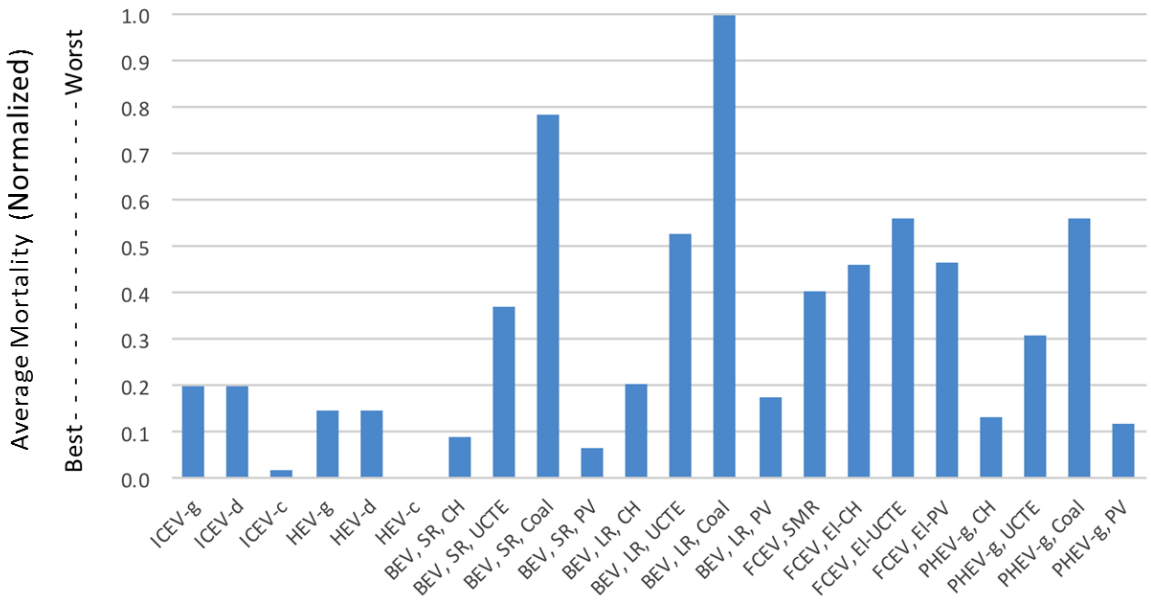

Figure C. 14 2012 Average Mortality (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

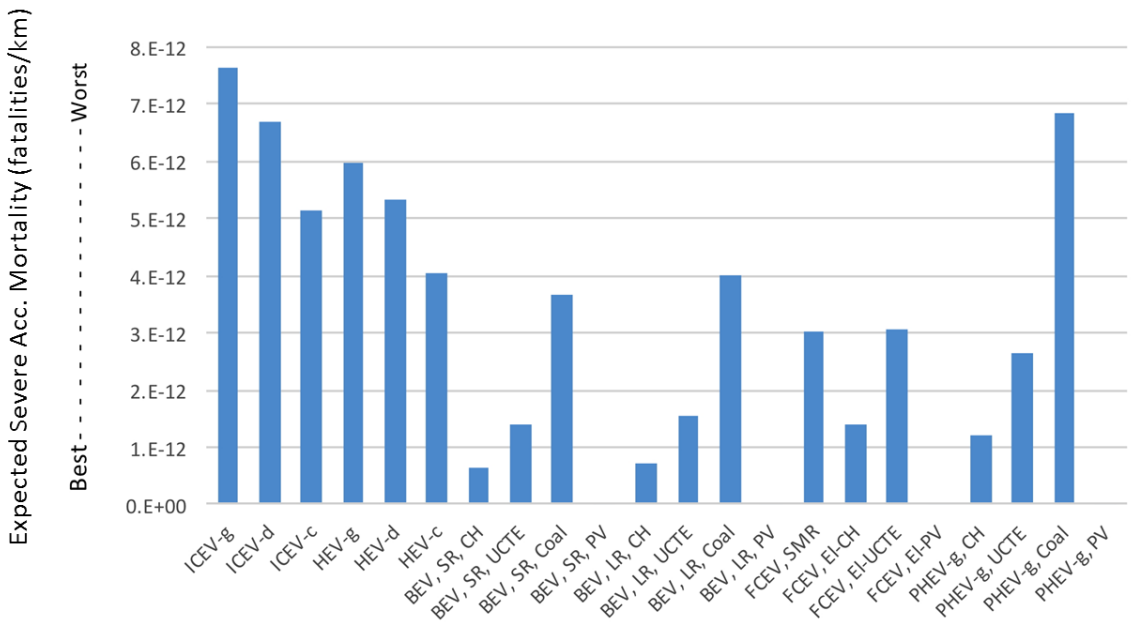

Figure C. 15 2012 Severe Accident Fatalities (absolute)

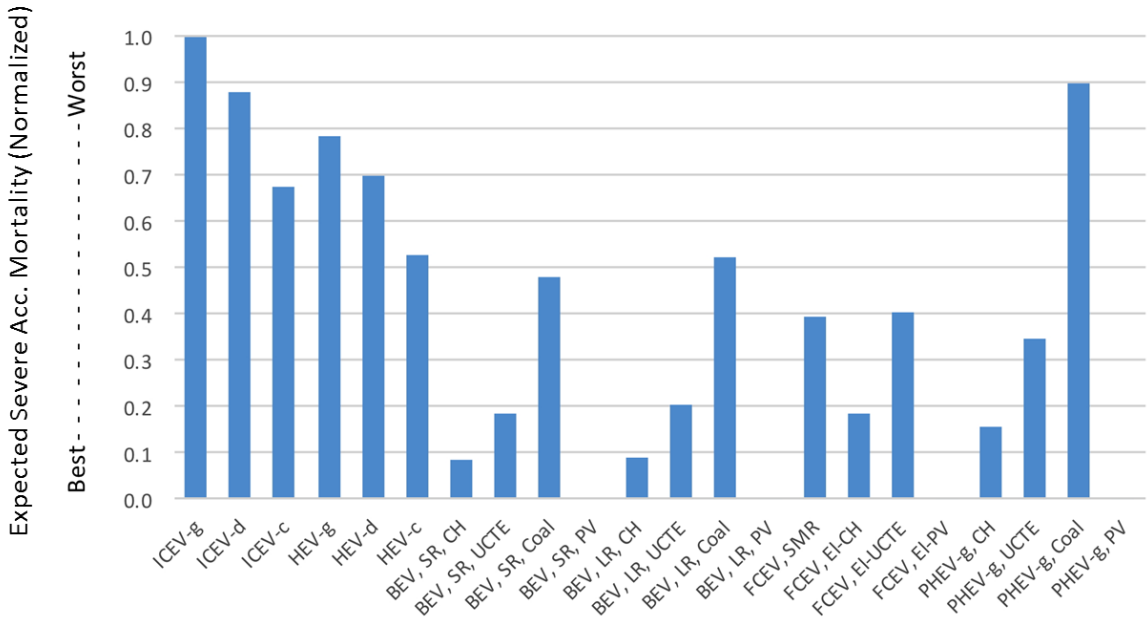

Figure C. 16 2012 Severe Accident Fatalities (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

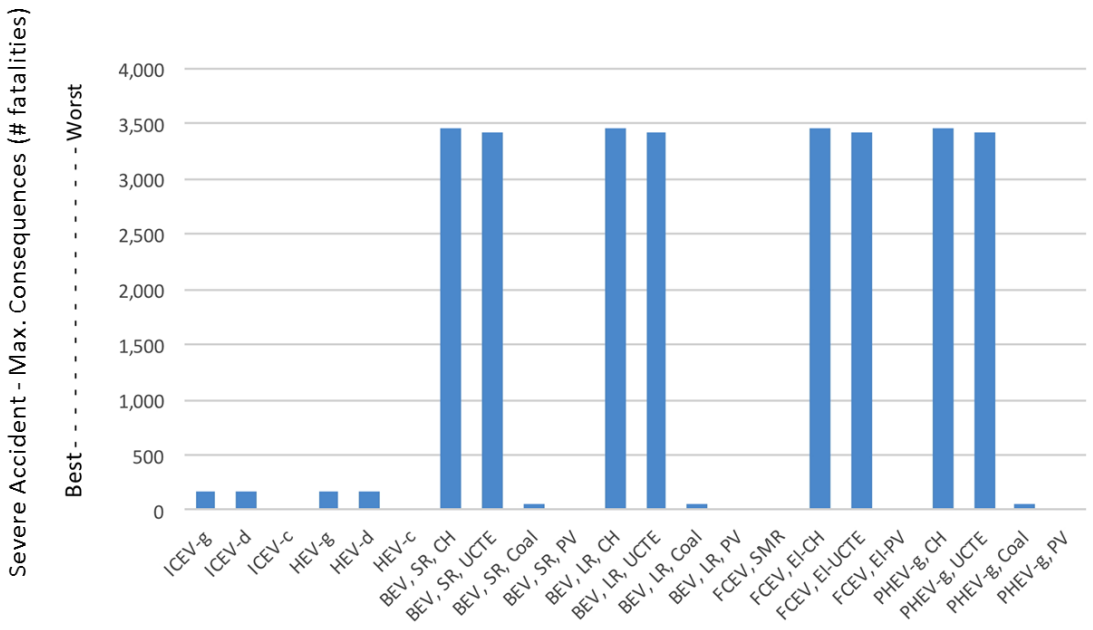

Figure C. 17 2012 Maximum Fatalities (absolute)

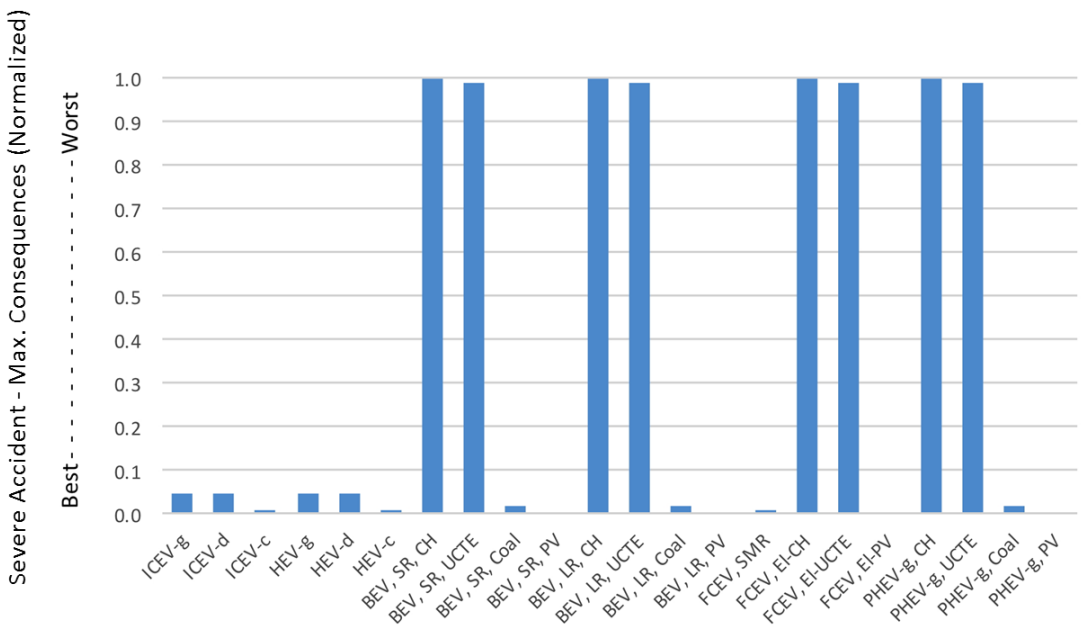

Figure C. 18 2012 Maximum Fatalities (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

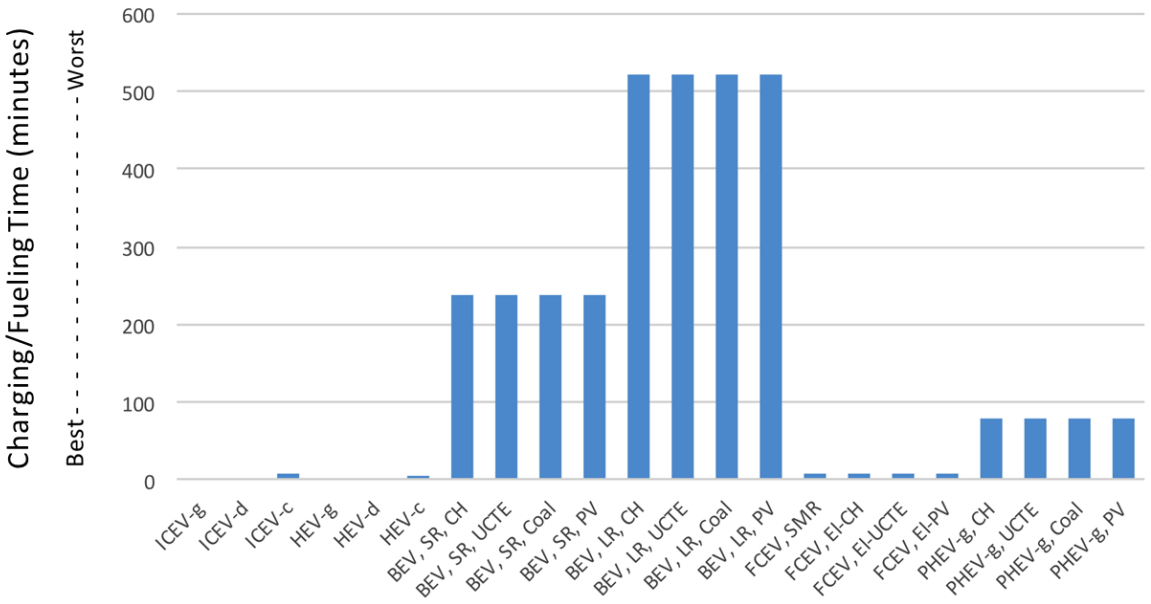

Figure C. 19 2012 Charging, Fueling Time (absolute)

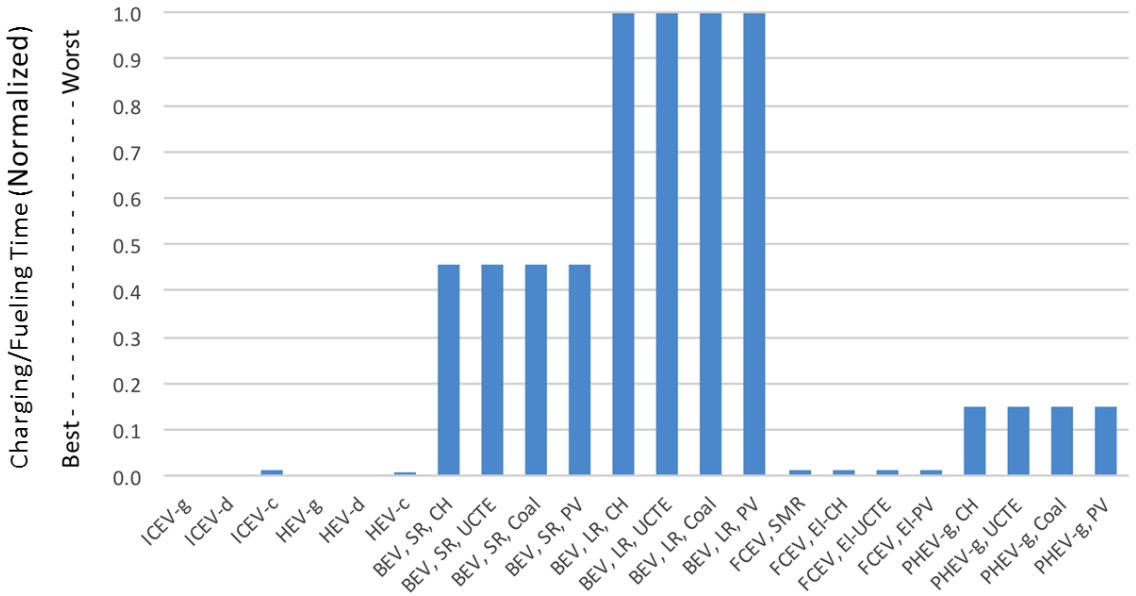

Figure C. 20 2012 Charging, Fueling Time (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

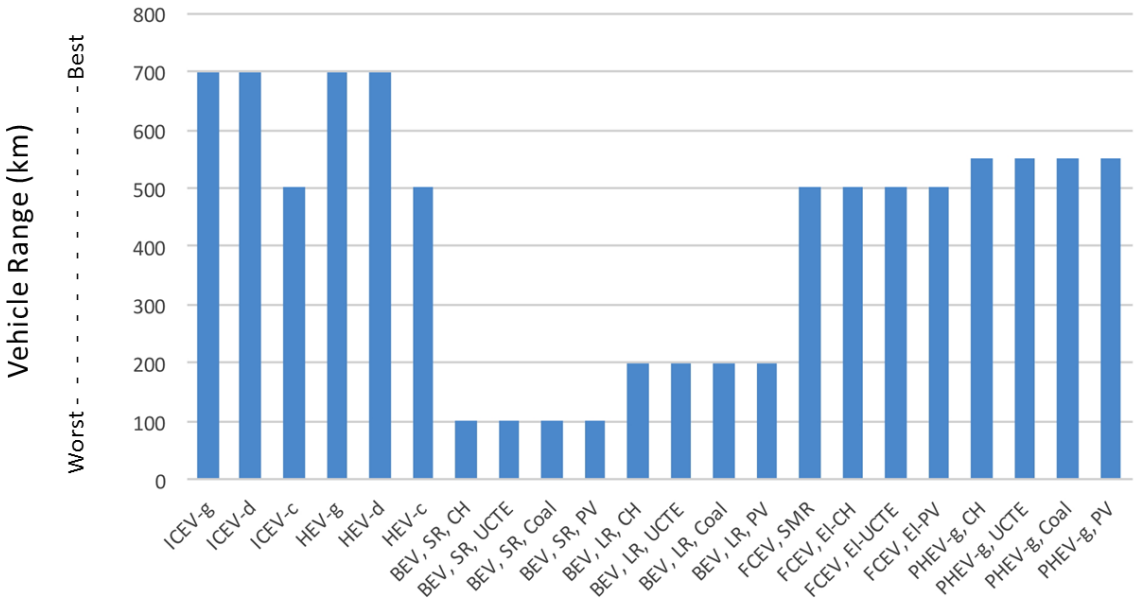

Figure C. 21 2012 Vehicle Range (absolute)

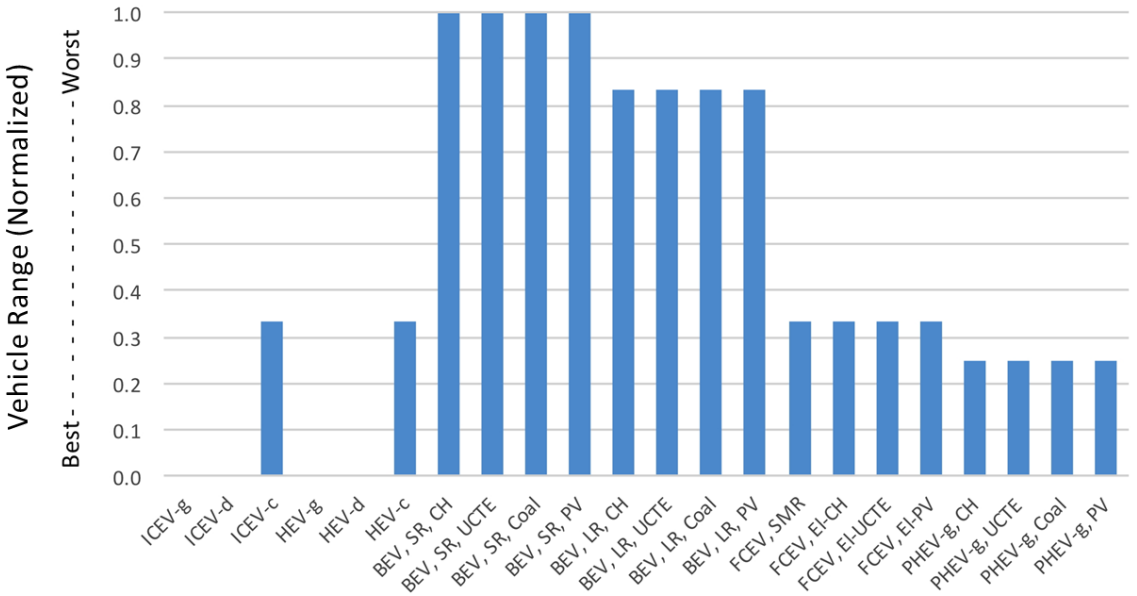

Figure C. 22 2012 Vehicle Range (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

CH - Swiss Elec. Mix
UCTE - UCTE Elec. Mix
Coal - Imported coal power
PV - Photovoltaic power

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

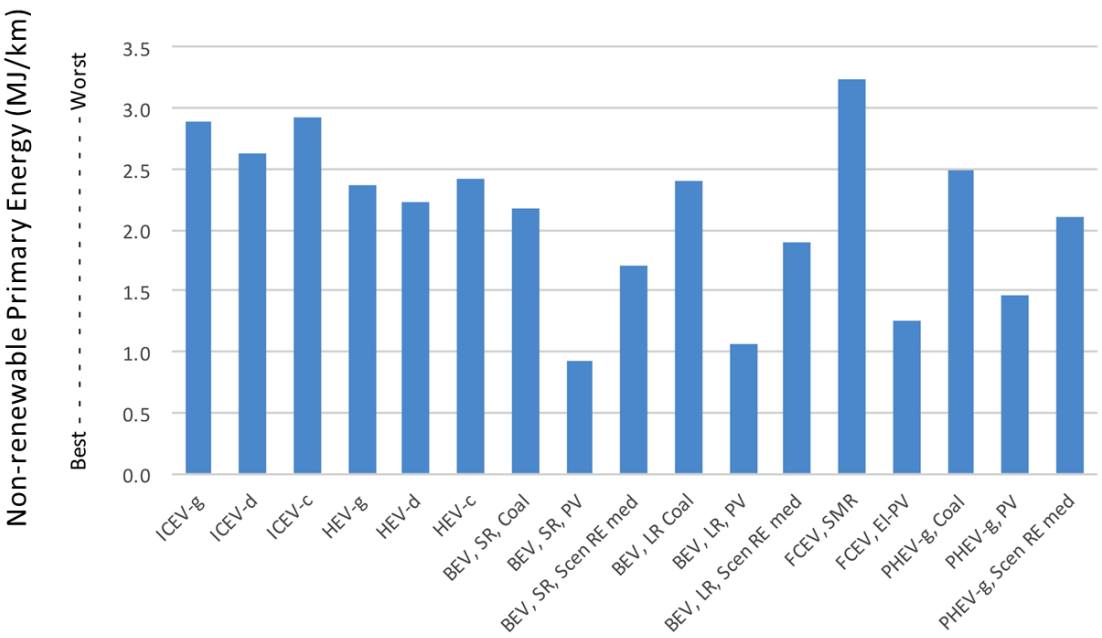

Figure C. 23 2050 Non-renewable Primary Energy (absolute)

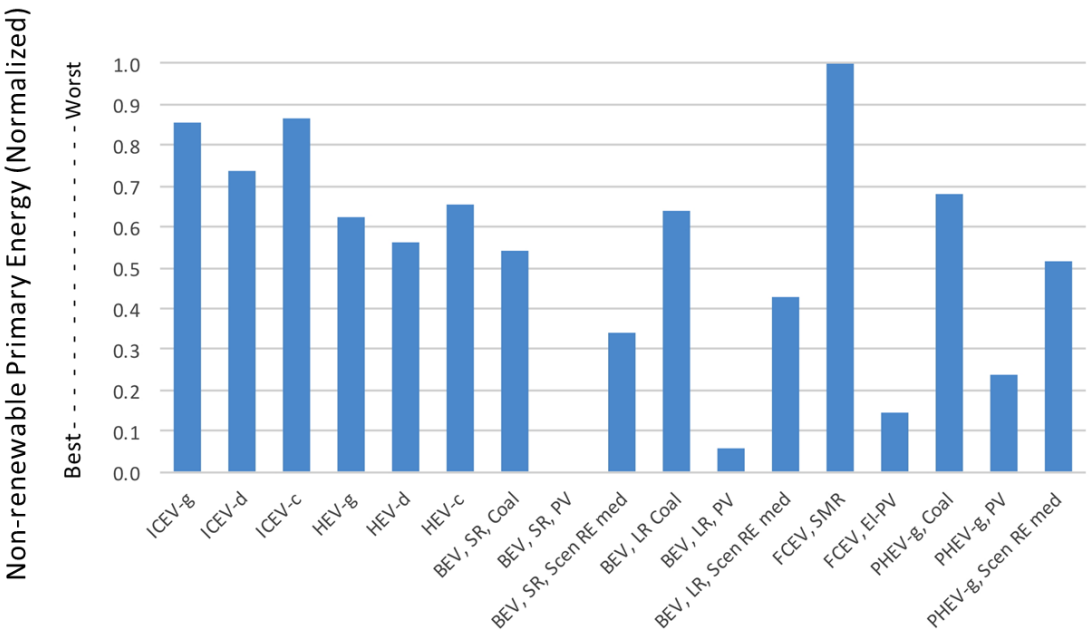

Figure C. 24 2050 Non-renewable Primary Energy (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

Coal - Imported coal power
PV - Photovoltaic power
Scen RE med – SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

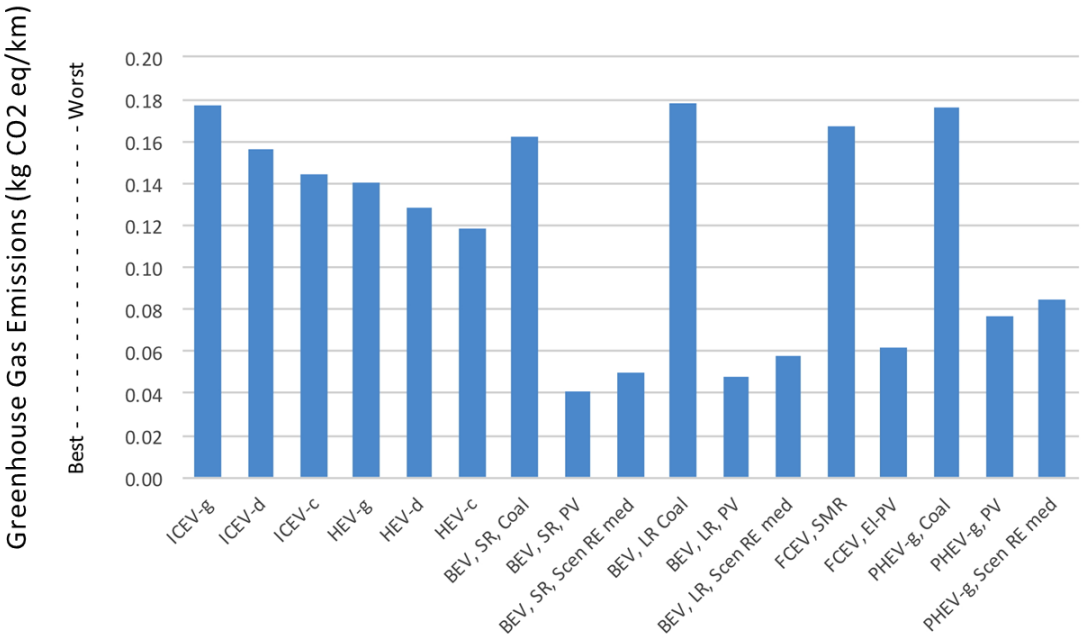

Figure C. 25 2050 Greenhouse Gas Emissions (absolute)

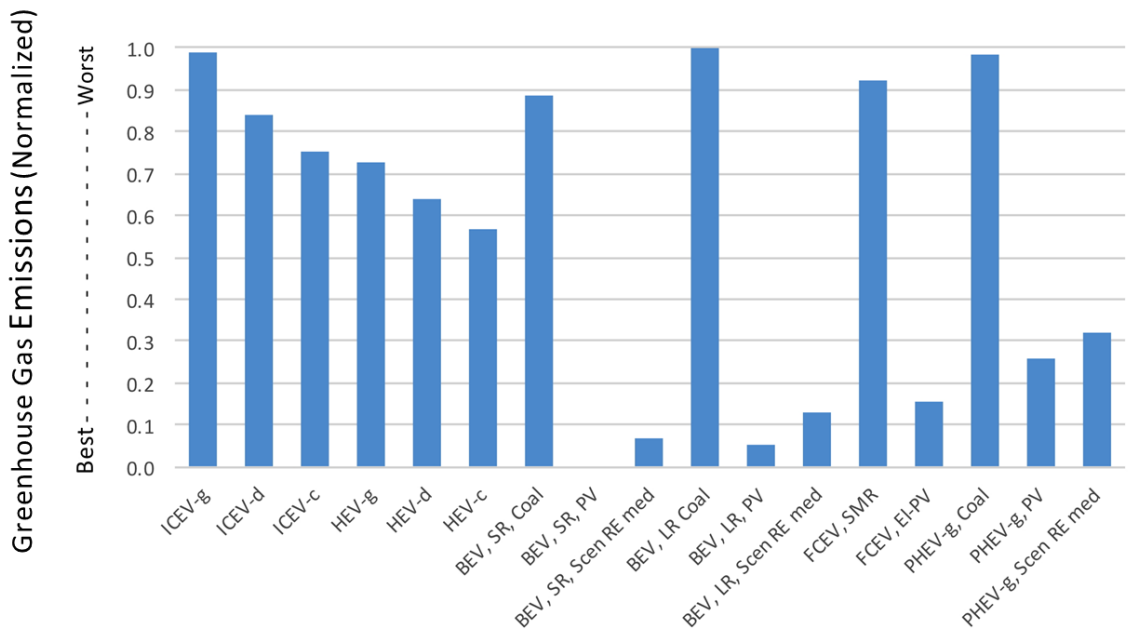

Figure C. 26 2050 Greenhouse Gas Emissions (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

Coal - Imported coal power
PV - Photovoltaic power
Scen RE med – SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

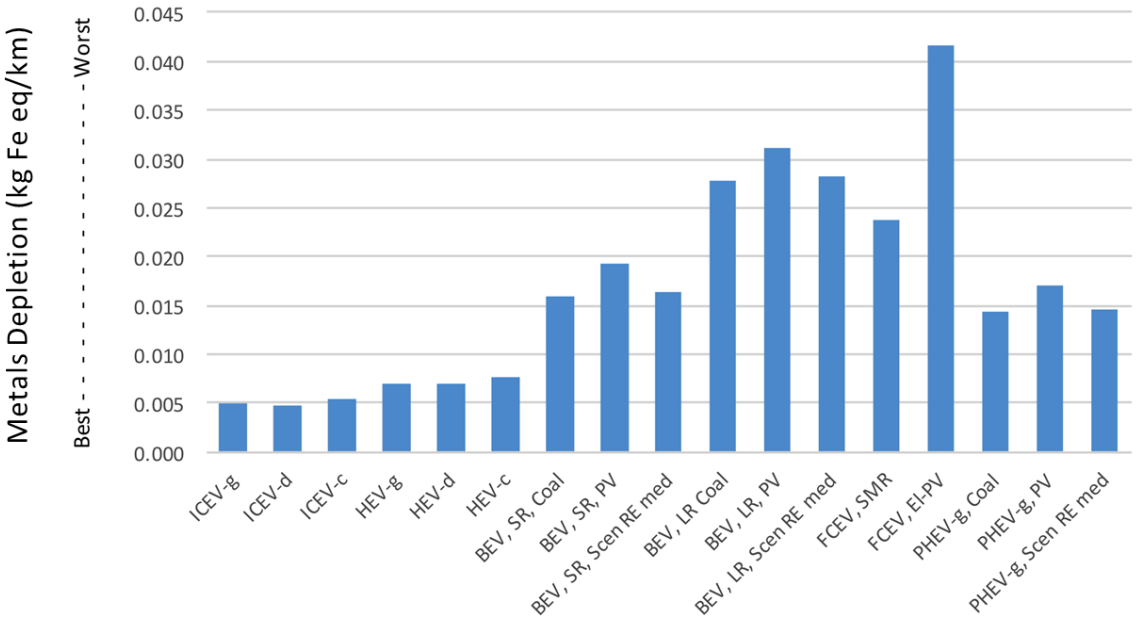

Figure C. 27 2050 Metals Depletion (absolute)

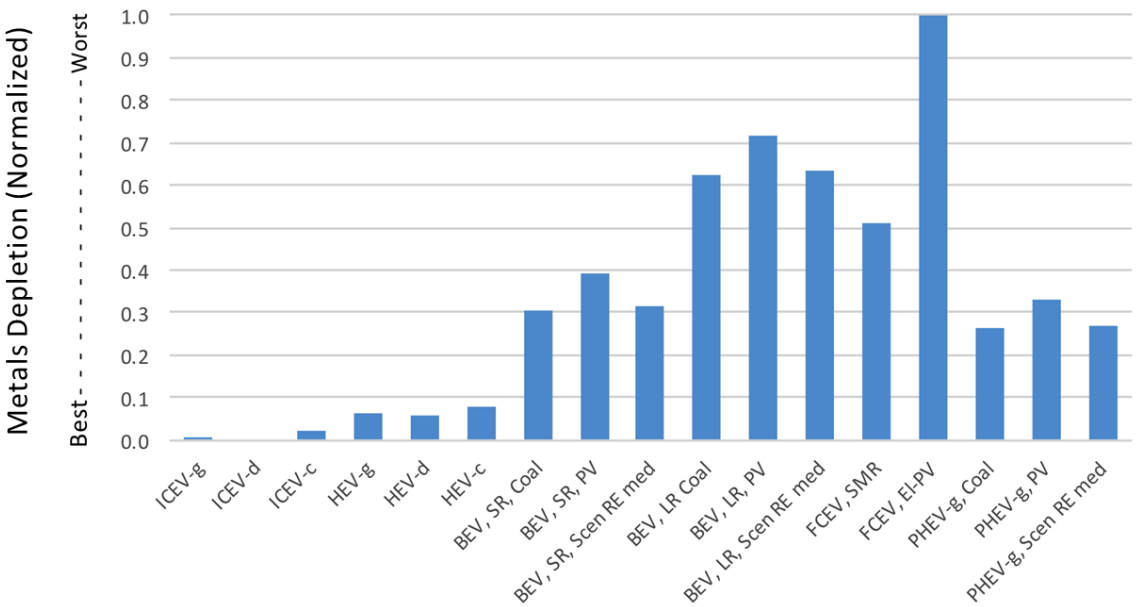

Figure C. 28 2050 Metals Depletion (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

Coal - Imported coal power
PV - Photovoltaic power
Scen RE med – SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

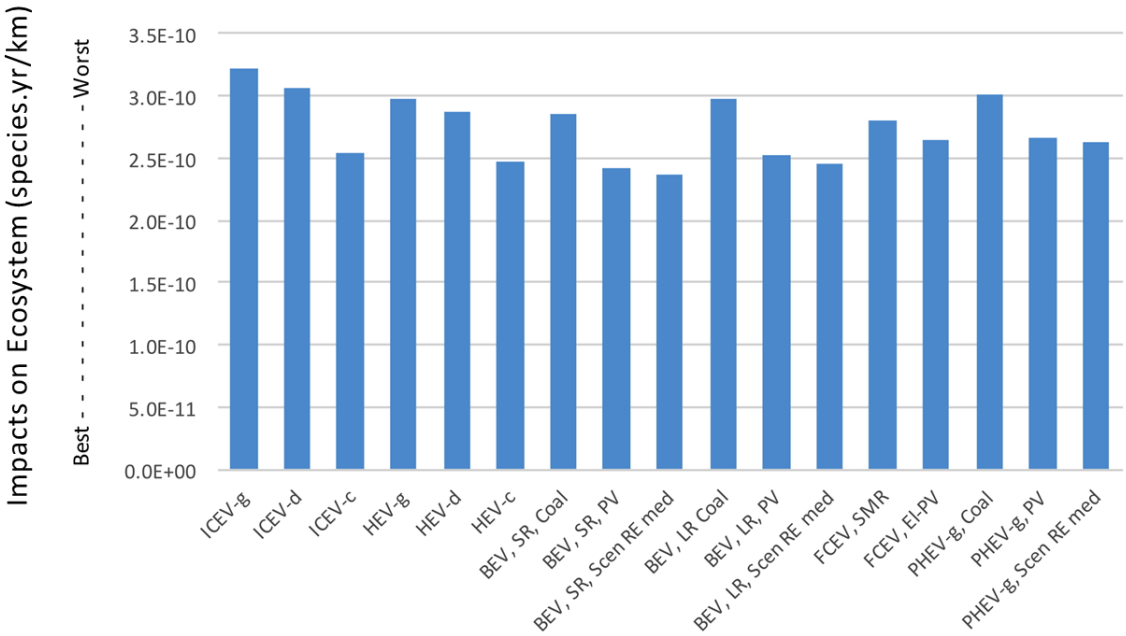

Figure C. 29 2050 Ecosystem Impacts (absolute)

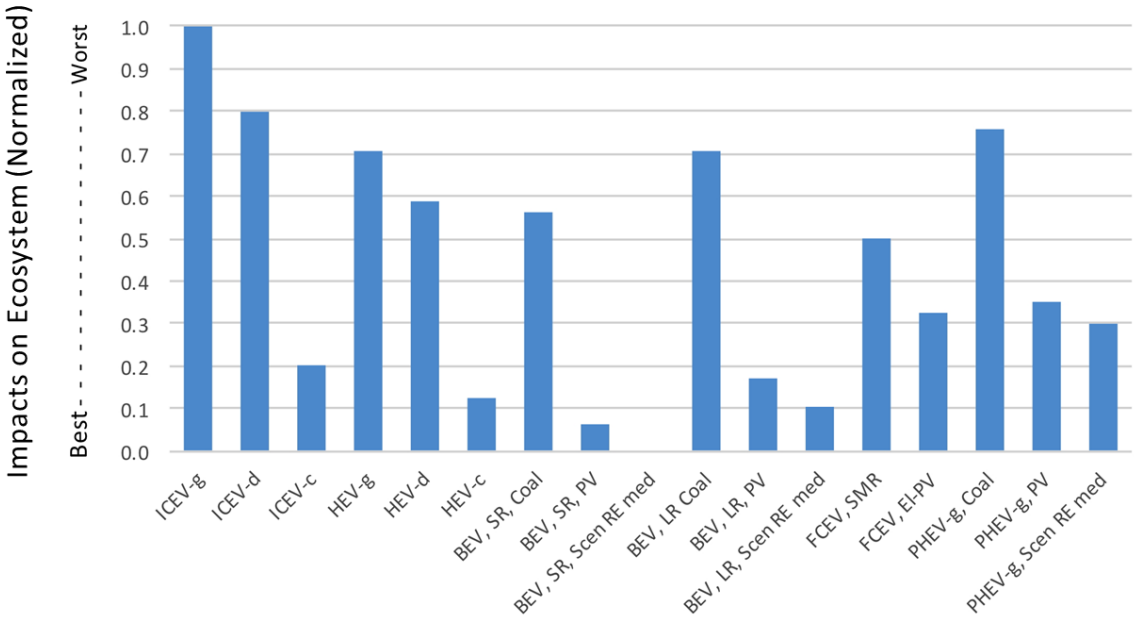

Figure C. 30 2050 Ecosystem Impacts (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

Coal - Imported coal power
PV - Photovoltaic power
Scen RE med – SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

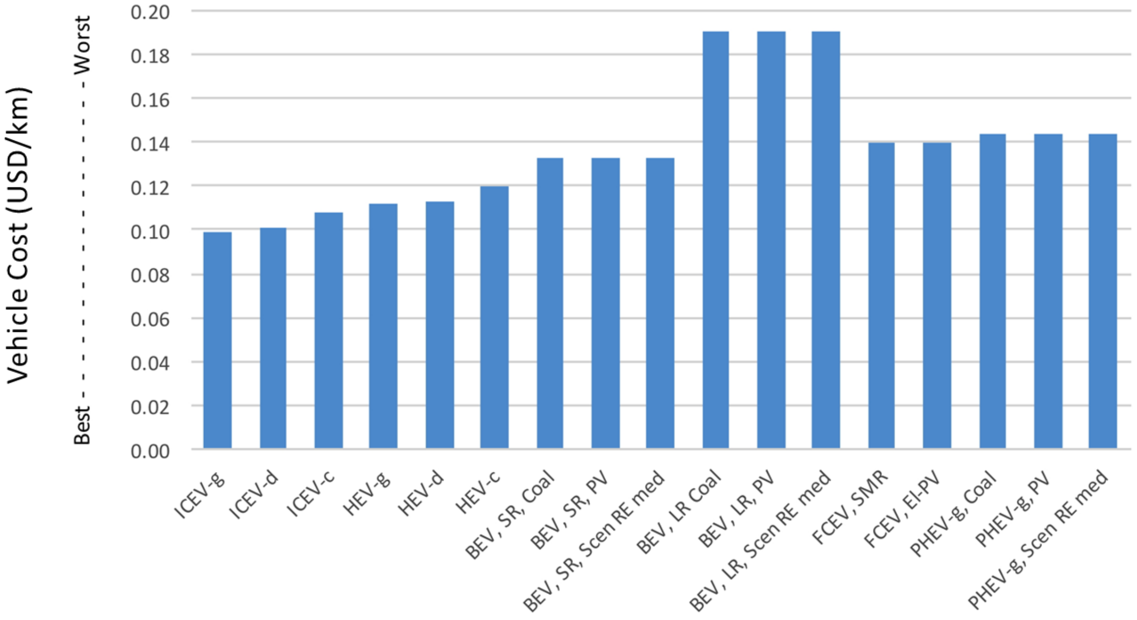

Figure C. 31 2050 Vehicle Cost (absolute)

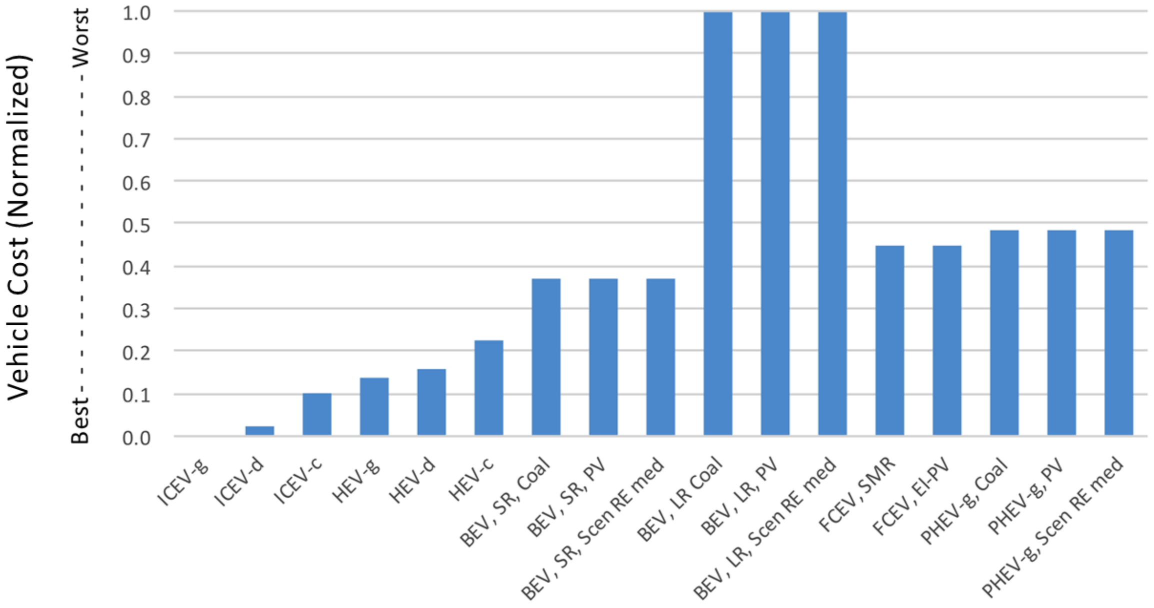

Figure C. 32 2050 Vehicle Cost (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

Coal - Imported coal power
PV - Photovoltaic power
Scen RE med – SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
El-UCTE - Electrolysis using UCTE Elec. Mix

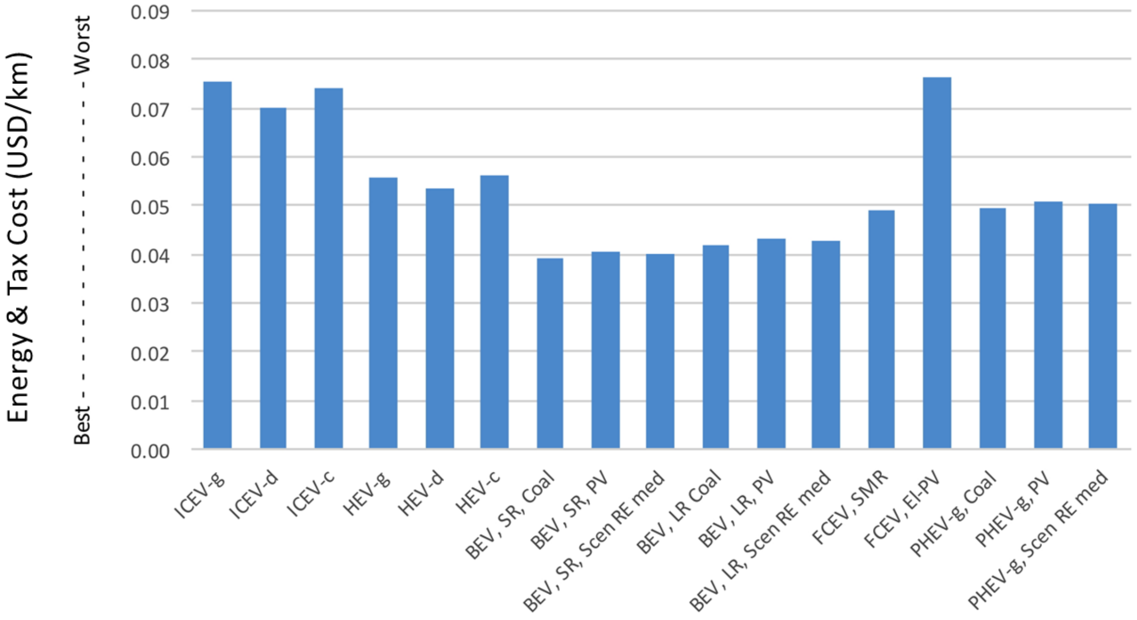

Figure C. 33 2050 Energy & Tax Cost (absolute)

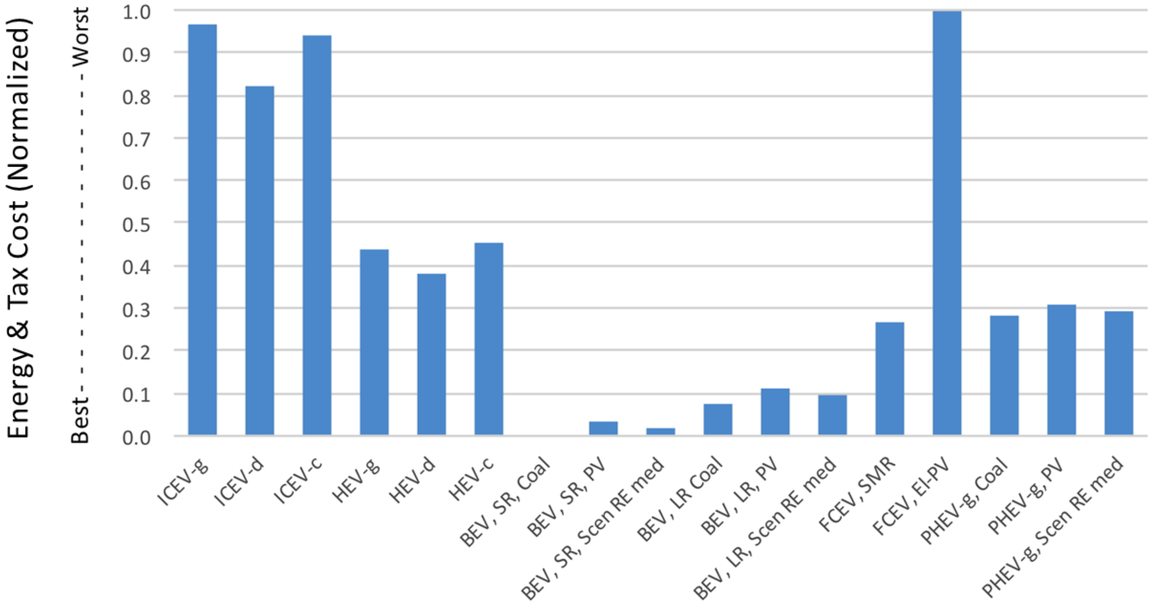

Figure C. 34 2050 Energy & Tax Cost (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

SR = Short Range, LR = Long Range

Fuel

g - Gasoline
d - Diesel
c - Compressed Natural Gas

Electricity

Coal - Imported coal power
PV - Photovoltaic power
Scen RE med – SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
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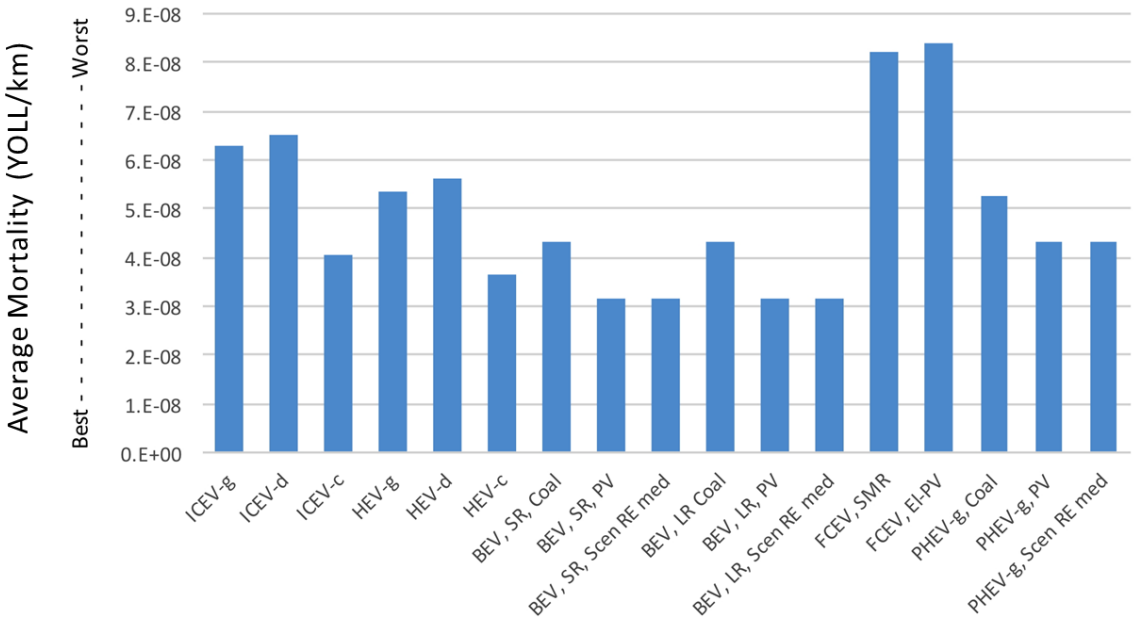

Figure C. 35 2050 Average Mortality (absolute)

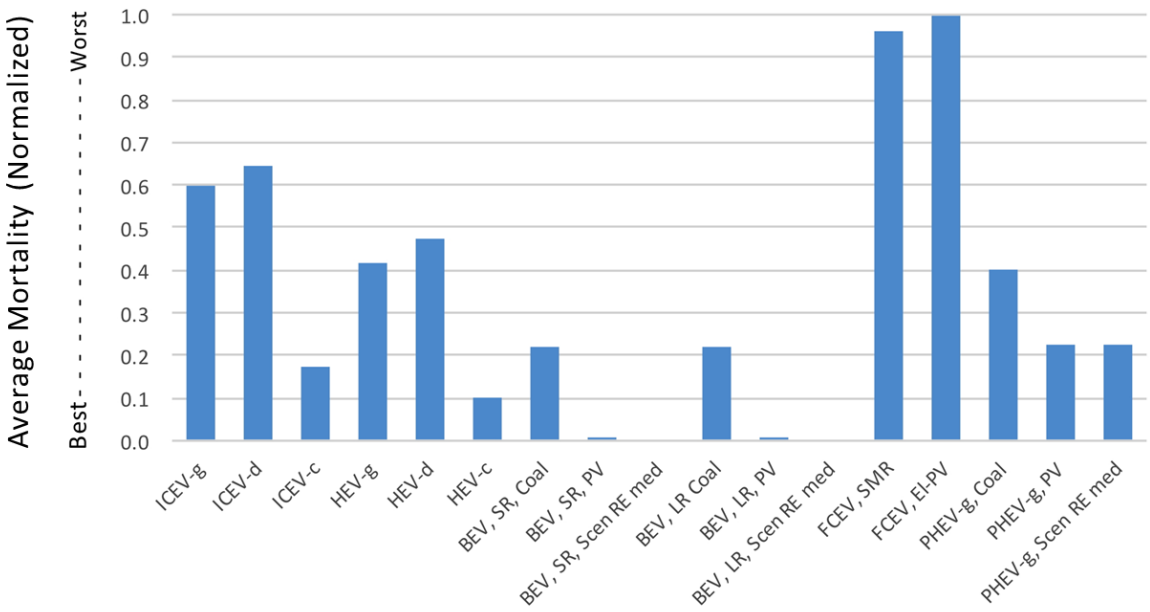

Figure C. 36 2050 Average Mortality (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

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Fuel

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d - Diesel
c - Compressed Natural Gas

Electricity

Coal - Imported coal power
PV - Photovoltaic power
Scen RE med – SFOE renewables scenario, medium demand growth

Hydrogen

SMR - Steam Methane Reforming
El-CH - Electrolysis using Swiss Elec. Mix
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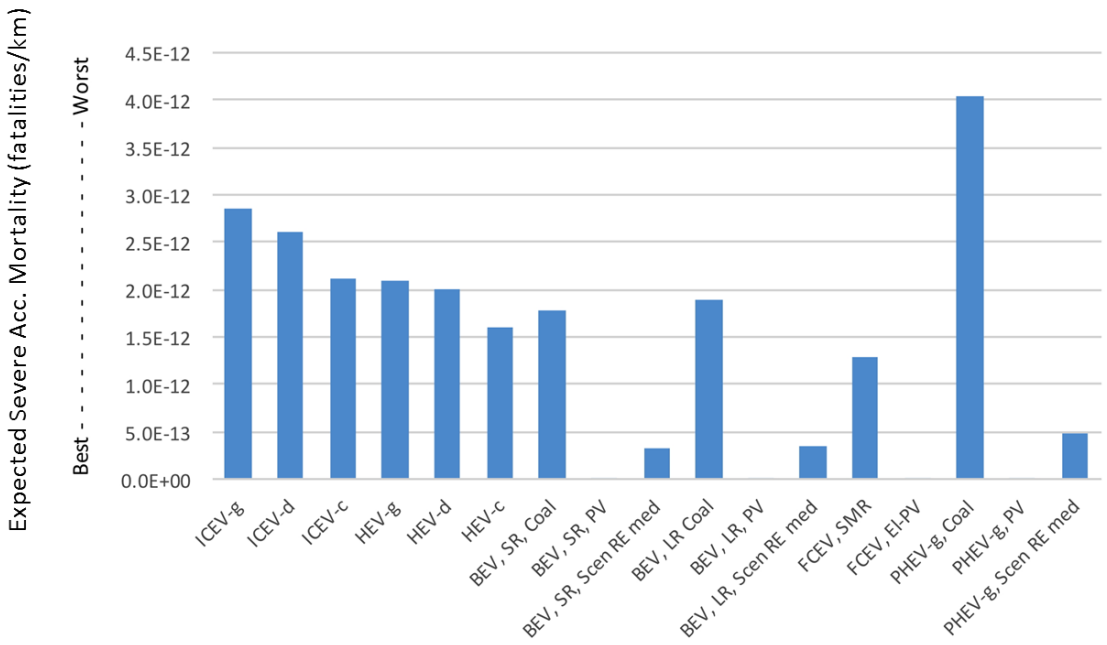

Figure C. 37 2050 Severe Accident Fatalities (absolute)

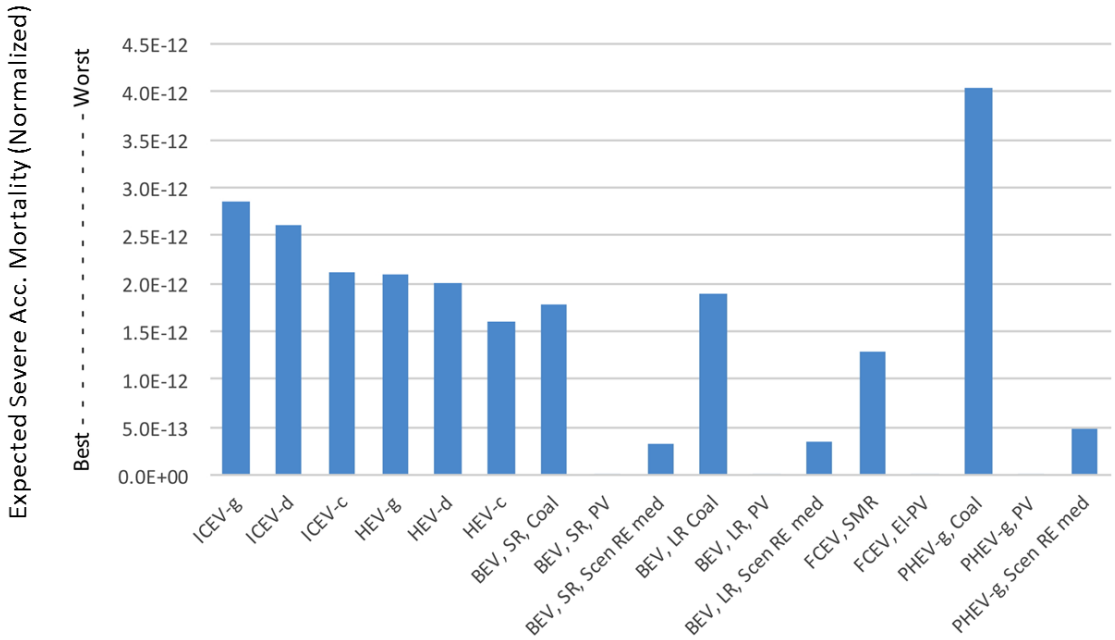

Figure C. 38 2050 Severe Accident Fatalities (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
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FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

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Electricity

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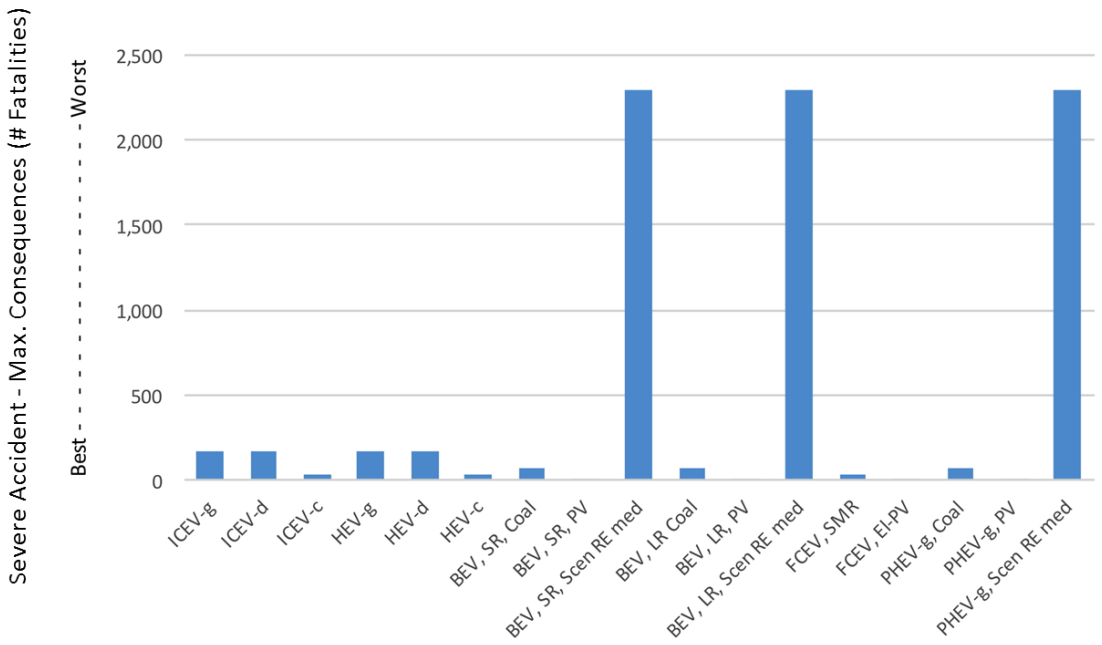

Figure C. 39 2050 Maximum Fatalities (absolute)

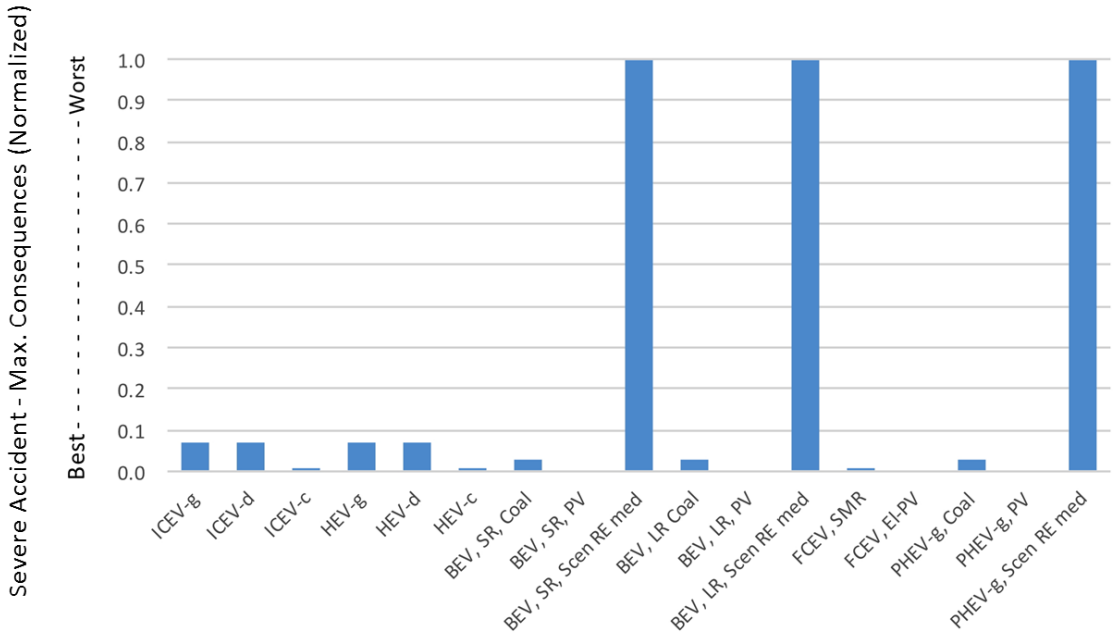

Figure C. 40 2050 Maximum Fatalities (relative)

Drivetrains

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FCEV - Fuel Cell Electric Vehicles
HEV - Hybrid Electric Vehicles
PHEV - Plug-in Hybrid Electric Vehicles

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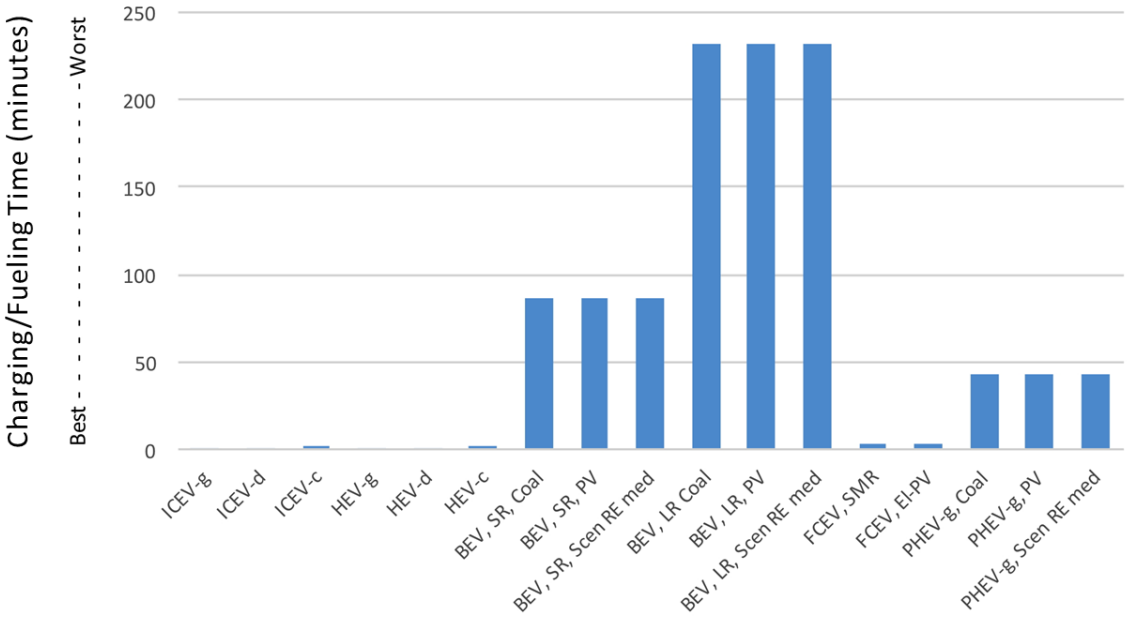

Figure C. 41 2050 Charging, Fueling Time (absolute)

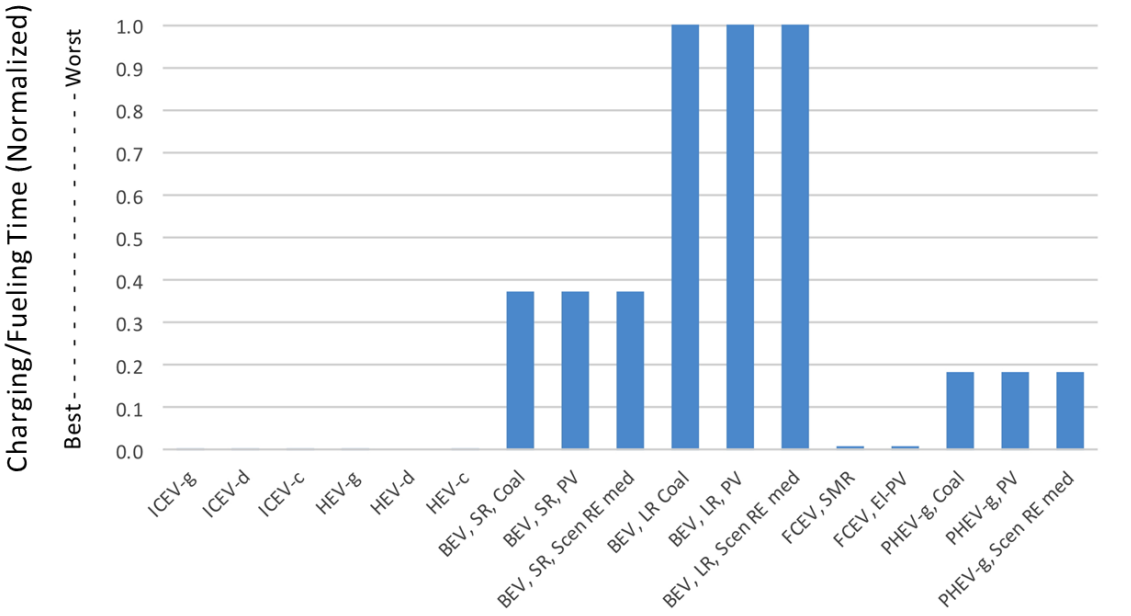

Figure C. 42 2050 Charging, Fueling Time (relative)

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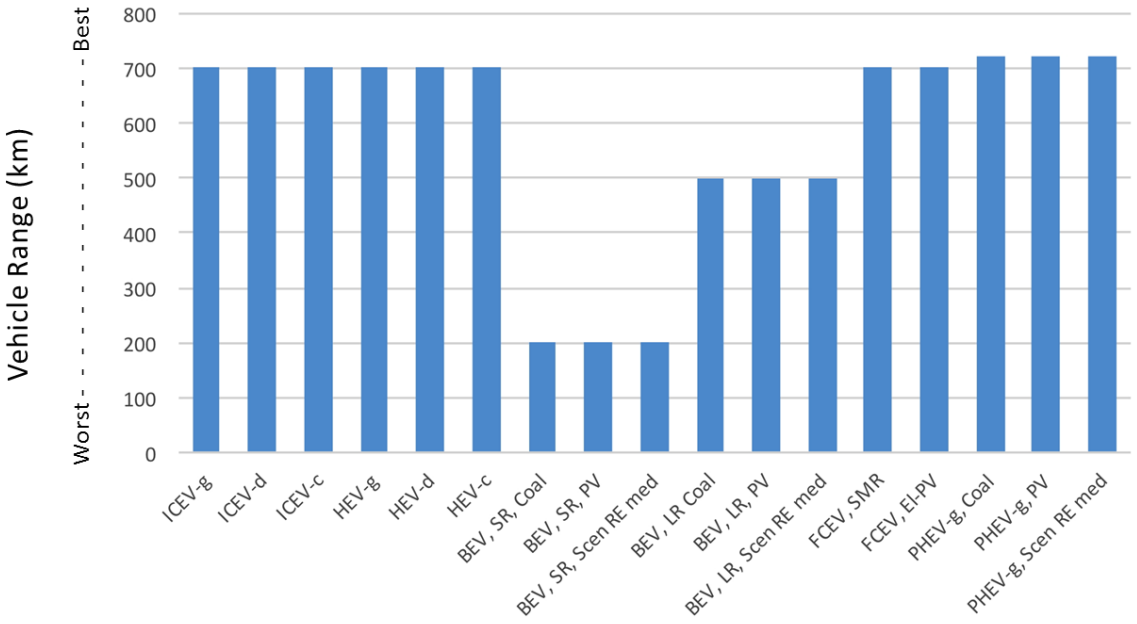

Figure C. 43 2050 Vehicle Range (absolute)

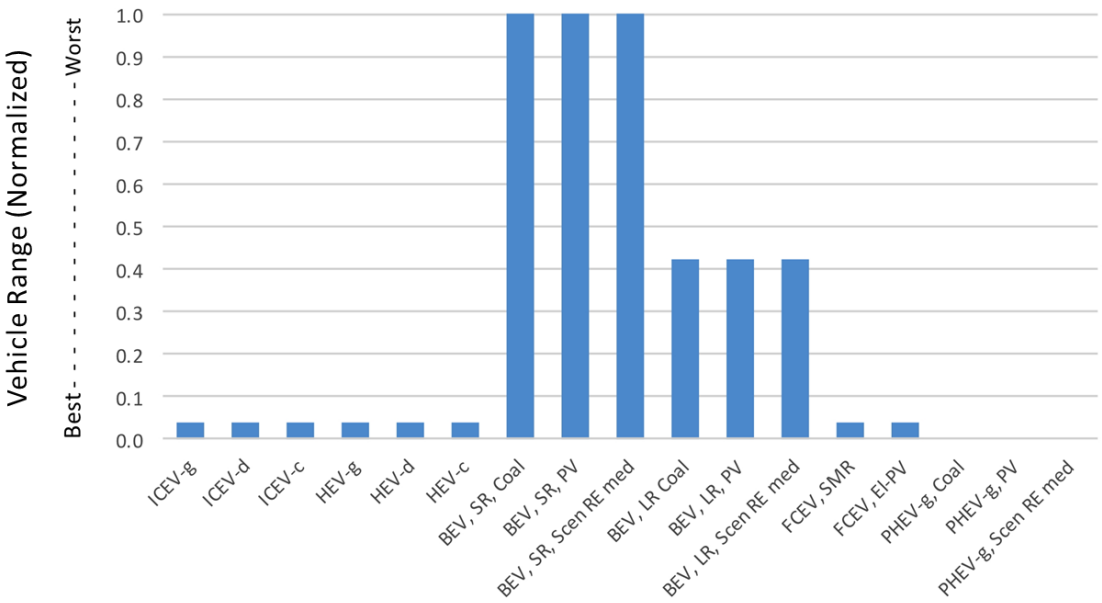

Figure C. 44 2050 Vehicle Range (relative)

Drivetrains

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Appendix D: Excerpt from PSI Energie Spiegel No. 21/ November 2012

Authors: Kannan Ramachandran[50], Hal Turton[51], Stefan Hirschberg[52] (PSI)

This text is reproduced from the PSI "Energie Spiegel" No. 21/ November 2012. www.psi.ch/info/MediaBoard/Energiespiegel_21_e.pdf

The new Swiss energy policy: Where will the electricity come from?

Politics has set the guidelines: no more new nuclear power plants in Switzerland. That means that 40% of today's electricity must come from other sources in the future. So much is clear - we must reduce demand and strengthen use of renewable energy. But if this is not enough? Are gas power plants needed? Or should we depend on electricity imports? These and other similar questions are investigated by PSI within the framework of energy scenarios.

After Fukushima it quickly became clear that the electricity supply of Switzerland in 40 years should look different than today. There should be no more electricity from new nuclear power plants, and the use of sun, wind and biomass should be massively increased. Whether this will be enough to fill the electricity gap is certainly questionable, particularly if one looks at the development of electricity demand to date, and considers the forecast increase of the population to 9 million and economic growth of about 50% by 2050.

Switzerland stands before a great challenge: For a successful transformation of the electricity supply the renewable energy sources must each be built rapidly up to the limits of their usable potentials. And electricity must be used more efficiently – the means for this are available. But if we do not manage to significantly reduce demand, then our foreign dependence will grow. To depend fully on electricity imports is risky in view of security of supply. Above all in winter, when demand is high and the hydro power plants produce less. If gas power plants are chosen, then lots of natural gas must be imported. Gas power plants produce a lot of CO_2. So otherwise challenging climate policy goals will become even more difficult to achieve.

Even if future development is difficult to estimate: there is evidence that by 2050 electricity will cost at least 50% more than today.

Electricity Demand: What if…?

"*Prediction is hard, especially about the future*." It's not clear to whom this quotation should be ascribed.[53] What is clear is that it should at least be kept in mind whenever the public is presented with new energy scenarios.

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[51] Previous Affiliation: PSI, Laboratory for Energy Systems Analysis (LEA), Energy Economics Group
[52] PSI, Laboratory for Energy Systems Analysis (LEA), stefan.hirschberg@psi.ch
[53] Karl Valentin, Mark Twain, Winston Churchill (among others)

No one can predict today how the Swiss energy and electricity supply will look like in the year 2050. That is impossible either by looking in a dark crystal ball, or by complicated modeling – even when this impression is gladly given by predictions of remarkable precision. The uncertainties behind the most important influencing factors are simply too large. Population development and economic growth, the price of oil and other energy carriers, technological development, and international frameworks: these are only some of the influencing factors that cannot be precisely forecast over such a long time horizon. But this does not mean that model calculations are useless. On the contrary, scenarios for energy and electricity supply can answer many "what if" questions. They sketch developments that can be expected under quite specific assumptions and conditions, and show their costs and consequences for the CO_2 balance of Switzerland.

How much electricity will we need?

The level of electricity demand is one of the most important parameters when scenarios are calculated on how our electricity supply could look in 40 years. How demand will develop depends on many factors. And the bandwidth of different forecasts is accordingly broad (Figure D. 1).

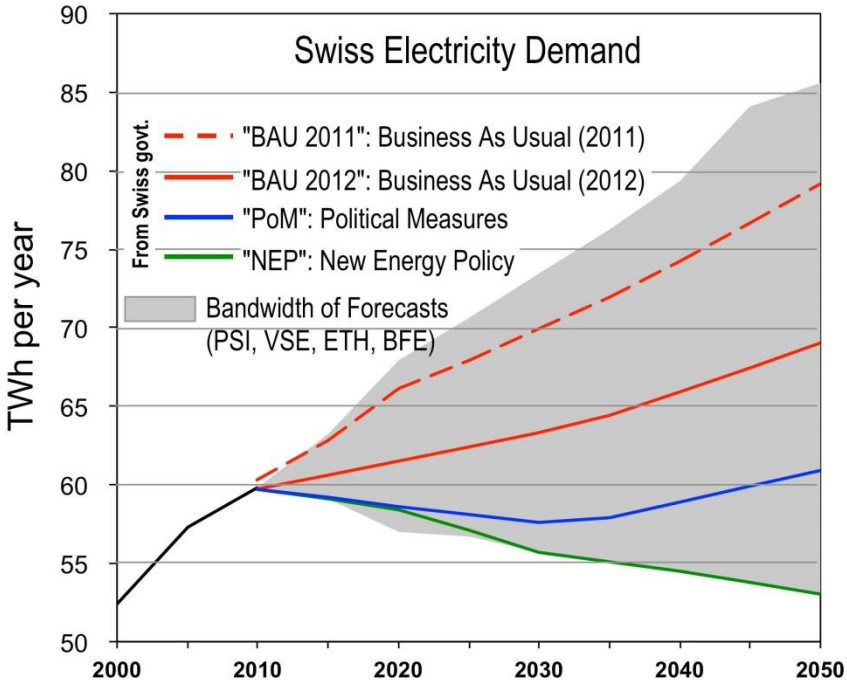

Figure D. 1 Bandwidth in assumed Swiss electricity demand trajectories to 2050 (Source: Federal Energy Strategy 2050; PSI. Laboratory for Energy System Analysis; VSE; ETH).

For the Swiss electricity supply it makes a difference whether 50 or 85 terawatt-hours per year are needed – because the potential of individual sources of electricity is limited. This applies particularly to renewable energy sources, whose domestic production cannot be arbitrarily increased.

The Swiss federal government expects development (Figure D. 1) based on specific conditions - but demand that declines almost immediately, and by 2050 is significantly below the current level (the New Energy Policy, or "NEP") can only be implemented by massive, fast acting controls and savings measures. And not just in Switzerland, but in step with international action. The measures now under debate in Switzerland within the framework of the Energy Strategy 2050 would produce demand in 2050 around the current level (Political Measures, "PoM"). Without these measures (Business As Usual, or "BAU") demand would continue to increase. The current business-as-usual

forecast ("BAU 2012") is significantly more optimistic than just a year ago ("BAU 2011"). For comparison, demand grew about 14% between 2000 and 2010.

How realistic it is that the demand grows no further, or that in 2050 even less electricity is needed than today remains to be seen. Current expectations are that in 2050 there will be 9 million people living in Switzerland, the economy will grow by about half, and electricity will increasingly replace fuel in the growing transportation sector (see Figure D. 2).

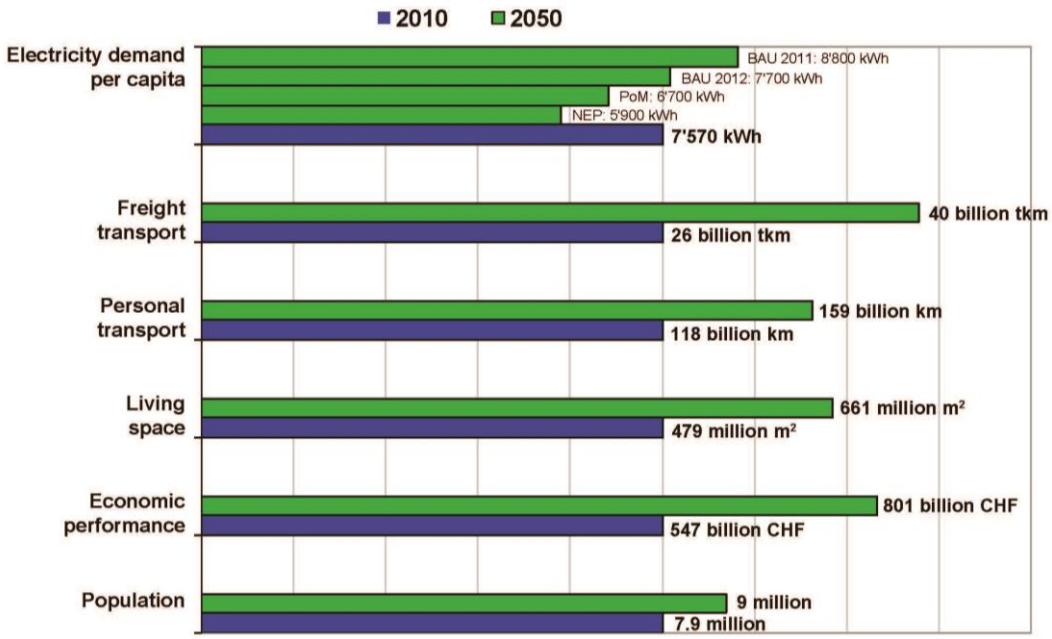

Figure D. 2 Development of various Swiss parameters to 2050, according to federal forecasts.

Electricity Supply: Gas power plants or electricity imports?

Domestic renewable resources will only suffice if, thanks to new energy policies, we can get by with much less electricity than today – despite of growing population and economy. Otherwise there needs to be a Plan B.

PSI has calculated various scenarios for the three current demand forecasts shown in Figure D. 1. How can the electricity demand be covered most economically, and what will be the consequences with regards to costs and CO_2 emissions? To answer this question PSI has used a cost minimization model for the next 40 years. The conclusion: No matter how high the demand may be in 40 years, the electricity supply for Switzerland will still pose a challenge if the political climate policy goal of a 60% CO_2 reduction by 2050 is maintained and no new nuclear plants are built.

Boundary conditions

Figure D. 3 shows the results of the model calculation if the electricity demand can be held at about the current level (the "PoM" forecast in Figure D. 1). Three scenarios were analyzed: in the first ("Gas") the electricity imports and exports were required to balance over each year, while in the second ("Import") net imports were allowed, but no gas power plants. In both cases new nuclear plants were not allowed. The third scenario represents a reference case with conditions

corresponding to before Fukushima ("REF"). Here new nuclear plants were allowed, but annual electricity imports and exports were required to balance.

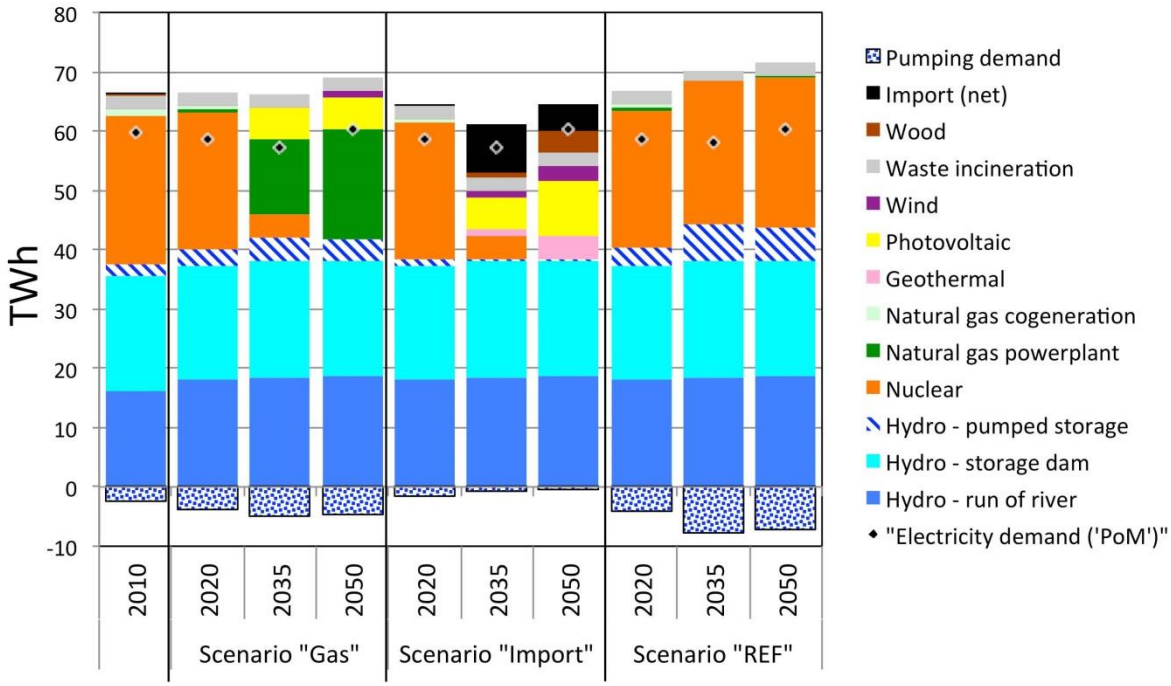

Figure D. 3 Swiss electricity supply in three scenarios to 2050 with different conditions, based on "PoM" electricity demand forecast.

Renewables at their limits

The scenario "Gas" shows that a combination of flexible gas power plants, photovoltaics and wind energy is the most economical solution, if annual electricity imports and exports must balance. Seven large gas power plants would then be required in the year 2050.

In the scenario "Import" without gas power plants more electricity can be imported, at most barely a fifth of the annual demand. The potential of all the new renewables – photovoltaics, wind, wood and geothermal – will then be fully exhausted. But that is not enough: much electricity must still be imported, above all in winter (see Figure D. 7).

Because nuclear electricity costs the least, nuclear plants together with pumped storage hydro displaces the gas power plants and renewables in the third scenario ("REF").

And if the electricity demand turns out differently? Figure D. 4 shows the same three scenarios with the same assumptions as before for only the year 2050, using all three of the demand forecasts shown in Figure D. 1.

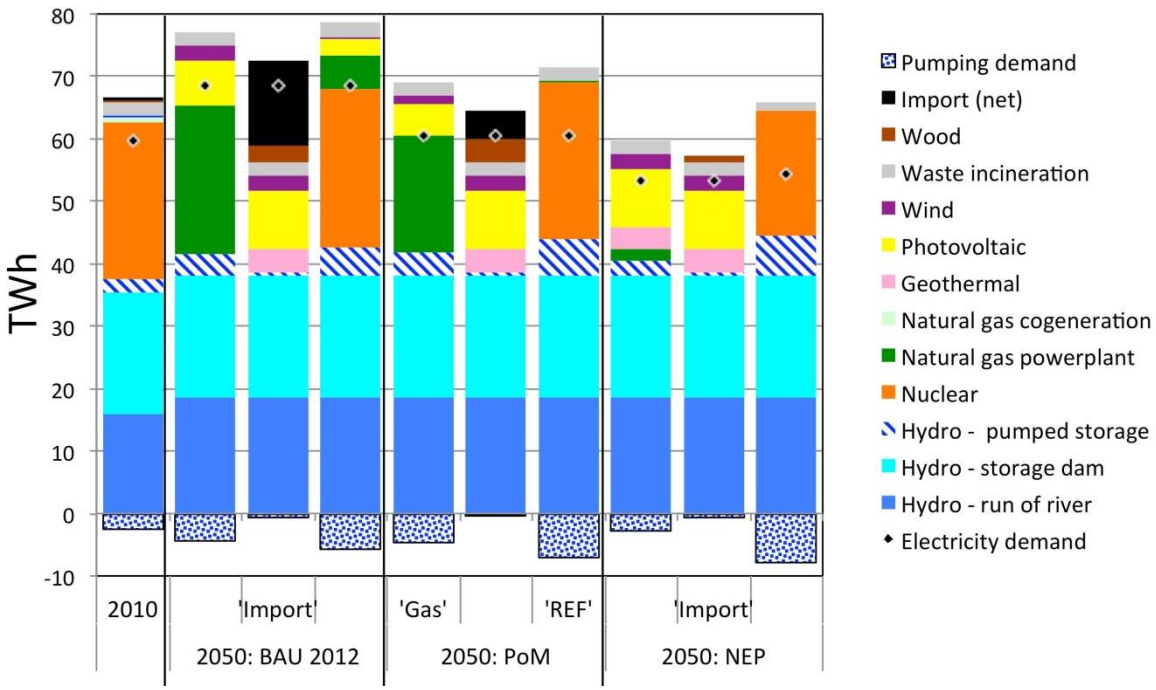

Figure D. 4 Scenarios for Swiss electricity supply in the year 2050 for different energy demands (equals gross production minus use in pumped storage plants).

If the demand goal of the new energy policy ("NEP") is reached, then Switzerland can avoid gas power plants and net electricity imports. Full use of the renewables will suffice averaged over the whole year, but as now electricity must still be imported in winter.

If the demand is higher than today (BAU 2011 and 2012), then there will need to be either more gas power plants or higher imports. If the same amount of electricity as today were still to come from nuclear plants, then additional gas plants and electricity from photovoltaics and wind energy would still be required.

CO_2 Emissions, Costs and Security of Supply

Without new nuclear power plants, the risk of nuclear accidents in Switzerland falls away. But the new energy policy is not for free. It will be noticeable in our household budgets and in the Swiss CO_2 budget. And electricity or gas imports could mean a less stable electricity supply.

If we cannot get by with significantly less electricity than today, then abstaining from new nuclear plants will mean importing natural gas or electricity from abroad. Both are more risk from the point of view of security of supply than importing fuel elements for nuclear plants. Germany will likely also depend upon electricity imports in the future. But as a strategy for all of Europe this will not work. And countries like Russia and Iran could turn out to be undependable suppliers of natural gas.

Consequences for Climate Policy

With an approximately level electricity demand in the year 2050 (forecast "PoM" in Figure D. 1), depending completely on natural gas generation would mean seven new gas power plants, which would result in as much additional natural gas would need to be imported as is used today for heating and industry. This would produce around six million tonnes of CO_2 more per year (Figure D.

5, scenario "Gas" in the middle). In comparison to the current Swiss emissions of around 40 million tonnes of CO_2 per year that is an increase of about 15%. These new emissions from gas plants would place an additional hurdle in the path of the target of a 60% CO_2 reduction by 2050. Compensating domestically for these additional emissions would be expensive. One solution could be so-called "carbon capture and storage," meaning that CO_2 from power plants is caught and permanently stored underground[54]. Whether this can be realized in Switzerland is still unclear.

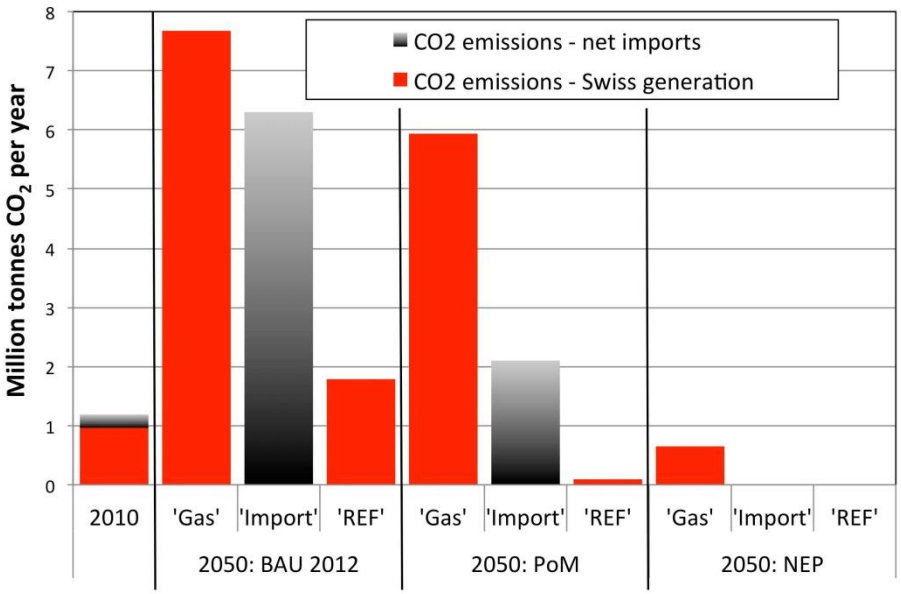

Figure D. 5 Direct greenhouse gas emissions from the Swiss electricity supply per year, depending upon the development of the electricity demand (compare with Figure D. 1).

With an import strategy (scenario "Import"), the CO_2 emissions depend on the composition of the imported electricity. With electricity demand following the "PoM" forecast, the range of CO_2 emissions can be from zero to 2 million tonnes per year. This bandwidth is based on the range from "CO_2-free" electricity from renewable sources or nuclear energy up to the CO_2 content of the current average electricity mix in the EU. Whether CO_2 is produced in Switzerland or abroad makes no difference for the climate. However the "gray" emissions of these imports would not count on the Swiss CO_2 balance sheet, but rather on that of the countries where the power originates.

Replacement nuclear plants (scenario "REF") would cause hardly any CO_2 emissions.

If the demand grows as in the BAU 2012 forecast, eight new gas plants would be needed in 2050, or higher electricity imports, and the CO_2 emissions would also climb.

Economic Consequences

Even if it is difficult to predict how much the generation of a kilowatt-hour will cost in 40 years, it will be considerably more than today (see Figure D. 6). In the "Gas" and "Import" scenario the average production costs are almost twice as high as today. The uncertainties behind the assumed costs of natural gas and electricity imports as well as nuclear power plants and new renewables up to 2050

[54] "Carbon Capture and Storage" describes technologies that can remove CO_2 emissions from power plants or cement manufacturing plants. The CO_2 is compressed and injected in appropriate geological structures at depths of at least 1000 m. The CO_2 remains stored there and does not contribute to climate change. A possible implementation in Switzerland is investigated in the CARMA project with the participation of PSI: www.carma.ethz.ch/

are large. And these costs have a decisive influence on the results of the scenarios. With the current assumptions (see table on the reverse side of this insert) avoiding replacement nuclear plants results in additional costs of about 60 billion francs alone for the electricity supply until 2050, if demand follows the "PoM" forecast. This is not including the costs that could results from grid expansion.

The costs for the electricity supply would be less if the electricity demand decreases, as assumed in the "NEP" forecast. But then there would be higher investments necessary in electric efficiency measures in the residential, industrial and transportation sectors. The theme of the overall energy supply until 2050 will be addressed in one of the next issues of the Energie-Spiegel.

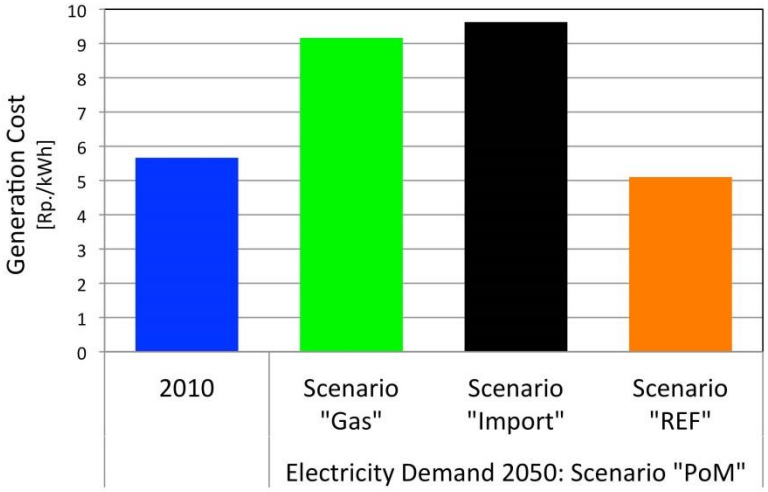

Figure D. 6 Generation cost of a kilowatt-hour of electricity in the three scenarios on average in the year 2050. The profits from electricity trading are included here.

Summer – Winter, Day and Night

To have enough electricity for the whole year is one thing. But is there also enough in winter, when all the heaters are running and the sun is hidden behind the clouds? Whether winter or summer, the middle of the night or holidays: electricity demand and production have strong swings.

For scenarios of future electricity to convey a realistic picture, the daily swings in demand and production must be considered. For example, photovoltaics deliver power only during the day, and more in summer than in winter. Demand is also somewhat higher in winter. And exactly as supply and demand change, the prices for imports and exports also change with the days and the seasons. The PSI model considers all these circumstances[55] (see table).

[55] The "TIMES-Model Switzerland" is used at PSI for analyzing scenarios of Swiss electricity supply. It finds the most economical system for the supply of electricity under given boundary conditions. To optimize the whole system, the properties of each technology are considered, e.g. costs, availability and flexibility. The time resolution of the model is one hour, so that daily swings in demand and production can be well modeled. The model includes weekdays, Saturdays and Sundays for each of the four seasons. Electricity can be imported and exported at any time.

Lots of Water and Sun in Summer, Little in Winter

Electricity demand and generation for the course of a typical weekday in summer and winter are shown Figure D. 7, for both the “Gas” and “Import” scenarios in the year 2050.

In the summer evenings and during the nights, cheap electricity is imported in both scenarios (black surface). The daily photovoltaic generation (yellow) is also clear to see with the much higher production during the summer. The hydro reservoir plants (light blue) produce during high demand and when electricity is expensive. In summer, most storage generation can be exported and bring financial profits.

In winter, imports are also needed during the days due to the smaller production of photovoltaic and hydropower. In the import scenario without gas power plants these imports are significantly higher: up to two thirds of the demand must be imported over many hours due to the lower base load capacity available in Switzerland.

Hydro reservoir plants can also be used to compensate for the production lacking from photovoltaics during nights and bad weather, or from wind turbines during calm weather. But doing so of course reduces the profits from power exports.

Table D. 1 Potentials and Costs of Electricity Generation for 2050 in the TIMES-Model for Switzerland

	Generation cost [Rp./kWh]	**Generation potential, assumed as possible by 2050 [TWh/a]**
Natural gas combined cycle	15.4	flexible
Nuclear	5.9	Zero in the scenarios “Gas” and „Import“ ~25 in scenario ”REF”
Hydro	14 (new powerplants)	38.3
Photovoltaic	10.3	9.7
Wind	14.5	2.6
Geothermal	16.5	4.4
Wood	8.9	3.8
Electricity imports	16.4 (avg) 8.5-22.7 by time of day	Max. 17% of demand in „Import“ scenario
Natural gas (fuel cost)	6.7 Rp. per kWh natural gas	

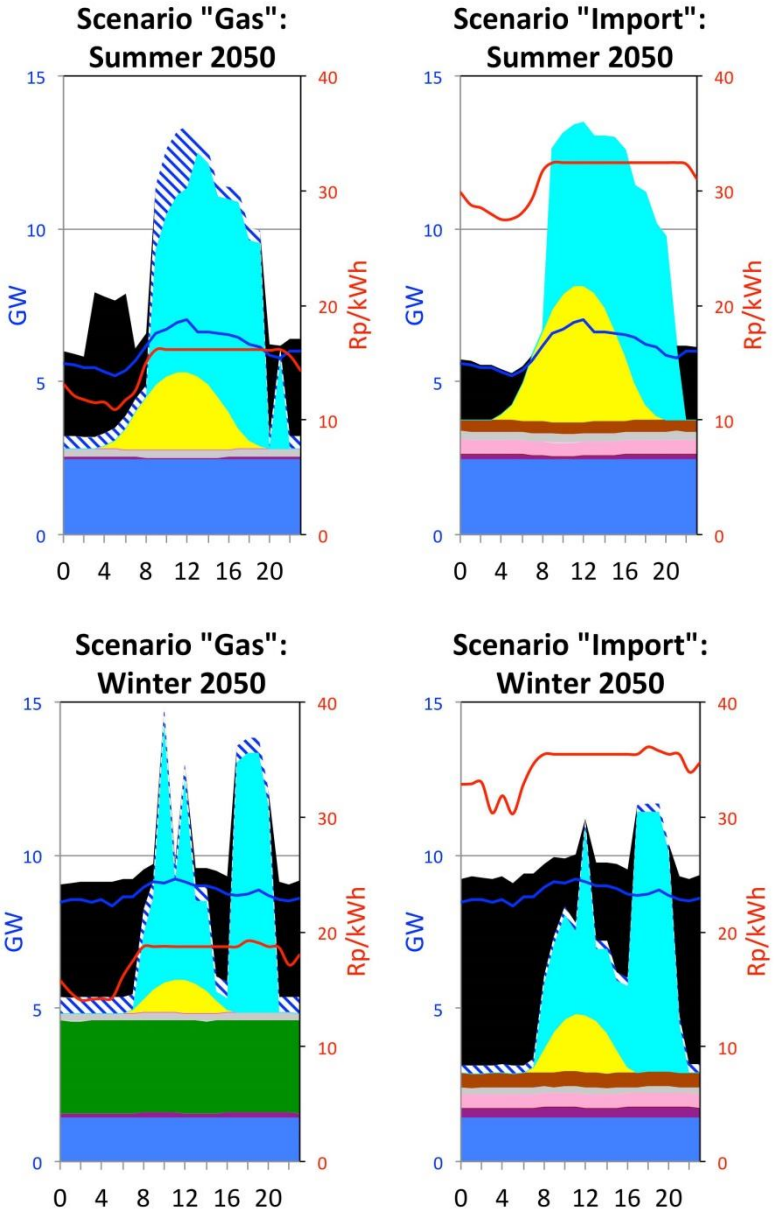

Figure D. 7 Daily electricity supply and demand curves for the scenarios "Gas" and "Import" for 2050 (left: summer; right: winter). The blue line stands for the demand, and the red for the production cost of an additional kilowatt-hour. The differently colored surfaces show the electricity produced from the different technologies and imports. The production must be around 7% higher than the demand to cover losses in the electricity grid. If the production is more than 7% higher than the blue line, the electricity is exported. The colors for the technologies are the same as in Figure D. 3 and Figure D. 4.

Appendix E: THELMA Fleet Indicators for 2012 and 2050, Full Scenario Set

Authors: Warren Schenler[56], Stefan Hirschberg[57] (PSI)

List of figures

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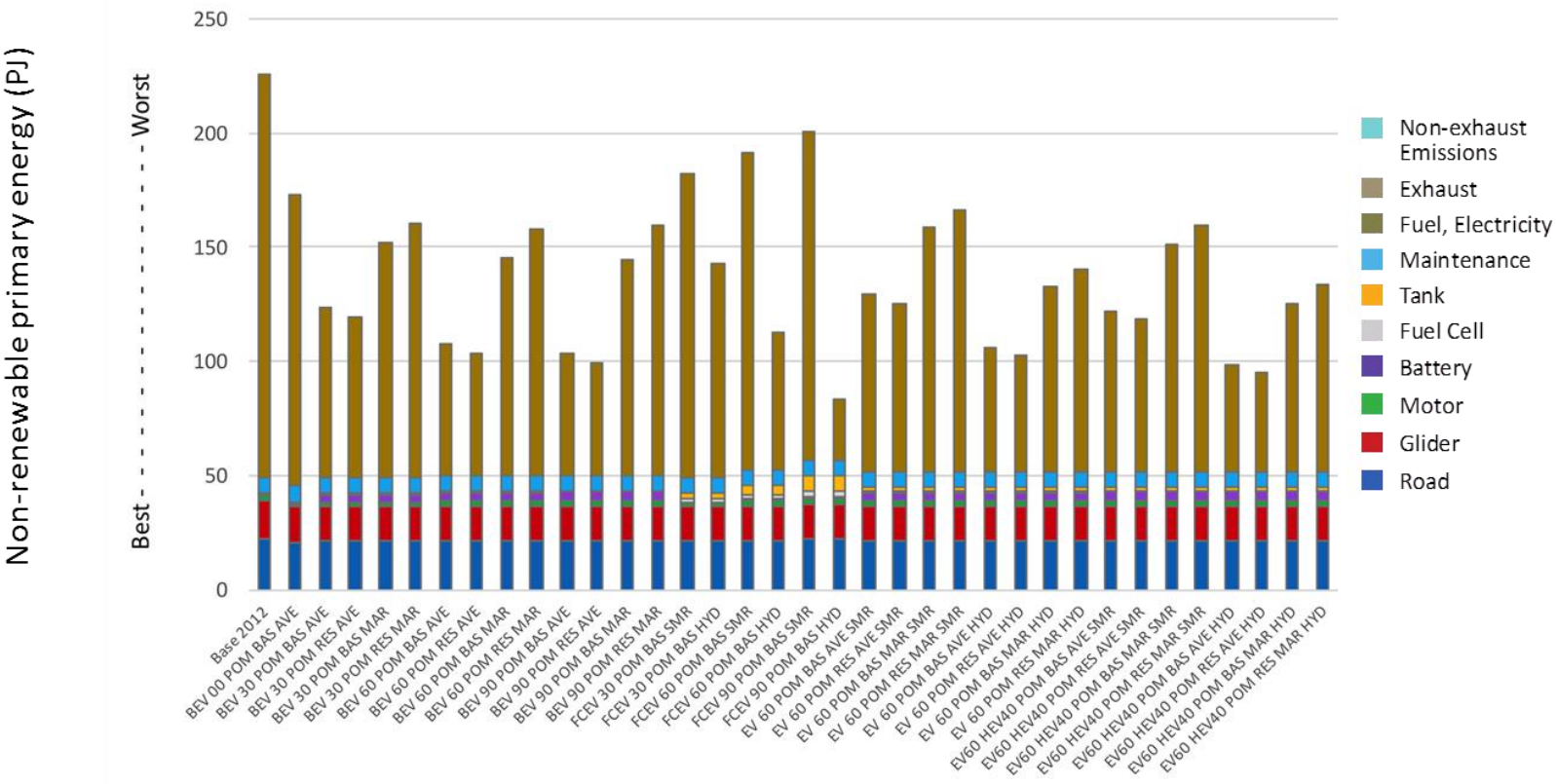
[57] PSI, Laboratory for Energy Systems Analysis (LEA), stefan.hirschberg@psi.ch



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

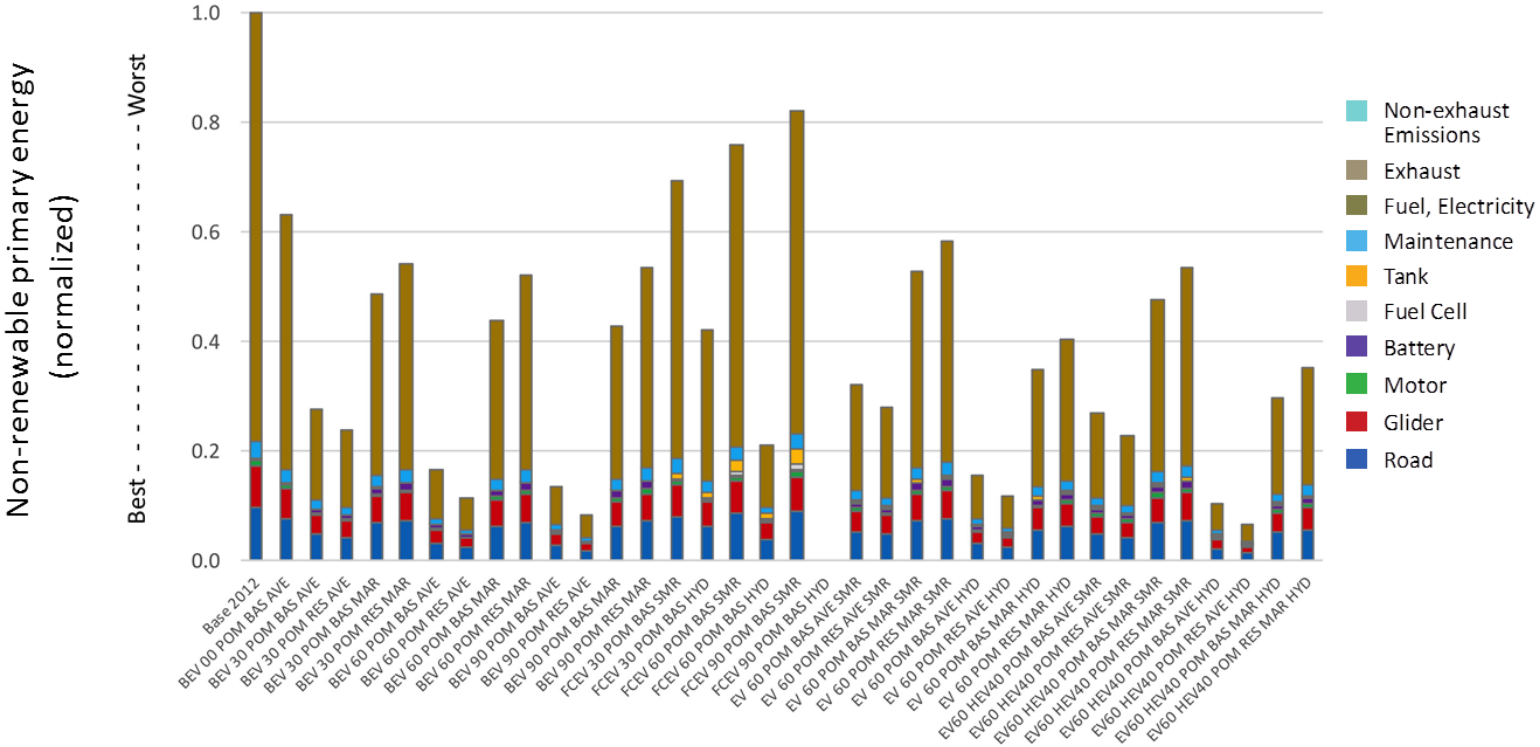
POM - Demand is SFOE “Political Measures”
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 1 Fleet 2050 Non-renewable Primary Energy (absolute), by component



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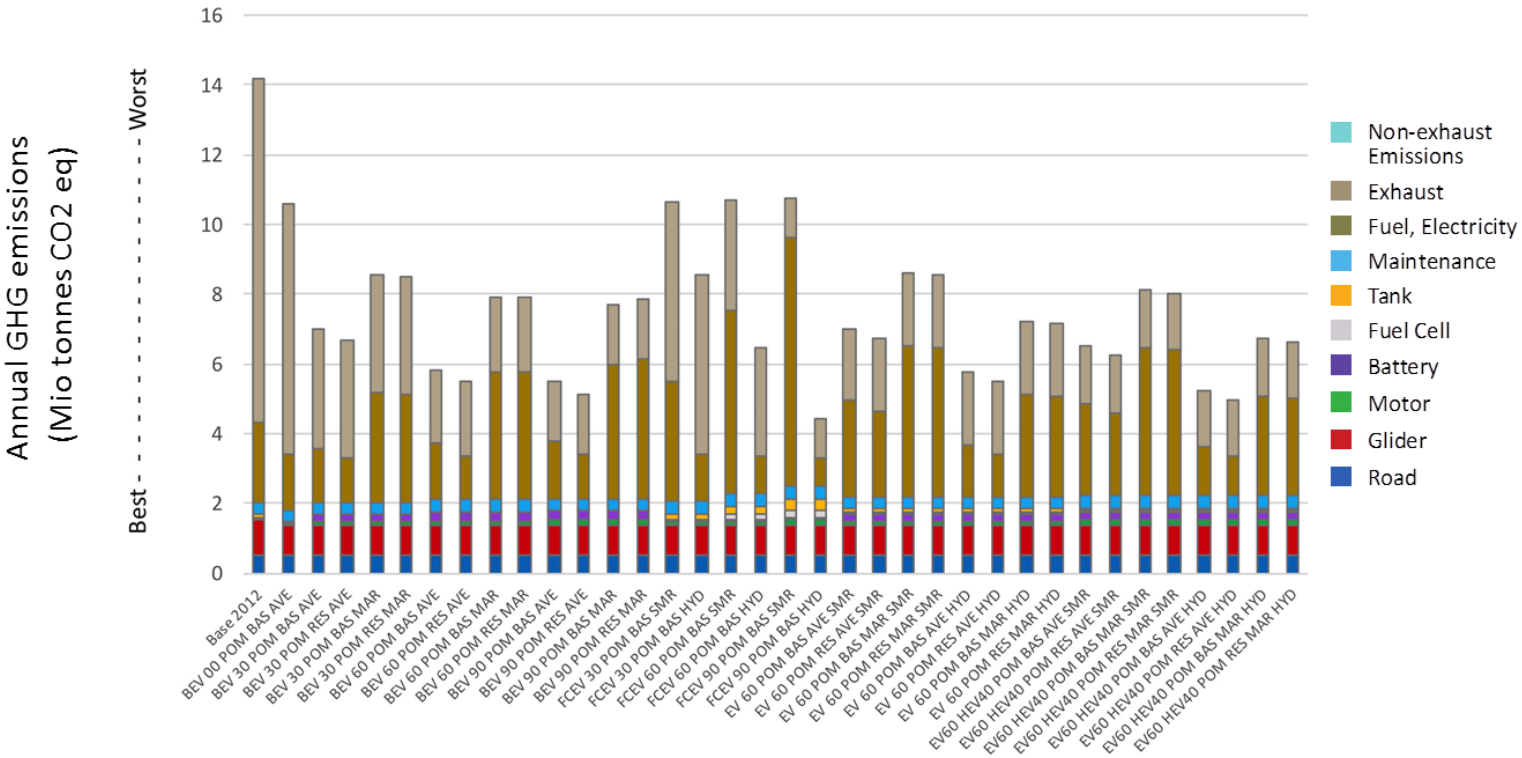
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 2 Fleet 2050 Non-renewable Primary Energy (relative), by component



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
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Electricity

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Hydrogen

SMR - Steam Methane Reforming
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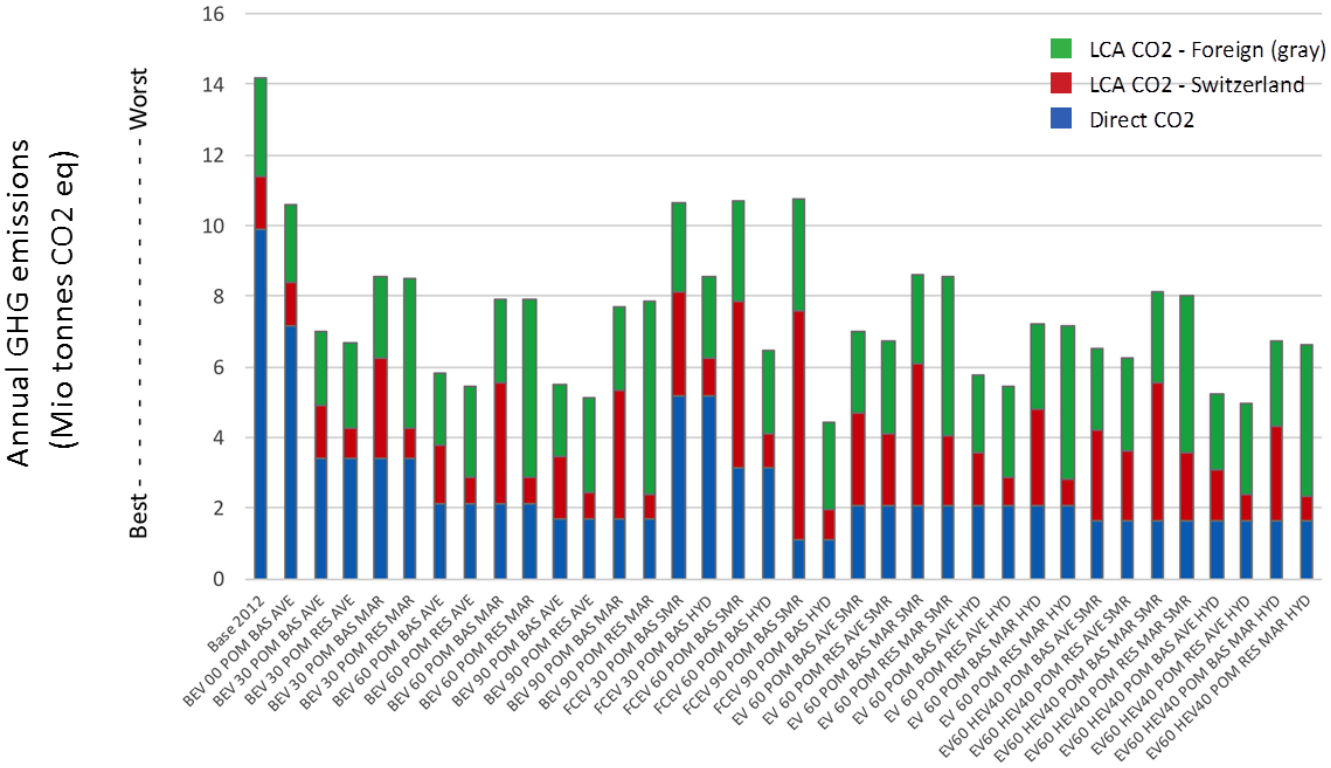
Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 3 Fleet 2050 Greenhouse Gas Emissions (absolute), by component



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Hydrogen

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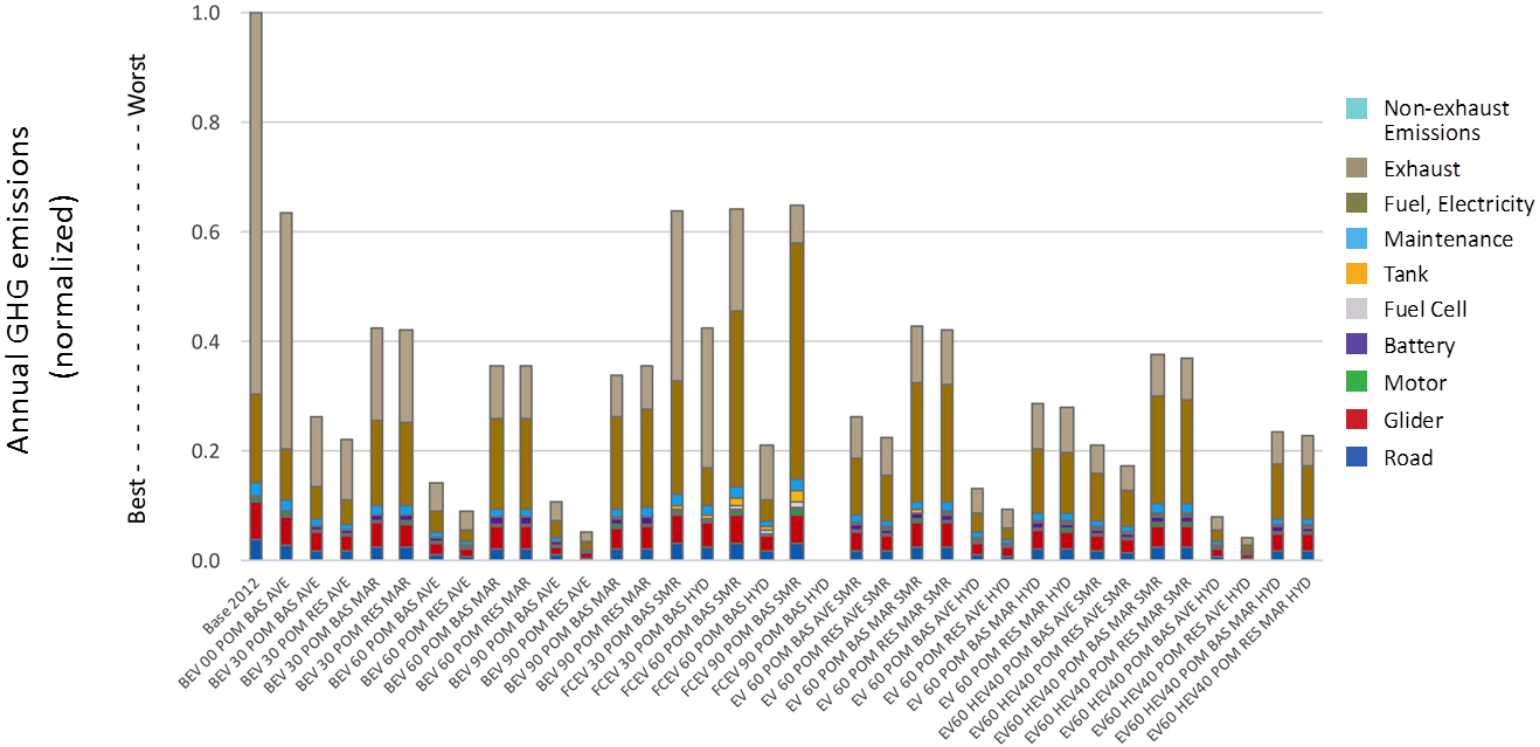
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 4 Fleet 2050 Greenhouse Gas Emissions (absolute), by location



Drivetrains

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Hydrogen

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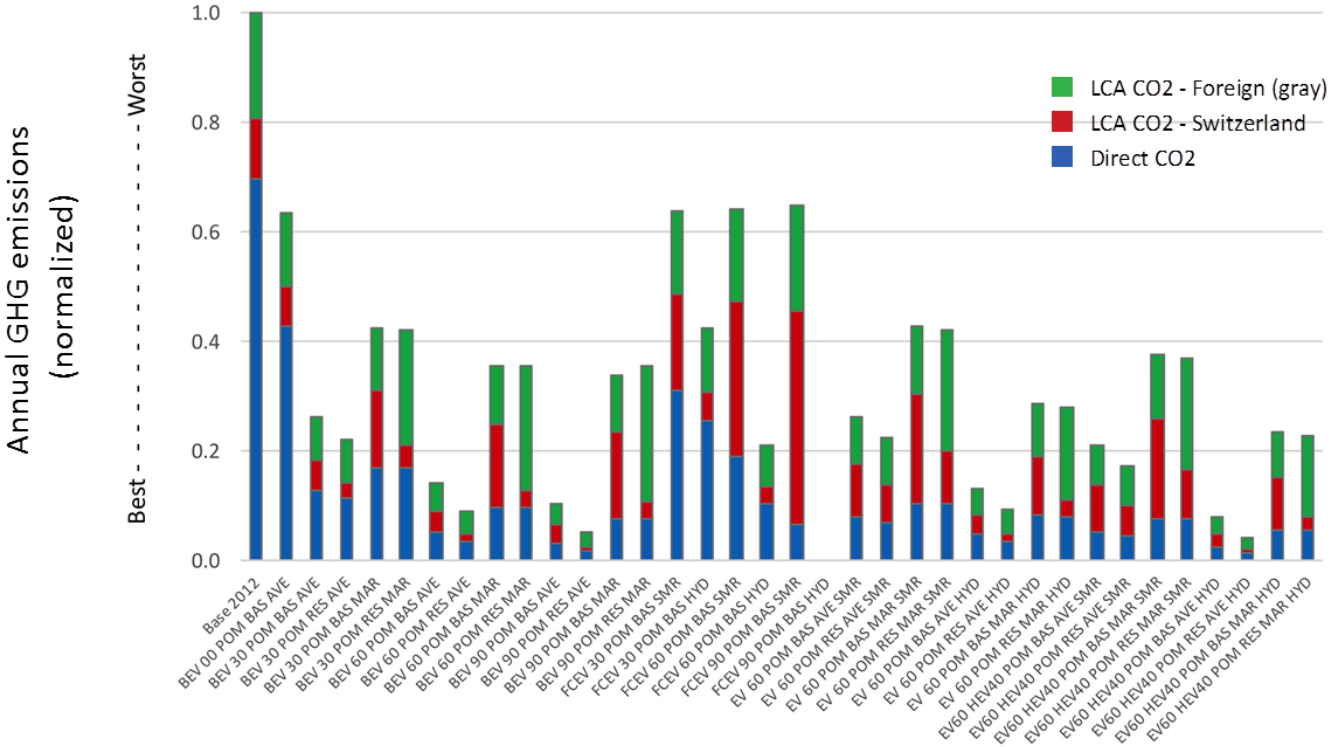
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 5 Fleet 2050 Greenhouse Gas Emissions (relative), by component



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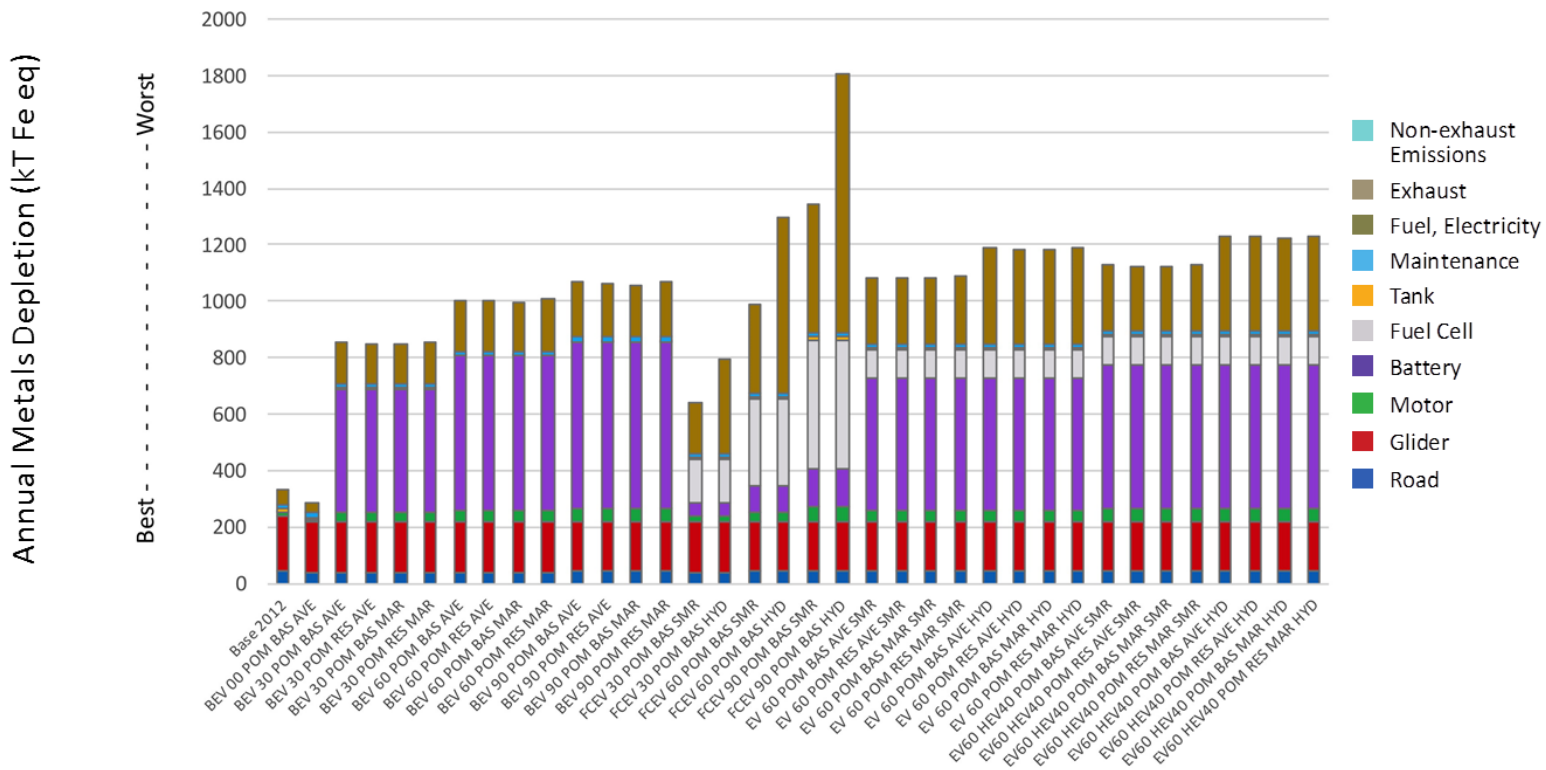
Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 6 Fleet 2050 Greenhouse Gas Emissions (relative), by location



Drivetrains

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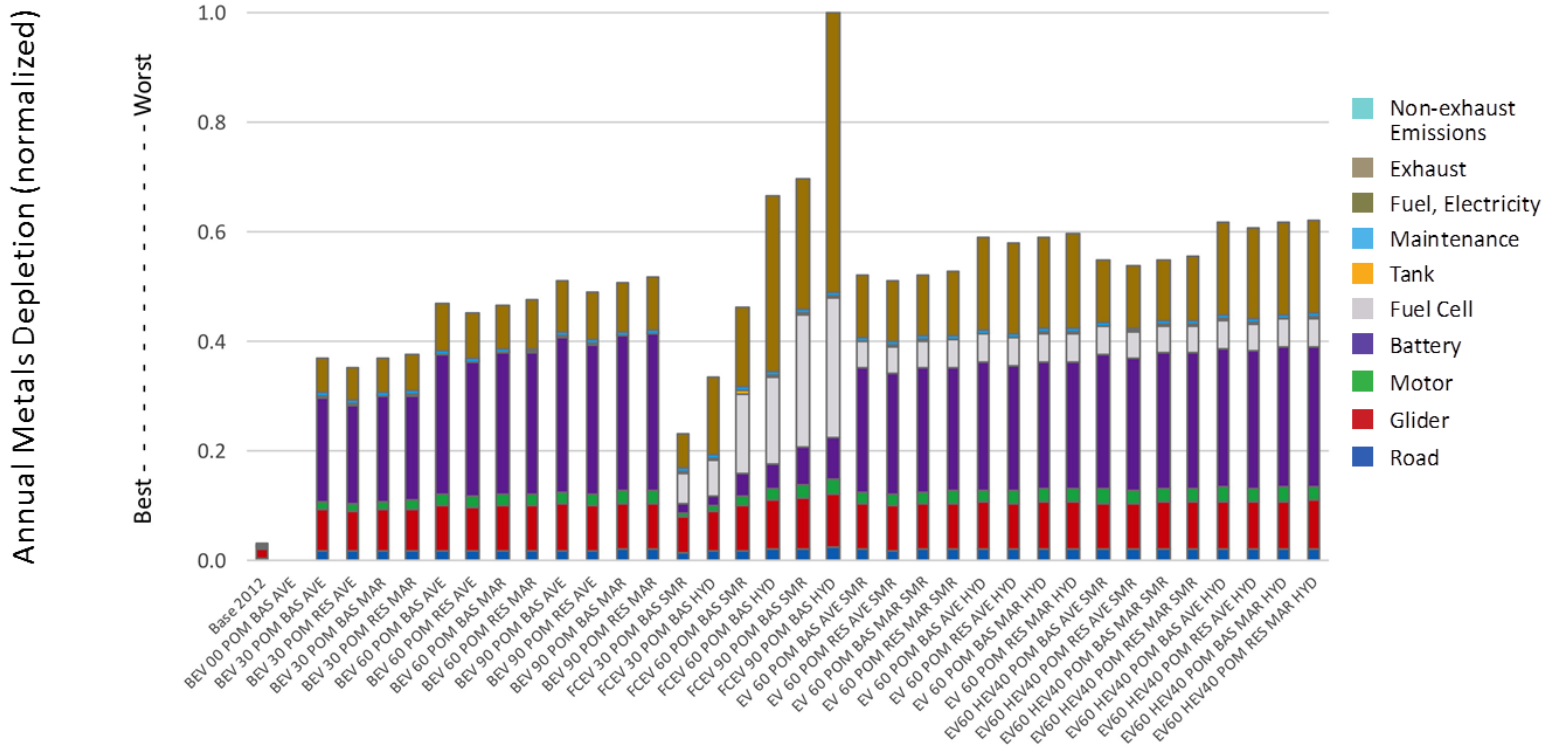
Figure E. 7 Fleet 2050 Metals Depletion (absolute), by component



Drivetrains

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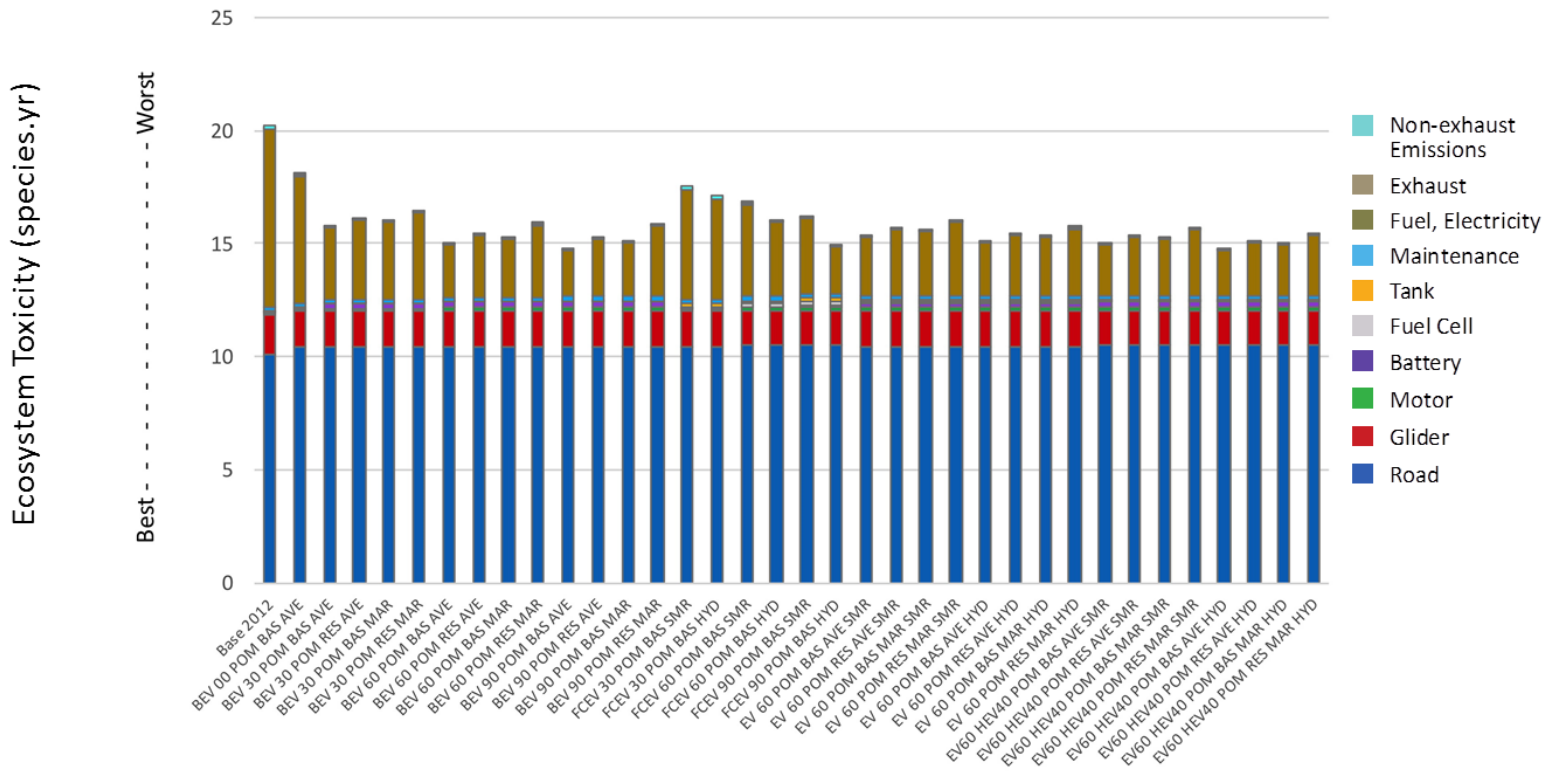
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 8 Fleet 2050 Metals Depletion (relative), by component



Drivetrains

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Figure E. 9 Fleet 2050 Ecosystem Impacts (absolute), by component

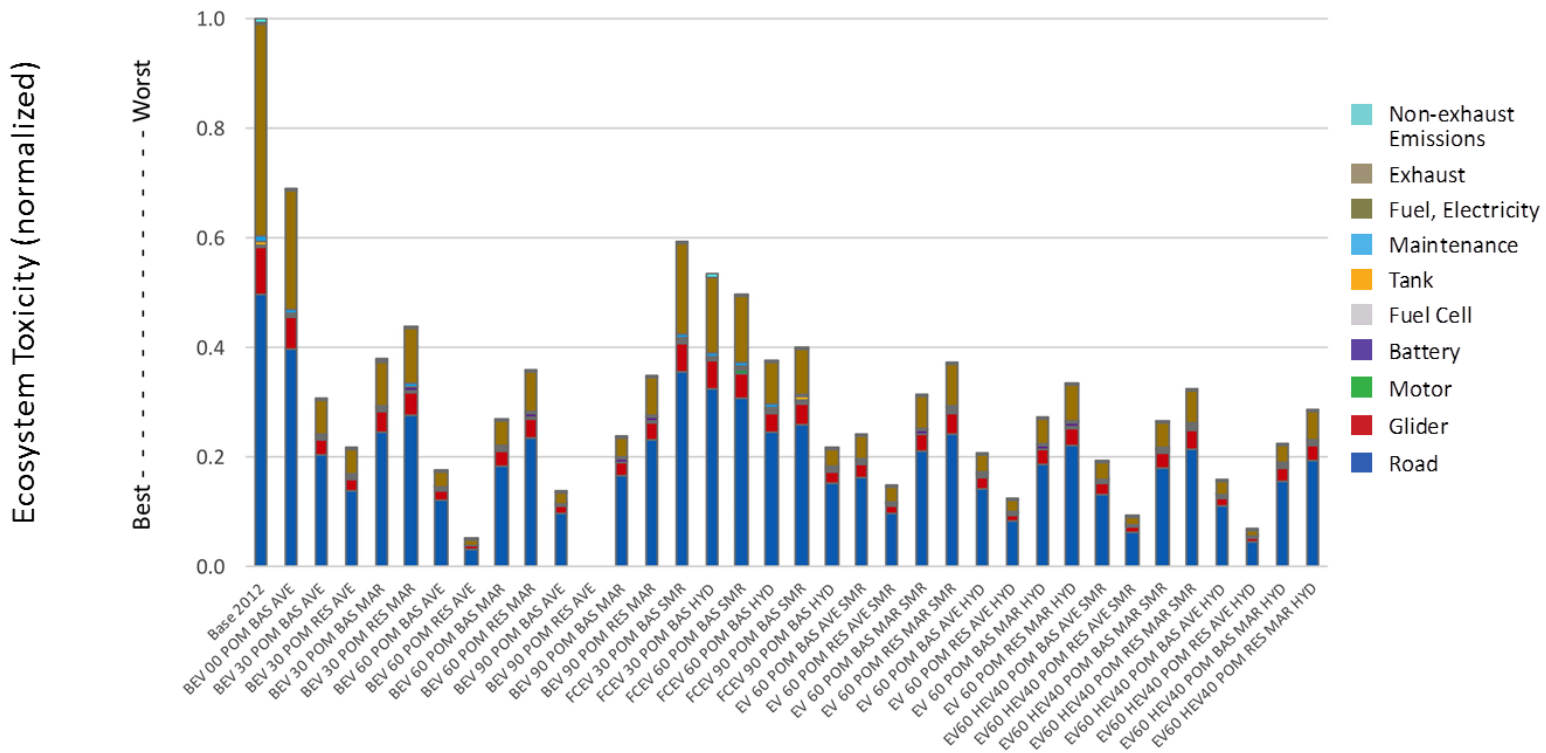

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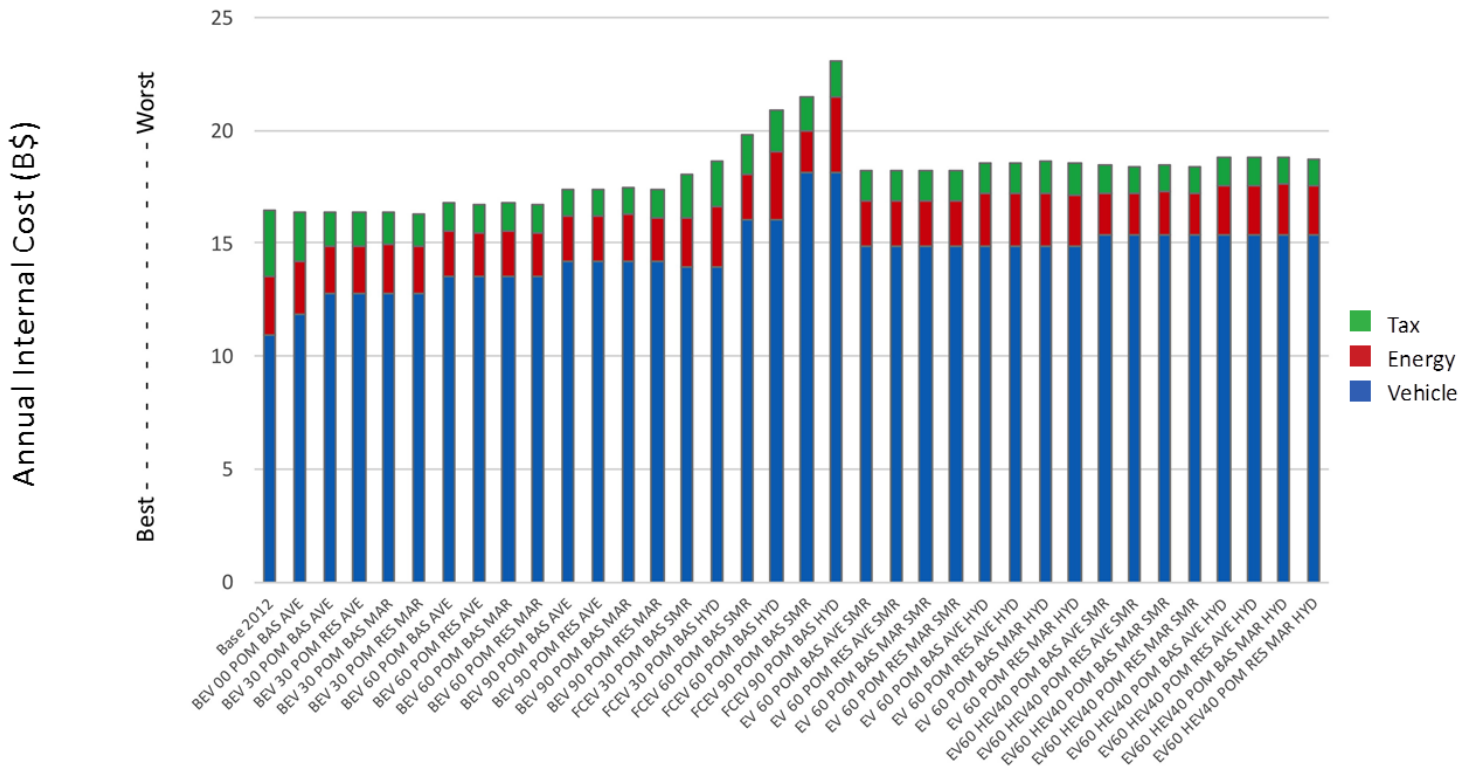
Figure E. 10 Fleet 2050 Ecosystem Impacts (relative), by component



Drivetrains

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Hydrogen

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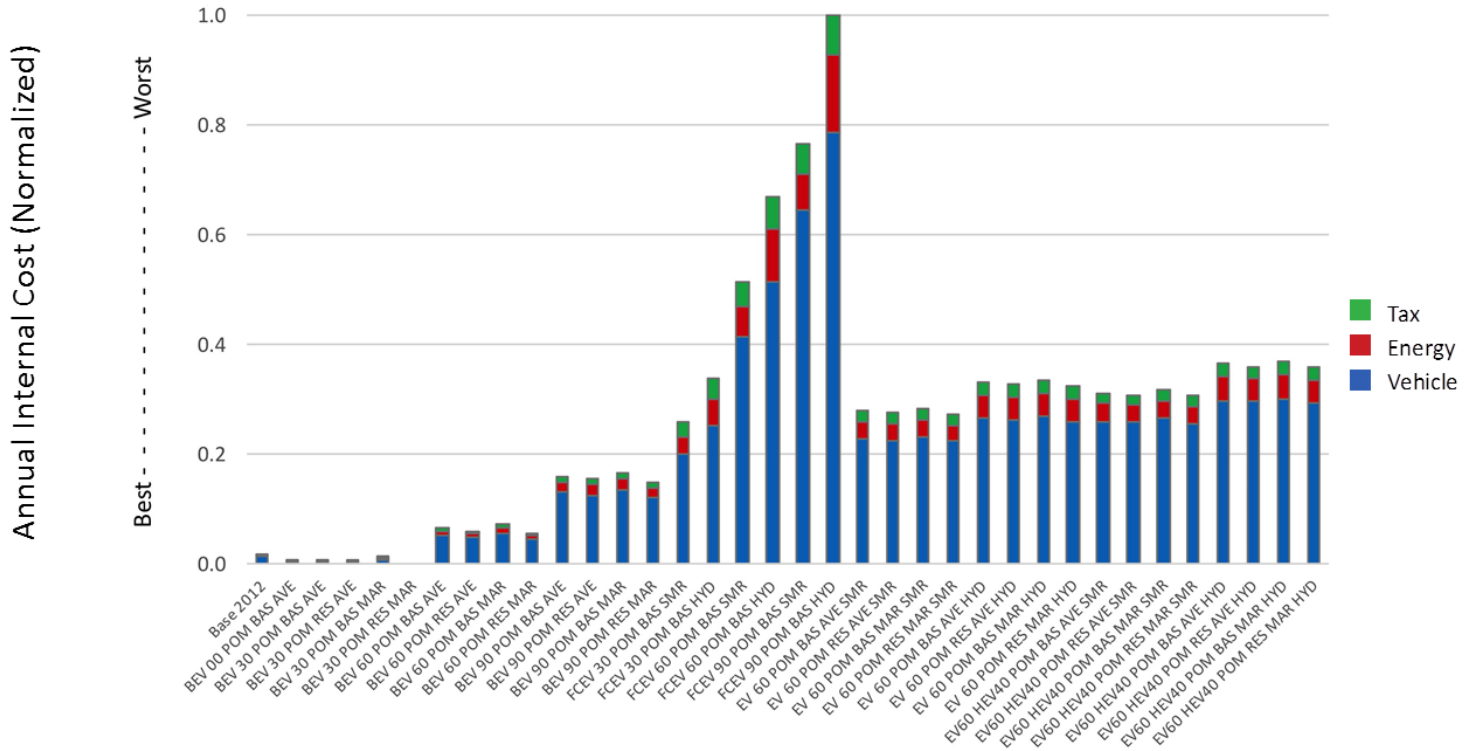
Figure E. 11 Fleet 2050 Annual Internal Fleet Cost (absolute), by component



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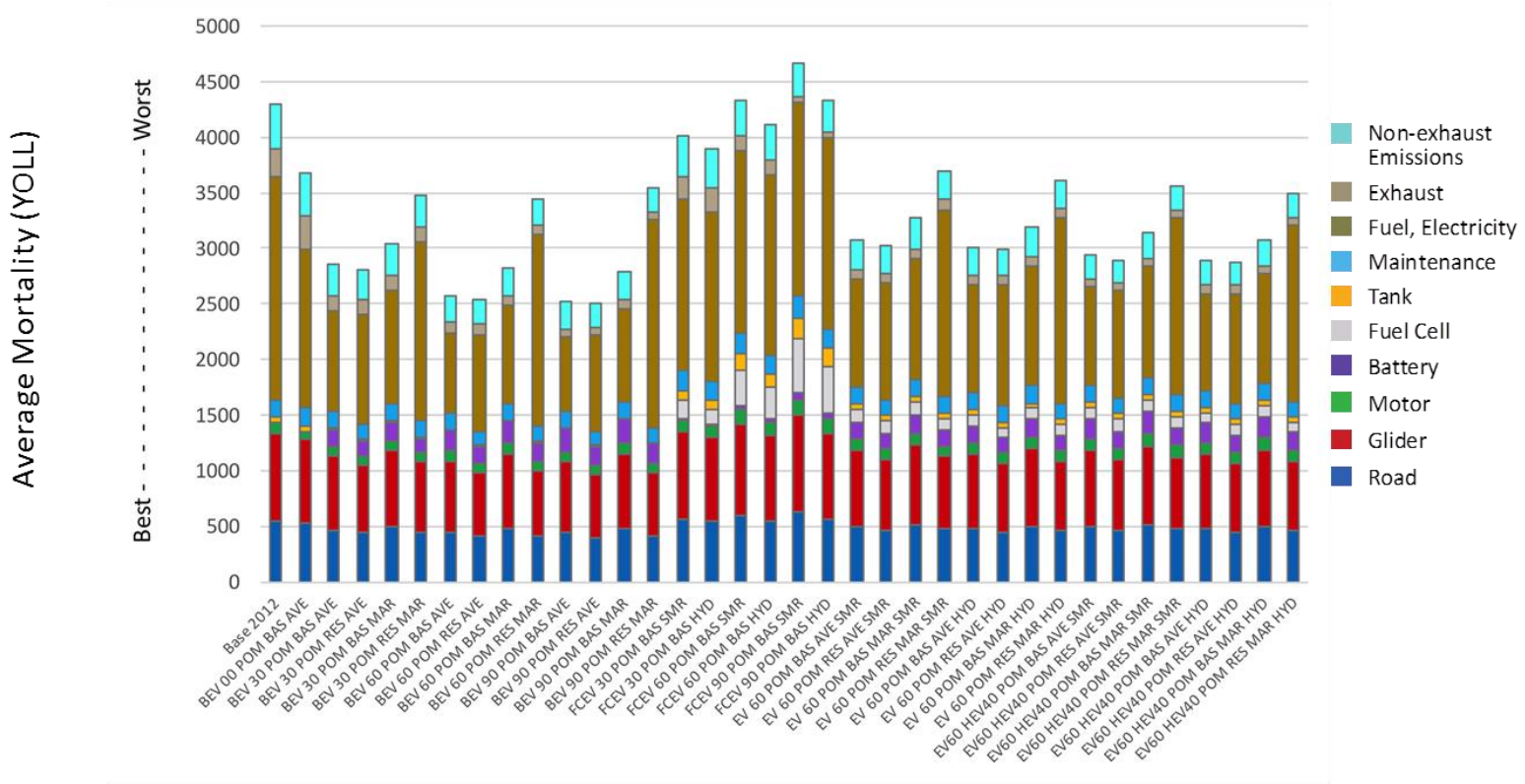
Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 12 Fleet 2050 Annual Internal Fleet Cost (relative), by component



Drivetrains

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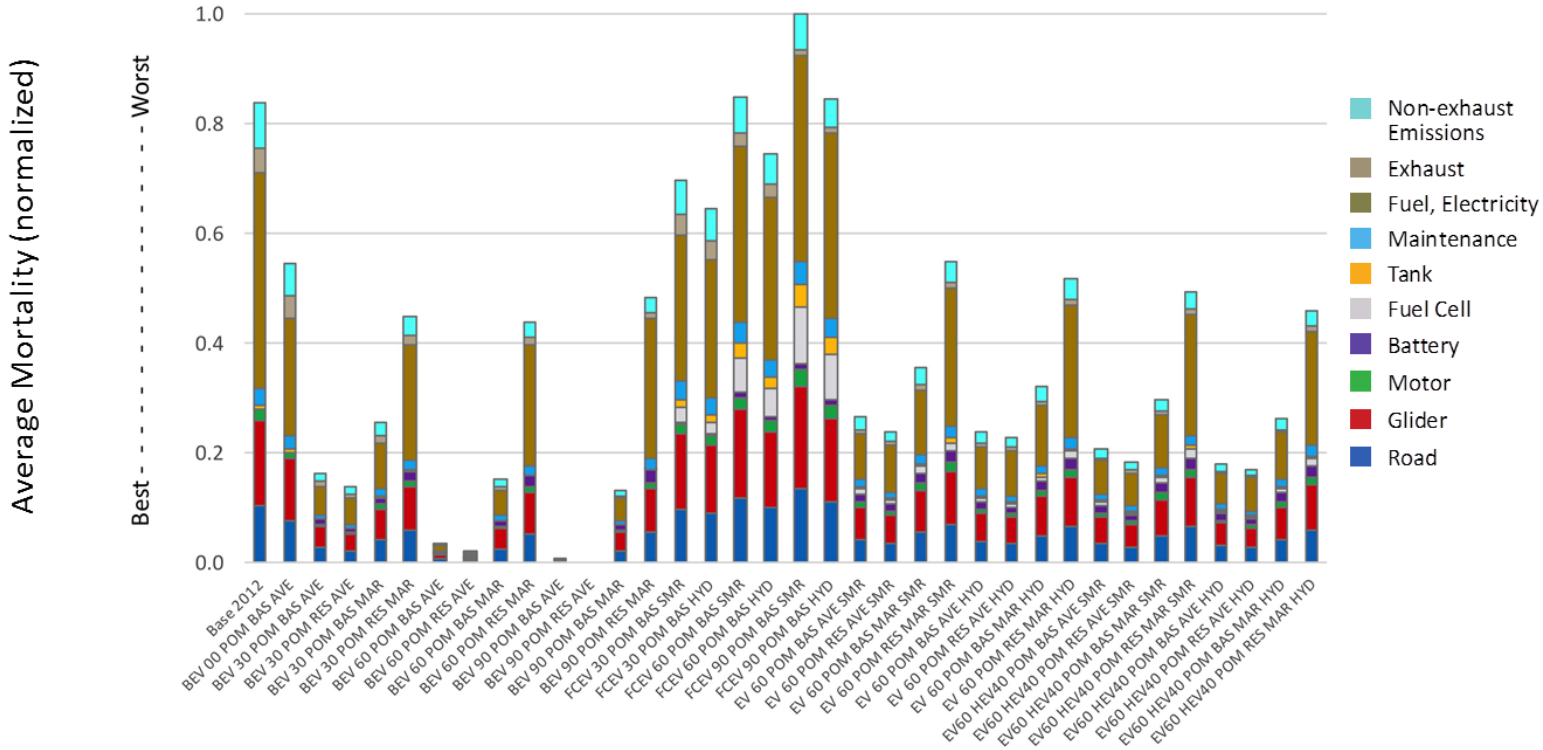
Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 13 Fleet 2050 Average Mortality (absolute), by component



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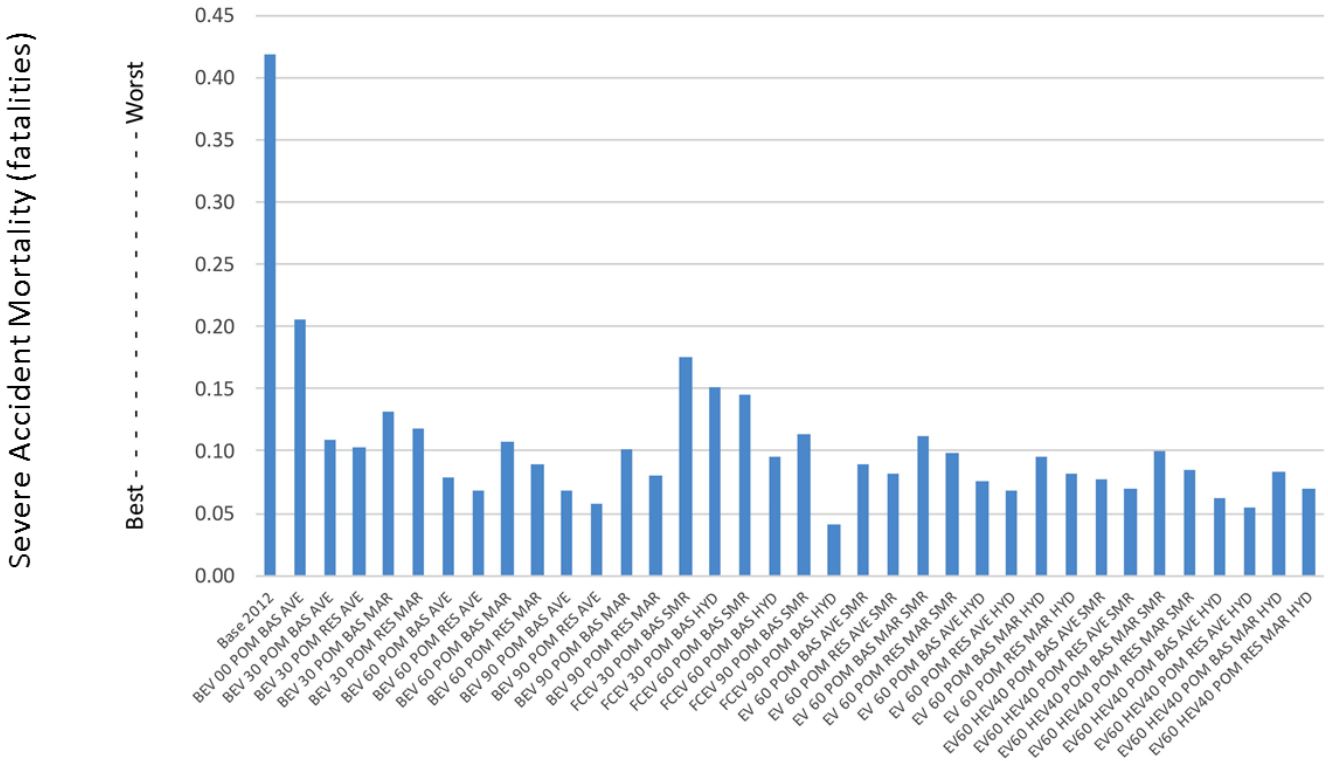
Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 14 Fleet 2050 Average Mortality (relative), by component



Drivetrains

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Hydrogen

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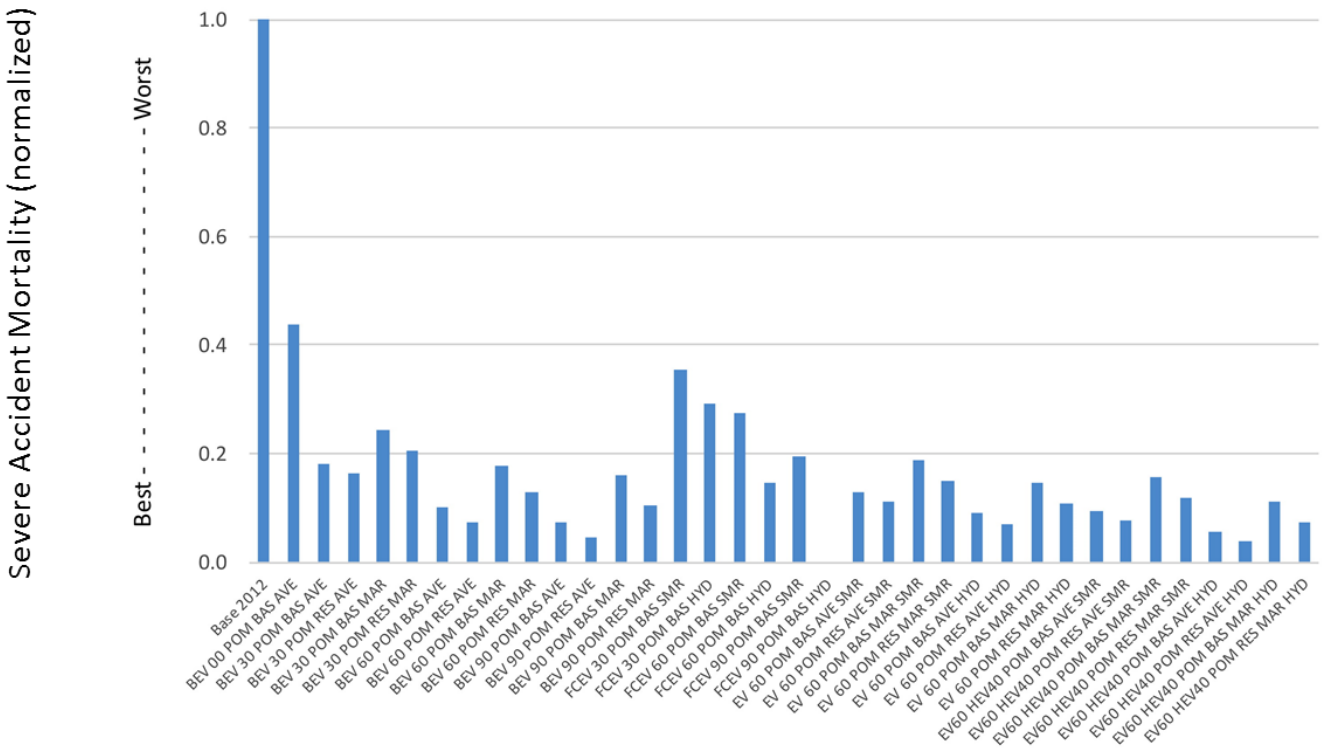
Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 15 Fleet 2050 Severe Accident Mortality (absolute)



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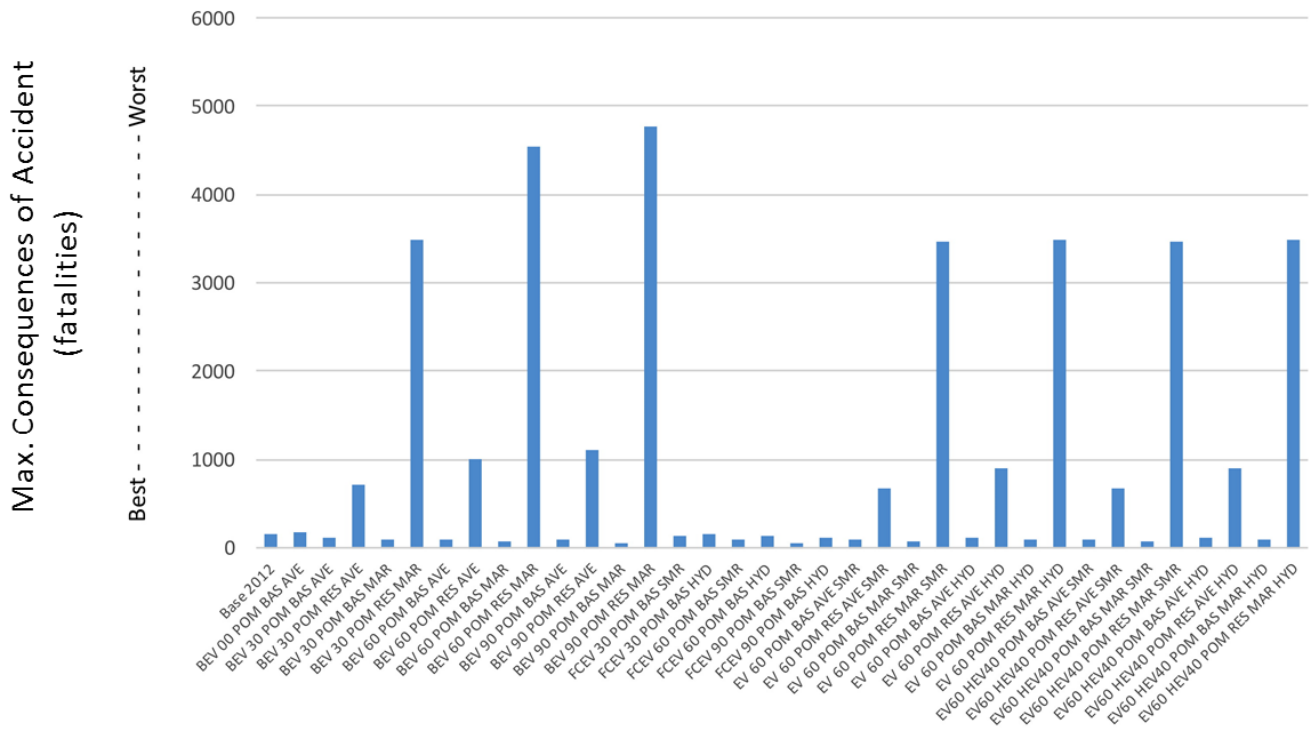
Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 16 Fleet 2050 Severe Accident Mortality (relative)



Drivetrains

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Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 17 Fleet 2050 Maximum Fatalities (absolute)

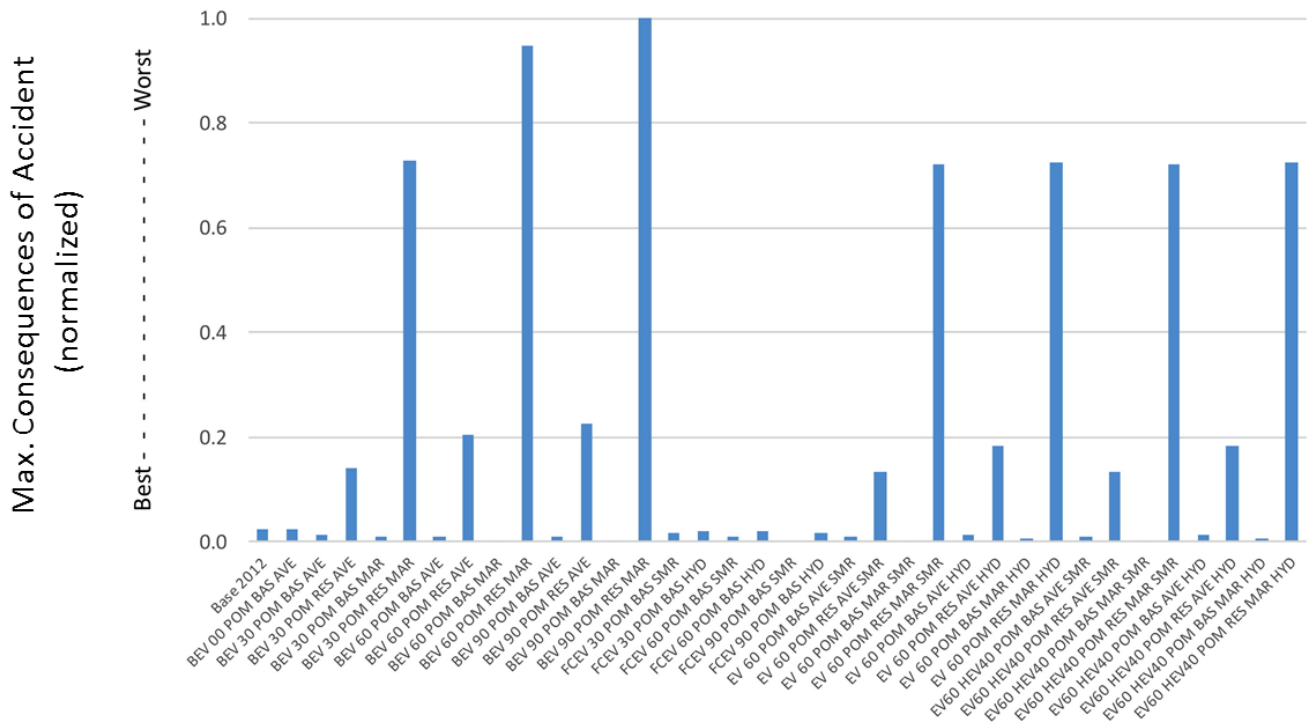

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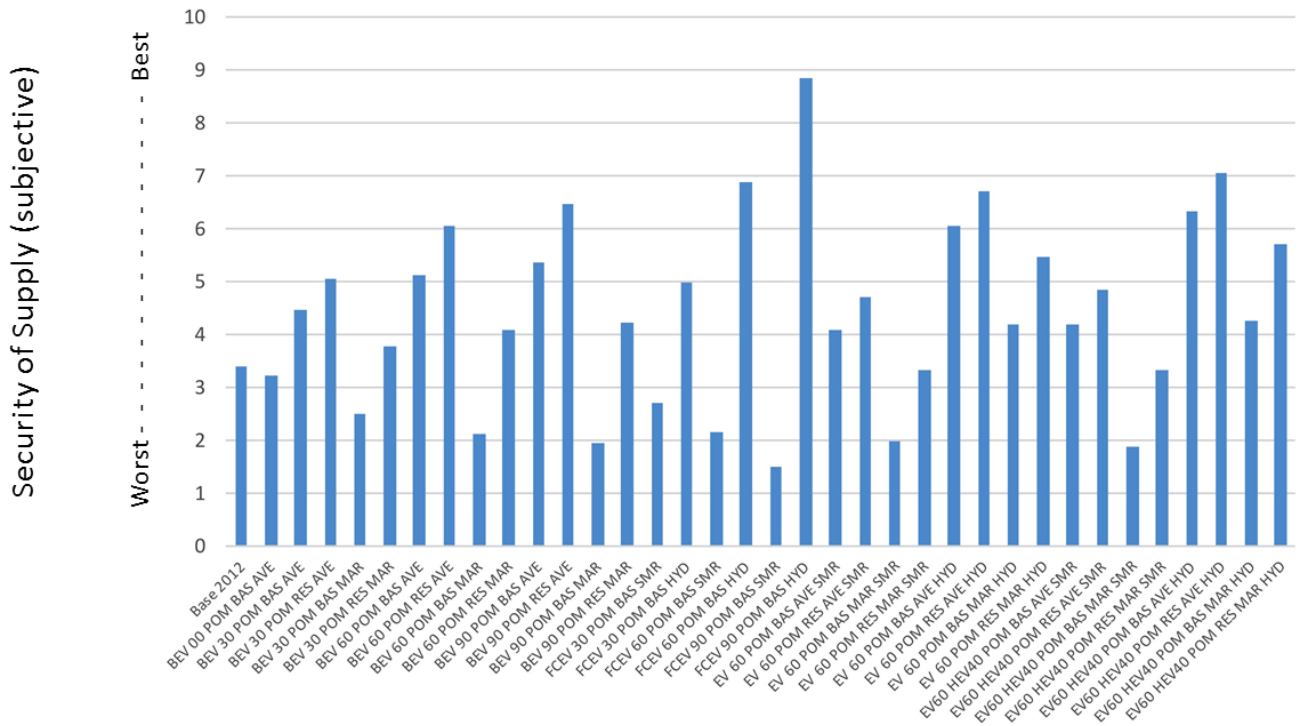
Figure E. 18 Fleet 2050 Maximum Fatalities (relative)



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Hydrogen

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Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 19 Fleet 2050 Security of Fuel Supply (absolute)

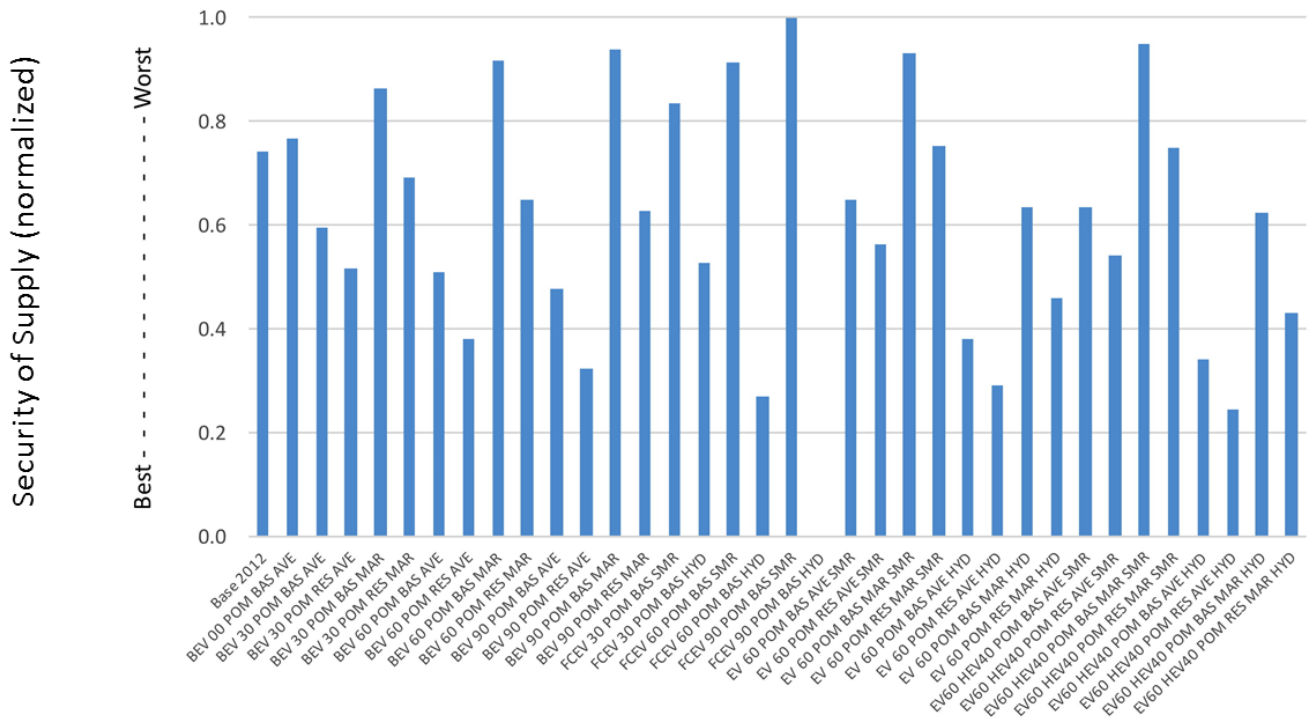

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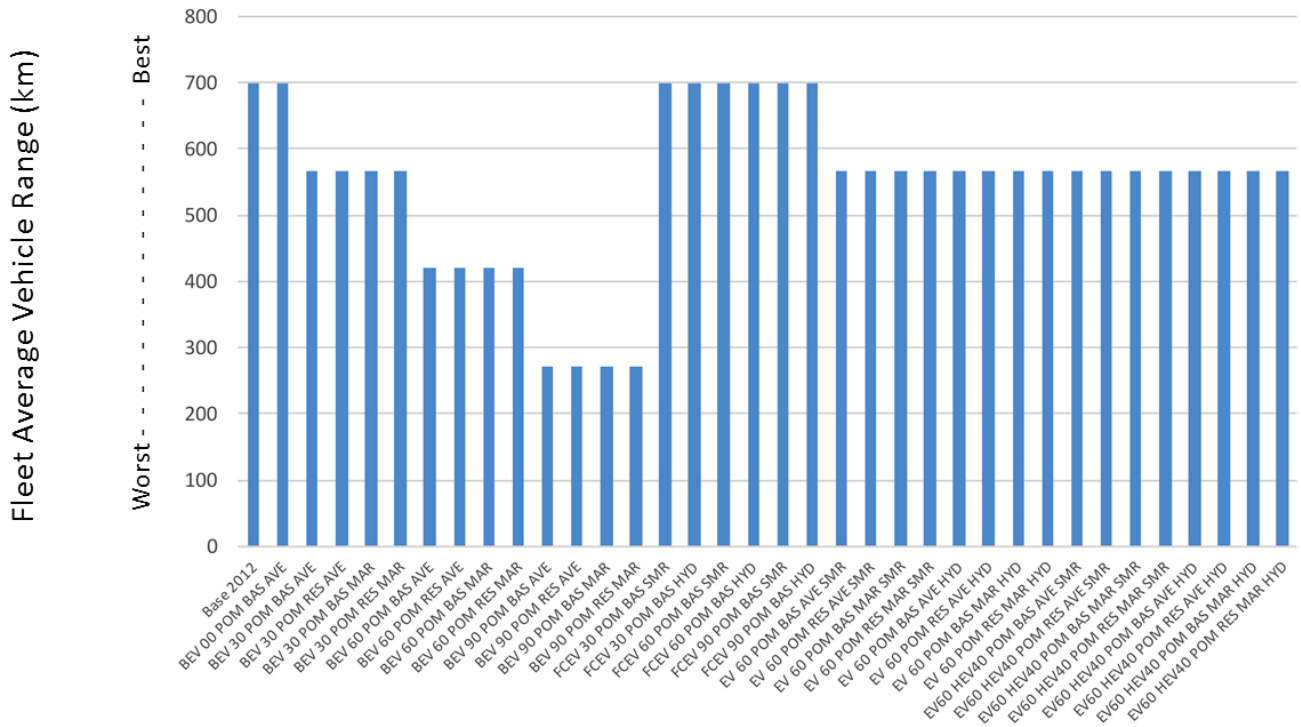
Figure E. 20 Fleet 2050 Security of Fuel Supply (relative)



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Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure E. 21 Fleet 2050 Average Vehicle Range (absolute)

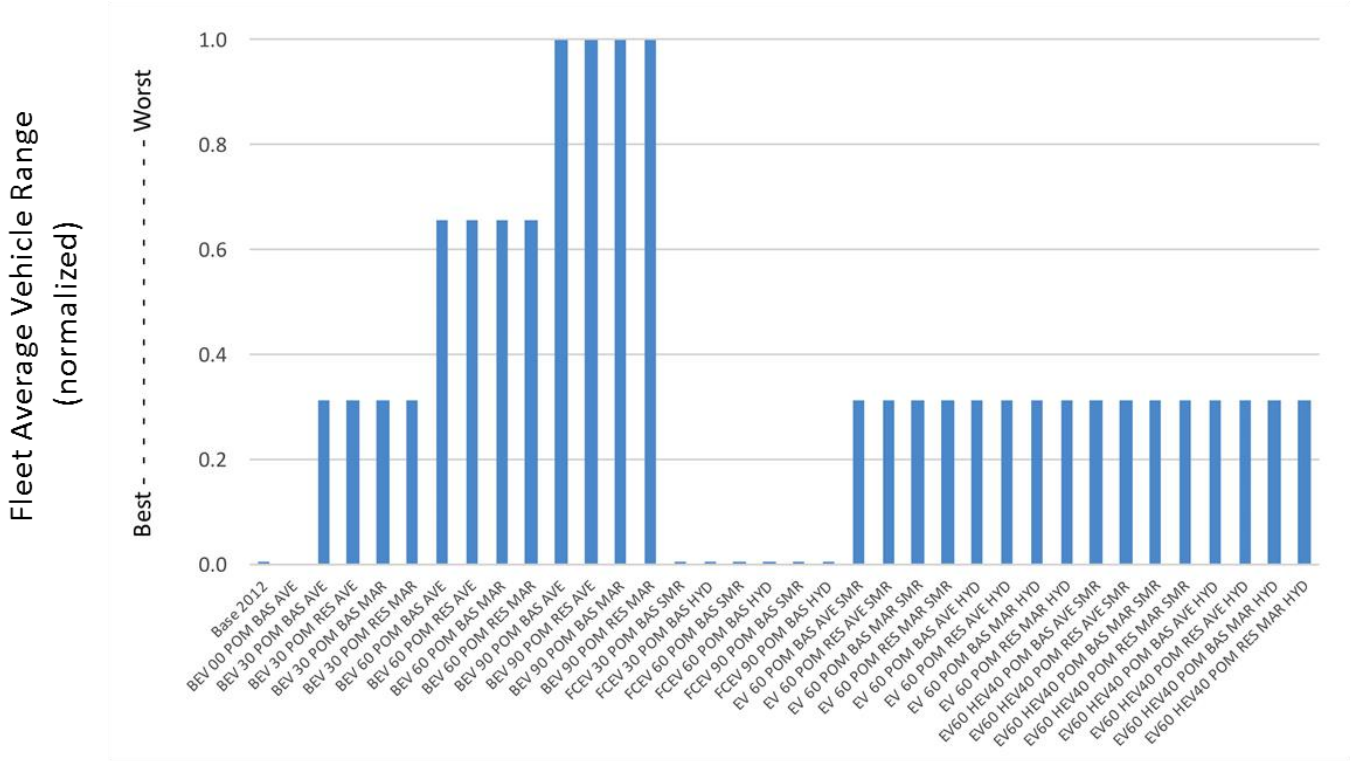

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Figure E. 22 Fleet 2050 Average Vehicle Range (relative)

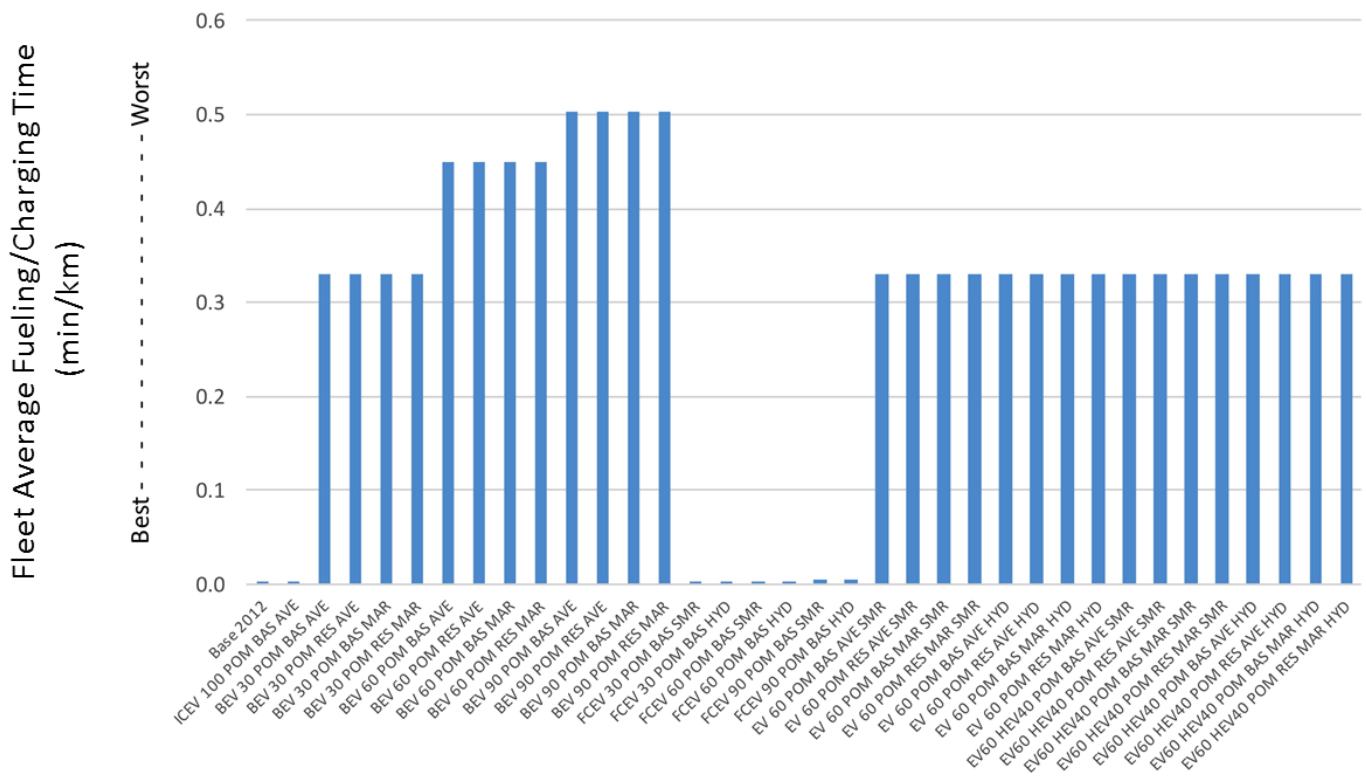

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Figure E. 23 Fleet 2050 Charging, Fueling Time (absolute)

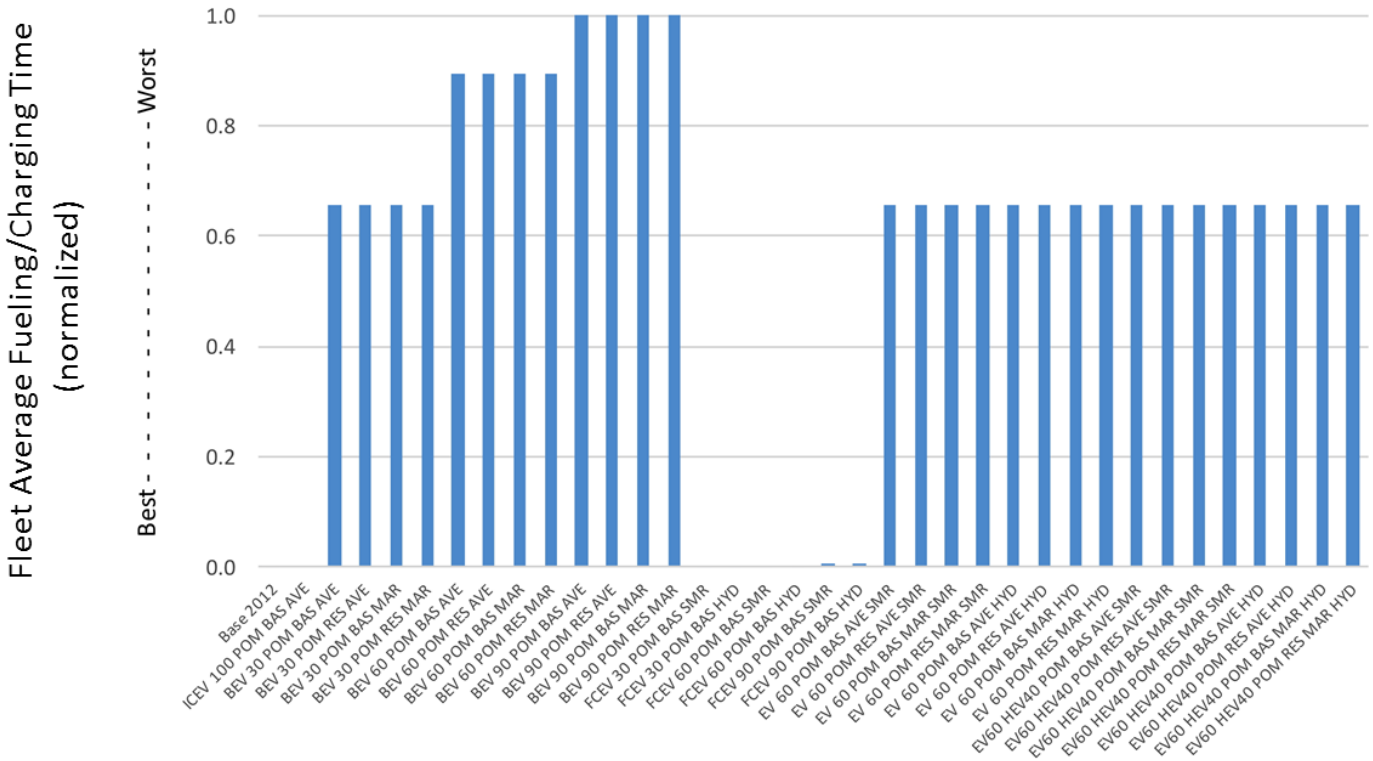

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Figure E. 24 Fleet 2050 Charging, Fueling Time (relative)

Appendix F: THELMA Fleet Indicators for 2012 and 2050, Scenario Subset

Authors: Warren Schenler[58], Stefan Hirschberg[59] (PSI)

List of figures

[58] PSI, Laboratory for Energy Systems Analysis (LEA), Technology Assessment Group, warren.schenler@psi.ch
[59] PSI, Laboratory for Energy Systems Analysis (LEA), stefan.hirschberg@psi.ch

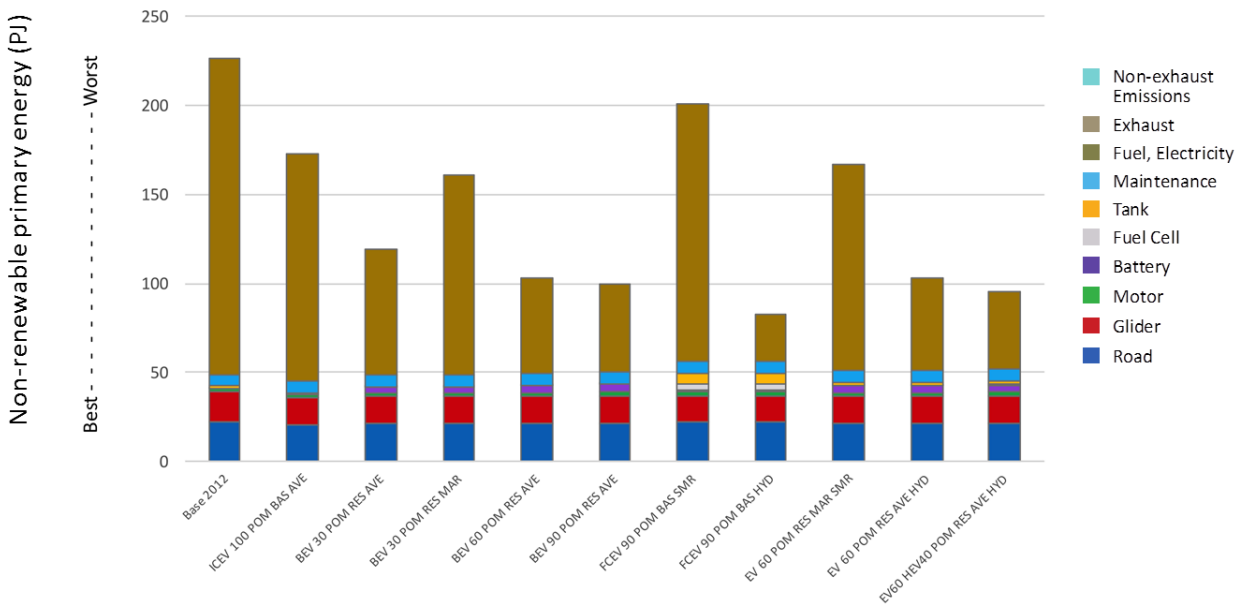

Figure F. 1 Fleet 2050 Non-renewable Primary Energy (absolute), by component

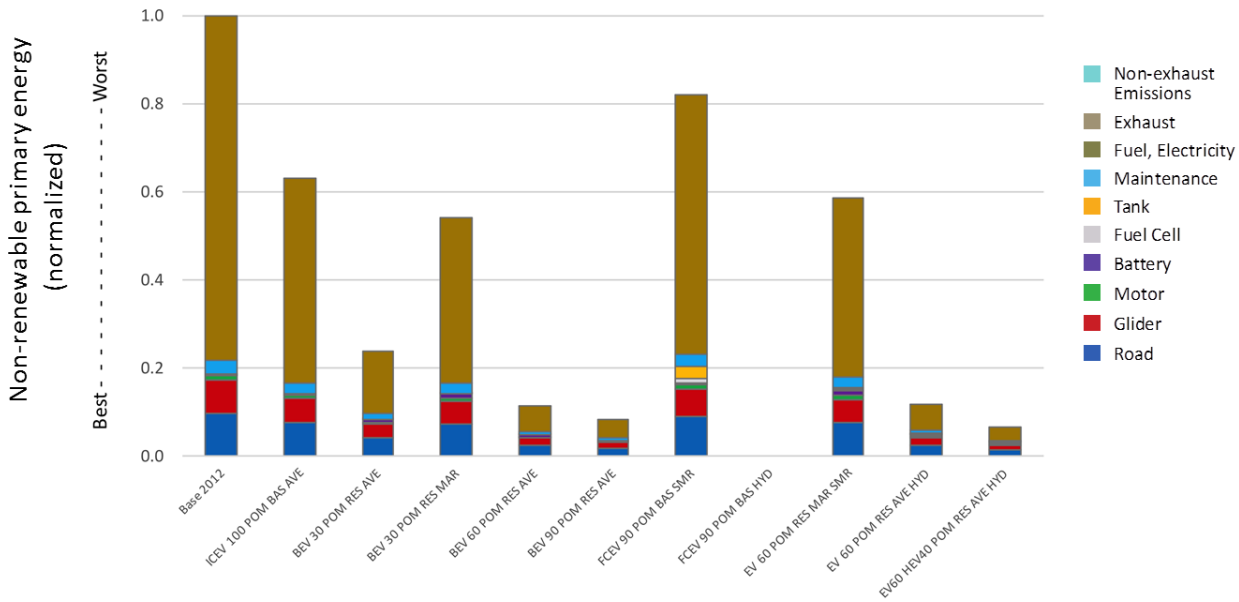

Figure F. 2 Fleet 2050 Non-renewable Primary Energy (relative), by component

Drivetrains

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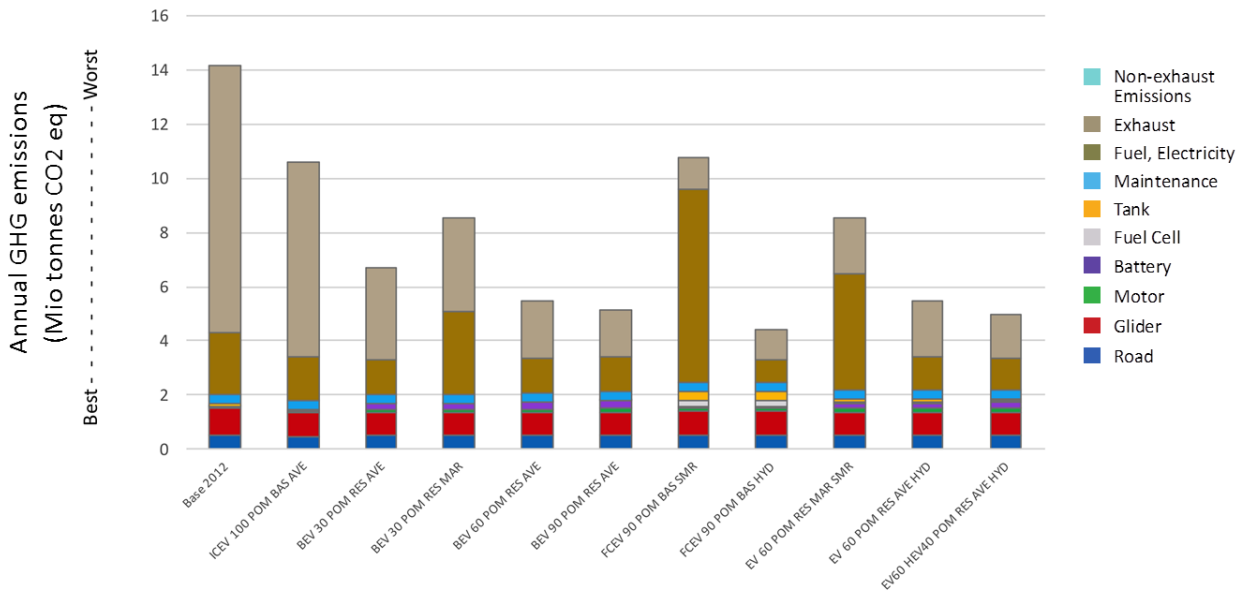

Figure F. 3 Fleet 2050 Greenhouse Gas Emissions (absolute), by component

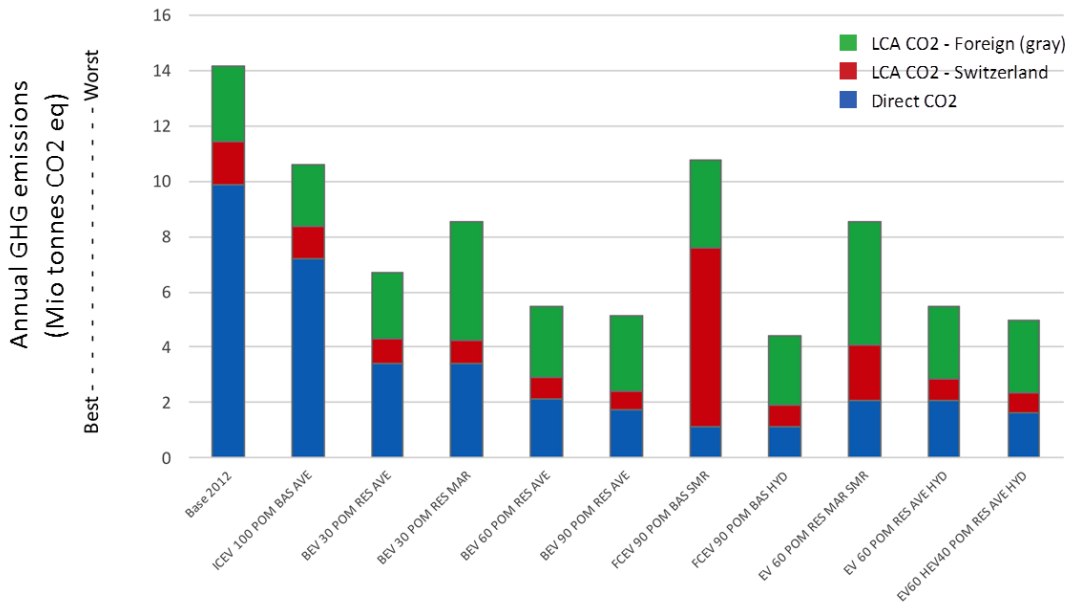

Figure F. 4 Fleet 2050 Greenhouse Gas Emissions (absolute), by location

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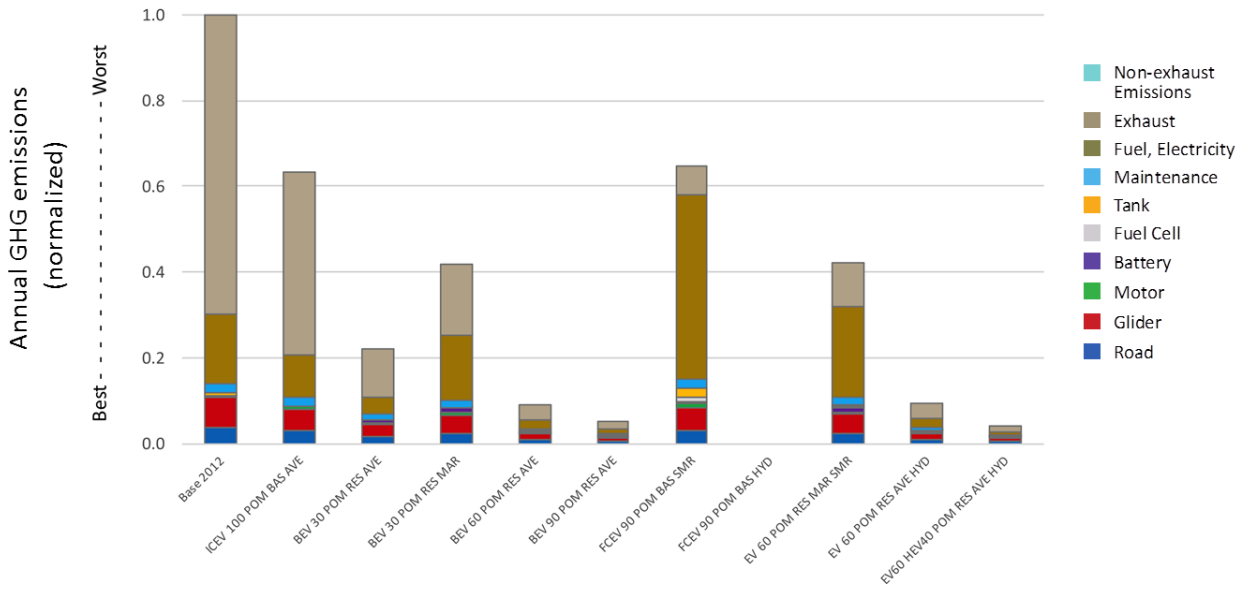

Figure F. 5 Fleet 2050 Greenhouse Gas Emissions (relative), by component

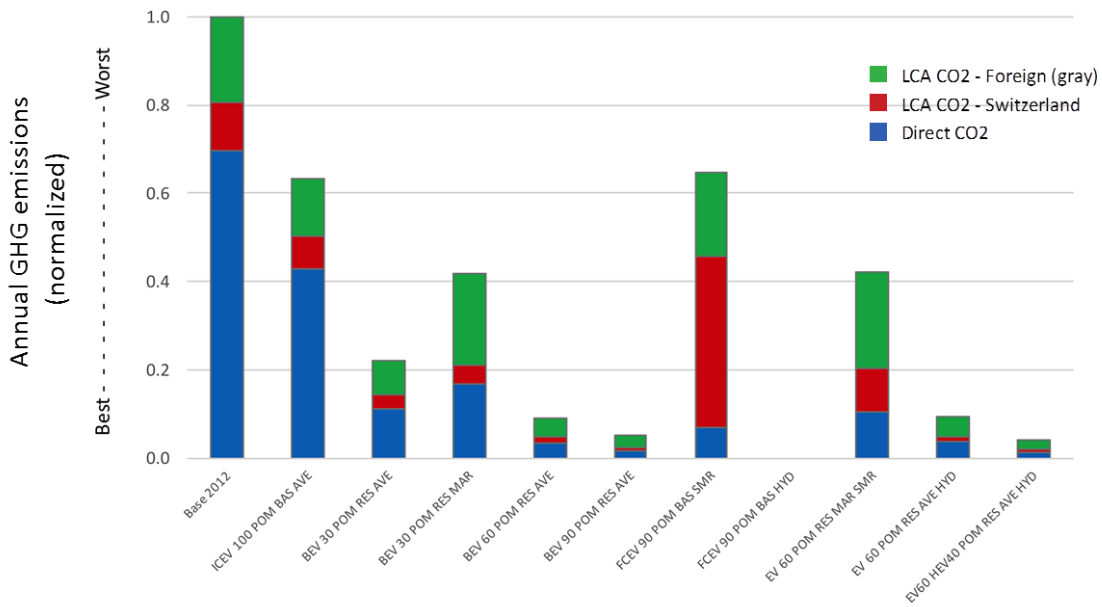

Figure F. 6 Fleet 2050 Greenhouse Gas Emissions (relative), by location

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

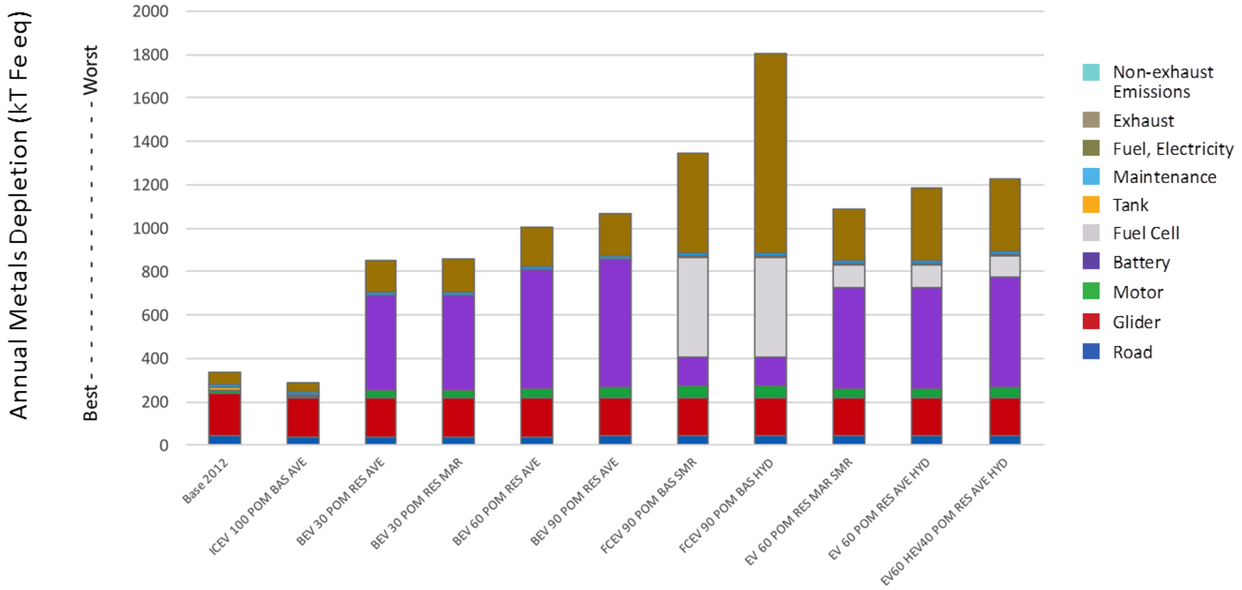

Figure F. 7 Fleet 2050 Metals Depletion (absolute), by component

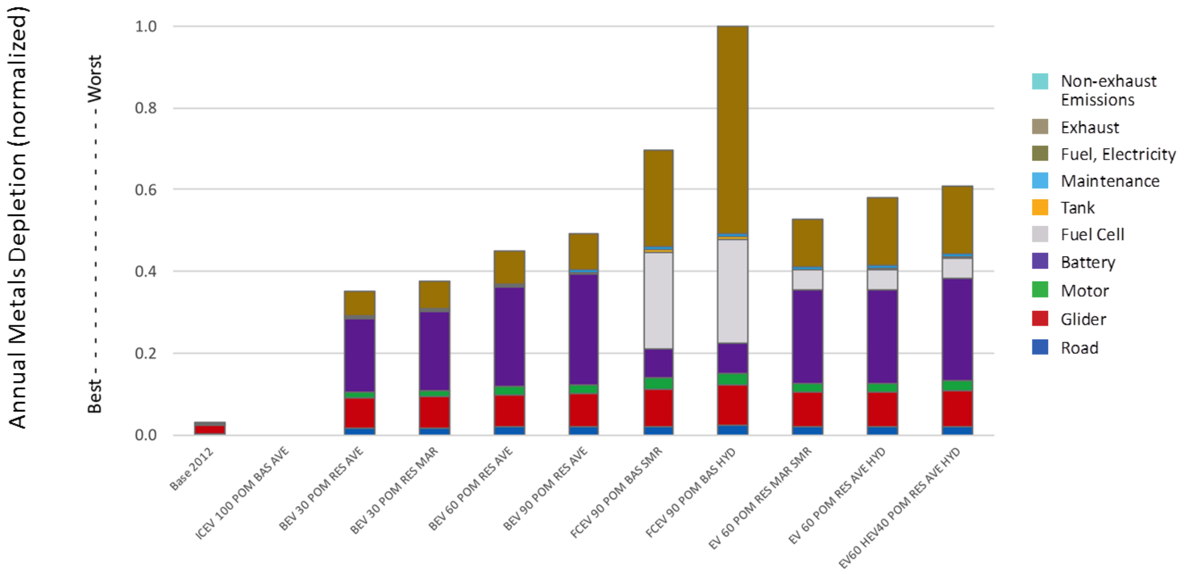

Figure F. 8 Fleet 2050 Metals Depletion (relative), by component

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
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MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

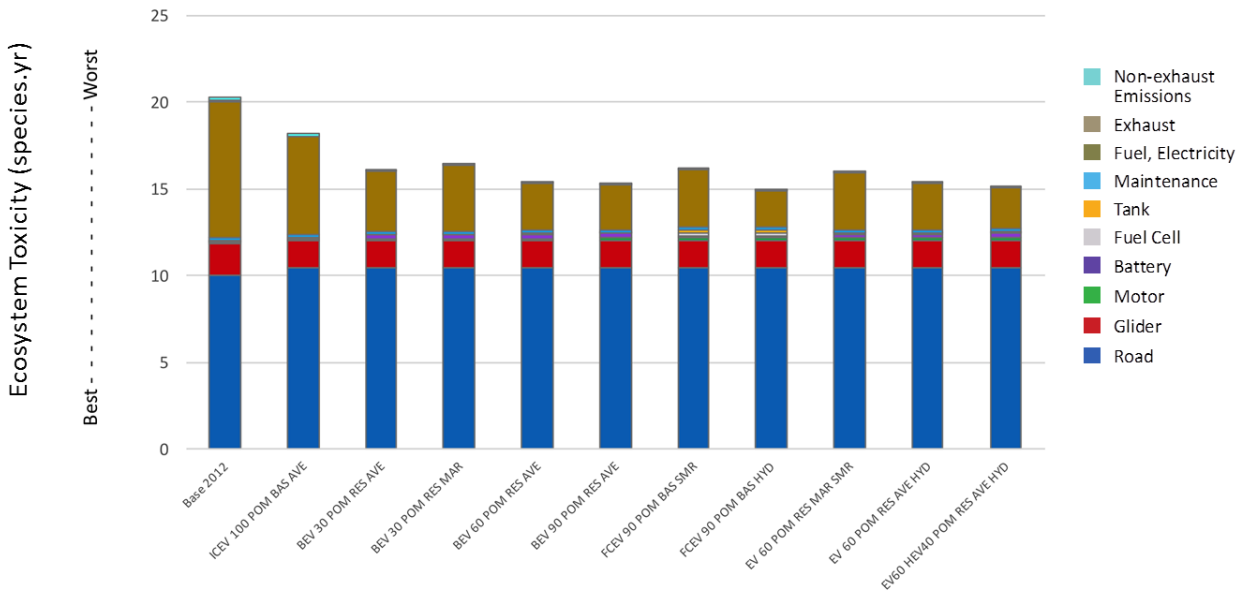

Figure F. 9 Fleet 2050 Ecosystem Impacts (absolute), by component

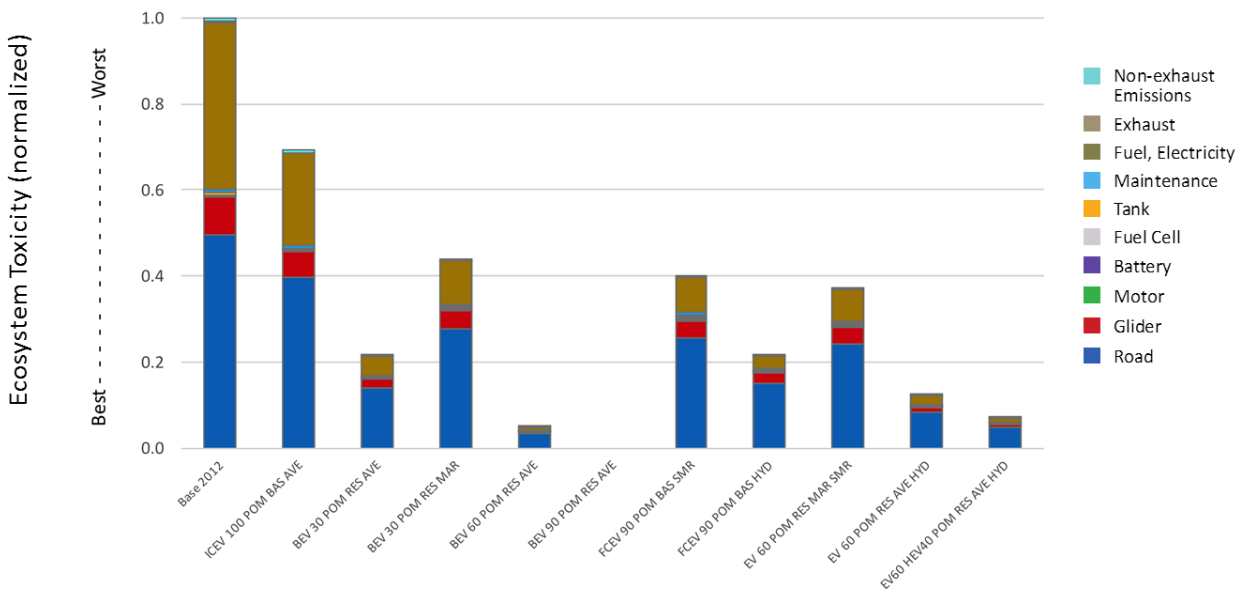

Figure F. 10 Fleet 2050 Ecosystem Impacts (relative), by component

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
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MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

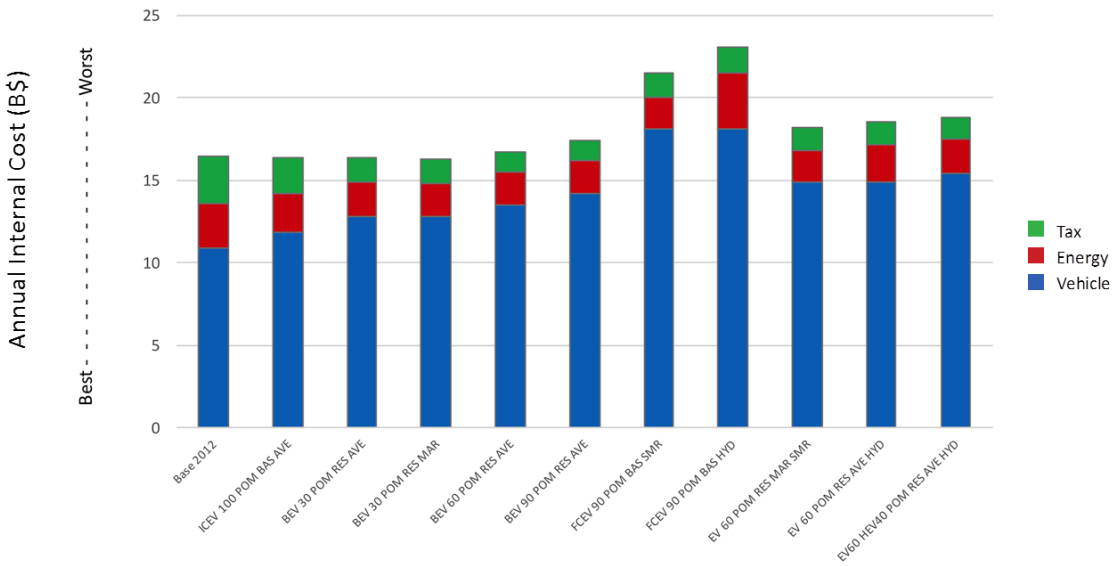

Figure F. 11 Fleet 2050 Annual Internal Fleet Cost (absolute), by component

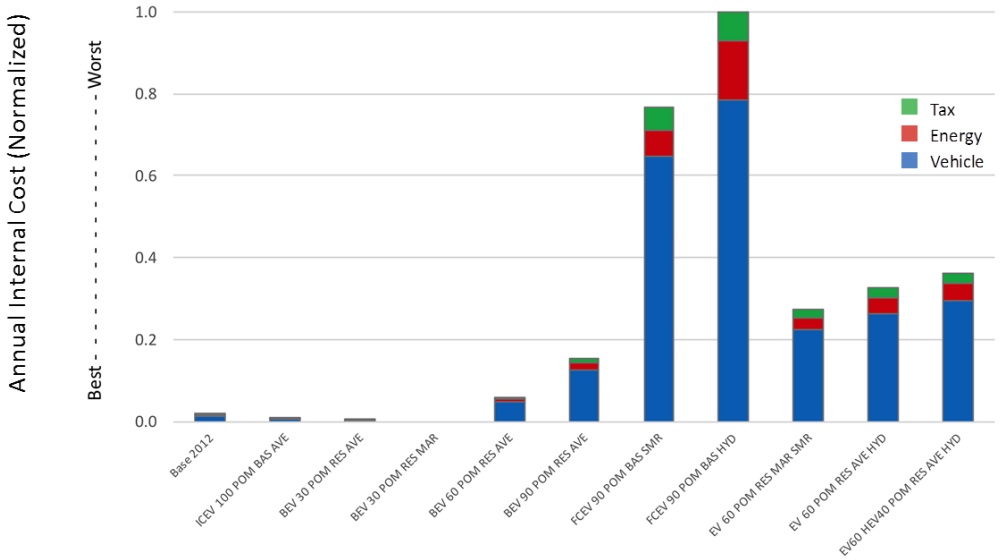

Figure F. 12 Fleet 2050 Annual Internal Fleet Cost (relative), by component

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
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MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

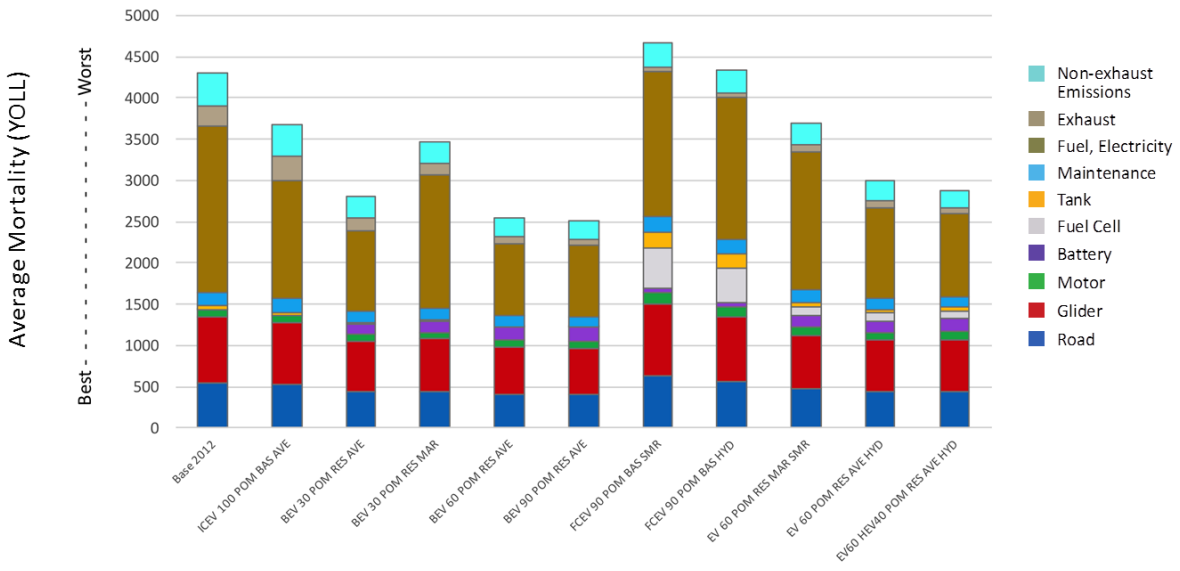

Figure F. 13 Fleet 2050 Average Mortality (absolute), by component

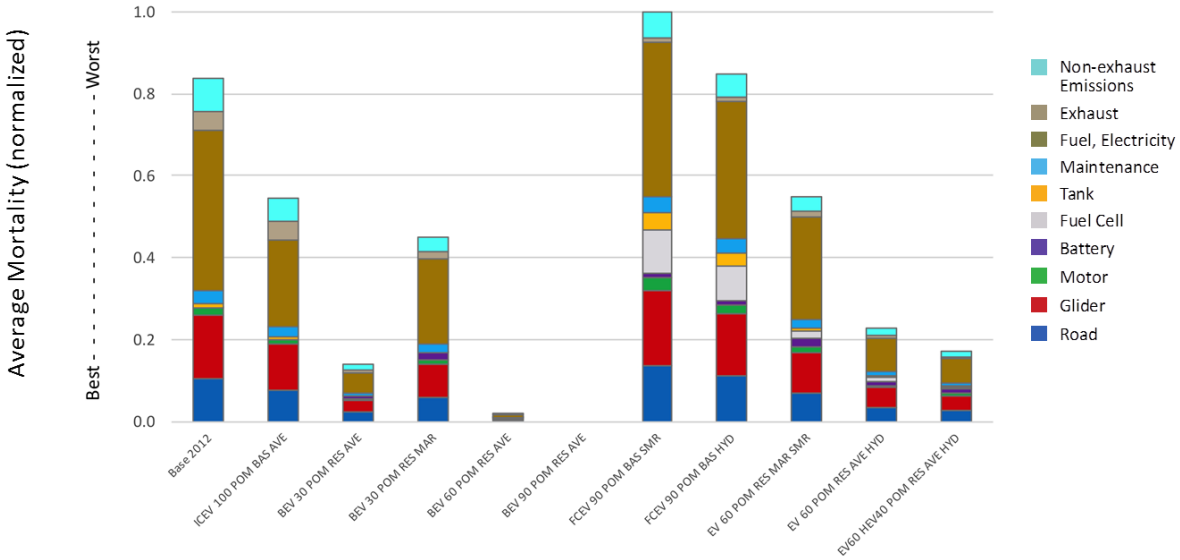

Figure F. 14 Fleet Average Mortality (relative), by component

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
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RES - Supply is renewables strategy
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MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

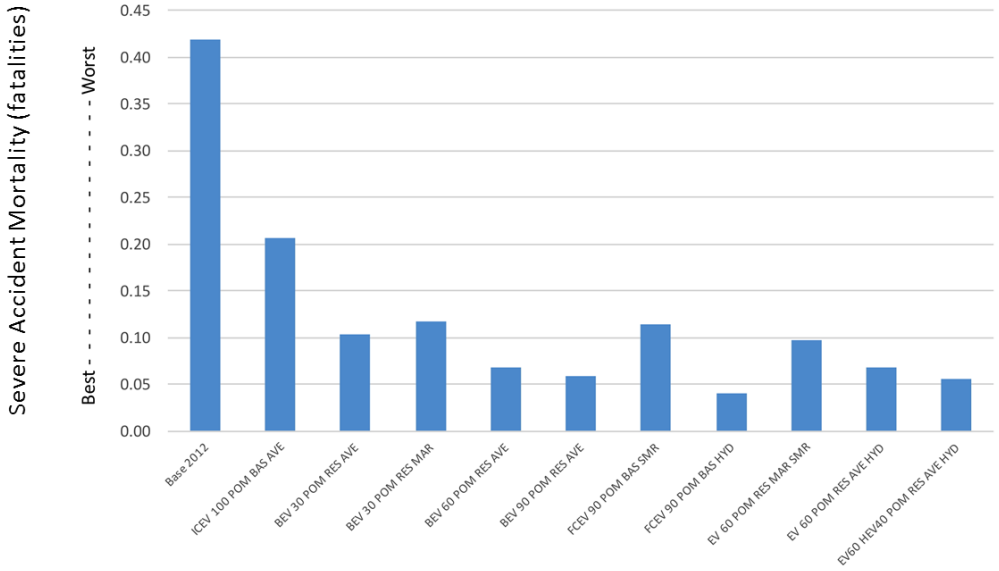

Figure F. 15 Fleet 2050 Severe Accident Mortality (absolute)

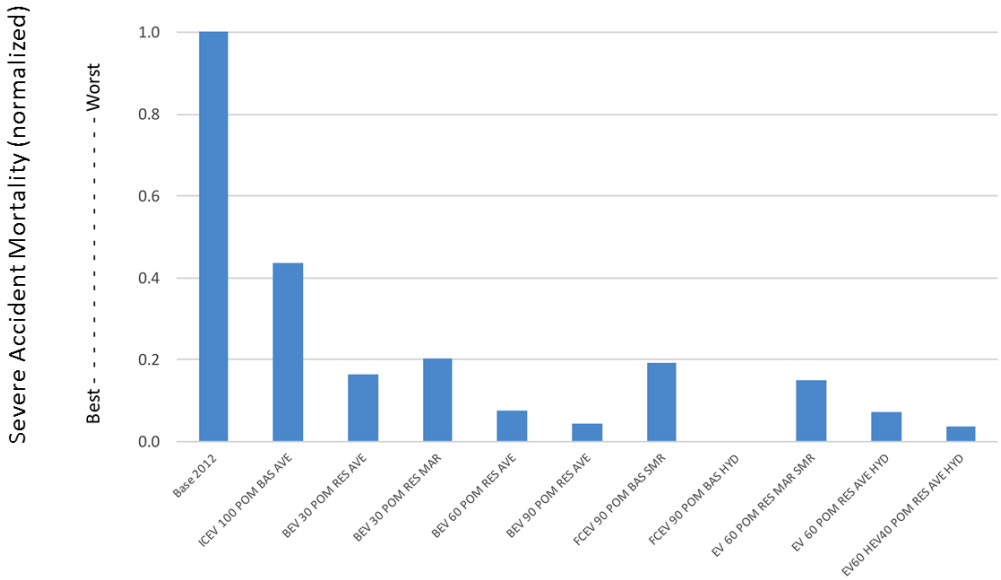

Figure F. 16 Fleet 2050 Severe Accident Mortality (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
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Electricity

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Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

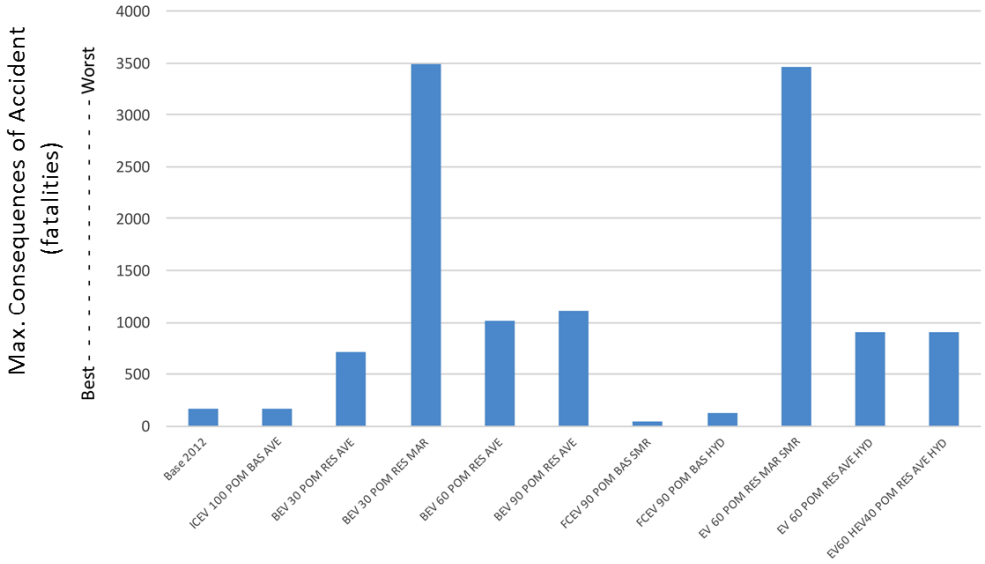

Figure F. 17 Fleet 2050 Maximum Fatalities (absolute)

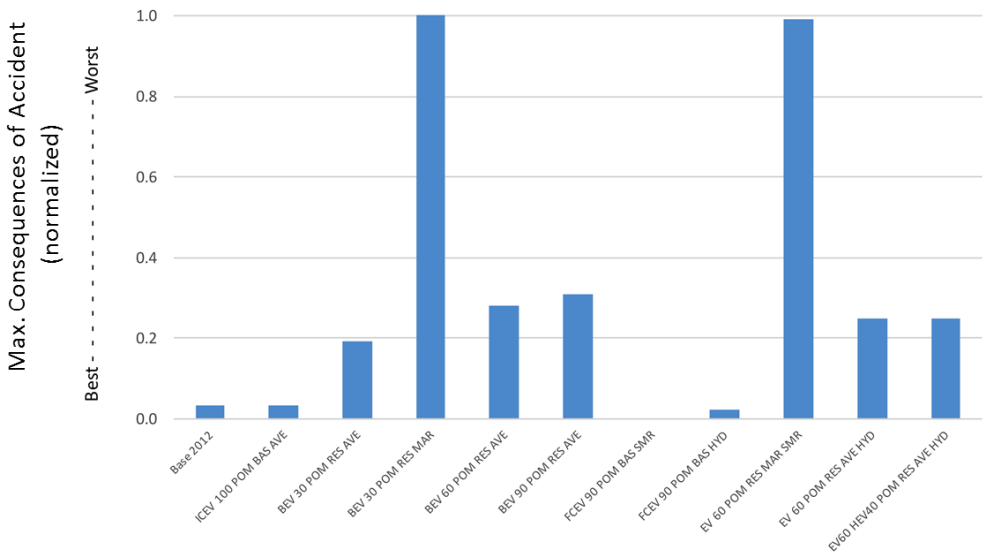

Figure F. 18 Fleet 2050 Maximum Fatalities (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
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Electricity

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RES - Supply is renewables strategy
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MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

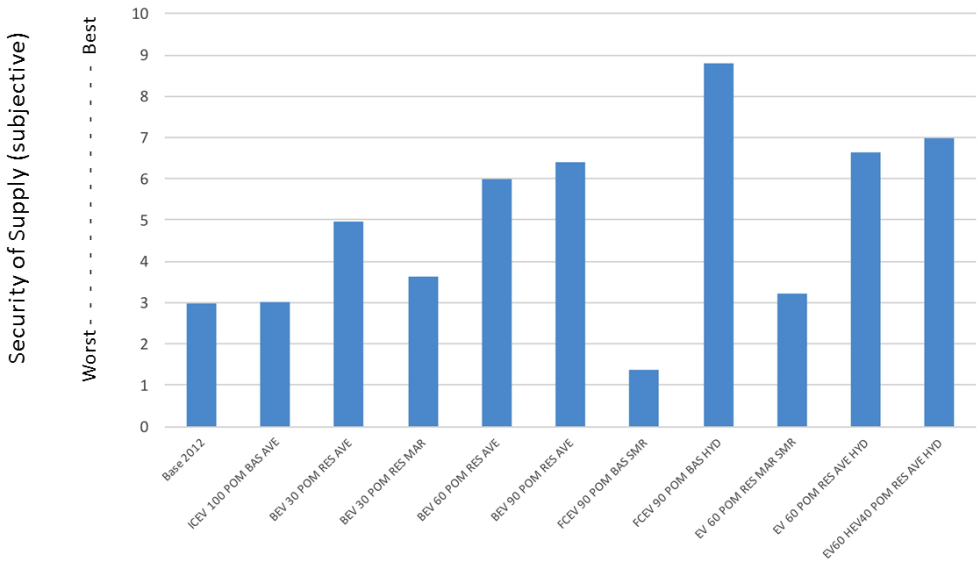

Figure F. 19 Fleet 2050 Security of Fuel Supply (absolute)

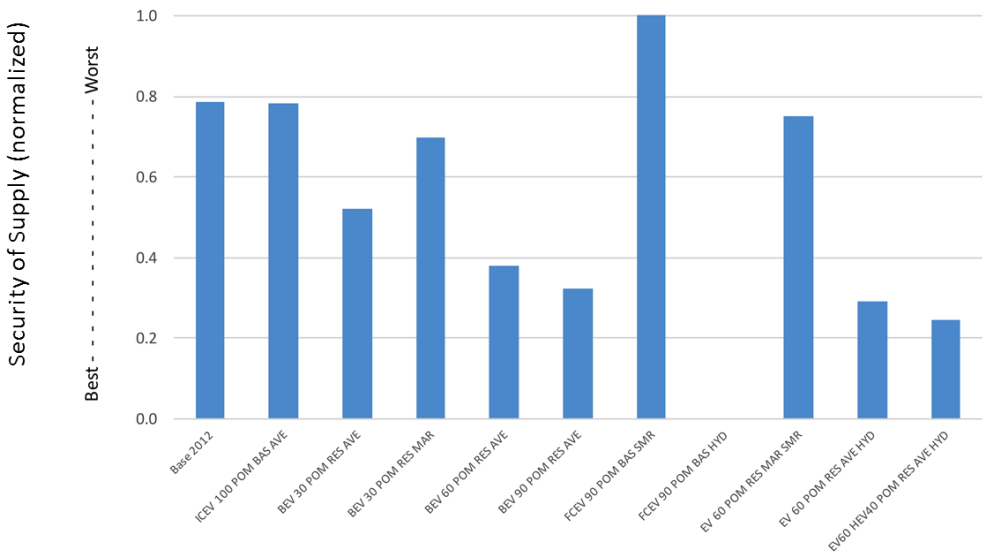

Figure F. 20 Fleet 2050 Security of Fuel Supply (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
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RES - Supply is renewables strategy
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MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

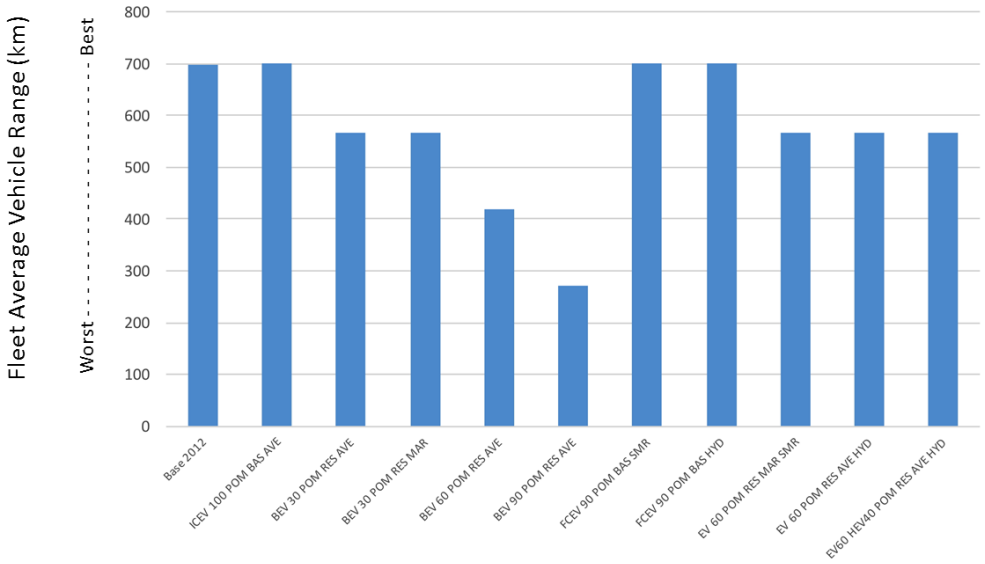

Figure F. 21 Fleet 2050 Average Vehicle Range (absolute)

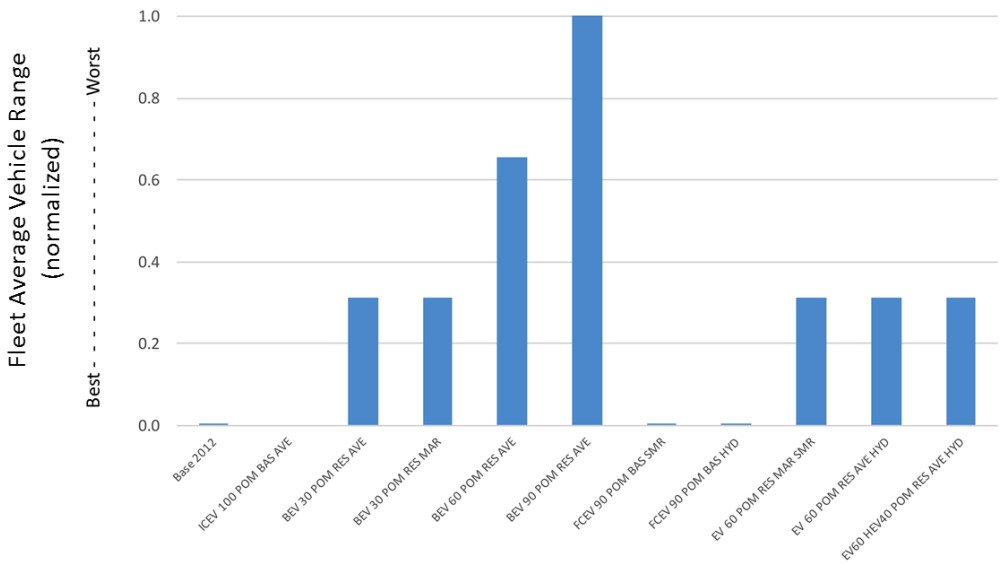

Figure F. 22 Fleet 2050 Average Vehicle Range (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

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Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

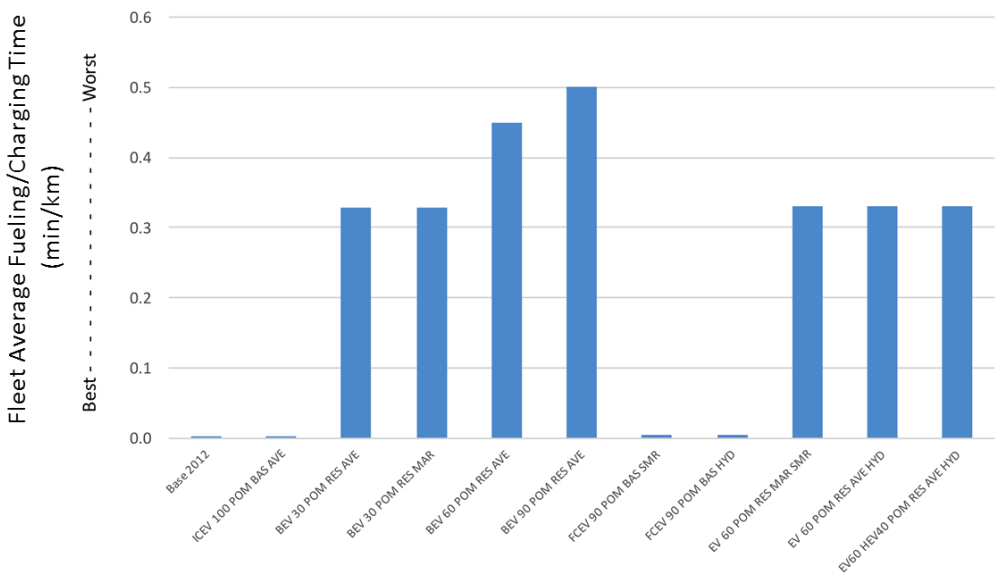

Figure F. 23 Fleet 2050 Charging, Fueling Time (absolute)

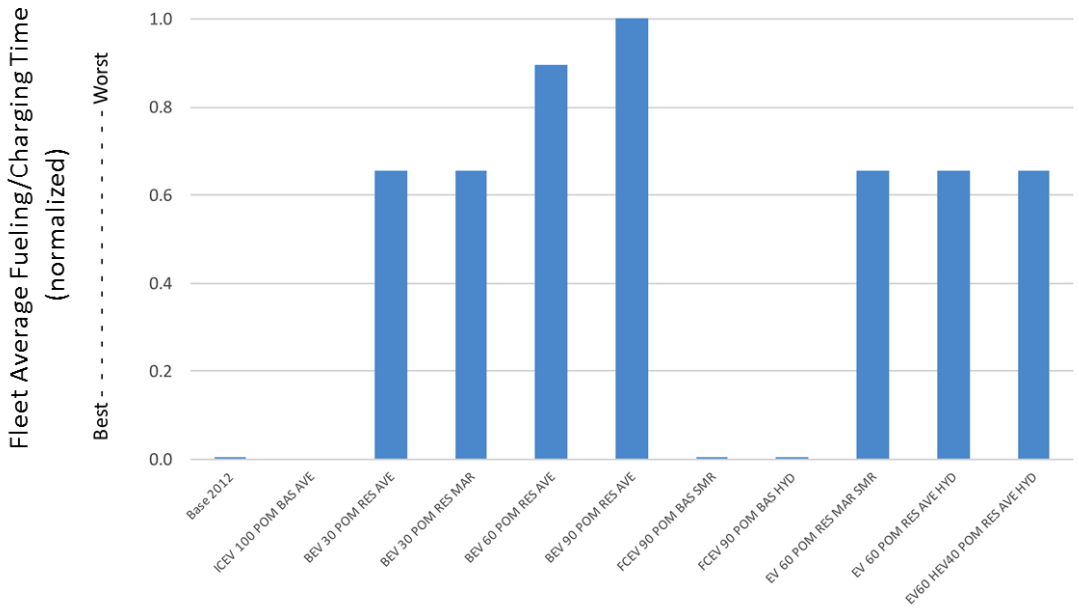

Figure F. 24 Fleet 2050 Charging, Fueling Time (relative)

Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
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RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

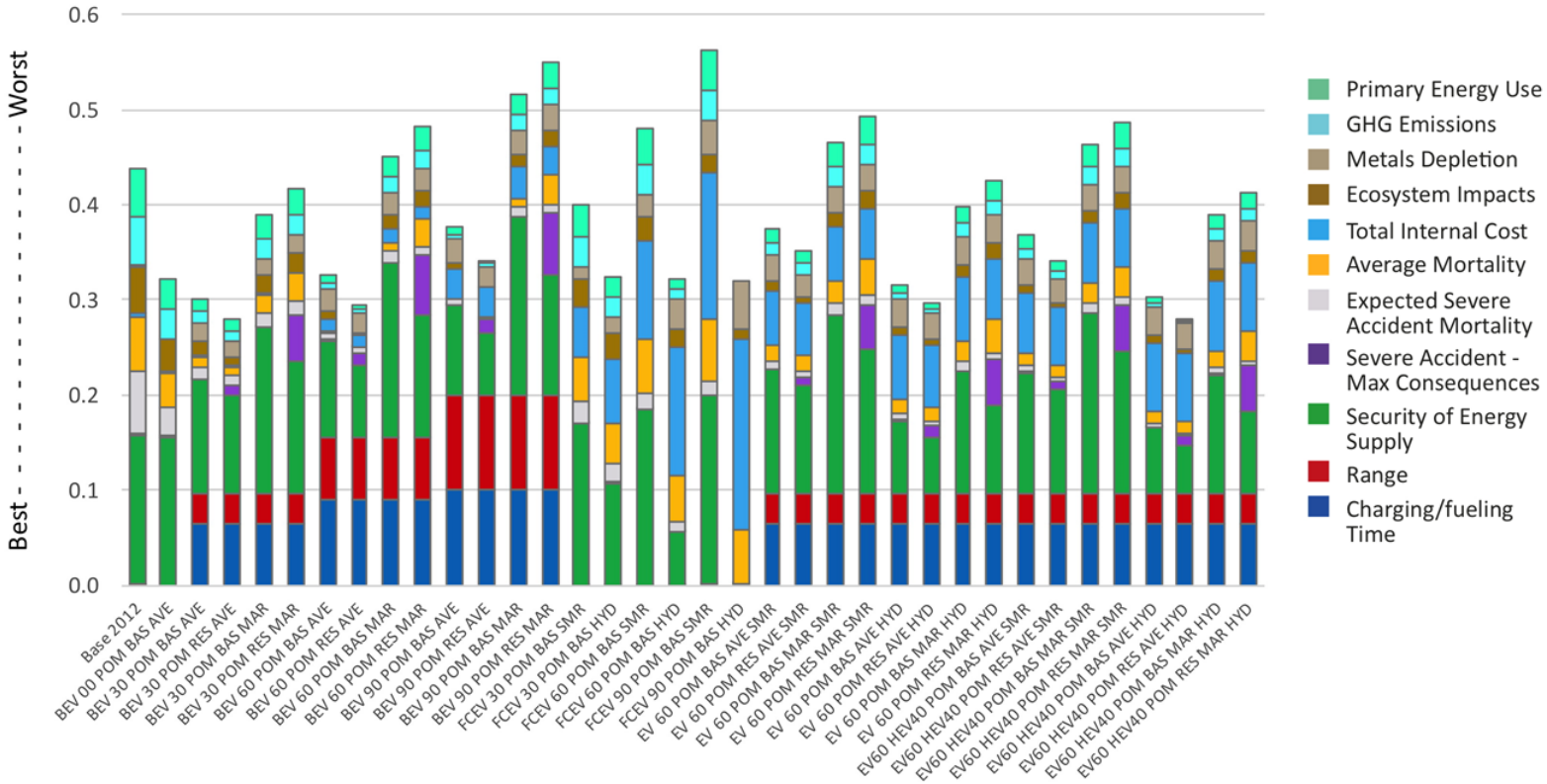
Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Appendix G: THELMA Fleet MCDA for 2050, Full Scenario Set

Authors: Warren Schenler[60], Stefan Hirschberg[61] (PSI)

List of figures

[60] PSI, Laboratory for Energy Systems Analysis (LEA), Technology Assessment Group, warren.schenler@psi.ch
[61] PSI, Laboratory for Energy Systems Analysis (LEA), stefan.hirschberg@psi.ch



Drivetrains

ICEV - Internal Combustion Engine Vehicles
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FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE “Political Measures”
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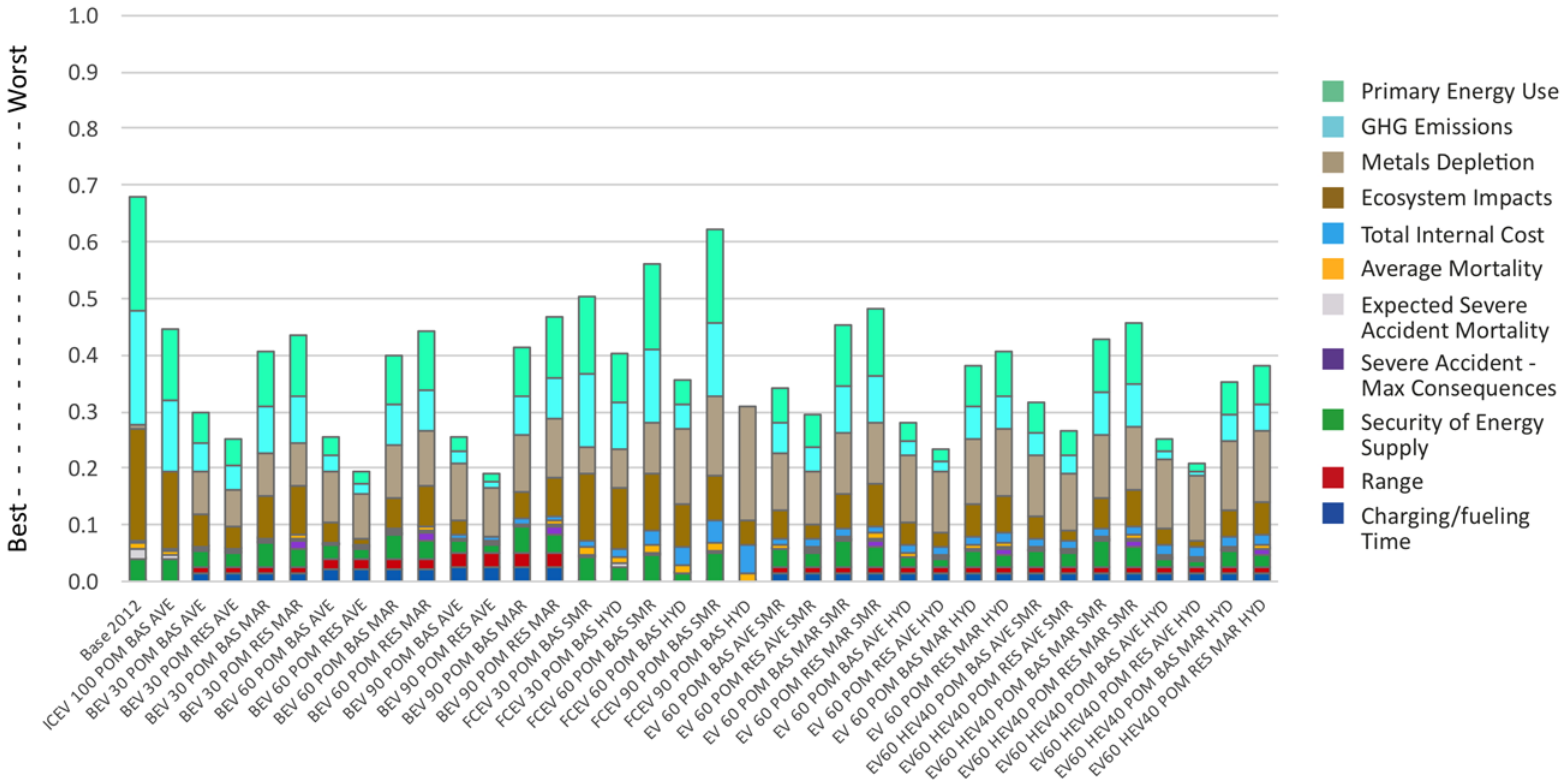
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure G. 1 Fleet 2050 Vehicle MCDA – EQUAL Weights (Environment, Economy, Society, Security of Energy Supply and Driver Utility equally weighted)



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

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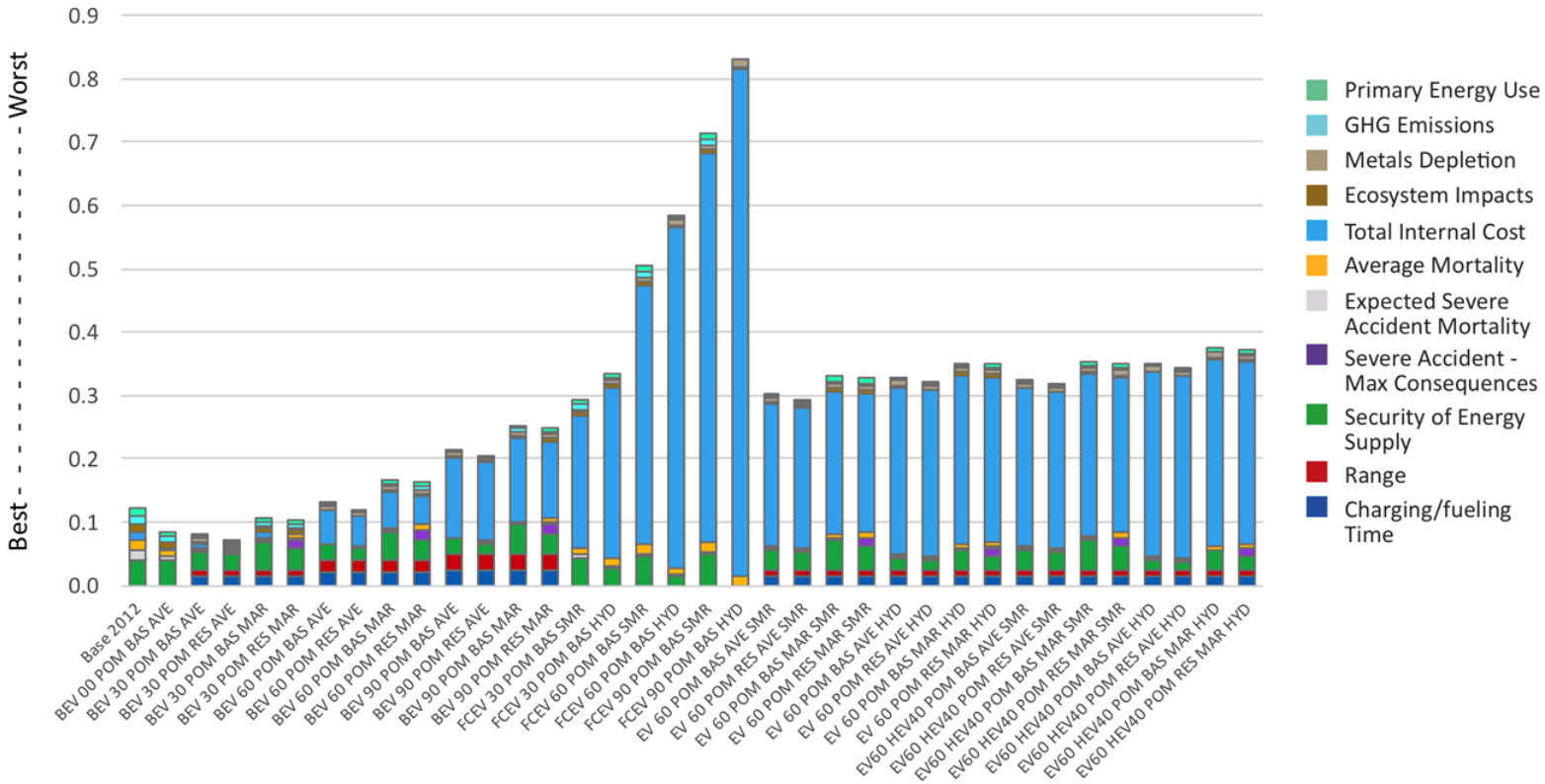
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure G. 2 Fleet 2050 Vehicle MCDA – ENV80 Weights (Environment 80%, Economy, Society, Security of Energy Supply and Driver Utility 5% each)



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE “Political Measures”
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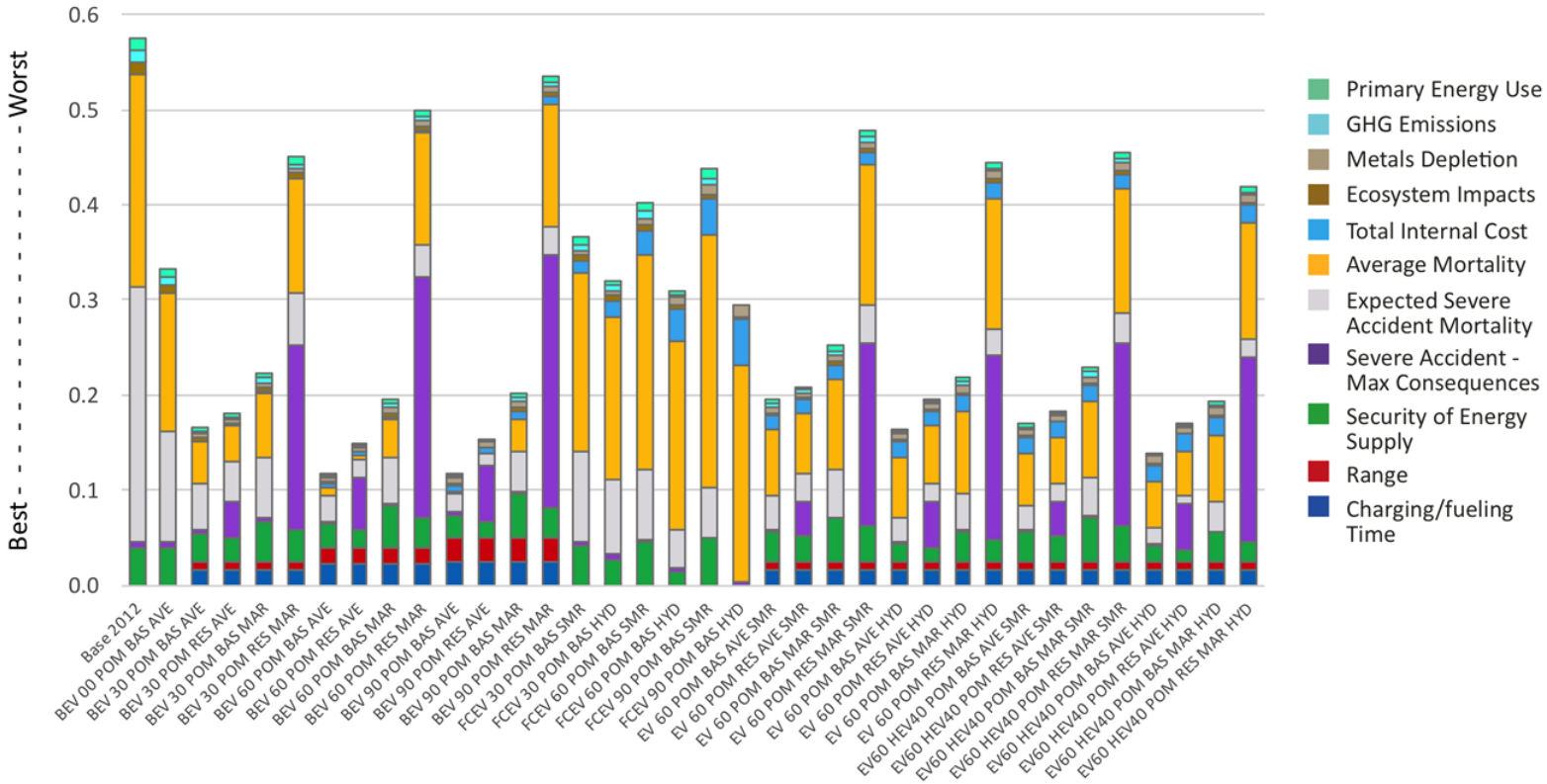
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure G. 3 Fleet 2050 Vehicle MCDA – ECO80 Weights (Economy 80%, Environment, Society, Security of Energy Supply and Driver Utility 5% each)



Drivetrains

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE “Political Measures”
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RES - Supply is renewables strategy
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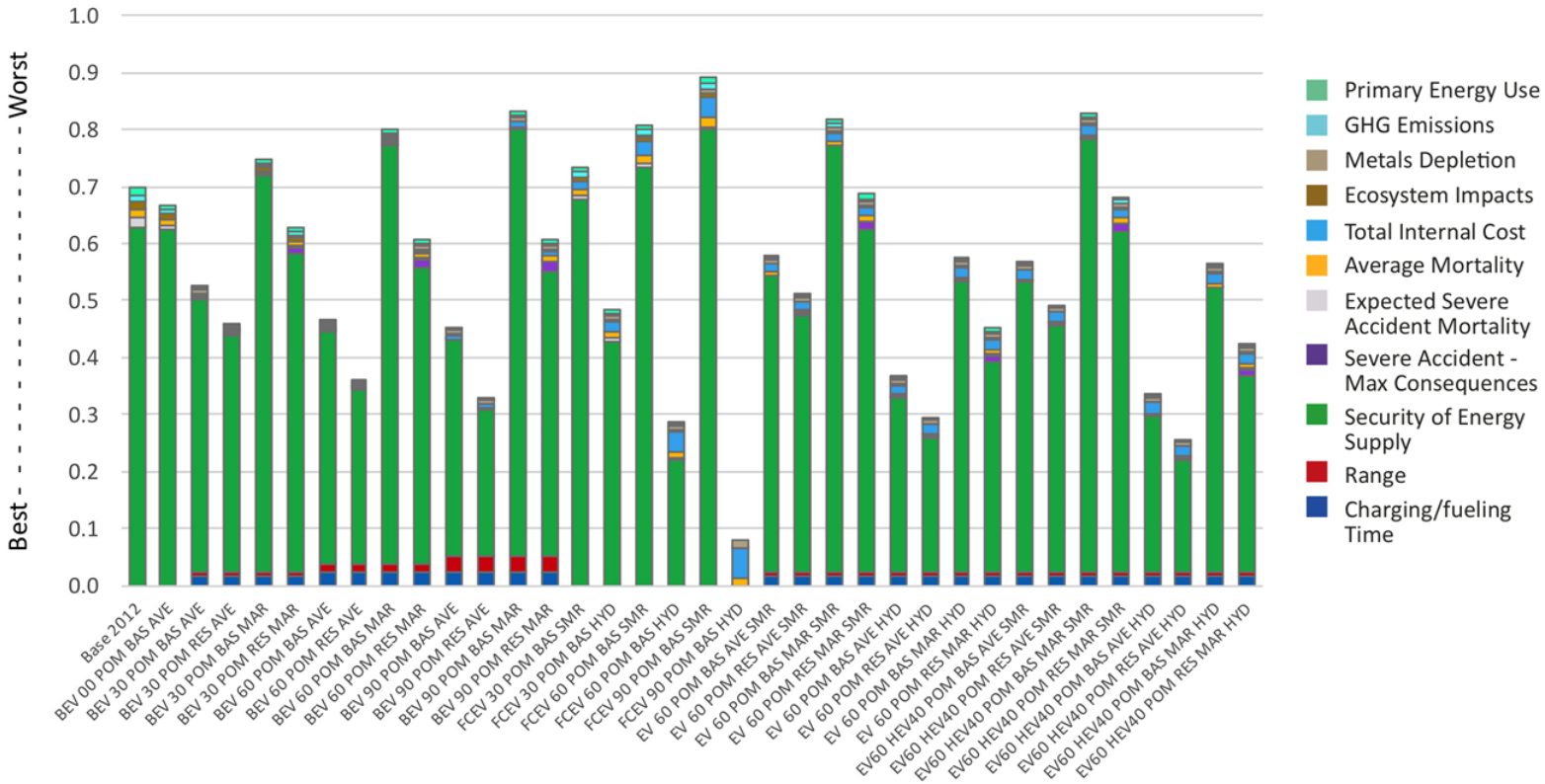
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure G. 4 Fleet 2050 Vehicle MCDA – SOC80 Weights (Society 80%, Environment, Economy, Security of Energy Supply and Driver Utility 5% each)



Drivetrains

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FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

Electricity

POM - Demand is SFOE "Political Measures"
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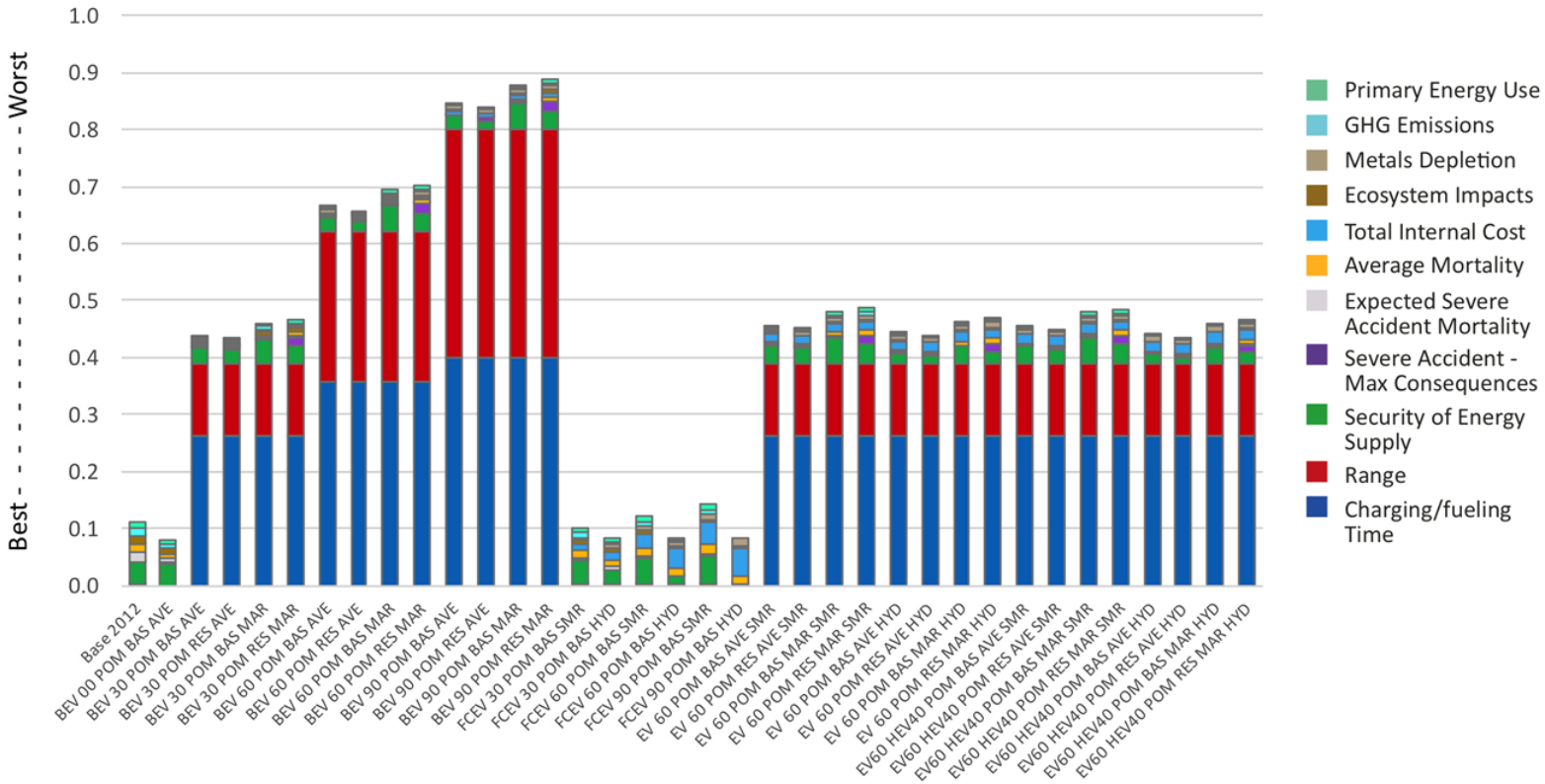
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure G. 5 Fleet 2050 Vehicle MCDA – SEC80 Weights (Security of Energy Supply 80%, Environment, Economy, Society, and Driver Utility 5% each)



Drivetrains

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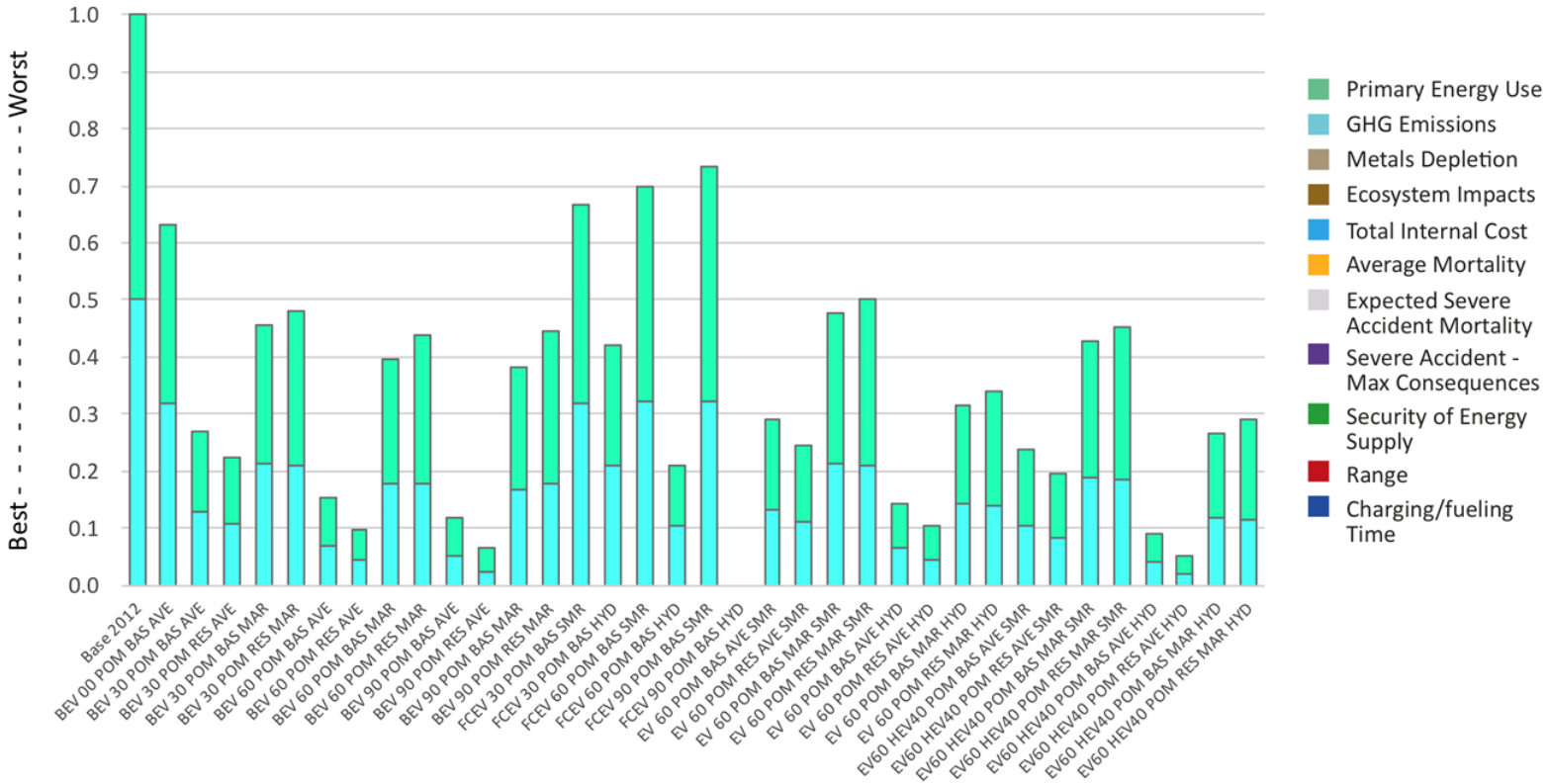
Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure G. 6 Fleet 2050 Vehicle MCDA – UTI80 Weights (Driver Utility 80%, Environment, Economy, Society, and Security of Energy Supply 5% each)



Drivetrains

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Hydrogen

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.

Figure G. 7 Fleet 2050 Vehicle MCDA – CO_2, Primary Energy 50/50 Weights (CO_2 Emissions and Non-renewable Primary Energy Use 50% each)