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Multi-Criteria Analysis of Passenger Vehicles Based on Technical, Economic, and Environmental Indicators

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Abstract

Many advanced vehicle and fuel technologies are currently being developed with the aim of reducing the environmental impacts of road transport and its dependence on fossil oil. In this paper we present a new methodology to compare a broad range of current and future passenger vehicle options in terms of technical, economic, and environmental criteria. Due to the spectrum of consumer preferences, usage profiles, and the high significance for cost and environmental impacts we consider not only various conventional and electric drivetrains but also different vehicle classes, energy sources, and driving patterns. A high level of integration between technical assessment, powertrain simulation, and life cycle assessment ensures a consistent development of future scenarios and comparison of the different technologies. Selected results for vehicle weight, cost, and life cycle greenhouse gas emissions are presented. Overall the results show that the sustainability implications of electric vehicles are very dependent on the primary energy source that is used and that there is no technology which performs best for all criteria, but that different technologies tailored for specific usage patterns can provide advantages relative to each other. The full set of results can be accessed within a graphical user interface for more detailed analysis. The work presented is currently in further development and is planned to be available for online multi-criteria decision analysis.

Keywords: Passenger car, LCA (Life Cycle Assessment), LCC (Life cycle cost)

1 Introduction

The transportation sector is a major contributor to greenhouse gas emissions, and dependent on non-renewable petroleum. Economic growth in developing markets will also drive a demand for more cars, and exacerbate these problems. The exact response of the global climate system to anthropogenic CO2 as a forcing factor, and the timing of resource depletion and price increases may be in question. But the direction of these trends is clear - conventional solutions may yet serve a while, but there is a great need for sustainable alternatives for the long run.

For these reasons, several advanced vehicle and fuel technologies are currently being developed with the aim of reducing the environmental impacts of road transport and its dependence on fossil oil. These options include reduction of vehicle losses (due to mass, aerodynamic drag, and friction), improvements to conventional internal combustion engine vehicles (ICEV), new electric powertrains such as hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell hybrid electric vehicles (FCHEV), and production of low-carbon fuels and/or electricity generation [1]. However these technologies enter the market incrementally and must meet performance, utility, and cost requirements to be accepted by consumers.

This study compares a broad range of current and future vehicles, combining different drivetrain technologies, primary energy sources, vehicle size and utility classes. This is necessary in order to allow stakeholders to compare available vehicle types and to evaluate aggregate fleet impacts. The comparison is based on an array of technical, economic, and environmental criteria. In this paper the methodology to calculate the options and criteria set is explained and selected criteria for a limited number of vehicle and energy options are shown. The whole set of indicators and results can be explored in a graphical user interface.

So far, many studies have already analyzed the technical, economic, and environmental aspects of advanced passenger cars individually, however an integrated assessment combining technology assessment, powertrain simulation, and life cycle analysis is not known to the authors. The strong integration allows a consistent development of future scenarios and comparison of technology options. The methodology and scenario assumptions are documented in a transparent way to make the results reproducible.

The paper first outlines the modeling framework, followed by a description of the drivetrain simulation, cost assessment, life cycle analysis, results, conclusions and outlook.

2 Methods and data

2.1 Framework description

This study calculates a set of technical, economic, and environmental indicators for current and future passenger vehicles for a range of possible technology options: conventional and electric powertrains, different vehicle sizes, ranges and performance classes, and relevant primary energy sources. Vehicle criteria can be split into exogenous and endogenous. Exogenous criteria are performance related vehicle options that are important to the individual consumer of the car (e.g. size, range, acceleration, etc.) and at the same time necessary input parameters to define a car and execute the vehicle simulation and life cycle assessment. Endogenous criteria are the simulation results, such as vehicle mass, energy consumption, cost, and environmental impacts. Fig. 1 illustrates the modeling framework used. 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 the resulting economic and environmental criteria. The approach shown here is also implemented in an interactive tool in which the user can analyze the resulting vehicle criteria for a specific car of interest.

The technology options set is split into powertrain and fuel type, vehicle size, range and performance, primary energy source, and year of assessment. The latter influences the inputs passed on to the powertrain, cost and LCA submodels in various ways as the following parameters are a function of time:

- Reduction of vehicle weight (using advanced lightweight materials), aerodynamic drag, and tire rolling friction are expected to be continously improved by manufacturers to reduce vehicle energy consumption and emissions. Similarly powertrain component efficiencies are adjusted over time to take into account technical progress.
- Specific energy and power of not yet fully developed technologies (such as batteries) are expected to increase over time. This mass-related data is used further in the vehicle simulation to calculate vehicle weight and energy consumption.
- Specific components costs decrease over time as technologies improve and/or increase in production volume. Component costs and energy prices are used together with calculated component sizes and energy consumption to calculate manufacturing and total costs.
- Cumulative LCA 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 LCA results.

All of these future developments are uncertain and dependent on interlinked parameters such as technical developments, policy measures, consumer acceptance, production volumes, etc. The scenario assumptions used in this work are mainly based on data from the literature which are described and cited in the following subsections. It should be pointed out, that the aim of this study is not to project vehicle costs and environmental impacts, but rather to show a possible method on how to include future developments within an integrated vehicle analysis framework. Robust conclusions about future developments should be based on more elaborate scenario analysis.

In the following subsections the calculation of vehicle energy consumption, cost, and LCA impacts as well as all input data is explained further.

2.2 Vehicle simulation

The simulation of vehicle mass and energy consumption for a specific driving cycle is performed with Advisor, a widely used, open source powertrain simulation software developed by NREL [2]. Fig. 2 shows the powertrain configurations considered here and the power flows between the components.

The internal combustion engine vehicle (ICEV) is modeled using a spark ignition engine with a peak efficiency of 36% (which is increased to 42% in 2030 and 45.5% in 2050) and a manual transmission including a clutch, gearbox and differential. Also diesel and compressed natural gas vehicles are modeled in this configuration, the engine efficiency map and speed-torque characteristic is however different. The battery electric vehicle (BEV) is modeled using a permanent magnet motor with a peak efficiency of 95%, a single-speed transmission, and a Li-ion battery with an average internal resistance of approximately 200 mΩ at moderate temperature and SOC. The hybrid electric vehicle (HEV) is modeled in a power-split configuration (also called

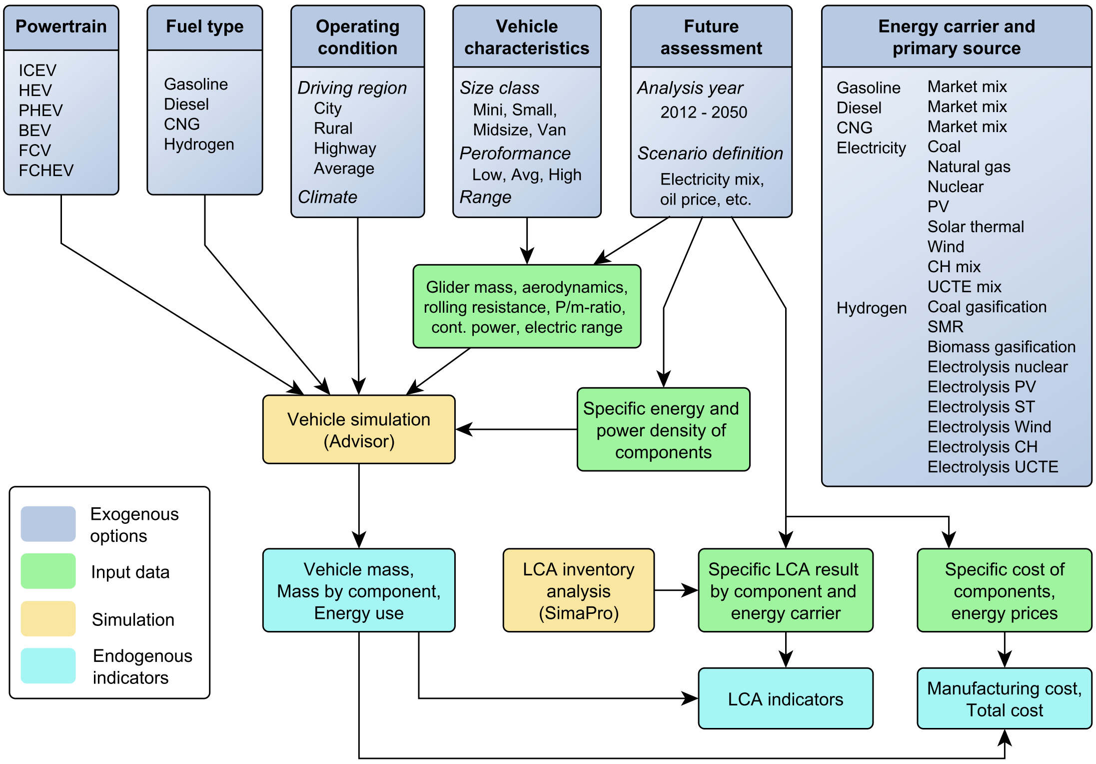

Figure 1: Analysis framework: From a given set of exogenous options technical, cost, and environmental indicators for current and future passenger cars are calculated.

series-parallel hybrid) with a planetary gear set which enables direct mechanical power transfer between the engine, electric motors, and the wheels. This configuration is used in several current, full hybrid passenger cars, e.g. the Toyota Prius. The hybridization ratio, i.e. the power of the primary electric motor to the total power delivered by the motor and engine is set to 0.4. The fuel cell hybrid electric vehicle (FCHEV) uses a battery for fuel cell startup phases, to store energy from recuperation, and to avoid operating the fuel cell at low efficiency. Relative to a fuel cell vehicle without energy storage, this configuration has the advantage of a lower energy consumption and possibly lower cost as the fuel cell can be downsized [3]. The hybridization ratio, i.e. the power of the battery to the total power delivered from the fuel cell and battery is set to 0.4, which provides a good compromise between lower energy consumption and cost on the one hand and performance on the other. The fuel cell should not be scaled too small as it still must provide enough power for continous power requirements (e.g. continous high speed or uphill driving). The hydrogen fuel cell system reaches a peak efficiency of 60% (relative to the LHV of hydrogen) and is fueled from a compressed hydrogen (700 bar) storage tank. The plug-in hybrid electric vehicle (PHEV) is modeled in a series configuration (also called range-extended electric vehicle) with the traction only provided by the electric drivetrain. The vehicle can be operated in charge-depleting (CD) mode until the battery is discharged and then uses a combustion engine and generator to prolong vehicle range in charge-sustaining (CS) mode. For all drivetrains an average electric auxiliary load of 0.3 kW (for lights, radio, etc.) and an average heating load of 1 kW is considered. It is assumed that all vehicles without an ICE are equipped with a heat pump that has a coefficient of performance of 2 (which increases to 4 by 2050). For the BEV and PHEV, grid-to-wheel (GtW) energy consumption is calculated by taking into account losses that occur during charging. To convert from battery-to-wheel (BtW) to GtW energy consumption a charging efficiency of 90% is assumed.

Table 1 shows an overview of the vehicle configurations that are analyzed in the following: A small city car, mid-size family sedan, and full-size SUV, for three assessment years each. The vehicles' glider mass, frontal area A_f, aerodynamic drag c_d, and tire rolling friction coefficient c_r approximately correspond to the values of current new cars on the European market. The vehicle power-to-mass ratio and continous power capability are calculated to reach the desired acceleration time and top speed, respectively [4]. The acceleration requirement is generally the design criterion that defines the power of the ICEV engine and BEV motor. However, for light vehicles continous top speed can be the factor determining the power of the fuel cell in the FCHEV and the engine-generator unit in the PHEV. In the future scenarios glider mass, c_d, and c_r are reduced annually by 0.8%, 0.5%, and 0.5%, which

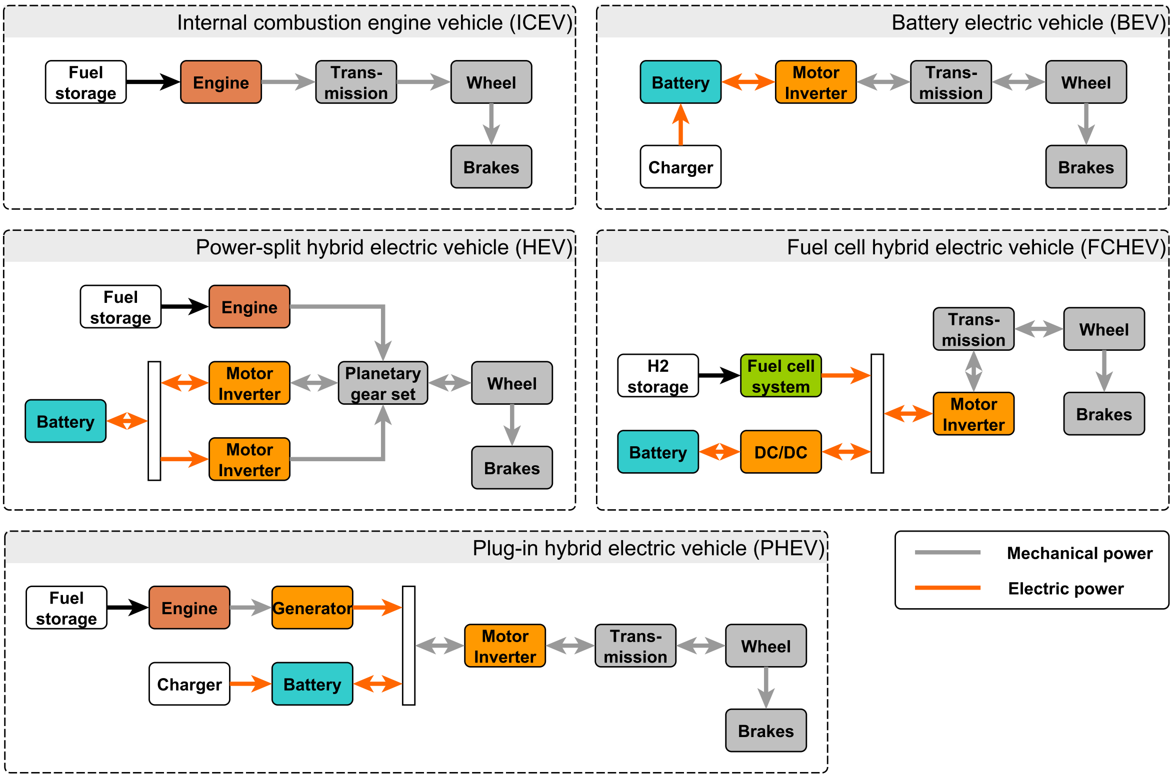

Figure 2: Drivetrain configurations considered and power flows between the main components.

equates to a total reduction of ca. 26%, 17%, and 17% in 2050. The rate of reduction is realistic considering historic developments for these parameters and projections used in other studies [5]. Please note that regarding the lightweighting of the glider, the cost and LCA impact of the glider are kept constant as moderate weight reduction can be achieved with the use of high strength steel. The electric driving range is set to 80 km for the PHEV, 100 and 400 km for the BEV, and 400 km for the FCHEV (which is increased to 700 km in 2030 and 2050).

In the simulation vehicle mass is calculated as the sum of the mass of the glider, energy storage system, powertrain, transmission, and additional structural support for parts beyond the glider baseline (e.g. additional suspension needed for the BEV battery and powertrain). In the following, platform mass is defined as the sum of glider mass and the mass of additional structural support. If range and performance requirements are fixed, vehicle weight is iteratively calculated, because it depends on the energy consumption of the vehicle (which is a priori not known) and itself dependent on vehicle mass. Table 2 summarizes the specific masses of the power and energy storage devices used throughout the paper.

Output of the simulation is vehicle mass by component and energy consumption for the driving cycle considered. The simulation is performed for a range of driving cycles representing different driving conditions, but due to limited space only results for the standard EU test cycle to measure passenger vehicle energy consumption, the New European Driving Cycle (NEDC), are shown in the following.

2.3 Cost assessment

Vehicle manufacturing costs are calculated as the sum of the cost for the platform, the energy storage, powertrain, and transmission. The latter are based on the fixed and variable costs indicated in Table 2 and the respective power capability and energy capacity of the components of the vehicle. Note that the values given in Table 2 refer to the cost to the vehicle manufacturer. To convert this to the retail price of the car, a markup factor of 1.4 is used [6].
Total cost of ownership is calculated as the sum of the vehicle purchase price and the discounted energy costs. A discount rate of 5%, a lifetime of 12 years, and a total driving distance of 150’000 km are assumed. Vehicle maintenance and repair costs, insurance, and parking costs are not considered. Furthermore it is assumed that the battery does not need to be replaced, but also no value of the battery after the indicated driving distance is credited. The PHEV utility factor, i.e. distance driven in CD to CS mode, depends on the electric range the vehicle is able to drive. For 80 km electric range, a utility factor of 0.65 reasonable [7].
Table 2 summarizes the assumed electricity and fuel prices to the end consumer at the charging or fueling station. Note that these prices do not

Table 1: Vehicle configurations analyzed.

	2012	2030	2050	2012	2030	2050	2012	2030	2050
Platform		Small			Mid-size			SUV	
Performance		Average			Average			Average	
Frontal area (m^2)		1.9			2.2			2.8	
Aerodyn. drag (c_d)	0.34	0.31	0.28	0.31	0.28	0.26	0.38	0.34	0.31
Tire friction (c_r)	0.009	0.008	0.007	0.009	0.008	0.007	0.01	0.009	0.008
Glider mass (kg)	704	609	519	979	847	721	1192	1032	879
Acc. 0-100 km/h (s)		11			11			11	
Top speed (km/h)		130			170			170	
P/m-ratio (kW/kg)		70.1			70.1			70.1	
Cont. power (kW)	23.6	20.9	18.3	50.6	45.3	40.2	77.4	69.5	61.7
Range PHEV (km)		80			80			80	
Range BEV (km)		100/400			100/400			100/400	
Range FCV (km)	400	700	700	400	700	700	400	700	700

Table 2: Assumed fixed and variable mass and cost of power and energy storage devices.

	Technology	Unit	2012	2030	2050	Unit	2012	2030	2050	Sources
Power devices	**Gasoline engine**	**kg**	61	56	50	**$**	1000	1237	1500	[8, 9, 6, 10]
		kg/kW	0.68	0.41	0.47	**$/kW**	7.4	9.2	11.1	
	Motor and controller	**kg**	22	18	18	**$**	500	429	350	[11, 12, 13]
		kg/kW	0.87	0.66	0.66	**$/kW**	28.0	18.9	19.9	
	ICEV transmission, exhaust system,	**kg**	65	65	65	**$**	800	895	1000	[6, 10]
		kg/kW	0.55	0.55	0.55	**$/kW**	6.0	6.0	6.0	
	EV transmission	**kg**	30	30	30	**$**	300	300	300	[6, 1]
		kg/kW	0.30	0.30	0.30	**$/kW**	3.0	3.0	3.0	
	Fuel cell system	**kg**	40	35	30	**$**	10000	5974	1500	[14, 15]
		kg/kW	1.20	0.60	0.50	**$/kW**	400.0	90.3	25.0	
	Li-ion power battery	**kg**	8	7	5	**$**	1000	600	400	[16, 17]
		kg/kW	0.98	0.77	0.54	**$/kW**	53.3	31.8	24.3	
Energy storage	**Li-Ion energy battery**	**kg**	30	20	16	**$**	9000	2500	2000	[12, 18, 17]
		kg/kWh	8.27	4.43	3.33	**$/kWh**	400	127.1	116.7	
	Gasoline tank	**kg**	10	10	10	**$**	300	300	300	[6]
		kg/kWh	0.14	0.14	0.14	**$/kWh**	0.6	0.6	0.6	
	Hydrogen storage	**kg**	40	35	30	**$**	1500	1263	1000	[19, 20]
		kg/kWh	0.34	0.30	0.25	**$/kWh**	9.2	8.2	7.1	

Table 3: Electricity and fuel prices ($/GJ) to the end consumer at the charging or fueling station without tax.

		2012	**2030**	**2050**
	Gasoline	25.9	30.1	34.7
Electricity	**Coal**	60.1	71.2	82.3
	NGCC	57.3	68.4	72.6
	Wind	65.6	60.1	58.7
Hydrogen	**CG**	60.1	48.2	44.2
	SMR	42.1	37.3	37.2
	Elec-wind	90.2	66.8	57.6

include tax. For the results shown below an energy based tax of 24.1 $/GJ and a VAT of 8% was added, which corresponds to the taxation of gasoline fuel for transportion in Switzerland. In the scenario from 2012 to 2050 it is assumed that the oil price increases from 95 to 149 $/bbl, and that the levelized cost of electricity generation for coal increases from 7 to 15 $cent/kWh, for a natural gas combined cycle (NGCC) power plant from 6 to 11.5 $cent/kWh, and decreases for PV utility-scale generation from 25 to 6.5 $cent/kWh [21]. Furthermore gasoline refining and station costs of 10.4 $/GJ, an electricity network cost of 8.6 $cent/kWh, and a charging station cost of 6 $cent/kWh are assumed. Hydrogen production costs for coal gasification (CG), steam methane reforming (SMR) of natural gas, and electrolysis using wind electricity (Elec-wind), as well as hydrogen delivery, compression and station costs are assessed according to [22].

2.4 Life cycle assessment

Life Cycle Assessment (LCA) aims to quantify the burdens and expected impacts on the environment and on human health considering all processes contributing to the production, use and end-of-life of each vehicle. The basic approach used here disaggregates the total LCA result into the contributions from road construction and maintenance, vehicle production and disposal by subcomponent, fuel and/or electricity supply, exhaust emissions, and non-exhaust emissions from tire, brake, road wear, and fuel evaporation. The LCA from subcomponent production is calculated by multiplying the mass of the component by a mass specific LCA impact factor. Similarly, fuel/electricity supply and exhaust emissions are calculated by taking into account vehicle energy consumption, while road infrastructure and non-exhaust emissions are vehicle mass dependent. This connection between vehicle simulation and LCA ensures consistency among the different models and easy calculation of LCA results for different vehicle types and energy sources. The actual inventory analysis of each vehicle component is performed within the SimaPro software using background processes from the Ecoinvent database [23] and special inventories for electric powertrains developed within the THELMA project [24, 25, 14, 26]. The functional unit that is used to compare the different vehicle and fuel options is one vehicle-kilometre (vkm), i.e. one kilometre driven with this vehicle and fuel type. In order to interpret the LCA results of consumed resources and emissions with regard to the potential impact on the environment and on human health, different life cycle impact assessment (LCIA) methods exist. The method used in this study is ReCiPe, which determines 18 relatively robust midpoint and 3 highly aggregated and uncertain endpoint indicators to evaluate the damage to human health, ecosystems, and resource availability [27]. The approach described above can be in principal applied using any available LCIA method. Due to the limited space, in the following only results for the midpoint category GHG emissions are shown, expressed in kg CO2 equivalent (calculated according to the IPCC equivalence factors).

3 Results

Fig. 3a shows the mass breakdown by component, sorted by the powertrain types and configurations described in 2.2. As can be seen from the figure, BEV weight is currently very sensitive to the range and vehicle class. This is however expected to decrease in the future as the specific energy of the battery improves. It is obvious that an increase in platform mass related to a change in class results in a higher mass for other components (mainly the battery) as the same range and performance requirements must be achieved. Over time the mass of all vehicles is decreasing due to glider lightweighting and an increasing specific power and energy of the powertrain and energy storage.

Fig. 3b shows the manufacturing cost breakdown for the same vehicle configurations. Today the costs for the BEV, FCHEV, and PHEV are still much higher than for the other technologies, mainly due to the high cost of the battery and fuel cell. BEV cost is very sensitive to the range and vehicle size class, but again this impact is expected to decrease in the future as the specific mass and cost of batteries decreases.

Fig. 4a compares life cycle GHG emissions in the year 2012 for the different powertrains, classes, and energy sources considered, showing the individual contributions of road infrastructure, vehicle production, fuel and/or electricity supply, exhaust and non-exhaust emissions. Overall GHG emissions from electric vehicles are very sensitive to the primary energy source of electricity or hydrogen production. Electric vehicles only provide a significant benefit relative to the ICEV and HEV if the electricity or hydrogen used stems from a non-fossil primary source. If coal is used it performs even worse. This result is in agreement with other studies analyzing the life cycle GHG emissions of electric vehicles [28, 29, 30]. Regarding the specific contributions to total GHG emissions, for the ICEV and HEV

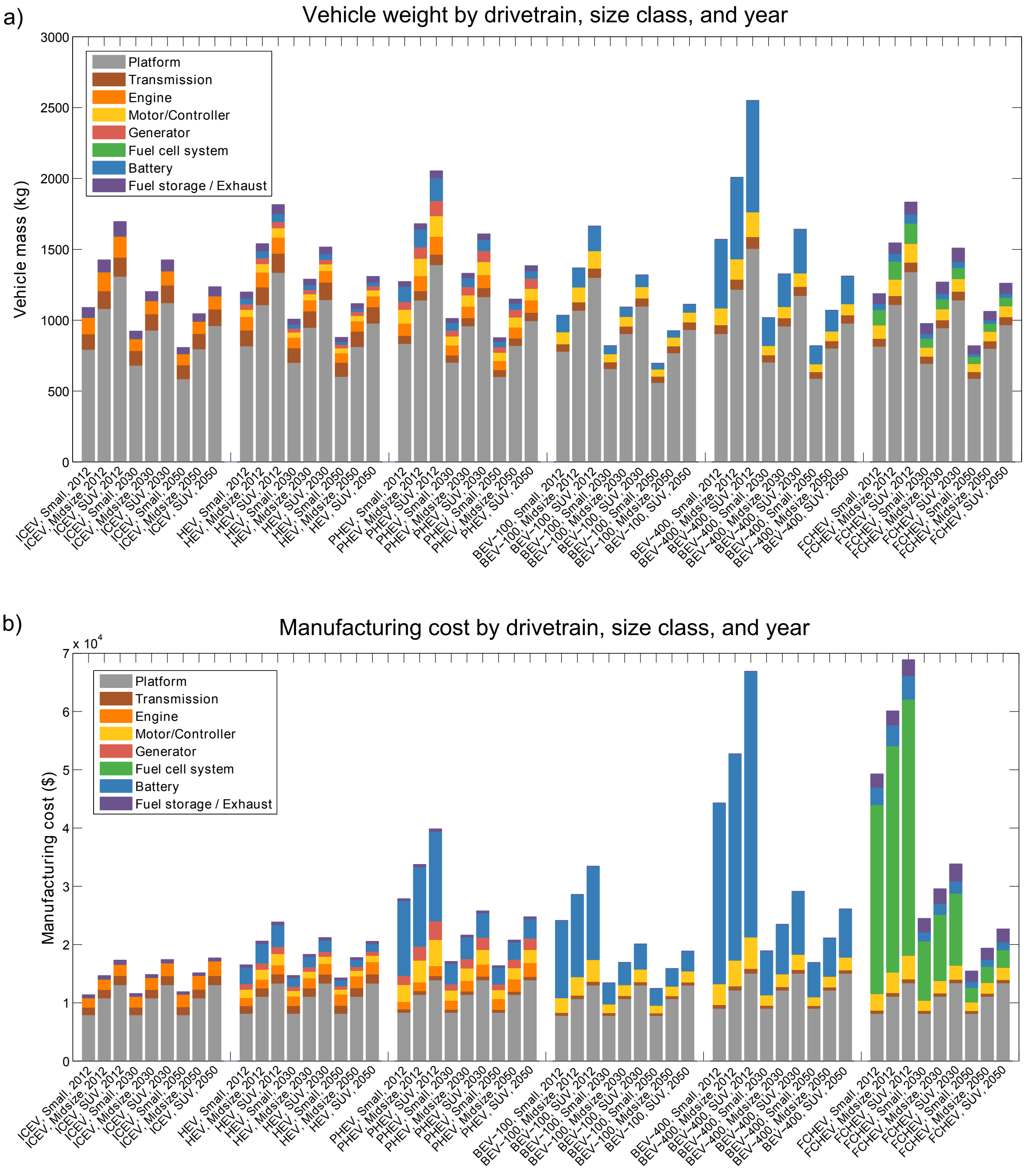

Figure 3: a) Mass breakdown for the drivetrain types and classes described in Figure 2 and Table 1. b) Manufacturing cost for the same configurations.

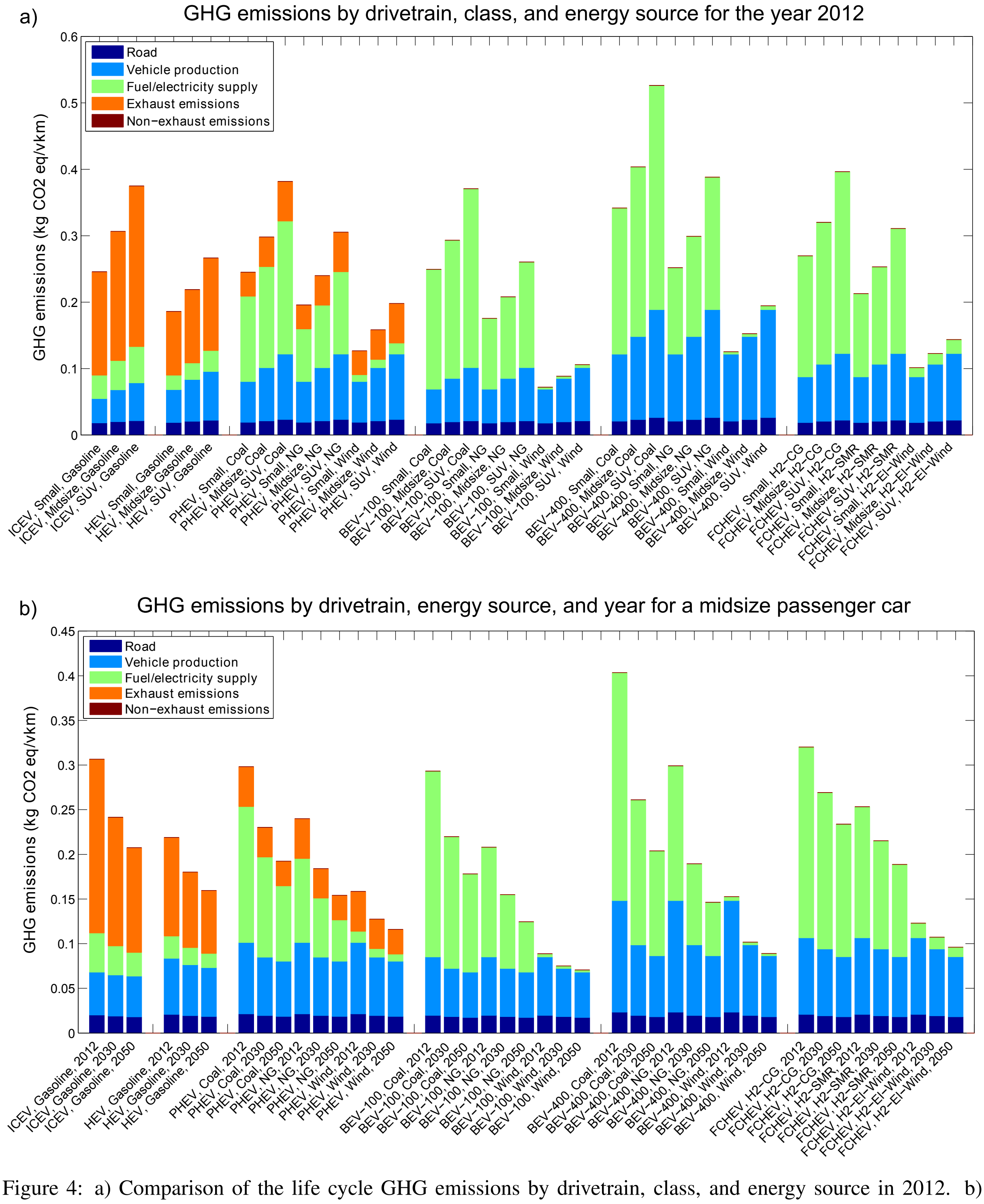

Figure 4: a) Comparison of the life cycle GHG emissions by drivetrain, class, and energy source in 2012. b) Comparison of the GHG emissions of a midsize passenger car by drivetrain, energy source, and year.

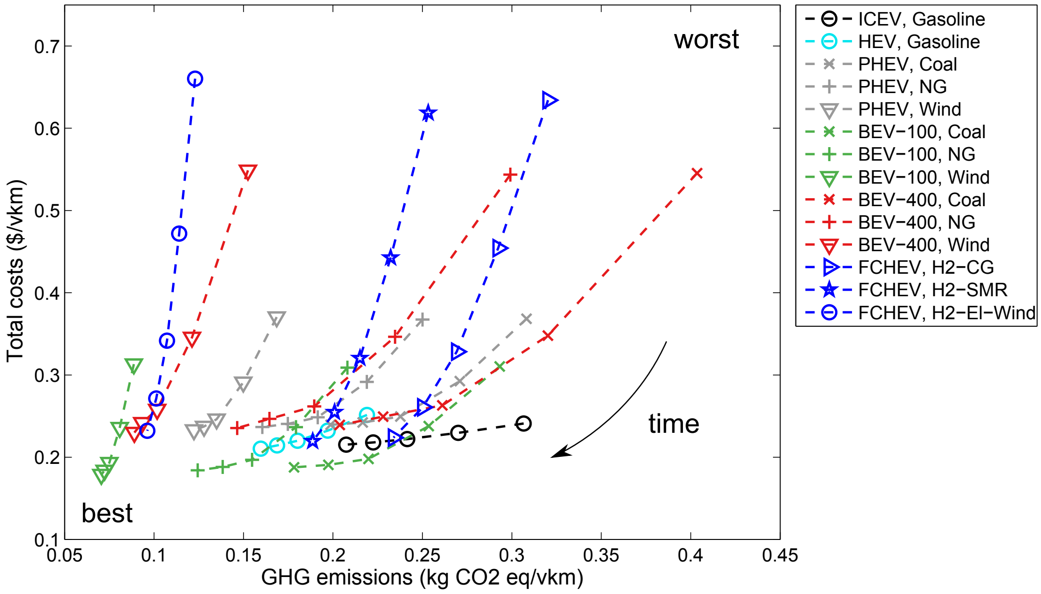

Figure 5: Development of the total costs vs. life cycle GHG emissions for a mid-size passenger car in five time steps from 2012 to 2050 (different points in time are connected by a line).

exhaust emissions dominate, while for the EV's it depends on the energy source which component dominates. Generally the impact from the production phase is higher for the EV's than the ICEV. For the BEV the production phase impact is very sensitive to the range.

Fig. 5 shows the relation of total costs to life cycle GHG emissions for a mid-size passenger car in five time steps from 2012 to 2050 for the powertrains and energy sources considered. The slope of the curve illustrates the direction of improvement over time: For the BEV, PHEV, and FCHEV the main improvement takes place in terms of total costs (vertical direction), while the ICEV and HEV mainly improve in GHG emissions (horizontal direction). For EV's with fossil primary energy, significant reductions of GHG emissions are also seen due to a combination of reductions in energy consumption, increasing efficiency in electricity and hydrogen production, and improvements in power and energy density. The latter is the reason why the curve is particularly flat for the BEV-400 relative to the BEV-100 and FCHEV. In this comparison the best overall performance over the long term is achieved for the BEV and FCHEV with electricity or hydrogen produced from wind power.

For other LCA indicators it is found that the production phase generally has a bigger influence for EV's than for ICEV's. Furthermore, the production phase often also dominates the results and leads to an overall worse performance of EV's relative to ICEV's for certain indicators (e.g. metals depletion or human toxicity) which is also found by other studies [28, 29, 30, 31]. It is expected however that this relatively bad performance of EV's in the production phase will decrease in the future due to the following trends in time: a) The energy and power density of the main components such as the battery and fuel cell is expected to improve, which means that less material will be necessary to meet the same performance requirements. b) Some of the steps in the production phase will become more energy efficient when produced in larger quantities. Also the production will be streamlined and recycling will become more relevant, so less scrap will be generated throughout the product life cycle. Both effects are considered in this study as the specific mass of components decreases over time and life cycle inventories for different states of technical development are used.

As pointed out earlier, the results shown here are based on the New European Driving Cycle and the results are different for other driving conditions. In urban driving the energy consumption of the ICEV is generally higher due to the low engine efficiency at partial loads and because kinetic energy lost in braking accounts for a high fraction of the total energy demand. For electric drivetrains on the other hand energy consumption for urban driving is usually lower because the powertrain efficiency remains high and part of the kinetic energy spent for acceleration can be regenerated. This causes higher fuel costs, exhaust emissions and fuel supply impacts for the ICEV, and a lower respective contribution for electric vehicles. For highway driving it is opposite, i.e. relative to the mixed driving condition the energy consumption is generally higher for electric vehicles and lower for the ICEV. For this reason electric vehicles make particular sense for urban driving. Reduced local pollutant emissions, limited range, and low noise are additional reasons for the suitability of electric vehicles for urban regions.

4 Conclusions and outlook

In this paper a new methodology has been developed to compare a broad range of current and future vehicle technologies in terms of technical, economic, and environmental criteria using different vehicle segments and energy sources. The high level of integration between technical assessment, vehicle simulation, and LCA allows a consistent development of future scenarios and comparison of different technologies. Selected results for vehicle mass, manufacturing cost, and GHG emissions have been presented and discussed. The results show that environmental impacts of electric vehicles are very sensitive to the primary energy source. If a non-fossil energy source is used for propulsion, GHG emissions are significantly lower for electric than internal combustion engine based vehicles. The cost and LCA impacts of the BEV are very sensitive to vehicle range. Overall there is no technology which performs best in terms of all criteria at the same time, but different technologies tailored for specific usage patterns can provide advantages relative to each other, e.g. EV's relative to the ICEV in urban driving, or a short-range BEV relative to a long-range BEV in terms of costs and environmental impacts.

A graphical user interface has been developed in which all indicators (including 45 LCA indicators) for the whole set of vehicle and energy options can be explored in more detail. Currently the simulation time of the model is limited by the numeric vehicle simulation. It is planned to use an analytic modeling methodology [32, 33] instead of the numeric simulation, which will allow fast and interactive analysis. The work presented also provides a strong opportunity for multi-criteria decision analysis tools.

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