Deepening the uncertainty dimension of environmental Life Cycle Assessment: addressing choice, future and interpretation uncertainties.

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Title: Deepening the uncertainty dimension of environmental Life Cycle Assessment: addressing choice, future and interpretation uncertainties.
Issue Date: 2018-10-09

4.

When the background matters: Using scenarios from Integrated Assessment Models in Prospective LCA

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Submitted: *The Journal of Industrial Ecology (2018).*

Abstract

To support more robust future environmental assessments and decision-making prospective life cycle assessment (LCA) should deal with the large epistemological uncertainty about the future. This study proposes a novel approach to dealing with uncertainty by systematically changing the background processes in a prospective LCA based on scenarios of an Integrated Assessment Model (IAM), the IMAGE model. Consistent worldwide scenarios from IMAGE are evaluated in the life cycle inventory using ecoinvent v3.3. To test the approach, only the electricity sector was changed in a prospective LCA of an internal combustion engine vehicle (ICEV) and an electric vehicle (EV) using six baseline and mitigation climate scenarios until 2050. This case study shows that changes in the electricity background can be very important for the environmental impacts of EV. Also, this study approach demonstrates that the relative environmental performance of EV and ICEV over time is more complex and multifaceted than previously assumed. Uncertainty due to future developments manifests in different impacts depending on the product (EV or ICEV), the scenario and year considered. Expanding this approach to other economic sectors can lead to more robust prospective LCAs since a more systematic and structured composition of future inventory databases driven by IAM scenarios helps to acknowledge epistemological uncertainty and to understand exogenous system changes in prospective LCA.

Keywords: Prospective LCA, epistemological uncertainty, background changes, Integrated Assessment Models

4.1 Introduction

A robust assessment of the environmental impacts of product systems is the basis for assertive policy, business, and consumer decision-making (Hellweg and Canals 2014). Life cycle assessment (LCA) has developed into an environmental decision-support tool to assess product systems. Some LCAs, however, refer to product systems that either do not yet exist or are not commercially available. These forward-looking applications of LCA, or so-called prospective LCA (Pesonen et al. 2000; Arvidsson et al. 2017), are thought to help in anticipating unintended consequences of future product systems and to support environmentally assertive product design (Miller and Keoleian 2015). Prospective LCA has proven to be valuable in a range of cases, from assessing future public policies (Dandres et al. 2012, 2014) and emerging technologies (Frischknecht et al. 2009; Arvidsson et al. 2017) to the analysis of future production and consumption systems (Van der Voet et al. 2018). Nonetheless, in addition to dealing with the uncertainty related to any complex system (ontic uncertainty), prospective LCA needs to deal with the lack of knowledge about the future (epistemological uncertainty) (Björklund 2002). Addressing epistemological uncertainty is therefore a crucial challenge in the development of prospective LCA.

A common approach for dealing with epistemological uncertainty in prospective LCA is to integrate future scenarios (Pesonen et al. 2000; Spielmann et al. 2005). A scenario is understood as "*… a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future*" (Pesonen et al., 2000, p.21). Common approaches to integrating scenarios in prospective LCA draw from multiple databases exogenous to LCA to address future socio-technical changes or so-called exogenous system changes (Miller and Keoleian, 2015). For example, the New Energy Externalities Developments for Sustainability (NEEDS) project (NEEDS, 2009) modelled the future supply of metals, non-metallic minerals, electricity and transport using different scenarios at various levels of optimism regarding technological improvements, cost reductions, and market growth rates. NEEDS and other external databases, such as the IEA (International Energy Agency 2010), were used in the 'Technology Hybridized Environmental-Economic Model with Integrated Scenarios' (THEMIS) (Gibon et al. 2015) to integrate future changes in electricity production, industrial processes, and climate change mitigation policies into a hybrid input-output (IO) LCA model (Bergesen et al. 2014, 2016; Hertwich et al. 2015; Beucker et al. 2016). Another example is 'macro-LCA' (Dandres et al. 2012), which combined LCA with future changes in economic structure and energy production based on computable general and partial equilibrium models, respectively. Lastly, Van der Voet et al. (2018) identified important supply-related variables that are likely to change in the future of metal production (e.g. technologies' shares of production, resource grade, and efficiencies of technologies), and then adapted these using various assumptions and external data sources.

While the above examples are valuable for prospective LCA, they suffer from limitations. A first limitation is that the development of future scenarios is often inconsistent and lacks transparency. Scenario development involves two steps: scenario generation and scenario evaluation (Fukushima and Hirao 2002). Scenario generation refers to the formulation of assumptions about the future, while scenario evaluation refers to the assessment of such assumptions during the LCA phases, especially the Life Cycle Inventory (LCI) phase and the Life Cycle Impact Assessment (LCIA) phase (Fukushima and Hirao 2002). Because scenario generation and scenario evaluation are often mixed, it is difficult to establish which inventory parameters have been changed and, most importantly, to discern whether assumptions are consistent among each other. Part of this issue arises from the use of different datasets as sources of scenario information, a procedure that increases inherent uncertainties (Gibon et al. 2015) and makes the process of scenario generation possibly un-harmonized. Another limitation is that technology maturity (e.g. penetration and efficiency) is often not accounted for, thus misrepresenting future technology mixes (Dandres et al. 2012). Moreover, because technological development is intertwined with both economic development and predictions of product technology-supply mixes, such relationships should be appropriately reflected in a scenario covering all economic sectors worldwide. Finally, the reproducibility of some approaches can be hampered by the large amount of required data and the difficulty to trace the assumptions that were made during the scenario generation.

To overcome the above limitations for scenario development in prospective LCA, we first propose to explicitly differentiate between scenario generation and scenario evaluation. For scenario generation, we propose the use of system-wide Integrated Assessment Models (IAMs) as a platform for calculations of consistent, worldwide scenarios covering all economic sectors. IAM scenarios are possible socio-economic and technological pathways of future development (van Vuuren et al. 2014) that can help explore different futures in the context of fundamental future uncertainties (Riahi et al. 2017). Masanet et al. (2013), Plevin (2016), and Pauliuk et al. (2017) highlight the unrealized potential of IAM scenarios as consistent sources of information for prospective assessments.

For scenario evaluation, we introduce a novel approach that systematically integrates the scenario information of the technology-rich IAM “Integrated Model to Assess the Global Environment” (IMAGE) (Stehfest et al. 2014) with one of the most broadly used life cycle inventory databases in the LCA community, the ecoinvent database (Wernet et al. 2016). In contrast to the recent work of Arvesen et al. (2018) and Pehl et al. (2017), we concentrate on evaluating the usefulness of IAMs for prospective LCA rather than on informing the IAM with the prospective LCA results. Our approach can thus be understood as an alternative opportunity to further reconcile the knowledge from the IAM and the LCA communities (Creutzig et al. 2012) that now hold different views on how to perform future environmental impact assessments.

The research question of this study was as follows: "How can IAM scenarios be systematically linked with LCI parameters to account for future changes in prospective LCA?" We focused on a case study comparing the relative environmental impacts of electric vehicles (EV) and internal combustion engine vehicles (ICEV), given that future changes play a key role in these impacts. Drawing from previous research, we focused on changes in the electricity sector. Specifically, the relative carbon footprint of EVs is highly influenced by the electricity mix (Bauer et al. 2015; Cox and Mutel 2018), and extreme cases can lead to counterintuitive results; for instance, in Australia, the prevalence of coal power causes EV to underperform (Wolfram and Wiedmann 2017). Our approach can thus address a range of questions, such as "What will be the impacts of EVs in 2050?" and "Will a transition to EVs in the future bring environmental benefits?". Finally, we contribute to further integrate knowledge from the IAM and the LCA communities, with the aim to increase the robustness of prospective LCA assessments by bringing macro scenarios into the micro- or product-level LCA (Guinée et al. 2011).

4.2 Methods

We first introduce an overview of the proposed approach (section 4.2.1). Further, we provide detailed insights into how scenarios are generated using IAMs and particularly IMAGE (section 4.2.2). Next, we present a novel method for scenario evaluation using the 'Wurst' software (section 4.2.3). Finally, we describe the case study and products (section 4.2.4) and the scenarios used in this study (section 4.2.5).

4.2.1 Method overview

This study presents a novel approach to introduce consistent and systematic future changes in a prospective LCA application (see Figure 10 for an overview). Such changes refer to the LCA background system, namely those processes and emissions that are part of the supply chain of the studied product system, e.g. the electricity mix used to charge and produce EV batteries. This means that indirect emissions are accounted for. In addition and in line with a full life cycle approach, direct emissions are accounted for but are left unchanged in the foreground system, in particular those processes and emissions describing the product itself, e.g. vehicle energy requirements and fuel use (See Cox and Mutel 2018). Following Fukushima and Hirao (2002), we developed scenarios in two steps: 1) scenario generation and 2) scenario evaluation.

- Scenario generation: This step refers to the process of scenario formulation and calculation. The IAM model IMAGE (Stehfest et al. 2014) was selected as the modeling framework used to generate consistent scenarios. Section 4.2.2 contains a description of the IMAGE model and the type of scenarios develop by it. Section 4.2.5 describes the specific scenarios used in the case study.

- Scenario evaluation: This step refers to the assessment of the scenarios in all the phases of LCA. Yet, in this study, attention is particularly given to the evaluation of scenarios in the life cycle inventory phase. We identified three steps needed to accomplish this: first, analyzing the background system to identify the inventory parameters (i.e. input and output flows, as well as processes) that are affected by future changes; second, adapting these parameters using information from the IAM scenarios; third, using the adapted inventories to calculate the prospective LCA results of specific products.

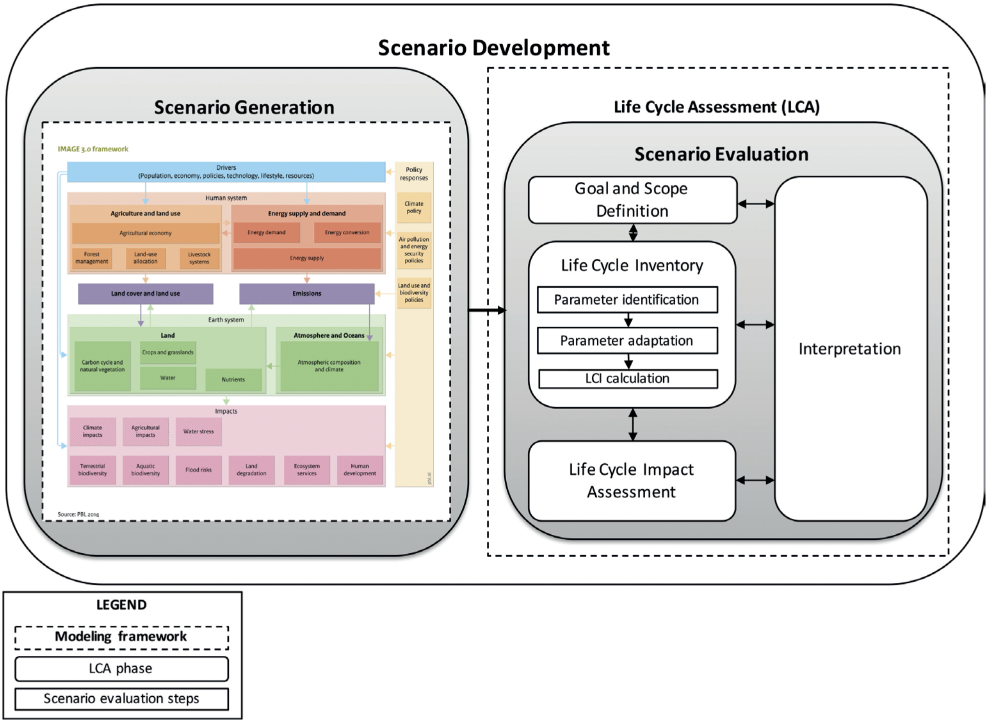


Figure 10. Overview of the proposed method for scenario development in prospective life cycle assessment (adapted from Fukushima and Hirao (2002)). Scenarios are generated using the IMAGE 3.0 framework and they are evaluated in the Life Cycle Assessment framework.

Relevant inventory parameters were adapted using so-called 'cornerstone' scenarios (Spielmann et al. 2005), as these scenarios refer to either unknown or new future situations. These scenarios have been chosen as they better inform long-term and strategic decision-making, which are fundamental characteristics of prospective LCA. The alternative is to use 'what-if' scenarios, which test changes in specific parameters to compare well-known alternatives in a sensitivity fashion (Pesonen et al. 2000). However, we did not choose this option as it is less structural than cornerstone scenarios because changes of only few parameters are captured. The approach of this study is distinct from other implementations of cornerstone scenarios (Spielmann et al. 2005) as we derived future changes of relevant parameters from the IAM-based scenarios instead of making separate assumptions for each parameter. We developed and applied the Wurst model (v0.1) in this study (https://wurst.readthedocs.io/index.html) for the parameter identification and adaption steps (see section 4.2.3). The LCA results of EV and ICEV were calculated with the Brightway2 (v2.1.1) software (Mutel 2017).

4.2.2 Scenario generation: Using IMAGE to develop scenarios

We used the IAM IMAGE 3.0 (from here on referred to as IMAGE) to generate scenarios (for a detailed model description, see Stehfest et al. 2014). In general, IAMs have been developed to describe the relationships between humans (the human systems) and the natural environment (the Earth system) and the impacts of these relationships that lead to global environmental problems, such as climate change and land use change. IAMs build on functional relationships between activities such as the provision of food, water, and energy and their associated impacts. The human system in IMAGE includes economic and physical models of the global agricultural and energy systems. The Earth system includes a relatively detailed description of the biophysical terrestrial, oceans and atmosphere processes.

Since this study focuses on the electricity sector, we will briefly describe the energy model of IMAGE, "The Image Energy Regional Model" (TIMER) (de Vries et al. 2001; van Vuuren 2007). TIMER consists of a technical description of the physical flows of energy from primary resources through conversion processes, transport systems and distribution networks to meeting specific demands for energy carriers or energy services. The model determines market shares for energy technologies based on the costs of competing technologies. It includes fossil fuels and renewable or alternative sources of energy in order to meet the demand, which depends on population size, efficiency developments, income levels, and assumptions on lifestyle. The model generates scenarios for future energy intensity and fuel costs, including competing non-fossil supply technologies. It models emission mitigation through the price signal of a carbon tax that induces additional investments in more efficient and non-fossil technologies, bioenergy, nuclear, and carbon capture and storage, thus changing market shares of different technologies. In this way, the model allows the generation of both baseline and mitigation scenarios in IMAGE, both of which are used to inform the background of the LCA in this study.

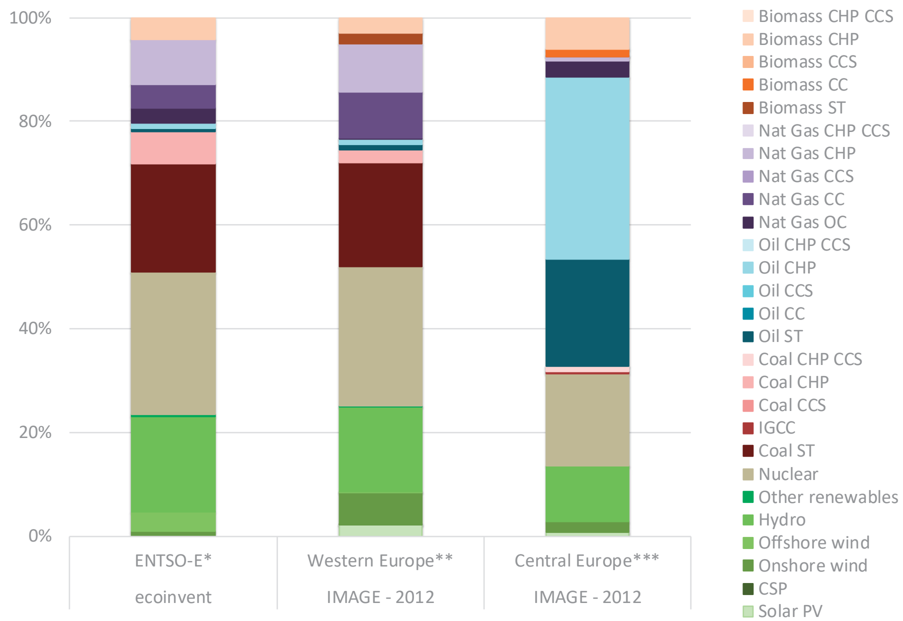
4.2.3 Scenario evaluation: The Wurst software

IMAGE scenarios serve as a source of information to adapt the LCI background data (Figure 10). Apart from being the most comprehensive and widespread LCI database, the ecoinvent database has also the advantage of distinguishing between two types of processes: transformation activities and markets (consumption mixes) (Wernet et al. 2016). This is an important feature because it simplifies identifying and changing parameters in ecoinvent when using IMAGE scenarios. To systematically approach the identification and changing of parameters in ecoinvent, we developed Wurst, a Python-based software that enables the systematic import, filtering, and modification of LCI databases. The current version of Wurst (available for download at: https://github.com/IndEcol/wurst) focuses on ecoinvent but includes other scenario data besides IMAGE. Other LCI and scenario databases are to be incorporated in the future. For this study, a specific functionality of the software was developed to link data formats of ecoinvent v3.3 (from here on referred to as ecoinvent) and IMAGE. The corresponding functions for import, filtering and modification of LCI databases are provided in the Supporting information (SI) in the format of Jupyter Notebooks. These notebooks call up functions in Wurst, for example those related to the regional match between databases, to generate ecoinvent LCI databases for different years into the future based on the IMAGE scenarios.

Data import

We first imported ecoinvent and IMAGE scenarios data into Wurst, for which we wrote specific importing and cleaning functions. In particular, the "cut-off system model" of the ecoinvent database was imported (see Weidema et al. 2013 for details of this model). This means that mono-functional processes were adapted using the IMAGE scenario data to generate modified (future) mono-functional processes. After importing the data, we mapped the available technologies for both datasets (Supporting information-SI, Annex I) as well as for all regions (SI, Annex II). For the technology mapping, technologies with greater detail in ecoinvent were grouped and assigned to an overarching IMAGE technology (SI, Annex I). Moreover, technologies that will be relevant in the future according to the IMAGE scenarios but that are missing in ecoinvent were added to the latter to create an *extended ecoinvent*. These technologies are concentrated solar power (CSP) and carbon capture and storage (CCS), which we included using datasets from ecoinvent v3.4 and from Volkart et al. (2013), respectively. For other technologies, such as natural gas combined heat and power generation with carbon capture and storage, which are missing in ecoinvent but less relevant in the future, we used proxy inventories from already existent technologies in ecoinvent (See SI, Annex I for all proxy technologies). Technologies were left unchanged if they were related to other sectors, such as fossil-fuel and biofuel production, transport and raw materials production.

For the regional mapping, a one-to-one correspondence was assigned between IMAGE and ecoinvent regions where possible (SI, Annex II). For regions in ecoinvent that involve more than one region from IMAGE, we used an average of IMAGE data. For smaller regions in ecoinvent, for instance provinces in a country, we used the data of the larger region from IMAGE. An example of region and technology mapping is shown in Figure 11, which illustrates that the electricity mix in ecoinvent has a closer match with that of IMAGE Western Europe, as electricity demand is dominated by Western European countries. In the interest of transparency, the complete region and technology mapping and the associated Python scripts are presented in the SI (Annexes I and II).



According to ISO 3166-1 2 letter country code:
*ENTSO-E countries are: AT, BE, CH, DE, FI, FR, GB, GR, IE, IS, IT, LU, LV, NL, NO, RS, SE, BA, BG, CZ, EE, HR, HU, LT, MK, PL, RO, SI, SK
**Western Europe countries are: AD, AT, BE, CH, DE, DK, ES, FI, FR, FO, GB, GI, GR, IE, IS, IT, LI, LU, MC, MT, NL, NO, PT, SE, SM, VA
***Central Europe countries are: AL, BA, BG, CS, CY, CZ, EE, HR, HU, LT, LV, MK, PL, RO, SI, SK

Figure 11. The 2012 electricity mix for Western and Central Europe regions in IMAGE and for the ecoinvent v3.3 process 'electricity, high voltage, production mix' for the European Network of Transmission Systems Operators for Electricity (ENTSO-E). Ecoinvent technologies are aggregated according to the map in the SI, Annex I and exclude the proxies for biomass steam turbine, oil combined cycle and biomass combined cycle to show original ecoinvent data without modifications.

Parameter identification (data filtering)

Parameters from ecoinvent that are to be modified were identified according to the process name and unit of the reference output flow. For instance, for electricity production technologies that use coal, the ecoinvent process names include the words 'hard coal' or 'lignite' and the unit of the reference output-flow is 'KWh'. For electricity markets, the same reference output-flow unit is used, but the names include 'market for electricity, high/medium/low voltage'. Such keys determine the processes that contain the parameters to be modified. These are technology-related parameters, i.e. economic and environmental flows (input and outputs) such as GHG emissions, for instance CO_2

emissions to air, or market-related parameters, i.e. electricity market mixes in ecoinvent, such as technology shares in high voltage electricity markets. The corresponding IMAGE parameters were filtered using the years, the sector (in this case electricity production), the overarching technology (e.g. coal steam turbine), the regions and the scenarios of interest. This procedure generates two sub-sets of data, one from ecoinvent and one from IMAGE, which are related to one another via the region and the technology, as was explained in the previous section.

Parameter changes

Starting with the ecoinvent and IMAGE sub-sets, we modified the ecoinvent parameters according to a number of rules (Figure 12). for GHG emissions available in both ecoinvent and IMAGE (i.e. CH_4, SO_2, CO, NO_x, N_2O emissions to air), we used the emission factors from the IMAGE scenarios as technology parameters, replacing those of ecoinvent for the different technologies. Emission factors in IMAGE were adapted by dividing them by the efficiency per technology in IMAGE because in IMAGE they are reported per MJ_{input} and not per $MJ_{electricity\text{-}output}$ as in ecoinvent. All other flows (economic and environmental), e.g. emissions other than greenhouse gases (GHG) emitted to air, were scaled using future technology efficiencies of the IMAGE scenarios. The final amounts of these flows, in their original ecoinvent units, was multiplied by a scaling factor (SF) calculated as shown in equation 2.

$$SF = \frac{efficiency_{ecoinvent}}{efficiency_{IMAGE}}$$

Eq.2

In ecoinvent, changes of market shares are applied to high voltage electricity markets (Treyer and Bauer 2016). We replaced the shares of electricity producing technologies defined in ecoinvent by the electricity mixes from the IMAGE scenarios. A different procedure was used for solar photovoltaics and small combined heat and power plants that supply electricity at the low or medium voltage level. We connected these technologies to the high voltage level and assumed that all electricity generation is supplied at the high voltage level. This procedure was chosen in favour of the systematic approach we propose, despite the error that this assumption might introduce, which we believe is small[1]. Moreover, as only electricity markets change, transmission grid markets and SF6 emissions generated during transmission were not adapted and were kept at the original ecoinvent levels. In the SI (excel files), we present per year tables, generated in the modification functions provided in the SI, with the changes made to technology and

1 The error is introduced because of the additional losses when converting from high to medium to low voltage, which technically does not take place if technologies supply the grid already at the low voltage level. Furthermore, imports and exports happen at the high voltage level, so technically technologies supplying at the medium or low voltage would not be in the import export mix. This is important for some countries with high losses (Treyer and Bauer 2016). For other countries the error introduced is smaller.

market parameters for one of the scenarios used in this study. The final output consists of future ecoinvent databases that are year- and scenario-dependent.

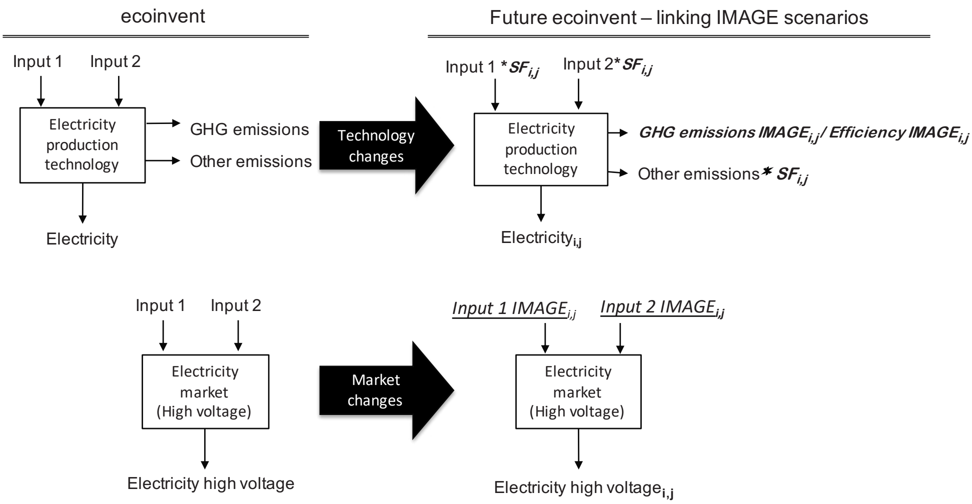


Figure 12. Schematic representation of technology and market parameters and their changes. Technology changes are presented in bold and market changes are represented with underlined font. Both are year- and scenario-dependent. The scaling factor (SF) is calculated as shown in equation 2.

LCI calculation

The final step of the scenario evaluation involves the calculation of the LCI results using the modelled future ecoinvent databases. Brightway2 (Mutel 2017) uses as input the future ecoinvent databases and calculates the inventory for the specified EV and ICEV (see section 4.2.4). The base year is 2012 because ecoinvent mostly represents the economy for this year. Selected future years are 2020, 2030, 2040 and 2050.

4.2.4 Case study

For the case study an EV is compared with its closest alternative, a small ICEV-EURO5 diesel vehicle. The foreground description corresponds to processes as defined in ecoinvent, and they remain unchanged in the future (See Cox et al. 2018 for foreground changes). The EV is based on the unit process 'transport, passenger car, electric' for the global average vehicle (Simons 2016), whereas the ICEV-EURO5 is based on the process 'transport, passenger car, small size, diesel, EURO 5' (Del Duce et al. 2016). These processes include the assembly, operation, maintenance and end of life of each vehicle. The functional unit is 1 kilometre driven by each vehicle, and so differences in use and further spending patterns are not considered (Font Vivanco et al. 2014, 2016). The effects of background changes on the LCIA results are studied separately for changes of technology and market parameters. The impact categories were chosen in line with those used in previous studies and relevant for the comparison (e.g. Bauer et al. 2015;

Nordelöf et al. 2014). The impact categories are climate change, particulate matter formation, fossil cumulative energy demand, human toxicity, metal depletion, and photochemical oxidant formation. The characterization factors are defined according to RECIPE 2008 (Goedkoop et al. 2013) hierarchist perspective at the mid-point level. For climate change, we use the global warming potentials (GWPs) of the IPCC Fifth Assessment Report, with a time horizon of 100 years (IPCC 2014), considering biogenic carbon (SI, Annex III for characterization factors).

4.2.5 Scenarios used in this chapter

The IMAGE scenarios we used are the Shared Socio-Economic Pathways (SSPs) (O'Neill et al. 2014). This family of climate scenarios consists of a set of five storylines on possible human development trajectories and global environmental change in the 21st century (van Vuuren et al. 2017a). Of the five storylines (Riahi et al. 2017), we used three that cover different challenges for mitigation and adaptation to climate change as well as a broad range of primary energy supply technologies from different sources (e.g. coal, oil + gas, renewables and nuclear) and different levels of final energy demand (Riahi et al. 2017; van Vuuren et al. 2017b). The storylines are SSP1 – Taking the green road, SSP2 – Middle of the Road and SSP3 – Regional Rivalry.

For each storyline, a baseline scenario was developed, assuming that such a pathway can unfold without specific additional policies and measures to limit climate change or to increase the adaptation capacity (Riahi et al. 2017). Each SSP baseline has been used as a starting point for exploring climate policy scenarios. The climate targets explored correspond to the radiative forcing levels of the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011). The RCPs were used in the International Panel for Climate Change Fifth Assessment Report (IPCC-AR5) as a set of scenarios exploring different long-term climate targets in 2100, i.e. 2.6, 4.5 and 6.0 W/m^2. The SSPs explored these and an additional target of 3.4 W/m^2, which is more policy-relevant. In this study, we used the data for the scenarios reaching a 2.6 W/m^2 target, which is consistent with a two-degree target (UNFCCC 2010). Also, a 3.4 W/m^2 target is used for the SSP3.

The results for both types of vehicles were compared for the following scenarios (see Table 8 for a summary): GreenRoad (SSP1), MidRoad (SSP2), RegRivalry (SSP3), GreenRoad-2.6 (SSP1-2.6), MidRoad-2.6 (SSP2-2.6) and RegRivalry-3.4 (SSP3-3.4). Also, we present a so called 0-scenario, in which no background changes are assumed, i.e. ecoinvent (original data) for 2012. For comparison, we also added the results for the 2012 IMAGE data, which are the same for all scenarios, as they correspond to historic data and not to forecast (scenario) data. The combination of the selected years, scenarios and products yields a total of 52 inventories that were calculated. Finally, for reference, the SI (Annex IV) shows the electricity mix for the IMAGE scenarios for Western and Central Europe regions.

Table 8. Scenarios, years, and databases used for the prospective life cycle assessment of a ICEV and a EV. ICEV: internal combustion engine vehicle; EV: electric vehicle; SSP: shared socio-economic pathway.

Vehicle	Database used for background	IMAGE scenario (SSP)	Year(s)	Label in this chapter
ICEV/EV	ecoinvent	n.a.	2012	ICEV/EV-ecoinvent
ICEV/EV	ecoinvent adapted with IMAGE scenario	n.a.	2012	ICEV/EV-IMAGE-2012
ICEV/EV	ecoinvent adapted with IMAGE scenario	Green Road (SSP1)	2020,2030,2040,2050	ICEV/EV-GreenRoad
ICEV/EV	ecoinvent adapted with IMAGE scenario	Green Road 2.6 (SSP1-2.6)	2020,2030,2040,2050	ICEV/EV-GreenRoad-2.6
ICEV/EV	ecoinvent adapted with IMAGE scenario	Middle of the Road (SSP2)	2020,2030,2040,2050	ICEV/EV-MidRoad
ICEV/EV	ecoinvent adapted with IMAGE scenario	Middle of the Road 2.6 (SSP2-2.6)	2020,2030,2040,2050	ICEV/EV-MidRoad-2.6
ICEV/EV	ecoinvent adapted with IMAGE scenario	Regional Rivalry (SSP3)	2020,2030,2040,2050	ICEV/EV-RegRivalry
ICEV/EV	ecoinvent adapted with IMAGE scenario	Regional Rivalry 3.4 (SSP3-3.4)	2020,2030,2040,2050	ICEV/EV-RegRivalry-3.4

4.3 Results

We present the prospective LCA results for EV and ICEV in section 4.3.1, and the disaggregated results according to market and technology changes in section 4.3.2.

4.3.1 Prospective LCA results for EV and ICEV

Our results show that the uncertainty about future developments in the electricity sector is overall large but manifests differently according to the studied product (EV or ICEV), the impact category, and the scenario and year considered (Figure 13). Regarding the product, uncertainty is larger for the EV, as is evident from the larger range of results, particularly in the long-term (see purple lines versus orange lines in 2050, Figure 13). As electricity production contributes more to the background impacts of the EV than to impacts of the ICEV, this result is expected. For the impact categories, we observe that for climate change, particulate matter formation, and fossil cumulative energy demand, the selected IMAGE scenario has a larger influence on the future impacts of the EV. These are impacts due to GHG emissions and use of fossil fuels. Thus, baseline scenarios which have a larger share of fossil-based technologies display a smaller reduction of these impacts than the original ecoinvent impacts for the EV. By contrast, ambitious mitigation scenarios that have larger shares of technologies emitting less GHG show large reductions of these impacts, particularly in the long-term. For impacts such as metal depletion, almost no effect of the scenario is observed for the EV and the ICEV.

This is mostly related to the fact that sectors that might contribute more to this impact, such as the raw materials production sector, were kept the same.

Considering the uncertainty about the future also makes it more complex to assess the relative environmental performance of EV over time (See SI, Annex V). There are impact categories such as particulate matter formation for which the results of the EV overlaps with those of the ICEV (see purple lines crossing orange lines, Figure 13). To understand these results, it is important to compare the ICEV and EV results within the same scenario. For climate change, for instance, the impacts of both types of vehicles overlap in 2050 for EV-RegRivalry and ICEV-RegRivalry-3.4. However, this comparison is not fair, as effectively these scenarios represent different futures. For particulate matter formation, on the other hand, EVs perform better than ICEVs in the MidRoad-2.6 and the GreenRoad-2.6 scenario after 2040, while the opposite is true for other years and scenarios. Thus, for ambitious mitigation scenarios, EV would lead to improvements in particulate matter formation while for non-ambitious scenarios, such as the baseline scenario, the ICEV would be preferred regarding this impact category.

Lastly, we observed striking differences in some cases between the original ecoinvent and the IMAGE-based adaptation of ecoinvent for 2012 (EV-ecoinvent and ICEV-ecoinvent, Figure 13). Such differences comprise reductions of up to 16%, 15,5% and 13,8% of the EV impacts in the categories climate change, photochemical oxidant formation and particulate matter formation, respectively. For the ICEV, the differences are smaller, with reductions ranging between 0.1 to 4.6% for all impact categories. In the case of climate change and photochemical oxidant formation, the relative environmental impacts of both vehicles were reversed in the scenario results for 2012 compared to those of the original ecoinvent. To better understand these results, a breakdown in market and technology changes is necessary.

4.3.2 Prospective LCA results for EV and ICEV by market and technology changes

Of the technology and market changes, the latter have the largest influence on the total change of impacts in general (see Figure 14 for climate change impacts as an illustration and SI, Annex VI for other impacts). Technology changes alone lead to the same impacts in both the baseline and the mitigation scenario, as technology efficiency is expected to improve in the future regardless of which electricity production technology has a larger penetration. Market changes are different for both scenarios given the higher penetration of technologies emitting less GHG in the ambitious mitigation scenarios. Together, both changes account for technology improvements but also for market penetration of electricity technologies. The impacts calculated with both changes are in line with those of market changes alone, particularly for the mitigation scenario (Figure 14).

Furthermore, market changes appear to interact with technology changes when both are taken into account (Table 9). Impacts calculated with technology or market

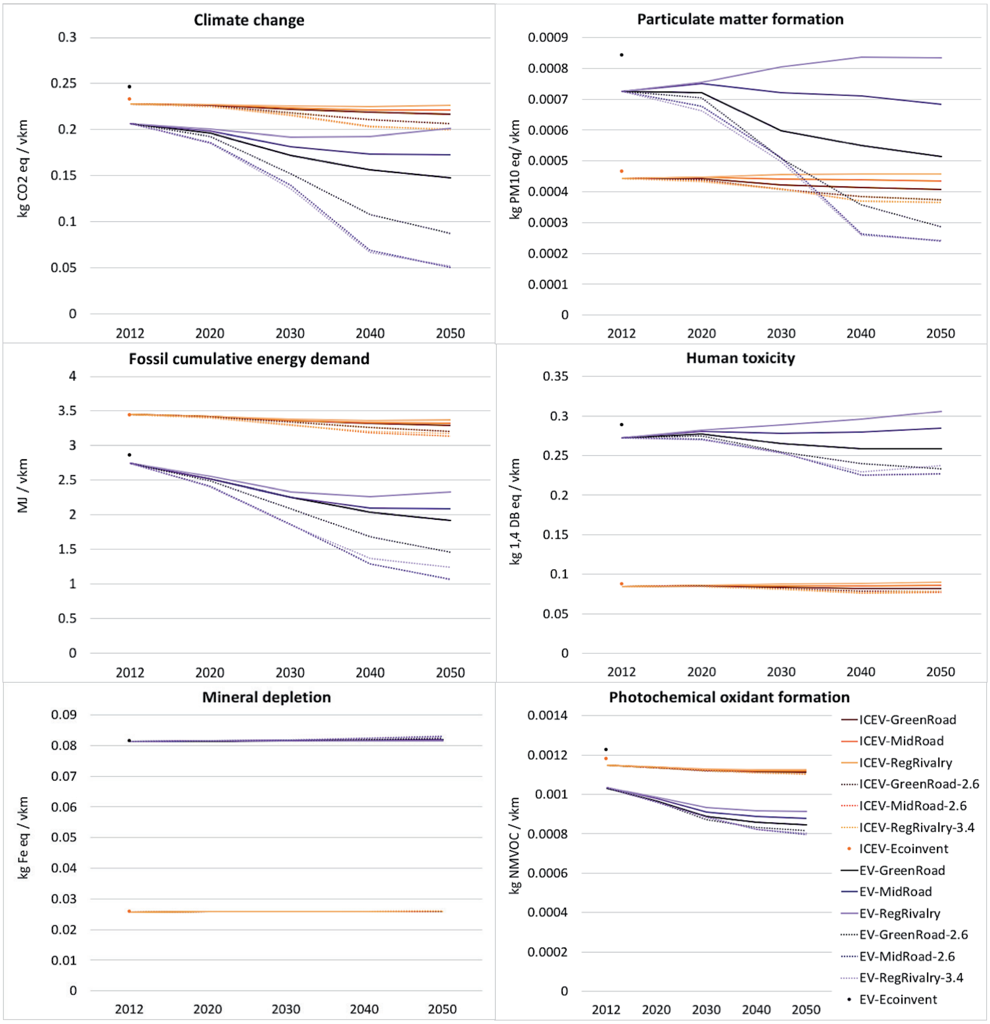


Figure 13. Prospective life cycle assessment results for an EV and an ICEV, for various impact categories, per vehicle-kilometer and considering background changes based on six IMAGE scenarios. ICEV: internal combustion engine vehicle; EV: electric vehicle.

changes alone do not capture joint effects of technology improvement and market penetration of different technologies. This becomes more evident in Table 9, where the changes in impacts for market and technology changes alone do not add up to the impacts calculated with both. To account for the actual individual contributions of each effect to the total impacts, one could use structural decomposition analysis (Hoekstra and Van Den Bergh 2002). However, this is beyond the scope of the present study.

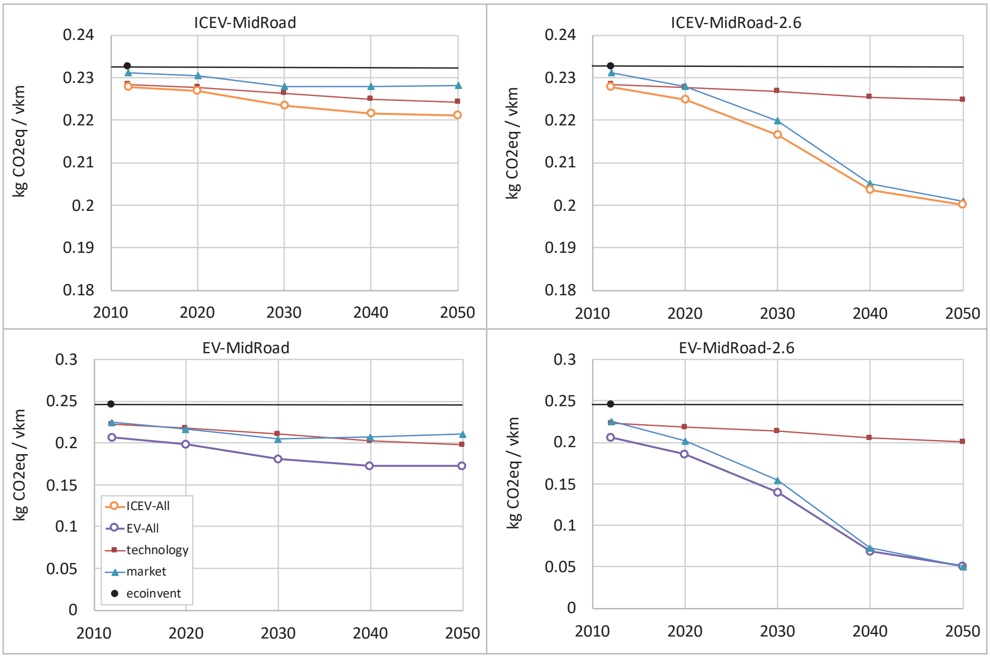


Figure 14. Prospective life cycle assessment results, for climate change impacts and per vehicle-kilometer (vkm), of an EV and an ICEV. The results correspond to the MidRoad and MidRoad-2.6 scenarios including background adaptions of technology parameters only (red squares), market parameters only (blue triangles) and including both changes (purple line for EV and orange line for ICEV, corresponding with the results shown in Figure 13. Impact using original ecoinvent background data is shown with a black dot and constant black line in time. ICEV: internal combustion engine vehicle; EV: electric vehicle.

Table 9. Change in the impacts per vehicle-kilometer (as % change from the original ecoinvent) for an EV and an ICEV using the MidRoad and MidRoad-2.6 scenarios, considering background adaptions of technology parameters only ('technology' rows), market parameters only ('market' rows) and both changes simultaneously ('all' rows). Shades of red represent an increase and shades of green represent a decrease of impacts compared to ecoinvent and hold for the range of outcomes for all impacts per scenario and type of vehicle. ICEV: internal combustion engine vehicle; EV: electric vehicle.

	year	Background adaptation	Fossil Cumulative Energy Demand	Climate Change	Human Toxicity	Mineral Depletion	Particulate Matter Formation	Photochemical Oxidant Formation		Fossil Cumulative Energy Demand	Climate Change	Human Toxicity	Mineral Depletion	Particulate Matter Formation	Photochemical Oxidant Formation
ICEV-MidRoad	2012	technology	1,1%	1,8%	1,7%	0,1%	6,4%	2,9%	EV-MidRoad	7,1%	9,4%	3,0%	0,1%	19,5%	15,0%
	2012	market	-1,4%	0,6%	2,2%	0,1%	-1,2%	0,7%		-2,6%	8,4%	2,4%	0,1%	-3,7%	5,6%
	2012	All	-0,5%	2,1%	3,9%	0,1%	4,6%	2,6%		3,9%	16,0%	5,3%	0,2%	13,8%	15,5%
	2020	technology	1,4%	2,1%	2,0%	0,1%	7,5%	3,5%		9,0%	11,2%	3,5%	0,1%	22,8%	18,4%
	2020	market	-0,5%	1,0%	-0,2%	0,0%	-2,8%	1,3%		5,0%	12,0%	-0,9%	0,0%	-8,8%	9,5%
	2020	All	0,5%	2,4%	1,8%	0,0%	3,7%	3,5%		11,6%	19,4%	2,6%	0,1%	11,0%	20,1%
	2030	technology	1,8%	2,7%	2,6%	0,1%	8,9%	4,3%		12,2%	14,1%	4,5%	0,2%	27,4%	22,6%
	2030	market	0,6%	2,0%	-0,4%	-0,2%	-3,2%	1,7%		11,9%	16,5%	-1,4%	-0,3%	-11,1%	11,7%
	2030	All	2,0%	3,9%	2,3%	-0,1%	5,1%	4,6%		20,9%	26,2%	3,3%	-0,2%	14,4%	25,6%
	2040	technology	2,3%	3,3%	3,4%	0,1%	10,1%	4,7%		15,9%	17,7%	5,9%	0,2%	31,1%	24,5%
	2040	market	1,0%	2,0%	-1,7%	-0,3%	-4,6%	1,8%		13,5%	15,8%	-3,9%	-0,5%	-16,4%	11,6%
	2040	All	3,1%	4,8%	2,1%	-0,2%	5,6%	5,0%		26,4%	29,5%	2,8%	-0,4%	15,7%	27,6%
	2050	technology	2,6%	3,6%	3,8%	0,1%	10,7%	4,9%		17,5%	19,3%	6,5%	0,2%	33,0%	25,8%
	2050	market	1,0%	1,9%	-3,1%	-0,4%	-4,1%	1,9%		12,3%	14,4%	-6,4%	-0,6%	-14,5%	12,3%
	2050	All	3,3%	4,9%	1,3%	-0,3%	6,5%	5,2%		26,7%	29,6%	1,3%	-0,5%	18,7%	28,2%
ICEV-MidRoad-2.6	2012	technology	1,1%	1,8%	1,7%	0,1%	6,4%	2,9%	EV-MidRoad-2.6	7,1%	9,4%	3,0%	0,1%	19,5%	15,0%
	2012	market	-1,4%	0,6%	2,2%	0,1%	-1,2%	0,7%		-2,6%	8,4%	2,4%	0,1%	-3,7%	5,6%
	2012	All	-0,5%	2,1%	3,9%	0,1%	4,6%	2,6%		3,9%	16,0%	5,3%	0,2%	13,8%	15,5%
	2020	technology	1,3%	2,1%	2,0%	0,1%	7,4%	3,5%		8,8%	10,9%	3,4%	0,1%	22,5%	18,3%
	2020	market	0,1%	2,0%	2,0%	0,0%	0,6%	1,9%		9,9%	17,8%	3,1%	0,0%	3,2%	12,8%
	2020	All	1,0%	3,3%	3,7%	0,0%	6,2%	3,8%		15,5%	24,2%	5,9%	0,0%	19,7%	21,5%
	2030	technology	1,7%	2,5%	2,4%	0,1%	8,7%	4,3%		11,4%	13,3%	4,1%	0,1%	26,5%	22,5%
	2030	market	2,9%	5,5%	5,4%	-0,2%	6,7%	3,0%		28,6%	37,1%	9,5%	-0,4%	25,8%	19,6%
	2030	All	4,0%	6,9%	6,8%	-0,2%	11,8%	4,9%		34,8%	43,1%	11,8%	-0,4%	39,6%	27,6%
	2040	technology	2,2%	3,1%	3,1%	0,1%	10,6%	5,1%		14,8%	16,4%	5,3%	0,2%	32,4%	26,6%
	2040	market	6,4%	11,8%	11,7%	-0,7%	18,0%	5,1%		50,7%	70,1%	21,2%	-1,1%	65,7%	31,2%
	2040	All	7,2%	12,5%	12,4%	-0,6%	20,3%	6,0%		54,6%	71,9%	21,9%	-1,1%	68,7%	32,8%
	2050	technology	2,4%	3,4%	3,4%	0,1%	11,2%	5,3%		16,6%	18,3%	5,9%	0,2%	34,3%	28,0%
	2050	market	8,1%	13,6%	11,3%	-1,1%	19,1%	5,6%		61,1%	79,6%	20,7%	-1,9%	69,7%	34,0%
	2050	All	8,6%	13,9%	11,9%	-1,1%	21,1%	6,4%		62,7%	79,3%	21,3%	-1,9%	71,4%	35,0%

Chapter 4

4.4 Discussion

The aim of the present study was to demonstrate how IAM scenarios can be systematically linked with LCI parameters to account for future changes in prospective LCA. Integrating electricity scenarios from IMAGE with data from the ecoinvent database served to account for future background changes in the prospective LCAs of EVs and ICEVs. We showed that it is possible to use six IMAGE scenarios covering different socio-economic pathways of development to calculate the impacts of two types of vehicles because the integration proposed in this study follows a systematic procedure. For prospective LCA, this is an important modelling effort that helps to understand the effects of background changes independent of the product evolution, which is represented in the foreground (Miller and Keoleian 2015). As the results showed, background changes are important in the case of some key impacts for EV and can determine the relative environmental performance differences between EV and ICEV. For uncertainty analysis, this is also an important effort as epistemological uncertainty can be acknowledged by means of relevant and consistent scenarios representing possible futures, as was shown in the results. This type of uncertainty cannot be reduced given the fact that the nature of the system we studied is nonstationary, complex and based on human behavior (Plevin 2016). However, this study showed that exploring future pathways and related impacts rather than predicting them can help to outline and better inform directions for action by acknowledging the presence of this type of uncertainty and by making the assumptions and constraints as transparent as possible.

Our results show that future developments in the electricity sector will critically affect whether and by how much EV outperform ICEV for key impact categories such as climate change. These findings are to some extent consistent with the literature, although previous studies have mostly focused only on market changes related to increased diffusion of low-carbon power technologies. For example, Wolfram and Wiedmann (2017) estimated that the carbon footprint of EV in Australia in a business-as-usual scenario for the diffusion of renewable energies would decrease about 50% from 2009 to 2050. This magnitude is within the range of our results for MidRoad scenarios (which would be conceptually equivalent) and for climate change, which describe a decrease due to market changes alone of 14 to 80% between 2012 and 2050. Similarly, Messagie and Brussel (2017) described reductions of about 60% in the carbon footprint of EV when replacing the average EU electricity mix by that of countries where renewable and nuclear power prevail, such as Sweden or France.

Some important limitations of our study need to be discussed. First, some future emissions for electricity technologies were not adapted using specific emission factors but using best available data. Therefore, future emissions for these substances should be carefully assessed. For instance, in the case of PM emissions, changes were made according to future technology efficiency as IMAGE does not explicitly model different sizes of Particulate Matter (PM) emissions despite modelling Black Carbon emissions, which cover several PM sizes altogether. Hence, results for particulate matter formation do not account for developments such as end-of-pipe solutions, which would be better captured in specific emission factors for PMs. In this sense, there is room for improvement of the present approach, and it would make sense to invest in finding more suitable proxies, other than technology efficiency, modelled within the IAM model to change the LCI parameters wherever possible.

Secondly, we focused on the electricity sector, leaving all other sectors unchanged. By doing so we ignored other layer of complexity, realizing that additional changes are to be expected for other technologies in other sectors (e.g. the steel sector in the case of vehicles) and that these would affect the life cycle impacts of ICEVs and EVs found in this study. For instance, if we had coupled changes in the background for the main industry sectors (e.g. the steel sector), fossil-fuels production, transport and other sectors, such as the agricultural sector, this would have resulted in the possibility to evaluate the life cycle impacts of each product accounting for a fully consistent macro-level scenario. We did not pursue this full scope of all sectors yet, as this article mainly aimed to prove the concept. The availability of datasets for these other sectors in the IMAGE scenarios suggests that including them is the logical next step towards a more systematic construction of future LCI databases using IAM scenarios.

We still consider the results of this study to be representative for EVs, because the largest contribution to the EV impacts is electricity production to recharge the battery (Cox et al. 2018). Also, the technology and market changes that we did consider have roughly changed about 75% of the ecoinvent processes and have reduced their overall impact by 10% using the MidRoad-2.6 scenario for 2040 (Cox et al. 2018). For ICEVs, there could be changes in the production of oil due to changes in the resource accessibility and possibly due to new extraction technologies. Hence our results can be read as an exploration keeping the status quo for fossil-fuels production.

Lastly, we relied on inventories of technologies that are yet to be deployed, in particular CCS and CSP. While these inventories are crucial for achieving ambitious climate targets, there still are large parameter uncertainties for these inventories. The robustness of the assessment would be increased by addressing such parameter uncertainty jointly with other sources of uncertainty (see chapter 2 and 3 of this thesis) as well as acknowledging epistemological uncertainty. Cox et al. (2018) already made an effort in this direction for the case of EVs.

4.5 Conclusions

For dealing with the large epistemological uncertainty about the future in order to support more robust future environmental assessments and decision-making, we were able to demonstrate a new approach for systematically capturing background changes in prospective life cycle assessment (LCA). We evaluated scenarios from an Integrated Assessment Model (IAM), the IMAGE model, in the life cycle inventory phase of a prospective LCA using ecoinvent v3.3 as a background dataset. Our case study on the effects of future changes in the electricity sector on the prospective LCA of an electric vehicle (EV) and an internal combustion engine vehicle (ICEV) shows that the new approach is both feasible and valuable. Future changes include technology developments in terms of efficiency and emission factors as well as market changes, which were more extensively studied in previous literature, for electricity market mixes in the future.

Advantages of our approach include a systematic integration of data, based on consistent worldwide scenarios, with reproducible, transparent and traceable assumptions and results. Also, the approach meets demands to include macro scenarios into the micro or product level of LCA to help increase the robustness of the assessment. For prospective LCA, this method is a modelling effort helping to understand exogenous background changes. For uncertainty analysis, this is an effort that acknowledges, rather than reduces, epistemological uncertainty via the use of a broad spectrum of socio-economically driven scenarios, which lead to explorative instead of predictive results that can help outline and better inform directions for action in product design and policymaking.

The case study shows that background changes can be very important for future environmental impact assessment of EVs and ICEVs. Climate change impacts can be altered up to 80% by 2050 in an ambitious mitigation scenario compared to impacts calculated without accounting for background changes. The uncertainty about future developments in the electricity sector is overall large, but it manifests differently depending on the studied product (EV or ICEV), the impact category, and the scenario and year considered. Considering the uncertainty about the future also makes assessing the relative environmental performance of EV over time more complex and nuanced. Depending on the scenario, year and impact, EV can perform better or worse than ICEV. Electricity market changes have a larger influence than technology changes on the total impacts of both types of vehicles. For both types of vehicles, market changes can thus determine if the impacts are better or worse with respect to the impacts calculated with original ecoinvent background. Interactions between market changes and technology changes are observed when both are taken into account.

It is still possible to find more suitable data within the IAM model to account for technology changes. Also, it is important to improve further the inventories for relevant future technologies in line with the scenarios, such as carbon capture and storage (CCS) and concentrated solar power (CSP), or to account for their parameter uncertainty. Moreover, it is also possible to expand the present approach to other economic sectors as well as other products in search of a more systematic construction of future inventory databases using IAM scenarios for more robust prospective LCA. Then, LCA results can be further calculated for products delivering the same function but with a different technological profile, thus enabling the comparison of their future impacts in a wider context.

Acknowledgements
Authors would like to thank the PhD students and postdocs summer school on "System Models in LCA" (2016) organized by the Paul Scherrer Institut (PSI), ETH Zurich and ecoinvent, for creating the environment to shape ideas and to kick-off the collaboration that led to this study. We would also like to acknowledge David Gernaat for his assistance in gathering relevant IMAGE data. David Font Vivanco acknowledges funding from the European Commission (Marie Skłodowska-Curie Individual Fellowship [H2020-MSCA-IF-2015], grant agreement no. 702869).

Supporting information
If not provided below the material is available upon request.

ANNEX I

Table S. 1 Technologies map between IMAGE and ecoinvent v3.3.

Where proxies are indicated for ecoinvent processes, we copy the inventories of the proxy process indicated and assume that these correspond to the technology indicated by the IMAGE technology. Copied proxy processes are further renamed and modified according to the IMAGE scenario. For oil CCS and Oil CHP CCS the Carma project did not create datasets. Because the contribution of these technologies in the IMAGE scenarios is small, we use the best available data we have i.e. for coal and natural gas. We expect this over simplification to have no significant effect on the results.

IMAGE technology	Ecoinvent processes
Solar PV	'electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted' 'electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted' 'electricity production, photovoltaic, 570kWp open ground installation, multi-Si'
Concentrated Solar Power (CSP)	'Electricity production for a 50MW parabolic trough power plant' 'Electricity production at a 20MW solar tower power plant'
Wind onshore	'electricity production, wind, <1MW turbine, onshore' 'electricity production, wind, 1-3MW turbine, onshore' 'electricity production, wind, >3MW turbine, onshore'
Wind offshore	'electricity production, wind, 1-3MW turbine, offshore'
Hydro	'electricity production, hydro, reservoir, alpine region' 'electricity production, hydro, reservoir, non-alpine region' 'electricity production, hydro, reservoir, tropical region' 'electricity production, hydro, run-of-river'
Other renewables	'electricity production, deep geothermal'
Nuclear	'electricity production, nuclear, boiling water reactor' 'electricity production, nuclear, pressure water reactor, heavy water moderated' 'electricity production, nuclear, pressure water reactor'
Coal Steam Turbine (Coal ST)	'electricity production, hard coal' 'electricity production, lignite'
Coal Combined Heat and Power (Coal CHP)	'heat and power co-generation, hard coal' 'heat and power co-generation, lignite'
Integrated gasification combined cycle (IGCC)	'Electricity, at power plant/hard coal, IGCC, no CCS/2025' 'Electricity, at power plant/lignite, IGCC, no CCS/2025'
Oil Steam Turbine (Oil ST)	'electricity production, oil'
Oil Combined Heat and Power (Oil CHP)	'heat and power co-generation, oil'
Oil combined cycle (Oil CC)	**Proxy: Same processes as oil ST:** electricity production, oil
Natural gas open Cycle turbine (Natural gas OC)	'electricity production, natural gas, conventional power plant'

Natural gas combined cycle (Natural Gas CC)	'electricity production, natural gas, combined cycle power plant'
Natural gas Combined Heat and Power (Natural Gas CHP)	'heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical' 'heat and power co-generation, natural gas, conventional power plant, 100MW electrical'
Biomass Combined Heat and Power (Biomass CHP)	Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014' 'heat and power co-generation, wood chips, 6667 kW' 'heat and power co-generation, biogas, gas engine'
Biomass combined cycle (Biomass CC)	**Proxy, Same processes as for biomass CHP** Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014' 'heat and power co-generation, wood chips, 6667 kW' 'heat and power co-generation, biogas, gas engine'
Biomass Steam Turbine (Biomass ST)	**Proxy, Same processes as for biomass CHP:** Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014' 'heat and power co-generation, wood chips, 6667 kW' 'heat and power co-generation, biogas, gas engine'
Coal Carbon Capture and Storage (Coal CCS)	'Electricity, at power plant/hard coal, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/hard coal, post, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, post, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, oxy, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/hard coal, oxy, pipeline 200km, storage 1000m/2025'
Coal Combined Heat and Power Carbon Capture and Storage (Coal CHP CCS)	**Proxy, Carma project didn't include Coal CHP CCS (Volkart et al. 2013)** 'Electricity, at power plant/hard coal, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/hard coal, post, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, post, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, oxy, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/hard coal, oxy, pipeline 200km, storage 1000m/2025'
Oil Capture and Storage (Oil CCS)	**Proxy, Carma project didn't include Coal CHP CCS (Volkart et al. 2013)** 'Electricity, at power plant/hard coal, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/hard coal, post, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, post, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, oxy, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/hard coal, oxy, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/natural gas, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/natural gas, post, pipeline 200km, storage 1000m/2025'
Oil Combined Heat and Power Carbon Capture and Storage (Oil CHP CCS)	**Proxy, Carma project didn't include Coal CHP CCS (Volkart et al. 2013)** 'Electricity, at power plant/hard coal, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/hard coal, post, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, post, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/lignite, oxy, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/hard coal, oxy, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/natural gas, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/natural gas, post, pipeline 200km, storage 1000m/2025'
Natural gas Carbon Capture and Storage (Natural Gas CCS)	'Electricity, at power plant/natural gas, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/natural gas, post, pipeline 200km, storage 1000m/2025'
Natural Gas Combined Heat and Power Carbon Capture and Storage (Natural Gas CHP CCS)	**Proxy, same processes as natural gas CCS:** 'Electricity, at power plant/natural gas, pre, pipeline 200km, storage 1000m/2025' 'Electricity, at power plant/natural gas, post, pipeline 200km, storage 1000m/2025'

Chapter 4

Biomass Carbon Capture and Storage (Biomass CCS)	‘Electricity, from CC plant, 100% SNG, truck 25km, post, pipeline 200km, storage 1000m/2025’ ‘Electricity, at wood burning power plant 20 MW, truck 25km, post, pipeline 200km, storage 1000m/2025’ ‘Electricity, at BIGCC power plant 450MW, pre, pipeline 200km, storage 1000m/2025’
Biomass Combined Heat and Power Carbon Capture and Storage (Biomass CHP CCS)	**Proxy, same processes as biomass CCS:** ‘Electricity, from CC plant, 100% SNG, truck 25km, post, pipeline 200km, storage 1000m/2025’ ‘Electricity, at wood burning power plant 20 MW, truck 25km, post, pipeline 200km, storage 1000m/2025’ ‘Electricity, at BIGCC power plant 450MW, pre, pipeline 200km, storage 1000m/2025’

ANNEX II

Table S. 2 Regional description for IMAGE used to match ecoinvent v3.3 processes.

IMAGE Regions	IMAGE countries in regions (ISO 3166-1 2 letter country code) See link for further reference: http://themasites.pbl.nl/tridion/en/themasites/_disabled_fair/definitions/datasets/index-2.html
Canada	CA
USA	US, PM
Mexico	MX
Central America	AI, AW, BB, BM, BZ, BS, CR, DM, DO, GD, GP, GT, HN, HT, JM, KY, MQ, MS, NI, AW, CW, SX, PA, PR, SV, KN, LC, VC, TT, TC, VG, VI
Brazil	BR
South America	AR, BO, CL, CO, EC, GF, GY, PE, PY, SR, UY, VE
Northern Africa	DZ, EG, EH, LY, MA, TN
Western Africa	BF, BJ, CF, CM, CV, CD, CG, CI, GA, GH, GN, GQ, GM, GW, LR, ML, MR, NE, NG, SL, SN, ST, SH, TD, TG
Eastern Africa	BI, DJ, ER, ET, KE, KM, MG, MU, RW, RE, SC, SD, SO, UG
South Africa	ZA
Western Europe	AD, AT, BE, CH, DE, DK, ES, FI, FR, FO, GB, GI, GR, IE, IS, IT, LI, LU, MC, MT, NL, NO, PT, SE, SM, VA
Central Europe	AL, BA, BG, CS, CY, CZ, EE, HR, HU, LT, LV, MK, PL, RO, SI, SK
Turkey	TR
Ukraine region	BY, MD, UA
Central Asia (Asia-Stans)	KZ, KG, TJ, TM, UZ
Russia	AM, AZ, GE, RU
Middle east	AE, BH, IL, IQ, IR, JO, KW, LB, OM, QA, SA, SY, YE
India	IN
Korea Region	KP, KR
China	CN, HK, MN, MO, TW
South Asia	BN, KH, LA, MM, MY, PH, SG, TH, VN
Indonesia Region	ID, PG, TL
Japan	JP
Oceania	AS, AU, CK, FJ, KI, MH, MP, FM, NC, NR, NU, NZ, PF, PW, SB, TK, TO, TV, VU, WS
Rest of South Asia	AF, BD, BT, LK, MV, NP, PK
Rest of Southern Africa	AO, BW, LS, MW, MZ, NA, SZ, TZ, ZM, ZW

Further details on the regional mapping in Wurst can be found in https://wurst.readthedocs.io/#spatial-relationships

ANNEX III

Global Warming Potentials (GWPs) from 2013 from the IPCC with a time horizon of 100 years as implemented by ecoinvent are used. All biogenic CO_2 flows are considered. The table below shows the GWPs used

Table S. 3 Global warming potential characterization factors used in the life cycle impact assessment.

Biosphere flow	kg CO_2 eq / kg	Biosphere flow	kg CO_2 eq / kg
Carbon dioxide, fossil	1	Ethane, pentafluoro-, HFC-125	3169.26
Carbon dioxide, from soil or biomass stock	1	Methane	29.7
Carbon dioxide, in air	-1	Methane, bromo-, Halon 1001	2.35
Carbon dioxide, to soil or biomass stock	-1	Methane, bromochlorodifluoro-, Halon 1211	1746.48
Carbon monoxide, fossil	4.06	Methane, bromotrifluoro-, Halon 1301	6291.63
Carbon monoxide, from soil or biomass stock	4.06	Methane, chlorodifluoro-, HCFC-22	1764.63
Carbon monoxide, non-fossil	2.49	Methane, chlorotrifluoro-, CFC-13	13893.35
Chloroform	16.4	Methane, dichloro-, HCC-30	8.92
Dinitrogen monoxide	264.8	Methane, dichlorodifluoro-, CFC-12	10239.23
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	1301.27	Methane, dichlorofluoro-, HCFC-21	147.66
Ethane, 1,1,1-trichloro-, HCFC-140	160.1	Methane, difluoro-, HFC-32	676.81
Ethane, 1,1,1-trifluoro-, HFC-143a	4804.44	Methane, fossil	29.7
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	5823.73	Methane, from soil or biomass stock	29.7
Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	782.04	Methane, monochloro-, R-40	12.18
Ethane, 1,1-difluoro-, HFC-152a	137.56	Methane, non-fossil	28.5
Ethane, 1,2-dichloro-	0.9	Methane, tetrachloro-, R-10	1728.47
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	8592.2	Methane, tetrafluoro-, R-14	6625.78
Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	1982.04	Methane, trichlorofluoro-, CFC-11	4662.94
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	79.37	Methane, trifluoro-, HFC-23	12397.6
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	526.55	Nitrogen fluoride	16070
Ethane, chloropentafluoro-, CFC-115	7665.36	Perfluoropentane	8546.7
Ethane, hexafluoro-, HFC-116	11123.49	Sulfur hexafluoride	23506.82

ANNEX IV

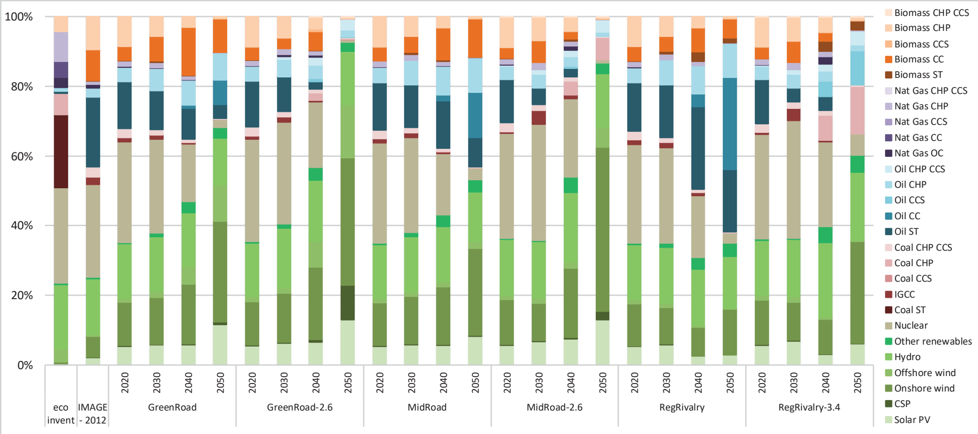


Figure S. 1 Energy mix for all scenarios and year for Western Europe in IMAGE.

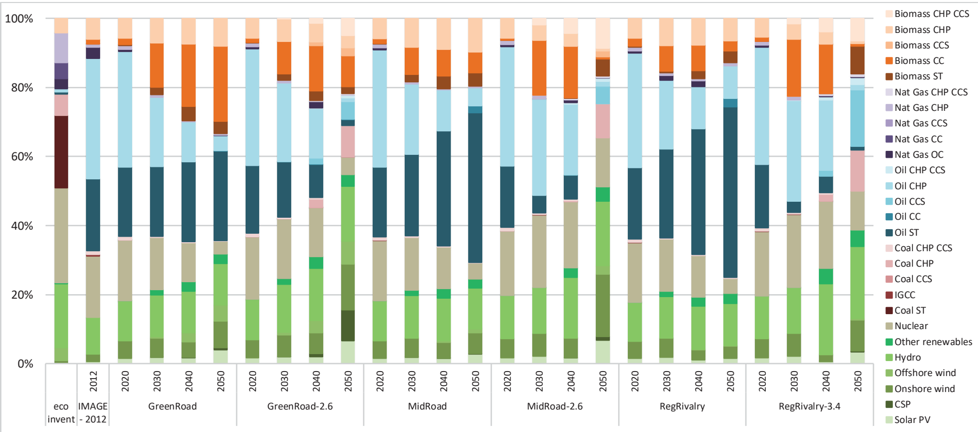


Figure S. 2 Energy mix for all scenarios and year for Central Europe in IMAGE.

ANNEX V

Relative impact category results of ICEV and EV. In the graphs below all data points above the diagonal represent years and scenarios for which EV performs better than the ICEV for each impact and points below the diagonal are years and scenarios for which EV performs worse than the ICEV.

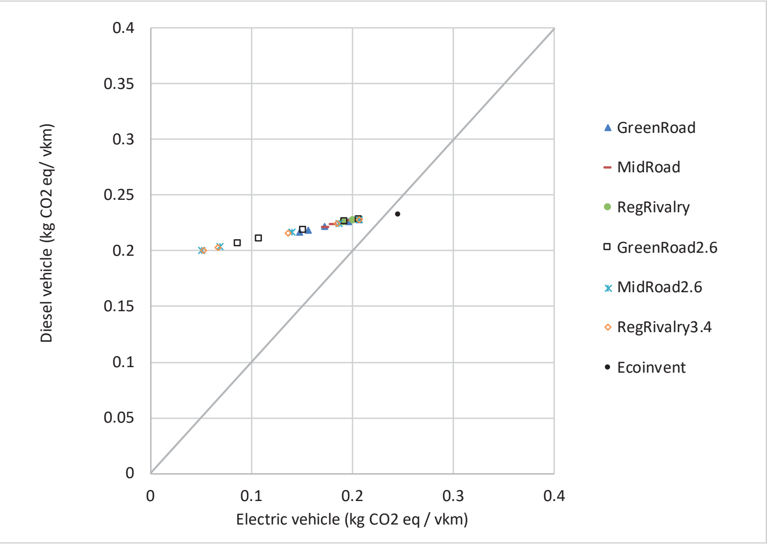


Figure S. 3. Climate change for ICEV and EV

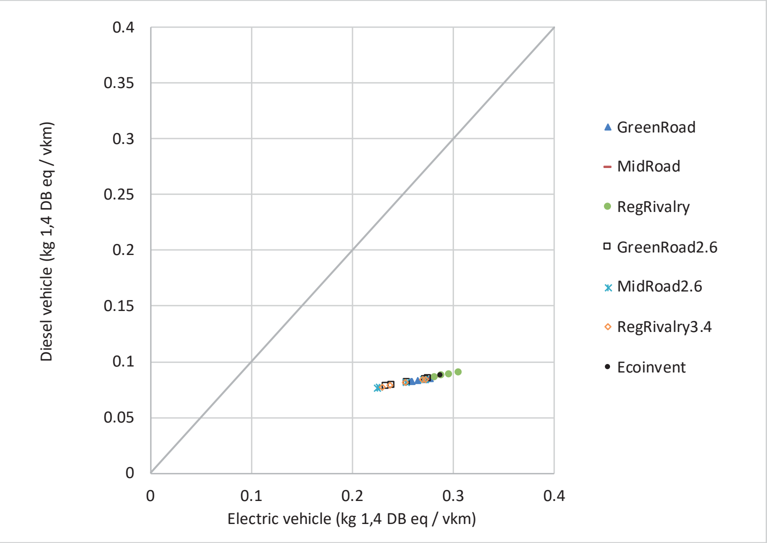


Figure S. 4 Human toxicity for ICEV and EV

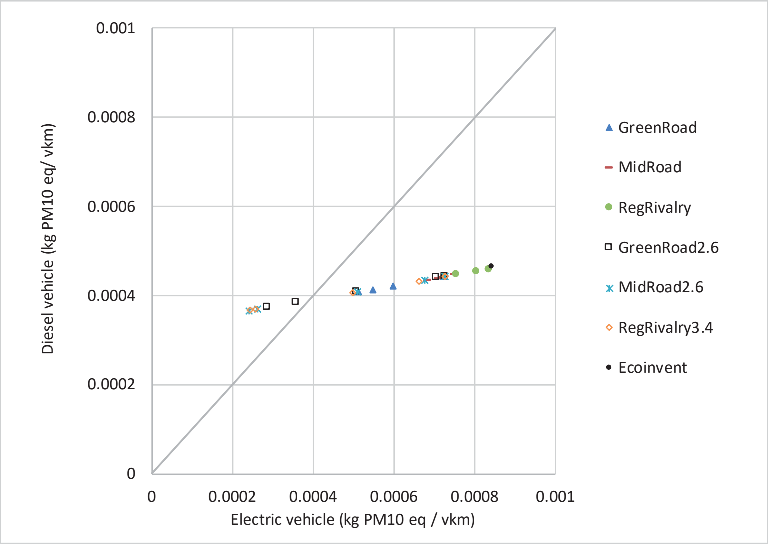


Figure S. 5 Particular matter formation for ICEV and EV

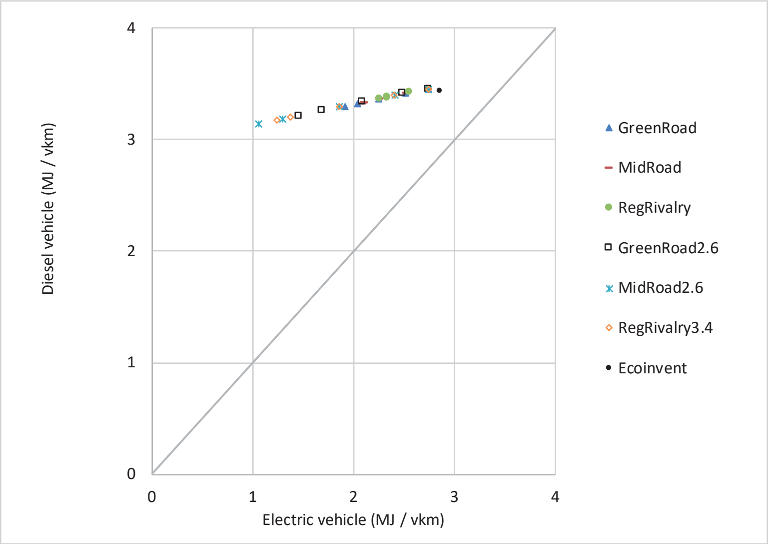


Figure S. 6 Fossil cumulative energy demand for ICEV and EV

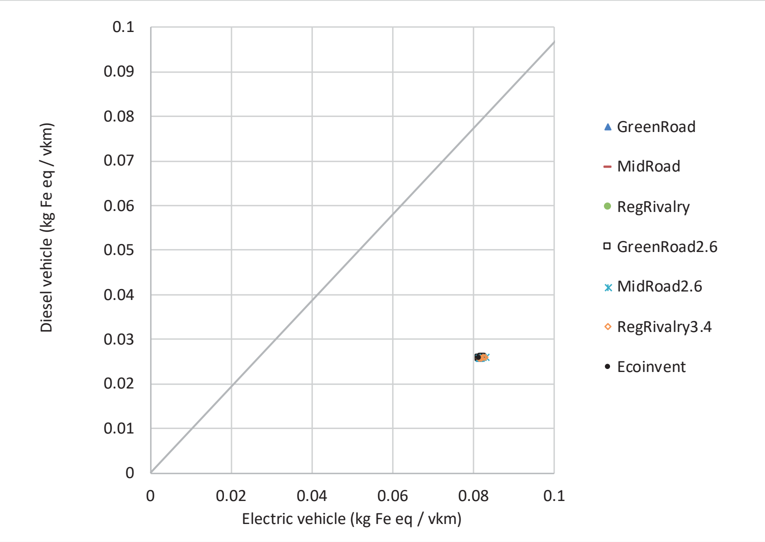


Figure S. 7 Mineral depletion for ICEV and EV

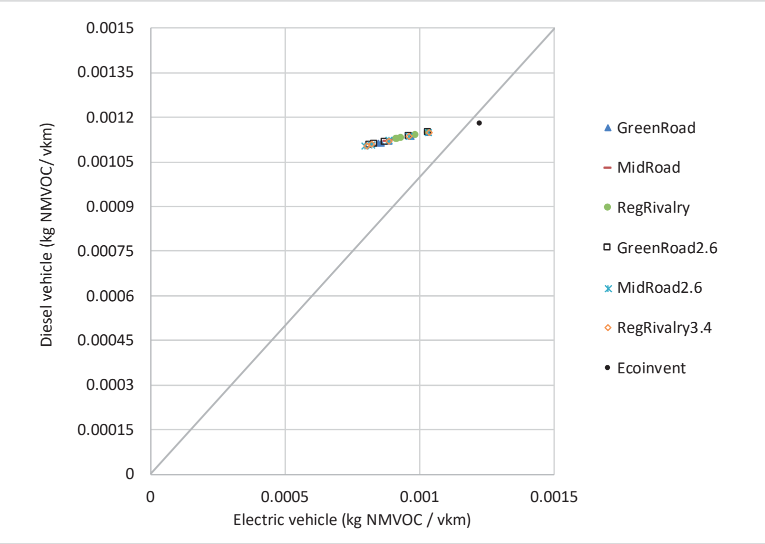


Figure S. 8 Photochemical oxidant formation for ICEV and EV

ANNEX VI

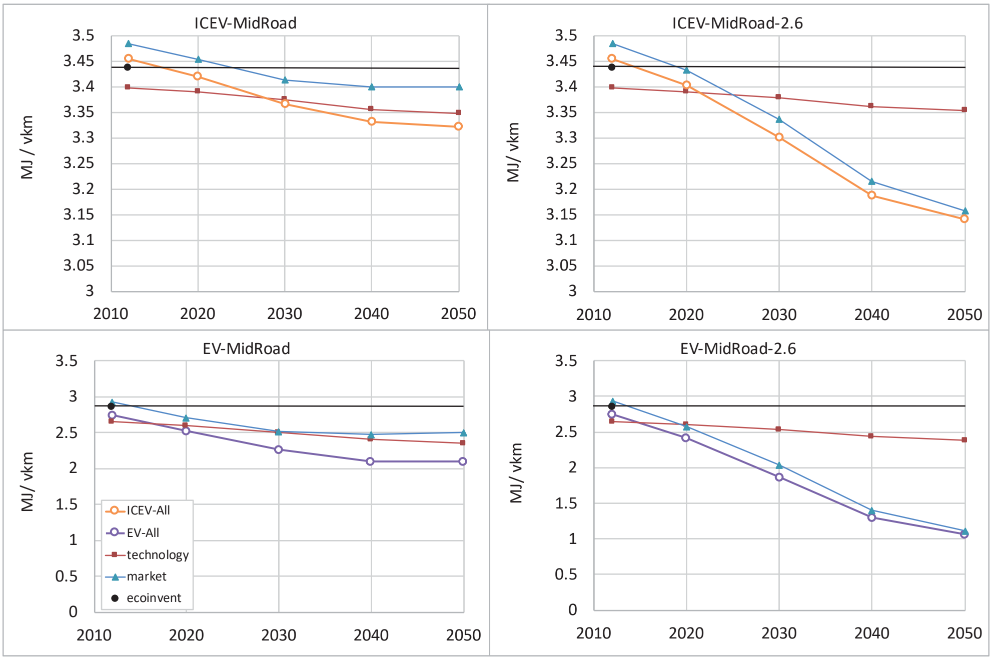


Figure S. 9 Technology (red squares), market (blue triangles) and both adaptations for the ICEV (orange line) and EV (purple line) for MidRoad and MidRoad-2.6 scenarios for Fossil cumulative energy demand.

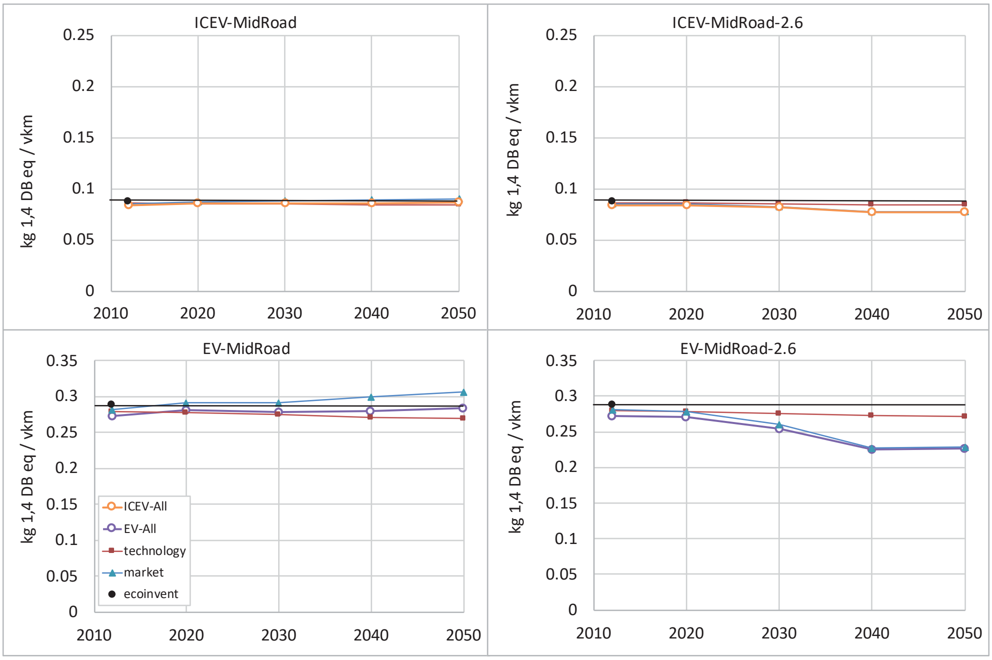


Figure S. 10 Technology (red squares), market (blue triangles) and both adaptations for the ICEV (orange line) and EV (purple line) for MidRoad and MidRoad-2.6 scenarios for Human toxicity.

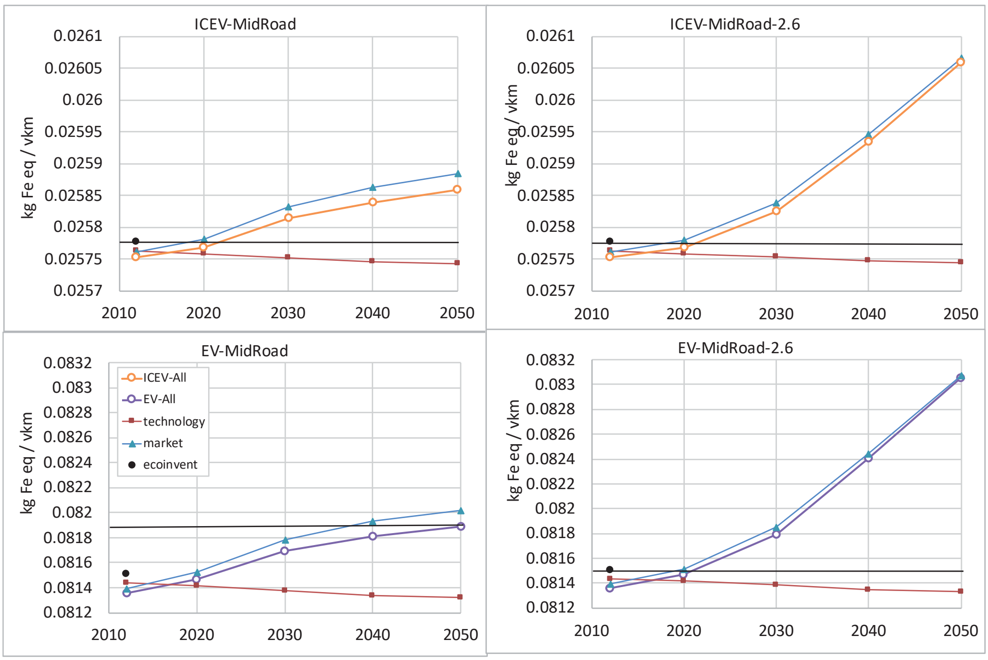


Figure S. 11 Technology (red squares), market (blue triangles) and both adaptations for the ICEV (orange line) and EV (purple line) for MidRoad and MidRoad-2.6 scenarios for Mineral depletion.

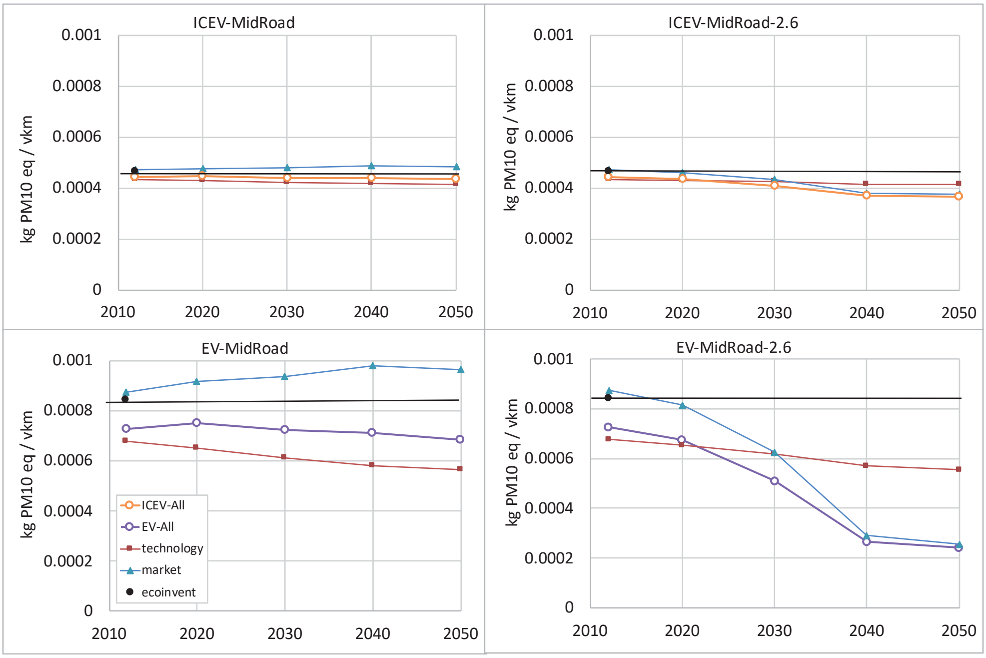


Figure S. 12 Technology (red squares), market (blue triangles) and both adaptations for the ICEV (orange line) and EV (purple line) for MidRoad and MidRoad-2.6 scenarios for Particular matter formation.

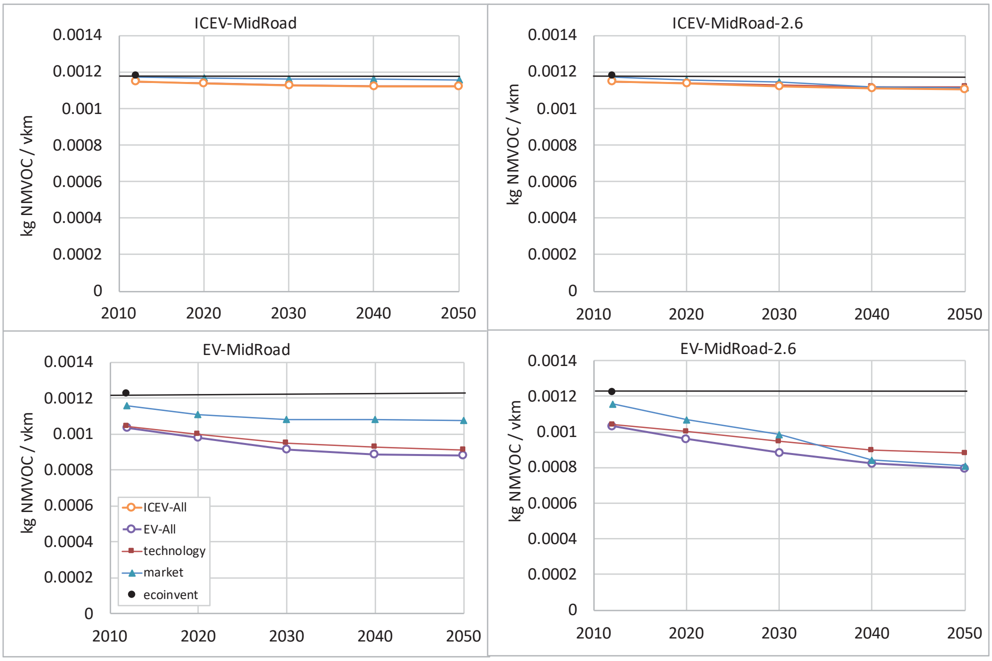


Figure S. 13 Technology (red squares), market (blue triangles) and both adaptations for the ICEV (orange line) and EV (purple line) for MidRoad and MidRoad-2.6 scenarios for Photochemical oxidant formation.