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IEA HEV Task 30

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Assessment of Environmental Effects of Electric Vehicles

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Summary

Electric vehicles (EVs) have the potential to substitute conventional vehicles to contribute to the sustainable development of the transportation sector worldwide, for example by reducing greenhouse gas (GHG) emissions, fossil energy consumption and particulate emissions. There is international consensus that the improvement of the sustainability of EVs can only be analysed based on life cycle assessment (LCA), which includes the production, the operation, and the end of life (EoL) management of the vehicles and the fuel cycle. All environmental impacts must include the whole value chain and - if relevant - interactions from recycling in the dismantling phase to the production phase, if recycled material is used to produce new vehicles.
The aim of Task 30 (2016 – 2022) was to analyse and assess environmental effects of EVs on water, land use, resources and air based on LCA in a cooperation of the participating countries in the International Energy Agency (IEA) in the Technology Program (TCP) on Hybrid and Electric Vehicles (HEV). With an eye on the three phases of LCA, such as production, operation and dismantling of EVs, various environmental effects of EVs on water, land use, resources and air, among others, are analysed and assessed. Thereby a strong accent is put on the comparison of environmental effects between pure battery EVs (BEVs) and plug-in hybrids (PHEVs) on one hand and conventional internal combustion engine (ICE) vehicles using gasoline and diesel on the other side.

The following partners in 7 countries cooperate in Task 30 with their own financing: Spain: IREC – Catalonia Institute for Energy Research, Canada: CIRAIG - International Reference Centre for the Life Cycle of Products, Processes and Services, Germany: DLR - Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center), Republic of Korea: Ulsam University, Turkey: Sabanci Universitesi, USA: Argonne and Austria: JOANNEUM RESEARCH. Beside global warming and primary energy consumption also other impacts like water issues, land use, resource consumption, local particulate matter (PM) and NO_x-emissions are addressed by life cycle based comparisons. Task 30 has further developed methods, compiled basic data for LCA, discussed case studies and documented the results in detail and made them available.

The results are:

- Expert Workshop on Water Issues
- Expert Workshop on Effects on Air
- Expert Workshop on Resources, Waste and Land Use (incl. LCA Autonomous Vehicles)
- Expert Workshop on Impact Assessment
- Rebound Effects of Electric Vehicles and Possible Implication on Environmental Effects in LCA
- Evaluation of the Environmental Benefits of the Global EV-Fleet in 38 Countries
- Issues on Dynamic LCA of Vehicle Fleets and
- Dissemination activities

The 10 lessons learnt summarize the results:

1. Environmental effects can only be analysed based on Life Cycle Assessment (LCA), other methods like Well-to-Wheel (WtW) are not adequate as all stages in the lifetime of a transportation system must be covered.
2. The system boundaries in LCA must cover all phases in the lifetime of a vehicles and the supply of energy: production, operation and end of life.
3. The considered transportation systems must be characterised by the type of vehicle, propulsion system, fuel/energy carrier, type of primary energy, state of technology and country/region.
4. The main factors influencing the LCA based environmental effects of EVs are: source of electricity generation and its future development up to 2030/2050, lifetime mileage, energy consumption of vehicle (incl. heating,

cooling, auxiliaries), electric driving share for PHEV, battery covering production (country, production capacity, source of electricity), battery capacity and end of life (material recycling or reuse in 2nd life).

5. In LCA, the way from Inventory Analysis to Impact Assessment is via mid- and end-point indicators. With regard to the geographical scope of the different impacts, the mid-point indicators are grouped for global, regional and local impacts, where global impacts are most relevant in LCA.
6. The minimum requirement in the impact assessment to compare different vehicles are the GHG emissions in CO_2-equivalent with its share of CO_2, CH_4 and N_2O and primary energy demand with its share of fossil and renewable energy.
7. The main water issues in LCA are for ICE (incl. blending of biofuels) the fossil fuel extraction and refining, cultivation of feedstock for biofuels, and the vehicle production. For EVs the electricity generation (e.g. thermal open/closed cycle, hydropower), battery and vehicle production.
8. The main global impacts to be addressed (in future) are climate change, primary energy use (fossil and renewable), resource use minerals and metals, water footprint (inventory level) and land use (inventory level). The results should be documented and communicated for the total life cycle but also for the three main phases in LCA.
9. The possible rebound effect can be considered in LCA by the definition of the functional unit and the substitution rate. In reflecting possible rebound effects in comparing the environmental effects of EVs with conventional ICE vehicles the following issues have to be considered: number of substituted ICE vehicles, substituted other transportation modes, e.g. public transport and walking, different annual mileage, vehicle lifetime, and driving distance with one charging or refill.
10. Issues on dynamic LCA, e.g. development of annual environmental effects, become relevant for the rapidly increasing of EV-fleets combined with the additional generation of renewable electricity. The timing of environmental effects is relevant in the three lifecycle phases, the increasing supply of renewable electricity, and substitution effects and timing of environmental effects of EVs substituting for ICE vehicles. The environmental effects based on LCA should be shown over time.

Zusammenfassung

Elektrische Fahrzeuge haben das Potential konventionelle Fahrzeuge zu ersetzen und so zur nachhaltigen Entwicklung des weltweiten Transportsektors beizutragen, z.B. Reduktion der Treibhausgas-Emissionen, fossilem Energiebedarf und Staub-Emissionen. Es besteht internationaler Konsens, dass die Umweltauswirkungen bzw. deren Veränderungen durch Elektrofahrzeuge nur im Rahmen von Lebenszyklusanalysen (LCA – Life Cycle Assessment) untersucht und bewertet werden können, indem alle drei Phasen im Lebenszyklus von der Herstellung, dem Betrieb und der Entsorgung bzw. Verwertung berücksichtigt werden. Alle Umwelteffekte müssen entlang der gesamten Wertschöpfungskette untersucht werden, sowie auch die Zusammenhänge von Sekundärrohstoffen aus dem Recycling in der Produktion.
Ziel der Task 30 (2016 – 2022) war es, die Umweltauswirkungen von Elektrofahrzeugen auf Wasser, Landnutzung, Rohstoffe und Luft auf Basis von Lebenszyklusanalysen in einer internationalen Kooperation mit Partnerländern in der Internationalen Energie Agentur (IEA) im Technology Program (TCP) zu Hybrid and Electric Vehicles (HEV) zu analysieren und zu bewerten. Mit dem Blick auf die drei Phasen im Lebenszyklus von Fahrzeugen – Produktion, Betrieb und Verwertung – wurden unterschiedliche Umweltauswirkungen von Elektrofahrzeugen auf Wasser, Landnutzung, Rohstoffe und Luft untersucht und bewertet. Hierbei wurde ein Schwerpunkt auf PKW gelegt, die mit batterie-elektrischem Antrieb, konventionellem Verbrennungskraftmotor (VKM) sowie der Kombination als Plug-In-Hybrid (PHEV) betrieben werden.

Die folgenden Partner aus 7 Ländern haben in der Task 30 zusammengearbeitet mit deren eigenen nationalen Finanzierungen: Spanien: IREC – Catalonia Institute for Energy Research, Canada: CIRAIG - International Reference Centre for the Life Cycle of Products, Processes and Services, Deutschland: DLR - Deutsches Zentrum für Luft- und Raumfahrt, Südkorea: Ulsam University, Türkei: Sabanci Universitesi, USA: Argonne und Österreich: JOANNEUM RESEARCH. Neben den Treibhausgas-Emissionen und dem Primärenergiebedarf wurden auch andere Umweltauswirkungen auf Wasser, Luft, Rohstoffbedarf, lokale Schadstoffemissionen (z.B. NOx, PM) untersucht. Die Task 30 hat dabei Methoden weiterentwickelt, Grunddaten für die LCA erarbeitet sowie Fallbeispiele diskutiert und die Ergebnisse ausführlich dokumentiert und verfügbar gemacht.

Die Ergebnisse sind:

- Experten-Workshop zu Wasser-Aspekten
- Experten-Workshop zu Auswirkungen auf die Luft
- Experten-Workshop zu Rohstoffen, Abfällen und Reststoffen sowie Landnutzung (inkl. LCA von autonomen Fahrzeugen)
- Experten-Workshop zu Umwelt-Bewertungsmethoden
- Rebound Effekte von Elektroahrzeugen und mögliche Auswirkungen auf die Umweltbewertung mit LCA
- Evaluierung der Umweltauswirkungen der globalen Flotte an Elektrofahrzeugen in 38 Ländern
- Methoden und Anwendungen der dynamischen LCA auf Fahrzeugflotten und
- Verbreitungs- und Vernetzungs-Aktivitäten.

Die folgenden Lessons Learnt fassen die Ergebnisse zusammen:

1. Umweltauswirkungen können nur auf Basis von Lebenszyklusanalysen untersucht und bewertet werden. Andere Methoden, wie z.B. Well-to-Wheel (WtW) sind hierzu nicht geeignet, da wesentliche Teile im Lebenszyklus nicht erfasst werden.

2. Die Systemgrenzen der LCA müssen alle Phasen im Lebenszyklus eines Fahrzeuges umfassen, die Fahrzeugherstellung, den Betrieb mit der Bereitstellung der Energie sowie die Verwertung bzw. Entsorgung.

3. Die untersuchten Transportsysteme müssen eindeutig festgelegt und beschrieben werden, wobei die Fahrzeugkategorie, das Antriebssystem, der Energieträger, der Primärenergieträger, Stand der Technik sowie das Land/Region angeführt werden müssen.
4. Die wesentlichen Parameter, die die Umweltauswirkungen von Elektro-Fahrzeugen beeinflussen, sind: Art der Stromerzeugung und dessen Entwicklung bis 2030/2050, Lebensdauer bzw. gefahrene Kilometer im Lebenszyklus, Energiebedarf des Fahrzeugbetriebes, Anteil an rein elektrischer Betriebsweise bei PHEV, Batterieproduktion (inkl. Produktionsland), Batterie-Kapazität sowie Reuse bzw. Recycling von Batterien.
5. In der LCA erfolgt die Bewertung von den Umweltauswirkungen ausgehend von der Sachbilanz zu Zwischen- bzw. Endpunkt-Indikatoren. Wenn die geografischen Orte der Umweltauswirkungen berücksichtigt werden, können die Mid-Point-Indikatoren in globale, regionale und lokale Umweltauswirkungen unterteilt werden, wobei die globalen Umweltauswirkungen für die Methode der LCA am wichtigsten sind.
6. Die Mindest-Anforderung bei der Umweltbewertung von Fahrzeugen ist es, im Rahmen der LCA die Treibhausgas-Emissionen mit den Anteilen an CO_2, CH_4 und N_2O und den Primärenergiebedarf mit den Anteilen an fossiler und erneuerbarer Energie zu ermitteln.
7. Die möglichen wesentlichen Auswirkungen auf das Wasser von konventionellen VKW (inkl. der Beimischung von Biotreibstoffen) sind die Förderung und Raffination von Rohöl, der landwirtschaftliche Rohstoffanbau und die Fahrzeug-Produktion; bei Elektro-Fahrzeugen die Stromerzeugung (z.B. Wasserkraft, thermische Kraftwerke), sowie die Batterie- und Fahrzeug-Produktion.
8. Die wesentlichen globalen Umweltauswirkungen, die (zukünftig) in LCAs von Elektro-Fahrzeugen untersucht werden müssen, sind: Treibhausgas-Emissionen, Primärenergiebedarf, Bedarf an mineralischen und metallischen Rohstoffen, Wasser-Fußabdruck (Sachbilanz) und Landnutzung (Sachbilanz). Die Ergebnisse zu diesen globalen Umweltauswirkungen müssen insgesamt, aber auch nach den 3 Hauptphasen der LCA dokumentiert und kommuniziert werden.
9. Mögliche Rebound Effekte können in der LCA bei der Festlegung der funktionalen Einheit und bei der Substitutionsrate berücksichtigt werden. Die Analyse der möglichen Rebound-Effekte hat gezeigt, dass beim Vergleich von Elektro- mit konventionellen VKM-Fahrzeugen die folgenden Aspekte erfasst werden sollen: Anzahl der ersetzten VKM-Fahrzeuge, Ersatz anderer Transportsysteme wie öffentlicher Verkehr und zu Fuß gehen, unterschiedliche Jahreskilometer, Lebensdauer der Fahrzeuge (inkl. Batterie) sowie Reichweite pro Tankfüllung bzw. Ladung.
10. Die Aspekte der dynamischen LCA, z.B. Entwicklung der jährlichen Umweltauswirkungen, werden relevant bei der stark steigenden Anzahl an Elektro-Fahrzeugen und dem damit verbundenen stark steigenden zusätzlichen Bedarf an erneuerbaren Strom. Der Zeitverlauf der Umweltauswirkungen ist relevant für die drei Phasen im Lebenszyklus, die zusätzliche Stromerzeugung sowie die Substitutionseffekte und den zeitlichen Verlauf der Umweltveränderungen bei Ersatz von VKM- und Elektro-Fahrzeuge. The Umweltauswirkungen aus der LCA sollten also im zeitlichen Verlauf dargestellt werden.

1 Aim of the activity

This chapter covers the motivation, the goal and scope, the approach and the cooperations and partners

1.1 Motivation

Electric vehicles (EVs) have the potential to substitute conventional vehicles to contribute to the sustainable development of the transportation sector worldwide, for example in the reduction of greenhouse gas (GHG) emissions, fossil energy consumption and particulate emissions. There is international consensus that the improvement of the sustainability of EVs can only be analysed based on life cycle assessment (LCA), which includes the production, the operation, and the end of life (EoL) management of the vehicles and the fuel cycle (Figure 1). All environmental impacts must include the whole value chain and - if relevant - interactions from recycling in the dismantling phase to the production phase, if recycled material is used to produce new vehicles.

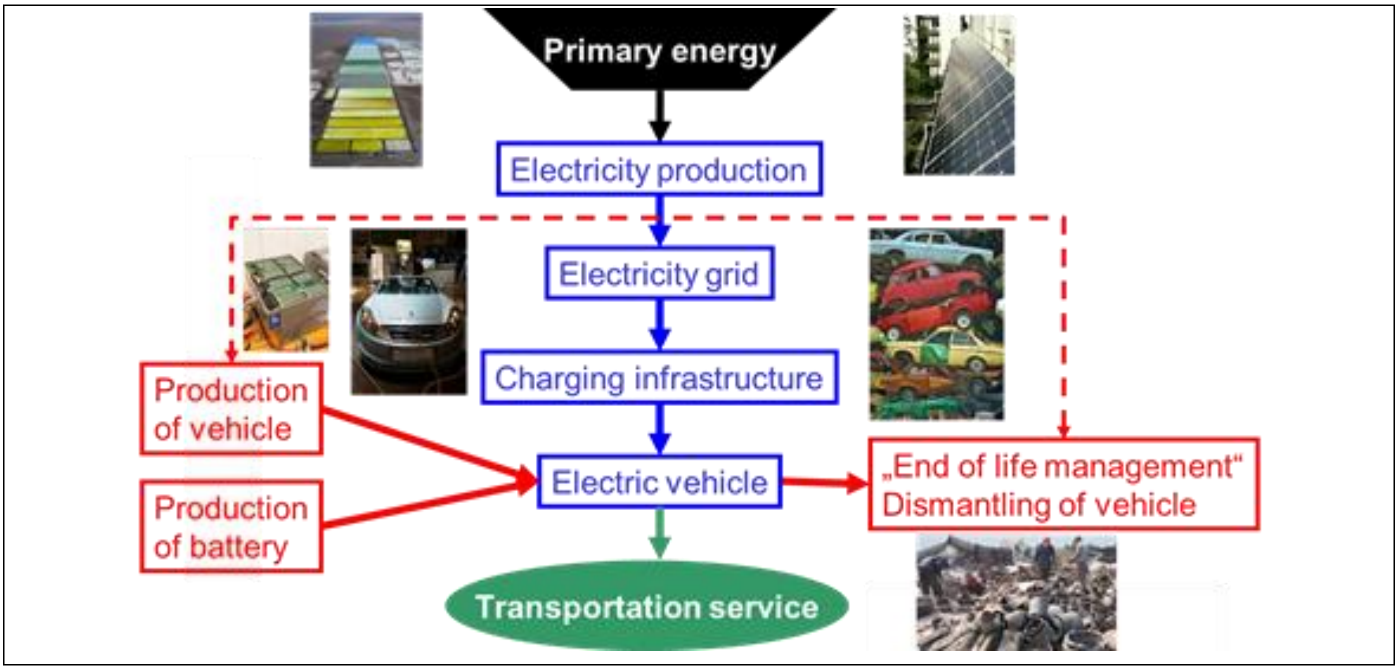

Figure 1: System boundaries for life cycle assessment of EVs

1.2 Goal and Scope

The aim of Task 30 (2016 – 2022) was to analyse and assess environmental effects of EVs on water, land use, resources and air based on LCA in a cooperation of the participating countries in the International Energy Agency (IEA) TCP.

Task 30 was using the results of the completed Task 19 "Life Cycle Assessment of Electric Vehicles" (2011 – 2015, www.ieahev.org/tasks/task-19-life-cycle-assessment-of-evs/, led by JOANNEUM RESEARCH) as a foundation to subsequently examine the environmental effects – benefits and impacts - of vehicles with an electric drivetrain (EVs), based on LCA.

With an eye on the three phases of LCA, such as production, operation and dismantling of EVs, various environmental effects of EVs on water, land use, resources and air, among others, are analysed and assessed. Thereby a strong accent is put on the comparison of environmental effects between pure battery EVs (BEVs) and plug-in hybrids (PHEVs) on one hand and conventional internal combustion engine (ICE) vehicles using gasoline and diesel on the other side.

In recent years, the focus in environmental assessments of EVs was on global warming and primary energy demand. But now it is recognized that other impacts gain additional relevance and must be addressed by life cycle based comparisons like water, land use, resource consumption, local particulate matter (PM) and NO_x-emissions. Therefore, Task 30 focuses also on following topics covering methodologies, data and case studies:

- effects of EVs on water (emissions to water, waste water, "Water Footprint" of EVs),
- effects on EVs on air (local emissions and effects of NO_x, PM and C_xH_y, human health effects and non-energy related emissions from tires and brakes),
- effects on EVs on land use – resources - waste (land use, occupation and degradation, demand of renewable and fossil resources, recycling), and
- overall environmental effects and their assessment (comparing and assessing different impact categories, single score methodologies, stakeholder involvement).

1.3 Approach

Within Task 30, methodologies are developed to help countries to implement EVs by identifying possibilities to maximize the environmental benefits. Besides, various case studies are analysed and networking combined with information exchange is supported within the Task's frames (Figure 2).

The Task proceeds by organizing a series of expert workshops addressing the following objectives:

- methodologies on assessment of environmental effects,
- analyses of necessary and available data,
- overview of international studies/literature,
- analyses of current knowledge and future challenges,
- overview of key actors and stakeholders and their involvement,
- communication strategies to stakeholders, and
- summarizing further R&D demand.

The results are continuously documented and disseminated via e.g. presentations, workshops, conference contributions and publications.

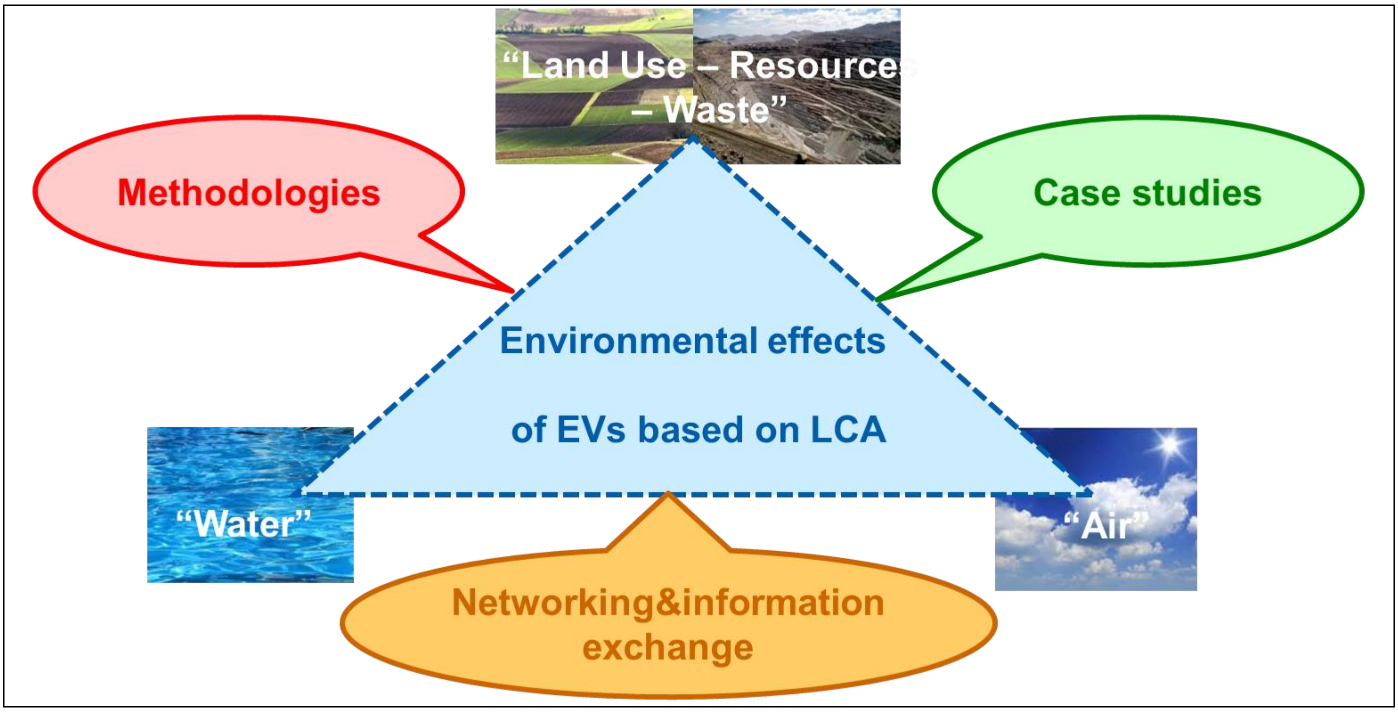

Figure 2: Approach of Task 30

1.4 Cooperations and Partners

1.4.1 IEA HEV TCP

The Hybrid and Electric Vehicle Technology Collaboration Programme (HEV TCP) enables member parties to discuss their respective needs, share key information, and learn from an ever-growing pool of experience from the development and deployment of hybrid and electric vehicles. (see www.ieahev.org)

The HEV TCP was formed in 1993 to produce and disseminate balanced, objective information about advanced electric, hybrid and fuel cell vehicles. It is an international membership group collaborating under the International Energy Agency (IEA) framework. TCPs are at the core of the IEA International Technology Co-operation Programme coordinated by the IEA Committee on Energy Research and Technology (CERT). HEV TCP is now in its sixth five-year term of operation that runs from March 2020 until March 2025. An annual report is published each year, which details work completed under the HEV TCP and news from member countries.

1.4.2 Membership to the HEV TCP

The HEV TCP offers two types of membership: Contracting Parties and Sponsors. Members designate a representative to serve on the Executive Committee that provides overall direction, approves the budget, and formulates policy and strategy. The HEV TCP's primary work is conducted through Tasks.

The 19 active Contracting Parties (member countries) as of May 2021 are

1. Austria,
2. Belgium,
3. Canada,
4. China,
5. Denmark,
6. Finland,
7. France,
8. Germany,
9. Ireland,
10. Italy,
11. The Netherlands,
12. Norway,
13. Republic of Korea,
14. Spain,
15. Sweden,
16. Switzerland,
17. Turkey,
18. United Kingdom and
19. The United States.

1.4.3 Governance and Management

The work of HEV TCP is governed by the Executive Committee ("ExCo"), which consists of one member designated by each Contracting Party. Contracting Parties are either governments of IEA countries or parties designated by their respective governments. The HEV TCP ExCo meets twice a year to discuss and plan the working programme.

1.4.4 Tasks

The actual work of the HEV TCP is achieved through a variety of different Tasks that are focused on specific topics. Each topic is addressed in a Task, which is managed by an Operating Agent (OA). The work plan of a new Task is prepared by an interim OA, either on the OA's own initiative or on request of the ExCo, and the work plan is then submitted for approval to the HEV TCP ExCo.

The currently ongoing tasks are (Status of webpage January 2022):

- Task 1 Information Exchange serves as a platform for information exchange among member countries.
- Task 23 Light-Electric-Vehicle Parking and Charging Infrastructure: aims to represent the interests of local governments in the standardisation of Light Electric Vehicle system architectures, infrastructure, communications and interchangeable batteries.
- Task 29 Electrified, Connected and Automated Vehicles: analyses the potential technological synergies of electrification, connectivity and automation of road vehicles and derive research, development and standardisation need.
- Task 30 Assessment of Environmental Effects of Electric Vehicles: aims to analyse and assess environmental effects of EVs on water, land use, resources and air based on LCA and in cooperation with participating countries in the HEV TCP.
- Task 32 Small Electric Vehicles: the objective of this task is to promote broader commercialisation, acceptance and further development of SEVs.
- Task 34 Batteries: aims to encourage the sharing and dissemination of current information about battery topics of interest to the vehicle community.
- Task 35 Fuel Cell Vehicles: aims at supporting a broader commercialization, acceptance and a further development of fuel cell electric vehicles (FCVs).
- Task 37 Extreme Fast Charging: aims to focus on the following objectives: investigating station siting – what factors are considered (i.e. space requirements, city centre, community/corridor).
- Task 38 Marine Applications (e-Ships): aims to focus on overviewing and encouraging the development and deployment of e-Ships, by building and sharing key knowledge on projects, performance, segments and demand.
- Task 39 Interoperability of e-Mobility Services: aims to focus on the charging infrastructure and more specifically on the interoperability aspects of e-mobility services like charging of passenger cars in the public and semi-public domain.
- Task 40 CRM4EV – Critical Raw Materials for Electric Vehicles: aims to focus on projected mass deployment of EVs, attention is drawn to potential supply chain issues for several Critical Raw Materials (CRMs) needed for EV manufacturing.

- Task 41 Electric Freight Vehicles: aims to monitor progress and review relevant aspects for a successful introduction of electric freight vehicles (EFV) into the market.
- Task 43 Vehicle/Grid Integration: analysing the challenges identified on the integration of the electric vehicles into our electricity and transport system in order to improve economic and environmental performance.
- Task 45 Electrified Roadways (E-roads): aims to develop a greater global understanding and awareness of electrified roadways (E-Roads), as well as related technologies developed and deployment activities in the participating countries.
- Task 46 LCA of Electric Trucks, Buses, 2-Wheelers and other Vehicles: aims to analyse environmental effects based on LCA of e-buses, e-trucks, e-2-wheelers and other e-vehicles in comparison to conventional vehicles and the use of e-fuel and hydrogen.
- Task 48 Battery Swapping: aims to focus on creating stronger infrastructure for battery swapping technology and swapping of information.

1.4.5 Partners in Task 30

The following partners in 7 countries cooperate in Task 30 with their own financing (Figure 3):

- Spain: IREC – Catalonia Institute for Energy Research,
- Canada: CIRAIG - International Reference Centre for the Life Cycle of Products, Processes and Services,
- Germany: DLR - Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center),
- Republic of Korea: Ulsam University,
- Turkey: Sabanci Universitesi
- USA: Argonne and
- Austria: JOANNEUM RESEARCH.

Figure 3: Countries and institutions in Task 30

1.4.6 National Project Advisory Board

A National Project Advisory Board was initiated by the funding agencies (FFG and Climate and Energy Fund) and established in 2018. The National Project Advisory Board had one meeting in each year (2018, 2019, 2020, 2021 and 2022) during the working period of Task 30.

The following activities of the National Project Advisory Board were mainly motivated to stimulate the information exchange in Austria:

- The operating agent informed on the actual activities and results (e.g. highlights) on the international level and the Austrian contributions.
- Strategic accompaniment, professional consultation and support on transferring the task activities and (interim) results.
- Information exchange on the Austrian actives in the TCP HEV – Hybrid and Electric Vehicle, AMF – Alternative Motor Fuels and AFC – Advanced Fuel cells.

The members of the National Project Advisory Board were:

- KLIEN: Gernot Wörther,
- FFG: Maria Bürgermeister-Mähr,
- BMK: Andreas Dorda, Constanze Kiener, Reiner Reinbrech,
- Energy Agency: Walter Mauritsch,
- JOANNEUM RESEARCH: Gerfried Jungmeier, Martin Beermann,
- BEST - Bioenergy and Sustainable Technologies: Dina Bachovsky, Andrea Sonnleitner and
- HyCentA – Hydrogen Center Austria: Alexander Trattner.

The following IEA tasks/annexes of the TCPs were represented by these members:

- HEV:
  - Task 30 „Environmental Effects of Electric Vehicles" (G. Jungmeier)
  - Task 33 „Battery Electric Buses" (G. Jungmeier)
  - Task 40 "CRM4EV Critical Raw Material for Electric Vehicles" (M. Beermann)
  - Task 41 "Electric Freight Vehicles" (A. Bhashyam)
  - Task 46 "LCA of Electric Trucks, Buses, 2-Wheelers and other Vehicles" (G. Jungmeier)
- AMF
  - Annex 58 „Transport decarbonisation" (D. Bacovsky)
  - Annex 59 „Lessons Learnt" (A. Sonnleitner)
- AFC - Annex 34 "Transport Applications" (A. Trattner)

2 Results

After an overview of the results, the detailed results are described.

2.1 Overview

The results are structured the following:

- Expert Workshop on Water Issues (see also Annex 1),
- Expert Workshop on Effects on Air (see also Annex 2),
- Expert Workshop on Resources, Waste and Land Use (incl. LCA Autonomous Vehicles) (see also Annex 3),
- Expert Workshop on Impact Assessment (see also Annex 4),
- Rebound Effects of Electric Vehicles and Possible Implication on Environmental Effects in LCA,
- Evaluation of the Environmental Benefits of the Global EV-Fleet in 38 Countries,
- Issues on Dynamic LCA of Vehicle Fleets and
- Dissemination activities.

2.2 Expert Workshop on Water Issues

2.2.1 Introduction

In January, 2017 Task 30 held an expert workshop on the environmental effects of electric vehicles (EVs) on water, energy consumption and air emissions based on life cycle assessment in Graz/Austria.

The aim of the workshop "Environmental Effects of Electric Vehicles (EV) – Water Issues and Benefits of EV-Fleets on Energy Consumption and Air Emissions" was to present and discuss the current status and the future perspectives of the environmental performance of electric vehicles in comparison to conventional vehicles with an internal combustion engine (ICE) in a life cycle perspective. The main focus is on Battery Electric Vehicles (BEV) and Plug in Hybrid Electric Vehicles (PHEV).

The two topics for the workshop were:

1. Water issues and
2. Benefits of EV-fleets on energy consumption and air emissions.

The format of the workshop was based on presentations, discussion and group work with focus on

- Data requirements
- Case studies
- Identification of main issues in LCA of EVs and ICE
- Identification of “hot spots” on water issues of EVs, PHEVs and ICEs
- Communication of LCA results to stakeholders, e.g. Fact Sheet
- Findings and Recommendations

2.2.2 Results

2.2.2.1 Overview

In an interactive group work, the following key issues were discussed, summarized and documented:

- Main drivers
- Water inventory
- Most relevant water issues for LCA of EV and ICE
- “Water footprint”
- Water issues in electricity production
- Water issues in value chain of EVs and ICE
- Research questions on water issues & EVs
- Possible activities of IEA HEV Task 30

2.2.2.2 Main Drivers

The key drivers to work on water issues are

- water is a key factor for sustainable development goals,
- agriculture (incl. biofuels),
- electricity production in thermal power plants and hydro power plants and
- waste water from industry and population as a pollution of rivers, lakes and seas.

2.2.2.3 Water Inventory

The starting point of an LCA on water issues is a water balance for the most relevant processes of EVs and ICE. Ideally, the water balance of each process is closed, as all inputs equal the outputs incl. the transformation of hydrogen into water, e.g. due to a chemical reaction. The water inventory must include the water inputs and water outputs by providing the data on process level with its geographical location:

- input water: source, volumes, temperature, quality,
- discharge water: sink, volumes, temperature, quality and
- emissions to water: specifically amounts of N, P, heavy metals and organic loading.

For a proper impact assessment the inventory data including uncertainties are needed by:

- region,
- timeframe (current, future),
- state of technology and
- data source: original, secondary and tertiary data.

2.2.2.4 Most Relevant Water Issues for LCA of EV and ICE

The most relevant water issues in LCA of EV and ICE are:

- Inventory:
  - water evaporated (blue water use),
  - water flow alteration (for hydro power),
  - water emissions (impurities that affect water quality),
  - thermal emissions,
- Impact assessment:
  - water consumption factor (WCF),
  - water scarcity,
  - water Stress Index or kind of such an index number,
  - water eutrophication and
  - water toxicity.

2.2.2.5 Water Footprint

Water Scarcity Footprint = Water Consumption * Water Scarcity Index

in analogy to

Carbon Footprint = Greenhouse Gas Emissions * Global Warming Potential

The commonly often used wording of “*water footprint*” gives only information on the amount of water and is, as such, on an LCA inventory basis, e.g. water consumption. Carbon footprint, on the other hand, is an LCA impact category. An LCA on water issues requires the water footprint but also water scarcity, eutrophication and toxicity.

Water issues in LCAs should be considered because water is relevant part of the sustainable development goals and will in future play an increasingly important role. As a result, water LCA and carbon footprint should be combined to create DALYs (disability/disease-adjusted life years lost) for impact category “Human health” and PDFs for “Ecosystem quality”.

2.2.2.6 Water Issues in Electricity Production

The water consumption is mainly relevant for thermal power plants and hydro power plants. For thermal power plants, the water consumption mainly depends on the type of cooling technology, whereas for hydro power the allocation of the water consumption to the different purposes of a hydro dam (e.g. electricity, flood control, navigation, recreation, and irrigation) is most influencing.

The total environmental damage (e.g. "Eco-Indicator 99" - Ei 99+) comparing different electricity generation systems might lead to two findings:

1) water is most relevant for hydro power but
2) the total environmental damage of hydro power is significantly lower compared to natural gas and coal.

2.2.2.7 Water Issues in Value Chain of EVs and ICE

The following processes are most important in the value chain of EVs and ICE (Figure 4):

- ICE (incl. blending of biofuels):
    - fossil fuel extraction and refining(e.g. Tar sands, oil shale or traditional oil),
    - cultivation of feedstock for biodiesel and bioethanol (e.g. for B5, E10),
    - vehicle production,
- EV (only BEV and PHEV):
    - electricity generation (e.g. thermal open cycle, closed cycle, or hydro power) and
    - battery production (specifically because of pollutants for mineral extraction and refining).

The comparison of water issues of EV and ICE shows that the life cycle based water consumption of EV might be higher than from ICE. Main reason is the electricity production from hydropower and thermal power plants. For ICE the most relevant influence on water consumption depends on the amount of biofuel blended (biodiesel in diesel or bioethanol in gasoline), as the agricultural production of the feedstock for biofuels is most relevant for water issues, e.g. most of the water consumption for E10 gasoline ICE vehicle in the USA derives from corn cultivation for bioethanol.

The comparison of water withdrawal and consumption for fuel supply show that

- for the ICE about 50% of the water withdrawal and about 80% of the water consumption is needed for the gasoline supply and

- for the EV about 90% of the water withdrawal and about 80% of the water consumption is needed for the electricity supply.

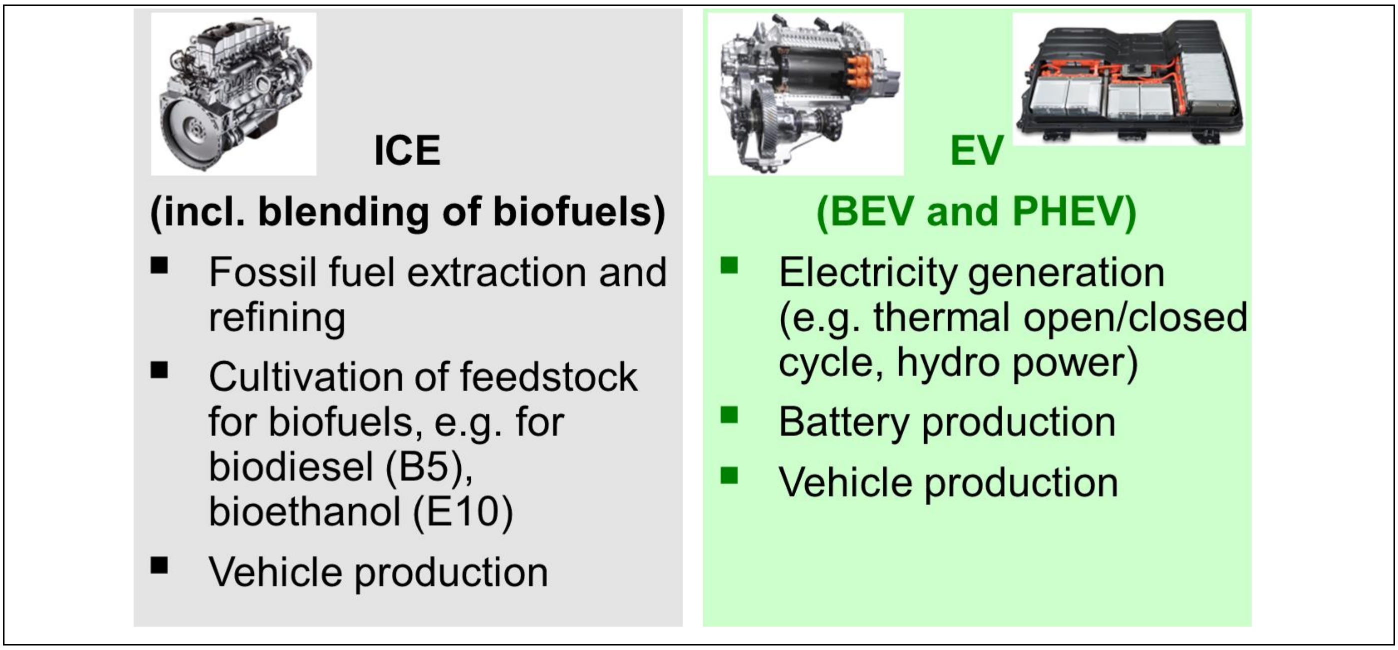

Figure 4: Main water issues in LCA of ICE and EV

2.2.2.8 Research Questions on Water Issues & EVs

- How to reduce the water impacts of EVs?
- Reduction of uncertainties in assessment. This requires:
    - basic data for the inventory at the regional level and
    - improved data of water inputs and emissions in the construction and dismantling of the EVs.
- How does a broader use of EVs impact water stress in a given region?
- Preparedness for the possibility that water becomes a “show stopper”. This requires a proper communication strategy of results and uncertainty of results.
- Including water vapour as a climate forcing.

2.2.2.9 Possible Activities of IEA HEV Task 30

The Task 30 might work on the following activities:

- A report giving a summary of the current state of knowledge on water issues in the LCA of EVs covering
    - methodological aspects,
    - data issues,

  - case studies comparing EVs and ICEs and
  - further R&D demand.
- Collection and compilation of water consumption (WCF) of global electricity production to analyse and assess water consumption of current global EV fleet. This might than be included in the FACT SHEETS for the IEA HEV countries and worldwide.
- Screen methodologies, data and case studies to expand analyses and assessment to include
  - stress index (or other kind of index) by region/scenario and
  - impact assessment (e.g. water quality, thermal pollution, etc.).

2.3 Expert Workshop on Effects on Air

2.3.1 Introduction

In September 2018, Task 30 held an expert workshop on emissions to air in the LCA of electric vehicles in Stuttgart/Germany.

The aim of the expert workshop of Task 30 was to analyse and assess environmental effects of electric vehicles (EVs) on emissions to air based on life cycle assessment in a cooperation of the participating countries in the International Energy Agency (IEA).

The aim of the workshop was to present and discuss the current status and the future perspectives of emissions to air in the LCA of Electric Vehicles in comparison to conventional vehicles with an internal combustion engine (ICE).

In a group of relevant stakeholders from government, industry, research and NGOs the relevant issues of effects on air emissions were identified and discussed referring to the ongoing large-scale market introduction of EVs.

2.3.2 Results

The summarized results of the workshop are the following:

- The main air emissions analysed in the inventory (LCI) and assessed (Impact Assessment) are CO_2, NO_x, SO_2, CO, PM, CH_4 and N_2O.
- The main sources of these air emissions in LCA of EVs and ICEs are
  - ICE-vehicle,
  - PHEV-vehicle,
  - thermal power plants providing the electricity for the EVs and
  - oil refineries to convert raw oil to gasoline and diesel.
- These main sources of air emissions must be documented in the foreground data in the LCA (beside the energy consumption of the vehicles) explicitly to allow better communication and comparison of the LCA results.
- The main impacts directly related to these air emissions are

  - global warming potential in CO_2-equivalent (CO_2, CH_4, N_2O),
  - acidification in SO_2-equivalent (NO_x, SO_2) and
  - ozone formation in C_2H_4-equivalent (CH_4, NO_x, CO, NMVOC).
- The Canadian Case Study also assessed Human health (DALY) and Ecosystem Quality (PDF m^2 year).
- The air emission of ICE and PHEV vehicles should be derived from real world driving conditions including user behavior and climate conditions reflecting the cooling and heating demand in different regions/countries.
- Most LCA studies presented comparing EVs and ICE vehicles mainly analyse and assess GHG emissions and primary energy demand, only few studies also assess other impact categories, e.g. air emissions.
- The emissions associated with the production and end of life of the automotive batteries are a very relevant issues, whereas currently the "generally accepted" GHG emissions are 175 (150 - 200) kg CO_2-eq/kWh (ivl 2017, ICCT 2018) and referring to about 35 g CO_2-eq/km (ICCT 2018) (Figure 5).
- Other air emissions from battery production where not presented.
- As the development of automotive batteries is very quick and innovate as well as the mass production of automotive battery production is starting these days, no new average data on battery production based on material demand and energy demand for cell and system assembling were presented.
- The end of life (EoL) of automotive batteries might become relevant for the impacts of battery production. Two different EoL strategies are discussed, the materials recycling and the 2nd use in a stationary application. Generally, it is not expected that the direct use of the old automotive batteries (<80% SOC) for stationary application (e.g. storage for PV plant) will gain commercial interest. A commercial business case could be to disassemble the cells and use the "best" cells to make a new stationary battery to give adequate warrantee.
- For the LCA of batteries the EoL might have significant influence in the case of 2nd use, as a significant part of the impacts of battery production might be allocated to the automotive and the stationary use, e.g. allocated according to the total electricity throughput in these two applications. The case of material recycling might not affect the total impact of automotive batteries significantly, as the increasing amount of battery production volume requires big amounts of primary materials while the recycling material is still limited to the small number of used automotive batteries available for recycling (Figure 5).
- The general results of the LCAs comparing ICE and EVs show the following
  - If the BEVs use a high share of renewable electricity, the impacts on air emissions are significantly lower than from ICE.
  - Besides using renewable electricity, the impacts of PHEV strongly depend on the share of electric driven kilometres. In electric mode the PHEV has similar impacts than the BEV. In combustion mode, the impacts of a PHEV are more or less equal to an ICE or an HEV.

  - If the electricity used for the EVs has a high share of fossil based electricity the impacts of the EVs are similar to the impacts of an ICE.
- Modelling can also be done using dynamic LCA data on electricity production in order to determine CO_2-eq, e.g. per half hour interval due to electricity production. This can help to set policies considering not only the supply and demand of electricity, but also for charging the vehicles when renewables are supplying electricity to the grid.
- Currently, the LCA based comparison of EVs and ICE is done for single vehicles, whereas now first applications of LCA to whole fleets of vehicles become relevant, e.g. when modelling future scenarios to fulfil PARIS targets.
- In applying LCA to vehicle fleets, the questions of really substituting ICEs by EVs become more and more relevant. It is observed, that the global, national and regional vehicle stocks of ICE are still growing while also the stock of EVs is growing, even much faster than those of ICEs. Additionally, it is observed that EVs become also the 2nd and 3rd vehicle in households. For LCA used in scenario analyses or for whole fleets of vehicles, these developments mean that not every new EV may replace an ICE in reality. These effects are called “(direct) rebound effects”.
- For applying LCA to EV fleets compared to ICE fleets, a methodological approach must be developed to integrate possible rebound effects in the LCA methodology, e.g. that 1 driven km by an ICE is not 100% substituted by an EV.
- The methodological combination of LCA with scenario analyses will become interesting in future, in which a burden shifting from transport sector in the electricity or industry sector becomes relevant and must be shown explicitly. There is also the possibility of using consequential LCA analysis to model this effect.

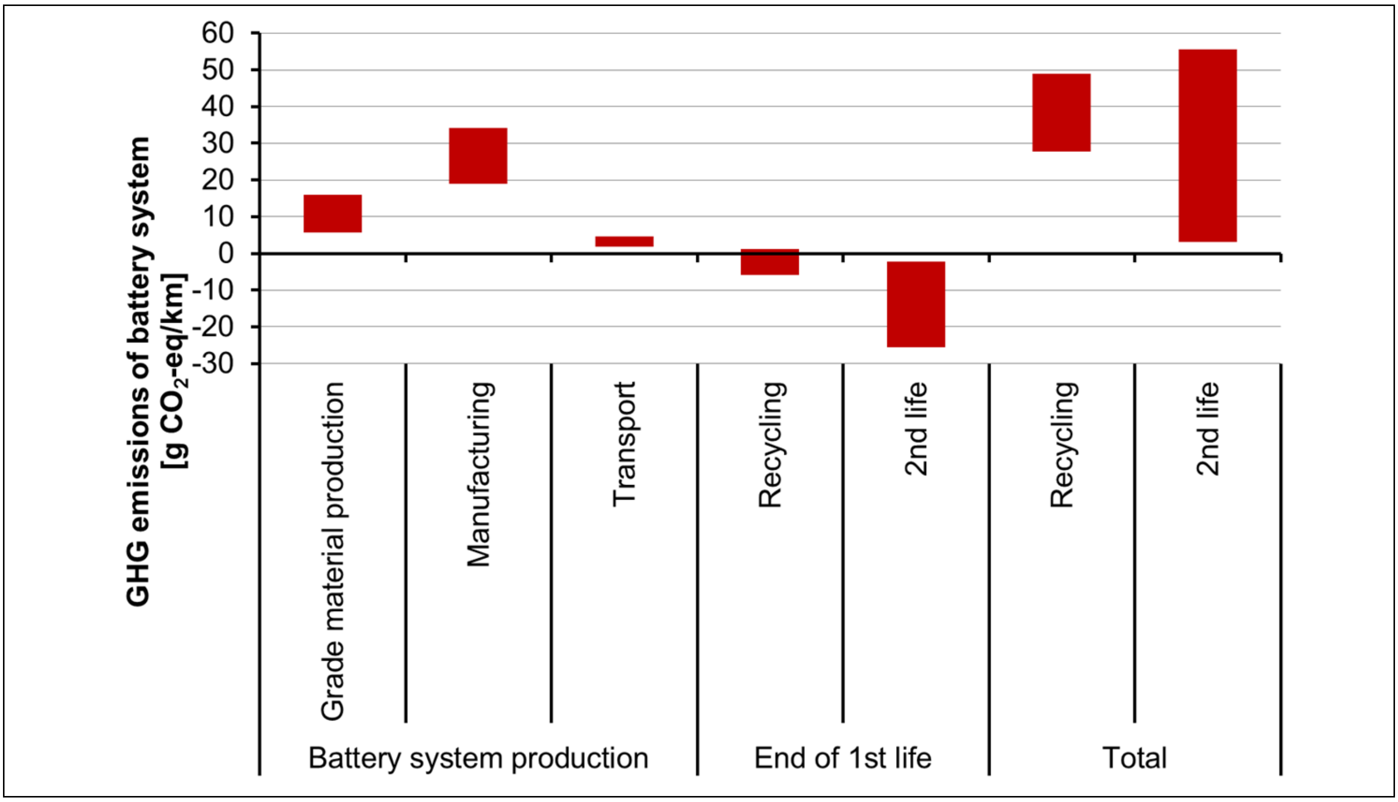

Figure 5: Estimated ranges of GHG emissions from battery system per km

2.3.3 Identified Key issues

In the workshop, the key issues on “Emissions to Air in the LCA of Electric Vehicles” were identified and discussed. The 6 key issues were grouped the following

- Manufacturing of vehicle and battery
- Vehicle operation
- Electricity for EVs
- End of life (EoL) of batteries
- Battery characteristics
- Data availability and quality

The details collected and discussed on these 6 key issues were

- Manufacturing of vehicle and battery
  - Air emissions of (future) battery production
  - New inventory data on battery production
  - Energy demand of battery production
  - Vehicle manufacturing
  - Impacts of mining the materials

- Vehicle operation
    - Use and document real world energy consumption and emission data for ICE, BEV and PHEV
    - Non greenhouse gases
        - Function of exhaust gas treatment
        - “non linearity”
        - Dependent on conditions
    - Influence of user
        - Driving profiles
        - Charging behaviors
        - Thermal comfort
        - Rebound effects
    - Influence of climate (cold weather can decrease battery efficiency, hot weather can cause faster battery degradation)
- Electricity for EVs
    - Reliable air emission data of electricity generation today and in future
    - Air emissions of renewable electricity generation mainly based on material used
    - Electricity generation mix and future developments
    - Influence of flexile charging (mix versus marginal)
    - Regional dynamic grid mix
    - Handling of import and export of electricity in region/country
    - Include storage for renewable electricity (esp. PV and wind)
- End of life (EoL) of batteries
    - Recycling vs. 2nd life
    - Assessing 2nd use and recycling
    - Estimation on influences of EoL for vehicles and batteries on LCA comparison
- Battery characteristics
    - Energy density of battery
    - Battery life time
- Data availability and quality
    - ICE and PHEV: NO_x, PM, C_xH_y
    - Thermal power plants: NO_x, PM, C_xH_y, SO_2; share of heat use in CHP plants
    - Pre-chain air emissions, e.g. steel, lithium, aluminum, copper
    - Indicators for data quality
    - Data availability: how to close data gaps

2.3.4 Future Developments on LCA of EVs

In the workshop, the following future developments in the LCA of EVs were identified and discussed:

- Air emissions of ICE, PHEV, power plants and refineries must be foreground data
- Are there any other relevant air emissions beside NO_x, SO_x, CO, PM?
- Find and define reasonable ranges for air emissions in LCI and LCA
- Consider regional and seasonal differences of vehicle operation and electricity
- Where is or might be a problem of air emissions with EVs? Are there possible solutions?
- Parameters to decide on electricity generation for EVs
- Criteria to decide on marginal vs. current/future electricity grid mix
- System boundaries with or without 2nd battery life as energy storage
- Consideration of building new infrastructure (macro level vs. functional unit level) (charging infrastructure)
- Criteria to include or exclude impacts from road infrastructure
- Impact assessment of GHG emissions with CO_2-eq or contribution to the future increase/decrease of global temperature
- Systematic description of results showing the shares of emissions of sectors and countries: burden shifting between countries and between sectors
- Possible rebound effects and influences on LCA results which might be reflected in the new functional unit
- Time effects in LCA: changing of electricity mix during lifetime of EV
- Develop LCA methodology to be applied for vehicle fleets and identify differences to “single vehicles”

2.4 Expert Workshop on Resources, Waste and Land Use (incl. LCA Autonomous Vehicles)

2.4.1 Introduction

In June 2019, Task 30 held an expert workshop on the effects of EVs on land use, resources and waste in Washington D.C., USA. The aim of this expert workshop was to analyse and assess environmental effects of EVs on land use, resources and waste based on LCA in a cooperation of the participating countries in the IEA. The current status and the future perspectives of LCA of EVs on these issues in comparison to conventional vehicles with an ICE were presented and discussed. The focus was on BEVs and PHEVs.

In a group of relevant stakeholders from government, industry, research and NGOs, the relevant issues of effects on land use, resources and waste were identified and discussed referring to the ongoing large-scale market introduction of EVs.

2.4.2 Results on Resources and Waste

Concerning the effects of resources and waste following topics were discussed:

a) LCA of battery production,
b) LCA of battery recycling,
c) LCA of electric motor recycling (mainly magnets) and
d) LCA of power electronics recycling.

2.4.2.1 LCA of Battery Production

The following key battery materials were updated in GREET (LCA model):

- cobalt: shares of Co coproduced with Ni/Cu; shares of sulphide/laterite; ore grade,
- nickel: shares of sulphide/laterite; ore grades; SO_x emissions control,
- lithium: shares of lithium produced form brine/minerals and
- graphite: shares of natural/synthetic graphite.

The most relevant categories on energy demand and emissions of an NMC111 LIB under baseline conditions are:

- NMC111 Cathode: Cobalt (sulfate production); Nickel (refining); other cathode steps (NMC11 precursor & powder production),
- aluminum: alumina reduction & SF_4/S_2F_6 abatement,
- battery management system (BMS): electricity source and
- cell assembly: heat and electricity source.

As an example in Figure 6 the Cradle-to-Gate environmental impacts of 1 kWh NMC111 battery are shown, where cathode, production energy and aluminum are notable contributors.

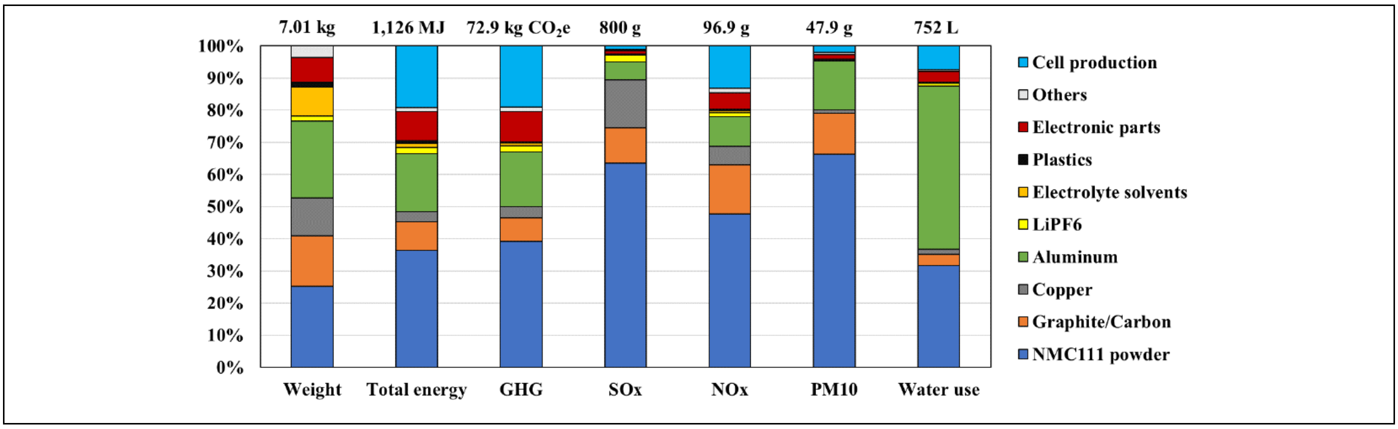

Figure 6: Cradle-to-Gate environmental impacts of 1 kWh NMC111 battery[1]

[1] L Gaines: *LCA and Direct Recycling for Lithium Ion Batteries*, Presentation at Task 30 workshop, June 2019

2.4.2.2 LCA of Battery Recycling

Actually, there are three main processes for recycling of batteries:

1. pyro process for recycling of batteries,
2. hydro process for recycling of batteries and
3. direct recycling of batteries (under development).

Based on current experiences in Germany initial conclusions on battery recycling are drawn:

- A careful dismantling offers significant environmental benefits.
- Major credits are possible from housing materials and other components (e.g. from recycling of steel, aluminum, copper, precious metals).
- Recycling of battery cells offers credits for Co, Ni, Cu; furthermore lithium recycling would be possible, but a further process development is necessary.
- Huge importance for attenuating pressure on primary demand for key materials.

2.4.2.3 LCA of Electric Motor Recycling (Magnets)

An LCA was performed within the German project “MORE – Recycling of components and strategic metals from electric motors”. The following three different processing routes were analysed with the major interest to recover neodymium (Nd) and dysprosium (Dy):

1. direct reuse (cleaning): production of 1 kg magnet via reuse,
2. remelt (closed loop magnet remelting): production of 1 kg secondary magnet (70% primary and 30% secondary materials) and
3. feedstock recycling (recovery of “rare earth” oxides from EoL-magnets): production of 1 kg “rare earth” oxide (mixed or separated).

The initial conclusions regarding LCA of electric motor recycling (magnets) are:

- Major GHG emission credits for recovery of RE oxides, also remelting with secondary share of 30% offers benefits.
- GHG emissions of recovery effort generally well outweighed by credits for Nd and Dy oxides, magnitude strongly depends on allocation method (economic or mass based).
- In addition, other categories show strong credits for recovery of RE oxides.
- Data availability for assessment of primary production of RE, especially Dy, is very limited and uncertain.

2.4.2.4 LCA of Power Electronics Recycling

An LCA was performed within the German project “ElmoRel 2020 – Electric vehicle recycling 2020 – key component power electronics”. The following three different processing routes were analysed

1. conventional car shredder (reference route),

2. dismantling & Waste of Electrical and Electronic Equipment (WEEE) recycling of power electronics and
3. dismantling & WEEE recycling of power electronics incl. chemical dissection of PCB.

The initial conclusions in relation to LCA of power electronics systems are:

- In comparison to the conventional car shredder route, extraction of power electronics unit enables high recovery rates for gold, silver and palladium; recovery rates of tin and copper can also be increased.
- LCA shows good results for both routes, with dedicated WEEE recycling providing additional benefits from some higher recovery rates and corresponding credits.
- Main benefit of dedicated WEEE recycling from a resource conservation perspective.
- The effort for the additional recovery of tantalum (Ta) from PCB seems to be too high as to be environmentally attractive.
- The WEEE recycling route is economically viable, but offers a lower profit margin than the car shredder route.

2.4.2.5 Results on Land Use, Resources and Waste

The possible relevant environmental effects and discussion points of land use are the following:

- more than half of the earth’s terrestrial land is actively being used by humans,
- resulting loss of biodiversity and soil functions expressed by ecosystem services is of scientific, political, societal and economic concern,
- many methods to address land use impacts in LCA are developed and
- mandatory requirement: globally available, country specific as well as region specific characterization factors (CF).

Land use is correlated to occupation of land and transformation of land. In relation to LCA, the inventory data are relevant for land occupation [m^2*a] and land transformation [m^2]. However, especially for mining processes these input data are often not known exactly and are therefore estimated. So far, there is no consistent comparison of possible land use effects of EVs and ICEs available, but for EVs mainly the mining activities for battery materials resources and the generation of renewable electricity might be relevant for land use, whereas for conventional ICEs the extraction of oil might be relevant for land use aspects.

Finally, the main issues of resources, waste, and land use that should be addressed in an LCA of EVs were identified in the workshop discussions. These are:

- resources:
    - minerals,
    - fossil fuels,
    - resource criticality,
    - resource depletion not as a primary environmental concern,
    - virgin,

  - recycled,
  - no consensus on impact assessment methodology in LCA,
- waste:
  - reuse,
  - recycling,
- land use:
  - land transformation [m²],
  - land occupation [m^2*a],
  - ecosystem services.

In Figure 7 a mind map on "Land Use – Resources – Waste in LCA of EVs" with further details on the key issues is shown.

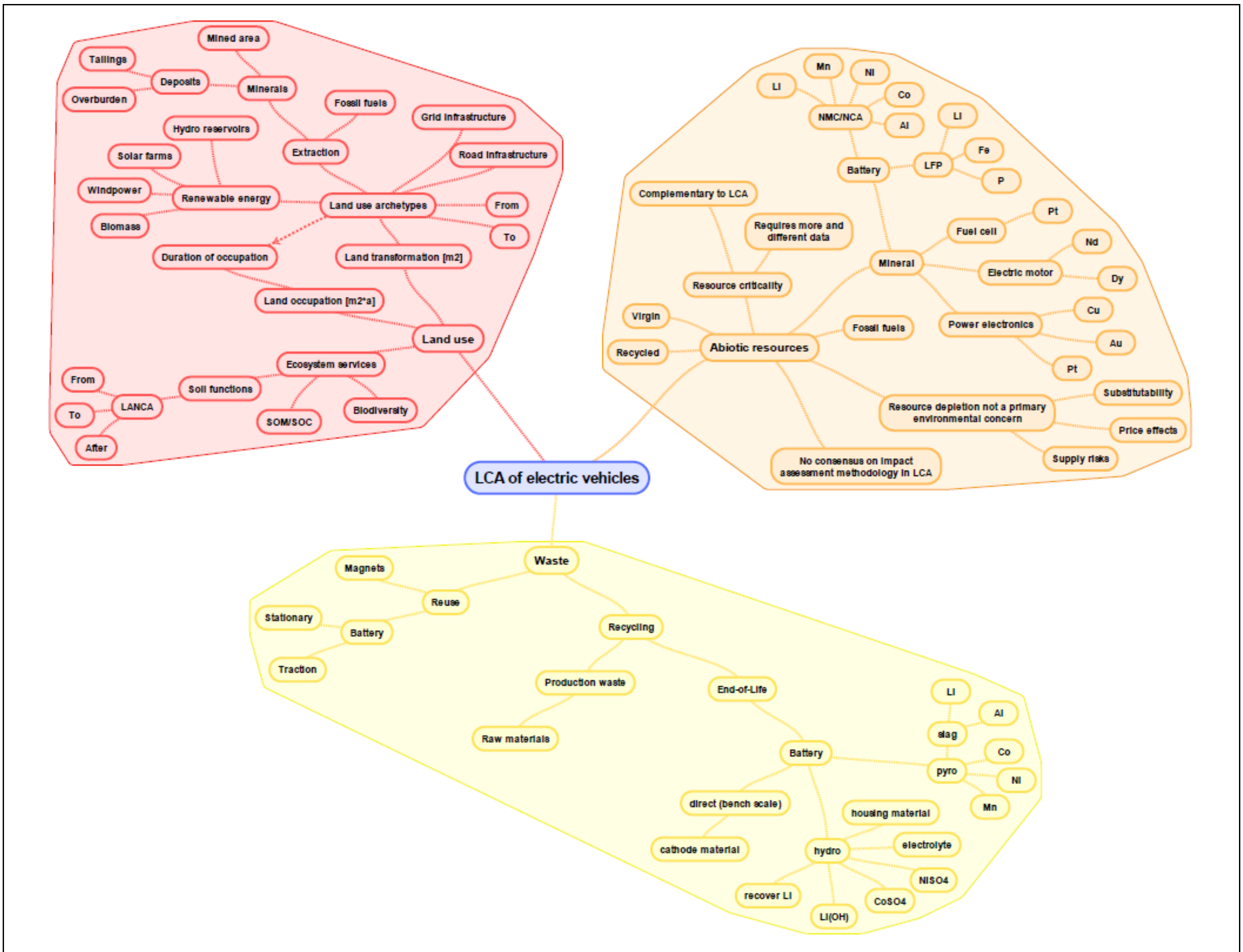

Figure 7: Mind map on "Land Use – Resources – Waste in LCA of EVs"

2.4.2.6 Results on Autonomous Vehicles

A special topic at the above mentioned workshop was on LCA of autonomous vehicles. The aim of this special topic was to present and discuss the evaluation of autonomous vehicles on LCA. Key issues on the LCA of autonomous vehicles were discussed and summarized within an interactive group work focusing on the rapid development of autonomous vehicles.

The vehicle automation is defined at multiple levels, e.g. the Society of Automotive Engineers (SAE) gives 5 levels, with level 0 for no automation:

- Level 1 – 2 require significant human interaction/monitoring of the environment all the times, and the human driver will serve as the fall back plan; this only applies to some driving modes, e.g. cruise control, lane keeping, parking.
- Level 3 – 5 have increasing degrees of "full automation" where the vehicle system is responsible for sensoring, actuation and environment monitoring,
    - Level 3: certain driving conditions automated, but driver must be able to intervene,
    - Level 4: certain driving conditions automated, no driver intervention,
    - Level 5: all conditions automated, no intervention.

The promises of vehicle automation are:

- convenience for drivers and passengers,
- reduced congestion,
- increased safety,
- increased productivity,
- faster travel,
- vehicle platooning (improved efficiency),
- lower "taxi" costs (taxi here is inclusive of mobility as service companies),
- drive smoothing (less abrupt start and stops) and
- right vehicle for the trip (mode matching).

The challenges of vehicle automation are:

- rebound effect for distance lived from work,
- increased number of trips, especially taxi trips,
- empty miles (dead-heading),
- automated hunting for parking,
- safety concerns and
- equity and less jobs.

The key parameters possibly affected by autonomous vehicles in an LCA are:

- fuel consumption affecting the operating of vehicles,
- the vehicle size and composition affecting the vehicle manufacturing and
- lifetime of the distance travelled affecting per kilometer/miles from manufacturing the vehicle.

Due to the additional necessary equipment of an autonomous vehicle, the vehicle mass and the additional load are increasing. Current estimations for the additional load are between 200 W and 2 kW. The additional mass can also be compensated by lightweight structures, for which a typical rule of thumb for light weighting is about 7% energy decrease by 10% mass reduction. The smoother driving might reduce energy consumption by up to 15%.

The five main areas of LCA of autonomous vehicles were identified as:

- vehicle level (e.g. energy consumption, vehicle mass changes, level of automation, vehicle lifetime mileage),
- operating conditions (e.g. climate, fleet composition, driving cycles),
- behavior (e.g. user acceptance, user misuse),
- infrastructure (e.g. V2I/V2V – vehicle to infrastructure/vehicle to vehicle, energy consumption, traffic lights, parking space) and
- system level (e.g. rebound effect, mode shift, ride sharing, ride smoothing).

2.5 Expert Workshop on Impact Assessment

2.5.1 Introduction

The workshop "Overall Environmental Assessment of EVs – From Inventory Analysis to Impact assessment" took place on October 13 and 14, 2021 virtually hosted and organized by IREC (Catalonia Institute for Energy Research) in Barcelona/Spain.

The aim of the expert workshop was to present, discuss and conclude on state of the art and experiences on the overall assessment of environmental effects in LCA of electric vehicles – from "Inventory Analysis to Impact Assessment of EVs".

2.5.2 Impact Assessment

The focus of the expert workshop of Task 30 was to analyse and assess different Impact Assessment methodologies of BEVs and conventional vehicles with an ICE. Based on the inventory analysis of elementary and physical flows in the LCA different impact categories beyond global warming and primary energy consumption are relevant. The way from Inventory Analysis to Impact Assessment is via mid- and end-point indicators. In the workshop the status, the future perspectives and limitations of the Impact Assessment and its impact categories relevant for LCA of vehicles were presented by LCA experts and discussed within the participants.

In Figure 8, the procedure from Inventory Analysis to the Impact Assessment in LCA is shown, where in step 1 the mid-point indicators and in step 2 the possible end-point indicators are assessed. In step 1 and 2 different impact assessment methodologies are applied.

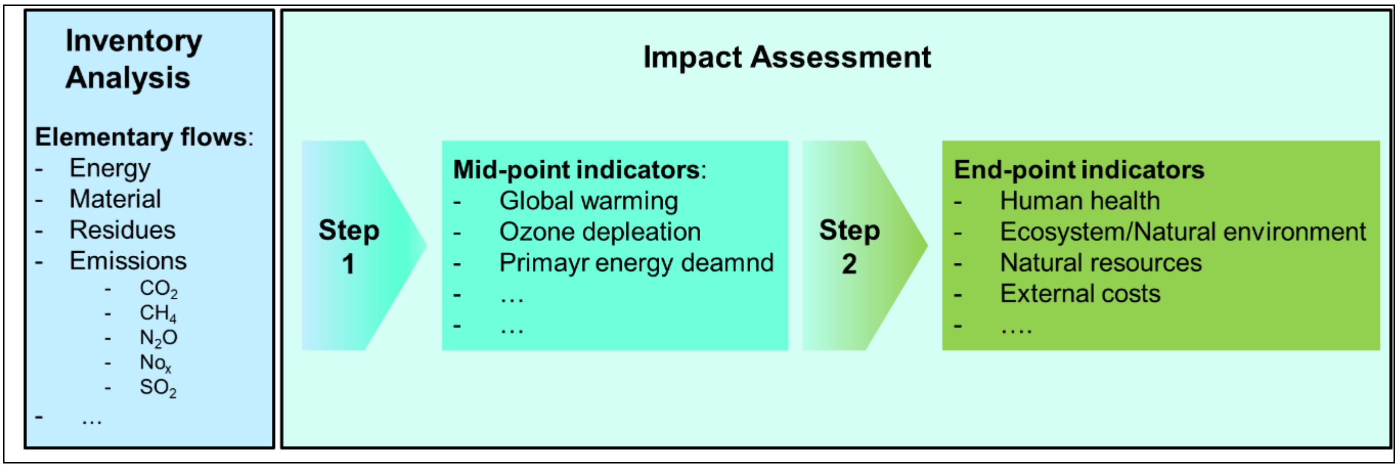

Figure 8: From Inventory Analysis to the Impact Assessment in LCA

Within the workshop, different mid- and end-point indicators with their assessment methodology were presented and discussed.

Regarding the geographical scope of the different impacts, the mid-point indicators are grouped for global, regional and local impacts. The mid-point indicators on these geographical scopes collected in the workshop were:

- global:
  - climate change,
  - ozone depletion,
  - primary energy use (consumption) (fossil and renewable),
  - resource use, minerals and metals,
  - water footprint (based on inventory level method),
  - land use (focus on inventory data),
- regional
  - acidification,
  - photochemical ozone formation,
  - smog formation,
  - eutrophication, terrestrial, freshwater and marine,
  - ionising radiation,
- local:
  - human toxicity, cancer and non-cancer,
  - particulate matter,
  - land use,
  - water scarcity,
  - biodiversity and
  - ecotoxicity, fresh water aquatic, marine aquatic and terrestrial.

Water and land use were allocated to the global and also to the local level. On global level, mainly results from inventory analysis are relevant, whereas on local level a very distinctive methodology might be applied for local impact assessment based on very localized data.

The end-point indicators, which are always assessed on global scale, collected in the workshop are:

- protection areas:
  - human health,
  - ecosystem health,
  - resource availability and
- external costs.

In the following sections, mid- and end-point indicators are described further.

2.5.3 Mid-point Indicators

The brief description of global mid-point indicators are:

- Climate change:
  - Radiative forcing as global warming potential - GWP 100 (kg CO_2-eq)
  - Increase in the average global temperature resulting from greenhouse gas emissions
- Ozone depletion:
  - Ozone depletion potential – ODP (kg CFC-11-eq)
  - Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation
- Primary energy use (consumption/demand) (fossil and renewable):
  - Use of fossil, renewable and nuclear primary energy resources (MJ)
  - Depletion/use of energy resources and deprivation for future generations
- Resource use minerals and metals:
  - Abiotic resource depletion – ADP ultimate reserves (kg Sb-eq)
  - Depletion of mineral and metal resources and deprivation for future generations
- Water footprint:
  - Amount of water consumed (m^3)
  - Amount and type of water used
- Land use:
  - Occupied land (m^2)
  - Amount and type of land occupied over a certain time.
  - Amount and type of land transformed

The brief description of regional mid-point indicators are:

- Acidification:
  - Accumulated Exceedance - AE (mol H^+ eq or kg SO_2-eq)
  - Acidification from air, water and soil emissions (primarily sulphur components) mainly due to combustion
- Photochemical ozone formation:

- Tropospheric ozone concentration increase (kg NMVOC or kg C_2H_4-eq)
- Potential of harmful tropospheric ozone formation ("summer smog") from air emissions on human health?

- Smog formation:
  - Formation of intensive air pollution with decreasing visibility deriving from combustion processes
  - Potential of smog formation ("winter smog") from air emissions
- Eutrophication, terrestrial, freshwater and marine:
  - Accumulated exceedance – AE (mol N eq)
  - Fraction of nutrients reaching freshwater/marine end compartments (kg N eq)
  - Eutrophication and potential terrestrial impact caused by nitrogen and phosphorus emissions mainly due to fertilizer, combustion, sewage systems
- Ionising radiation, human health
  - Human exposure efficiency relative to U – 235 (kBq U-235 eq)
  - Impact of exposure to ionising radiation on human health

The brief description of local mid-point indicators are:

- Human toxicity, cancer and non-cancer
  - Comparative toxic unit for humans on (non-)cancer (CTUh)
  - Potential impacts on human health via ingestion and inhalation routes. Contact and direct exposure not considered
- Particulate matter
  - Impact on human health (disease incident)
  - Impact on human health caused by particulate matter emissions and its precursors (e.g. sulphur and nitrogen oxides)
- Land use
  - Soil quality index, representing the aggregated impact of land use on: biotic production, erosion resistance, mechanical filtration, groundwater replenishment
  - Transformation and use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil filtration capacity, permeability
- Water scarcity
  - Weighted user deprivation potential
  - Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity
- Biodiversity
  - Impacts on biodiversity
  - Various methods under development that can be operable and in line with current life cycle inventory phase

Additional also ecotoxicity is a regional impact, which could be an aspect of water and land use as well as biodiversity

2.5.4 End-point Indicators

The discussed possible end-point indicators are:

- protection areas and
- external costs.

The protection areas are split in:

- human health, which is measured in DALYs - Disability-Adjusted Life Years or Disease-Adjusted Life Years caused by the various impacts,
- ecosystem health which is measured in $PDFm^2yr$ - Potentially Disappeared Fraction of species per square meter per year caused by the various impacts and
- resource availability, which is measured in MJ, covering mainly primary energy resources.

The external costs are measured in € (or $). The external costs assess the damage costs caused by the various impacts, e.g. on human health, ecosystem and infrastructure. Main damage costs caused by climate change impacts, regional air pollution and land use.

2.5.5 Assessment Methodologies for Local and Regional Impacts

The following most relevant assessment methodologies for regional and local impacts were identified.

2.5.5.1 Human Toxicity Potential

The Human Toxicity Potential (HTP) is a measure of the impacts on human health. The characterisation factors describe the fate, exposure and effects of toxic substances over an infinite time horizon.

In 2005, the UNEP-SETAC Life Cycle Initiative initiated a comprehensive comparison of the existing methods. The consensus model USEtox is now recommended as the "best" available method by UNEP-SETAC (http://usetox.org), and also recommended by EC-JRC for Product Environmental Footprints (PEF) for human toxicity potential. In USEtox, a distinction is made between "interim" and "recommended" characterisation factors (CF). This reflects the different level of reliability of the calculations. CFs for metals are classified as "interim" due to high uncertainty on fate and exposure:

- The mid-point CFs units for HTP are in "Comparative Toxic Unit for Human Health" (CTUh), which estimates the increase in morbidity in the total human population per unit mass of a chemical emitted (i.e. cases per kilogram). Separate "cancer" and "non-cancer" CTUh are provided, but both have default equal weighting, in lack of more precise insights.
- The end-point CF is "Disability-Adjusted Life Years" or "Disease-Adjusted Life Years" (DALY), taking into account the years lost to premature death and expressing the reduced quality of life due to illness in years as well, are also optionally provided. But these entail further assumptions and uncertainties, and are not ISO-compliant for all "comparative assertions intended for public disclosure" (ISO 14,044).

Another methodology developed for human health, e.g. particulate potential (HHPP) is TRACI - Tool for the Reduction and Assessment of Chemical and other environmental Impacts (https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci).

2.5.5.2 Abiotic Depletion Potential

The Abiotic Depletion Potential - Minerals & Metals (ADP_MM) concerns the extraction of scarce minerals. Values are determined for each extraction of minerals based on the remaining reserves and rate of extraction. AD methods mainly differ in terms of time horizon (e.g. focus on long-term depletion potential vs. short-term supply risk), and associated assumptions on reserve bases:

- The CML $ADP_{ultimate\ reserves}$ uses current extraction rates and assumes stock estimates = total crustal contents:
    - Total crustal content is chosen as the best available proxy for “ultimately extractable” reserve, since the latter is a moving target that depends on unknown future technological developments.
    - Mid-point CFs are expressed in terms of kg Antimony equivalent (kg Sb-equivalent).
    - Method was originally developed in 1995, then CFs updated in 2002 and 2019.
    - This method is “recommended” by UNEP/SETAC Life Cycle Initiative, and by EC-JRC.
- $ADP_{economic\ reserves}$ alternatively assumes stock estimates, those that are economically extractable at present:
    - Mid-point CFs are still expressed in terms of kg Sb-equivalent.
    - This method better highlights the more imminent pressure on resource availability.
    - But, it suffers from two main weaknesses:
        - anthropogenic stocks (e.g., secondary sources) are excluded and
        - economic reserve estimates tend to increase over time, leading to potential underestimation of depletion threat.
    - This method is only “suggested” but not officially “recommended” (a much weaker endorsement).

2.5.5.3 Water

To assess water related impacts two main methodologies are relevant:

- Water Footprint and
- Water Scarcity.

The Water Footprint Standard is an inventory-level method (https://waterfootprint.org/en/resources/publications/water-footprint-assessment-manual-global-standard/).

In the Water Footprint, the water withdrawal is analysed and classified in:

- off stream water use:
    - consumptive use of:

        - green water: evaporative from crops/forestry,
        - blue water: non-evaporative run-off,
        - grey water: additional water required to dilute pollutants to water quality standards,
    - degradative use, released as polluted water and
- in stream water use, released as unpolluted water.

For Water Scarcity, there are two impact assessment methodologies

- Water Stress Index (WSI) and
- Available Water Remaining (AWaRe).

The main aspects of these two impact assessment methodologies are:

- Water Stress Index (WSI):
    - Water stress index is typically defined as the relationship between total water use and water availability. The closer water use is to water supply, the more likely stress will occur in natural and human systems.
    - Regionalised mid-point characterization model is based on withdrawal-to-availability ratio.
    - WSI indicates the portion of $WU_{consumptive}$ that deprives other users of freshwater.
    - Further converted to end-point indicators for Ecosystem Quality (EQ) and Human Health (HH), the latter based on competition with irrigation.
    - This indicator has been used by the United Nations and others.
- Available Water Remaining (AWaRe):
    - Regionalised mid-point characterization model is based on withdrawal-to-availability ratio.
    - New consensus method of UNEP/SETAC working group on water use in LCA (WULCA).
    - Suggested by EC-JRC as new standard impact assessment method for water use in PEF.
    - WaterS is an indicator from the AWaRe characterisation model that provides an assessment for water consumption. Units for scarcity-adjusted water use are in m^3 world eq.

2.5.5.4 Biodiversity

Biodiversity is also much related to land use aspects. The impact assessment methodologies are therefore very complex and still under development e.g.:

- Ongoing efforts of the JRC within dedicated working groups.
- JRC is exploring LCIA methods and approaches addressing impact on biodiversity to be potentially integrated in the environmental footprint method in the future.
- Currently, operational and novel methods addressing impact on biodiversity at the midpoint and endpoint (that take into account different midpoint impacts such as climate change, land use, etc.) are under test by the JRC.
- Key aspect is to judge how these methods can be operable and in line with current inventory phase.

2.5.6 Selection of Indicators in LCA for EVs and ICEs

LCA as a system assessment method addresses environmental impacts best on global scale like global warming or resource use. The assessment of regional and local environmental impacts like acidification, human toxicity and biodiversity are depending very much on site-specific local conditions. An inclusion of regional and local impact categories needs a very site-specific inventory in LCA, e.g. in combination with GIS (Geographical information System).

Due to the high need of site-specific data and/or lacking of these data, the regional and local impacts are very difficult to be addressed in practice by LCA or EVs and conventional ICEs today. So further essential developments are needed to cover these impacts in future.

Otherwise, it is also argued that other methodologies than LCA can address these regional and local environmental impacts better; e.g. biodiversity is mainly relevant in agricultural and forestry systems, human toxicity is relevant for quality of life and living conditions.

Due to the methodological complexity and uncertainty, the practical addressing and calculation of end-point indicators are not recommended within experts participating in the workshop for LCA of electric vehicles and conventional vehicles.

The main relevant impacts with current state of impact assessment methodologies using available and robust inventory data in LCA are mainly for global impact categories.

These main global impact categories for transportation systems as discussed in the workshop? are:

- climate change,
- primary energy use (consumption) (fossil and renewable),
- resource use minerals and metals,
- water footprint (inventory level),
- oOzone depletion and
- land use (inventory level).

2.5.7 Framework

Taking these six identified global impacts for EVs into account, there are some recommendations concluded for current and future LCA practical application.

The recommendations are split into:

- current minimum requirements and
- future advanced requirements

for global impact assessment of EVs in comparison to other vehicles.

For all considered impacts of course the goal and scope of the LCA is essential.

The results on the considered global impact categories should be documented and communicated not only for the total value but also for the three main phases in the life cycle of a transportation system:

- production:
  - vehicle,
  - energy/battery storage,
- operation:
  - fuel/energy supply,
  - fuel use,
  - maintenance,
- end of life:
  - recycling and/or reuse and
  - substitution of secondary material.

The main influencing parameters on the global impacts should be identified and described.

2.5.8 Current Minimum Requirements

The current minimum requirements on LCA for EVs and ICEs should cover global warming and primary energy demand as major relevant global impact categories addressing the key issues of GHG emissions and energy efficiency.

The following should be considered on these two global impact categories:

- Global warming:
  - The Global Warming Potential (GWP) is given in kg CO_2-eq_{100}.
  - The individual greenhouse gases and their CO_2-equivalent factor should be described, e.g. according to IPCC AR; now also biogenic based CH_4-emissions have a different equivalent factor than fossil based CH_4 (e.g. form coal mining).
  - The contributions (%) of the most relevant individual greenhouse gases should be documented.
- Primary energy demand:
  - The Primary Energy Demand (PED) is also called Cumulative Energy Demand (CED) or Total Primary Energy (TPE) with analogue meaning.
  - The primary energy demand is given in MJ.
  - It must be specified if the methodology for the PED is based on the lower (LHV) or higher heating value (HHV). The difference might be up to 5%, but there is no general agreement on the type of heating value.
  - Beside the total PED also the share (%) of renewable and fossil and nuclear energy should be described.
  - Optionally, it is also useful especially for EVs to identify the major primary energy carriers used, e.g. coal, natural gas, wind, hydro, solar, nuclear.

2.5.9 Future Advanced Requirements

The future advance requirements for impact assessment address:

- resource use, minerals and metals,
- water footprint (inventory level),
- land use and
- ozone depletion.

For EVs (incl. batteries) and renewable electricity generation the type and amount of material used in the construction phase becomes more relevant than for conventional vehicles using raw oil. Therefore, the impact category of “resource use, mineral and metals” also becomes a more relevant global impact category. Concluding, an advanced requirement for LCA should be to calculate the amount of material in the inventory analysis especially for the most relevant materials like Cu, Li, Co, Ni, Mn and others. Based on the inventory the resource use should be assessed on the basis of kg Sb-eq and giving the main contributions from single minerals or metals.

Water issues are also relevant, especially for mining activities, lithium extraction and hydro power. So on global scale the Water Footprint using the inventory based methodology should be assessed in future LCA of EVs and ICEs.

In addition, land use aspects are relevant for mining of raw materials as well as for renewable electricity production. As a next step in LCA of EVs the amount of land or land occupation over time should be analysed in the inventory phase by at least differentiation on the type of land: agriculture, forestry, infrastructure, industrial area or any other type of land.

The impact category “Ozone Depletion” can easily be addressed in LCA of EVs and ICEs, but seems currently of lower relevance for transportation systems, except from losses of fluids from cooling systems or their end of life treatment.

2.5.10 Conclusion and Outlook

The global indicators also cover and address aspects of the two most relevant environmental aspects currently under public and political agenda e.g. within the GreenDeal:

- “Climate neutrality” and
- “Circularity”.

However, as these aspects are relevant in a dynamic system perspective, e.g. recycling to secondary material, further methodological developments are necessary to integrate them in LCA.

Considering current international LCAs on EVs in comparison to ICE, it becomes obvious that global warming and primary energy demand are a minimum requirement and state of the art in impact assessment. LCAs disregarding one of these two impacts are too limited or misleading in their conclusions and interpretations.

It is expected that the other global impacts - Resource Use, Water Footprint and Land Use – will be analysed and assessed in LCA of EVs in future more often, using the rapid international progress made for inventory data.

Considering the local and regional impact categories in LCA, further methodological developments, better inventory data and general acceptance are necessary. Alternatively, these environmental impacts (e.g. biodiversity) will be addressed with other methodologies than LCA more adequate in future.

The new IEA HEV TCP Task 46 (2022 – 2024) “LCA of electric Trucks, Buses, 2-Wheelers and other Vehicles” will address these global impact categories further and intends to develop and discuss new approaches to address “Climate Neutrality” and “Circularity” of transportation systems in (dynamic) LCA.

2.6 Rebound Effects of EVs and Possible Implication on LCA

2.6.1 Introduction

The introduction of electric vehicles globally is ongoing very fast. Currently, there are about 7.2 Mio. electric passenger vehicles (EV) in about 100 countries on the road (IEA 2020). The main share of this EV-fleet, which includes about 65% BEVs and 35% PHEVs, is in China, USA and Norway. The key drivers for the introduction of EVs are improvement of air quality in cities and reduction of GHG emission to reach the Paris Climate agreement. The overall improvements are determined by the environmental effects of EVs in the overall lifecycle including production, operation and end of life, which is done with the methodology of LCA. The main environmental issues in the lifecycle of an EV are the production of battery and the source of the electricity needed for driving.

Additionally, the overall environmental benefits depend on the number and type of substituted conventional vehicles with an ICE using diesel or gasoline.

As the global stock of passenger vehicles is still growing and the annual driving distance of each vehicle is still increasing, it becomes evident that not each EV is substituting an ICE vehicle in reality. Also the different daily use of an EV might be different compared to an ICE vehicle, the topic addressed in this document is, to estimate how many electric driven kilometres of an EV are substituting fossil driven kilometres by an ICE vehicle to reduce the annual and lifetime environmental impacts.

These possible substitution effects are called “rebound effects” which are described and analysed in this document and then the possible influence or integration of the rebound effects in LCA (Life Cycle Assessment) of EVs are analysed and discussed.

2.6.2 Types and Dynamics of Rebound

Many countries are relying on innovative, energy-efficient technologies to achieve climate targets (OECD 2010). Lowering energy use per unit output is an attractive option to reduce energy demand and to combat carbon emissions (IEA 2014). The strategy of advancing energy-efficient technologies is successful, if the gain in technical efficiency is not (over-)compensated by a gradual change in use, the so called rebound effect (or: takeback effect; Sorrell 2007). Thus, rebound is highly relevant for funding programs, policy strategies and innovation initiatives, which aim to account for the far-reaching transformative impacts of mobility innovations (Font Vivanco et al. 2016). If expected savings are obtained only partially due to rebound, the achievement of energy and climate targets is compromised. However, rebound may also be desirable, if the efficiency gain leads to cheaper resource use and consequently increases in economic growth and welfare (IEA 2014).

Commonly, three types of rebound effects are differentiated (Sorrell 2007, Santarius 2014, Gillingham et al. 2016). However, system boundaries between the three types overlap to a certain degree (Figure 9):

- *Direct rebound:* Consumer demand increases when improving efficiency makes the provision of a product or service cheaper. Direct rebound happens within the same consumption domain, e.g. former cycling trips are shifted to the electric car, or the overall number and length of trips increases.
- *Indirect rebound:* Income freed up by efficiency gains is spent for other energy-consuming products and services, or consumption in other domains is shifted to the now cheaper service. Indirect rebound involves redistribution between different consumption domains.
- *Economy-wide rebound:* Feedback effects from supply and demand adjustment processes accumulate across all economic sectors. Economy-wide rebound leads to an overall increase in energy use within an economy.

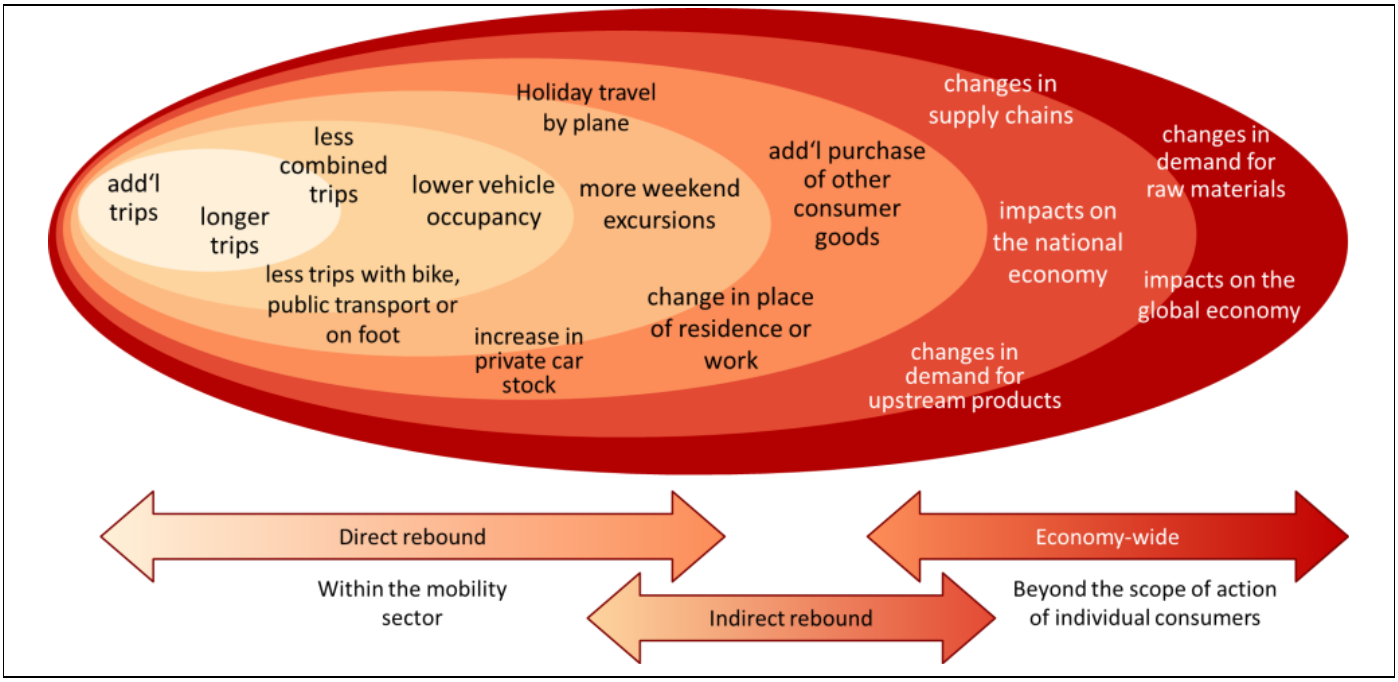

Figure 9: System boundaries between direct, indirect, and economy-wide rebound. (Source?)

Rebound emerges from consumers balancing their actions within and between consumption domains (Santarius & Soland 2018). In the prevailing economic view, households reallocate their available income according to price changes; this logic is not restricted to monetary savings, but applies similarly to savings in time and comfort (Boulanger et al. 2013). Consumers may also engage in mental accounting (or: moral licensing), distributing a personal allowance of moral credits and debits (Miller & Effron 2010). After purchasing an electric car, one has the feeling of having already made an ecological contribution. Now one can indulge oneself in other consumption domains without a guilty conscience (Friedrichsmeier & Matthies 2015).

2.6.3 Magnitude of Rebound Effects

Rebound is calculated as the discrepancy between expected and realised efficiency gains. A rebound of 0% means that expected savings are fully achieved in practice. A rebound of 100% means that the entire efficiency gain is compensated by increased use. To avoid conceptual ambiguity, rebound calculations should refer to changes in consumption patterns, and should control for overly optimistic savings expectations (Sunikka-Blank & Galvin 2012), for technical faults and difficulties in the field (Friedrichsmeier & Matthies 2015), and for parallel processes such as fuel costs, changes in household structure, or changes in workplaces (Galvin 2014). There is wide variability in the exact rebound definitions and the methods applied, which leads to high uncertainties (van den Bergh 2011, Turner 2013). Most rebound estimates in passenger transport refer to changes in vehicle mileage per litres fuel as an indicator of the demand for the energy service of undertaking everyday mobility (Sorrell et al. 2009). Stapleton et al. (2016) find only marginal differences when basing the rebound estimate on passenger kilometres instead of vehicle kilometres (to control for vehicle occupancy/load).

Most review studies agree on a direct rebound estimate of 10-30% in fossil-fuel powered propulsion technologies for personal automotive transport. In other words, up to 30% of expected direct savings are not achieved in practice. Differences between countries may be traced back to differences in alternative transport options and fuel prices (Gillingham et al. 2016). Rebound is typically higher in developing than in developed countries (van den Bergh 2011, Jenkins et al. 2011). There are no dedicated electric car rebound studies available. Most rebound studies address fuel-efficient conventional cars, because data on vehicle travel and fuel consumption are routinely collected by governmental authorities (Stapleton et al. 2016).

Table 1: Direct rebound in personal automotive transport.

Study	Country	Direct rebound
Sorrell (2007), Sorrell et al. (2009), Jenkins et al. (2011), Madlener & Alcott (2011), Maxwell et al. (2011), IEA (2014)	OECD countries (review)	10-30% range 5-87%
Greening et al. (2000)	USA (review)	10-30%
Thomas & Azevedo (2013)	USA (review)	3-22%
Gillingham et al. (2016)	USA (review)	5-25% range 4-34%
Gillingham et al. (2016)	Developing countries (review)	10-40% range 9-62%
Greene et al. (1999)	USA	23%
Small & van Dender (2007)	USA	2-11%
Su (2012)	USA	11-19%
Linn (2013)	USA	20-40%
Chitnis et al. (2014)	United Kingdom	25-65%
Stapleton et al. (2016)	United Kingdom	19% range 9-36%
Frondel et al. (2012)	Germany	57-62%
Odeck & Kjell (2016)	Norway	11-23%
Wang et al. (2012)	Urban China	96% range 2-246%

Direct rebound stems from how adopters of electric cars adjust their private vehicle stock (e.g. whether the e-car substitutes an existing car or is purchased as a second/third car), as well as how much and how often they use their e-car (mileage and modal share). Results on adjustments of the private vehicle stock are inconclusive and vary between countries: In Germany, 59% of the buyers of electric cars and 41% of the buyers of hybrid cars purchased the vehicle in addition to their existing car fleet (Frenzel et al. 2015). In a similar vein, in Norway, 91% of electric car buyers own two or more cars, whereas only 51% of normal car buyers do so (Klöckner et al. 2013). In contrast, 86% of Swiss hybrid car buyers replaced an old car (de Haan et al. 2006), and only 12 - 23% of Austrian electric car buyers acquired the electric vehicle in addition to their existing conventional cars (VCÖ 2018).

Evidence regarding everyday use is mixed as well: The mileage of German hybrid cars is smaller than of conventional cars (de Haan 2009). Californian hybrid car drivers increased their mileage by just 0.5%

(Afsah & Salcito 2012). Contrastingly, Japanese hybrid car drivers drove 1.6 times farther per year than with their previous vehicle (Ohta & Fujii 2011). Regarding modal share, Norwegian electric car users broadly substitute other transport modes such as public transport with the electric car (Klöckner et al. 2013, Holtsmark & Skonhoft 2014).

Besides direct rebound, indirect and economy-wide rebound also merit consideration. Indirect rebound in passenger transport amounts to 5-50% (Jenkins et al. 2011, Madlener & Alcott 2011, IRGC 2013, Thomas & Azevedo 2013). Estimates of economy-wide rebound originating from the transport sector span an even wider range from 20% to 300% (Allan et al. 2007, Turner 2009, Guerra & Sancho 2010), with most estimates around 20-60% (Jenkins et al. 2011, Gillingham et al. 2013). Santarius (2012) suggests as 'fifty-fifty' rule of thumb that at least half of expected efficiency gains are compensated in the long run.

2.6.4 LCA of EVs and Rebound Effects

In LCA of EVs and conventional ICE vehicles the environmental effects are given for the functional unit of 1 driven kilometre, in comparison to other transportation modes like buses, trains and trams the functional unit is often per passenger kilometre. Depending on the goal and scope of the LCA, also the annual environmental effects or the cumulated effects over the lifetime are relevant.

LCA methodology according to ISO 14,040 defines the functional unit as the basis for comparison of environmental effects of different systems, which provides the same service or function. Therefore, in the comparison based LCA it is assumed that the functional unit or service of a system can be provided and substituted by another system. However, due to the rebound effects described above it is possible that a system A cannot substitute for a system B for 100%. That is why in LCA of EVs especially for EV fleets it must be proven that no rebound effects are possible, or rebound effects have to be considered.

The possible rebound effect can be considered in LCA by the definition of the functional unit and the substitution rate. In reflecting possible rebound effects in comparing the environmental effects of EVs with conventional ICE vehicles the following issues are relevant and have to be analysed and described referring to possible different uses of the vehicles:

- number of substituted ICE vehicles,
- wubstituted other transportation modes e.g. public transport, walking,
- different annual mileage,
- vehicle lifetime and
- driving distance with one charging or refill.

These aspects must be considered carefully by defining the functional unit. The possible conclusion might be that the substitution rate is not 100%; it could be in most cases less than 100% but in specific cases also more than 100%, saying that 1 electric driven kilometre substitutes more than 1 fossil ICE driven kilometre.

The consideration of possible rebound effects in LCA of EVs to substitute for ICE vehicles should cover the following practical observed issues:

- energy costs for electricity compared to fossil fuels are lower because of taxation:
    - direct rebound effect: drive more because of lower energy cost,
    - indirect rebound effect: consume more because money is saved,
- higher investment costs of EV might lead to more driving to be more economic,
- EVs are seen to be „ green“:
    - Germany: EVs drive 2 – 3 times more than average ICE,
    - Austria: EVs drive 30% more than average ICEs,
    - use EV instead of walking, biking and public transport and
- EVs become 2nd or 3rd car in households.

The analysis of these issues should be documented in LCA to argument for the chosen substitution rate.

Current experiences in considering rebound effects in LCA show that these are most relevant by considering environmental effects of whole vehicle fleets over time and future scenarios for the development of environmental benefits of EVs in scenarios for transportation services and or mobility systems. In these cases, the influence of possible rebound effects have to be reflected in LCA. A recommendation for practical application is to make sensitivity analyses on various substitution rate to identify the order of magnitude on the final results.

2.6.5 Recommendations

Given the observed level of rebound effects, there is an urgent need to include rebound dynamics in energy scenarios and in projections of policy impacts. It seems overly optimistic to assume that efficiency gains will be fully realised in practice. More realistic calculations should instead include a rebound buffer in the expected savings. A rebound buffer of 15% is already implemented in the US Corporate Average Fuel Economy Standards (NHTSA 2009) and the British CERT programme for building retrofitting (Maxwell et al. 2011). However, 15% is most likely the lower bound of rebound effects, which might appear from market and consumption adjustments in the long run.

Ongoing policy initiatives should be screened and subsequently re-designed in regards to their rebound risk. For instance, subsidies for fuel-efficient cars increased new car sales in the Netherlands and in France by 4-8% (EEA 2018). European regulation on carbon emissions from light duty vehicles is associated with rebound effects of up to 60% (Gibson et al. 2015).

More comprehensive instruments for combating rebound are ecological taxes, low carbon product standards or emission caps spanning all consumption domains (Font Vivanco et al. 2016). Taxes take away the additional purchasing power gained from increased efficiency and therefore restrict an increase in material and CO_2-intensive consumption. If product standards apply to many areas of consumption, the proportion of fossil fuels used in the production of products and services decreases; as a result, indirect rebound from shifting to other consumption domains would be less carbon intensive. Individual emission caps, such as an annual personal carbon budget, would steer consumers towards low-carbon products and services. For counteracting rebound in the long run, the current material growth paradigm needs to be reconceptualised towards decarbonisation of the economy and the society.

Still, despite of rebound risk, energy efficiency remains a critical pillar for achieving energy and climate targets. It would be short-sighted to forgo efficiency measures just because they might be partially undercut by rebound. Instead, policymakers, businesses and consumers should jointly strive to reduce rebound so to leverage the full potential of energy efficiency improvements.

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2.7 Evaluation of the Environmental Benefits of the Global EV-Fleet in 38 Countries

2.7.1 Goal and Scope

Conventional vehicles with an ICE contribute significantly to global and local environmental effects. The development of a more sustainable mobility worldwide is a key challenge for society, industry and policy. EVs might substantially contribute to a sustainable development in the transport sector, e.g. reduction of GHG and particulate matter (PM) emissions, if adequate framework conditions to maximize the environmental benefits are considered.

The method of LCA – analyzing and assessing environmental effects from manufacturing, operation and end of life management in the whole life cycle of a transportation system – has been developed and used since more than 25 years. Today, it is state of the art that the environmental effects can only be estimated based on the LCA methodology, which is recognized by industry, government and relevant stakeholder groups, e.g. NGOs.

The IEA has a TCP on HEVs, in which currently 18 countries cooperate. In this TCP, a collaboration of international experts on the LCA of Electric Vehicles developed a methodology and a database to estimate the environmental effects of the growing worldwide electric vehicle fleet of about 5 million BEVs and PHEVs in 38 countries.

An LCA is made by analyzing and assessing the country specific framework conditions with a special focus on national electricity production for the electric vehicles. Based on the LCA the following environmental effects of the vehicle fleets are estimated in reasonable ranges:

- greenhouse gas emissions (CO_2, CH_4, N_2O) in CO_2-eq,
- acidification (NO_x, SO_2) in SO_2-eq, divided in local emissions from vehicle operation and global emissions,
- ozone formation (NO_x, CO, NMVOC, CH_4) in C_2H_4-eq,
- particulate matter emissions in PM, divided in local emissions from vehicle operation and global emissions and
- primary energy consumption (total, fossil, nuclear, renewable).

A comparison of these environmental effects to those of conventional ICE vehicles is done. The system boundary chosen for the LCA is shown in Figure 10 and covers the following main stages in the life cycle starting in nature with the extraction of necessary raw materials and primary energy carriers to the supply of a transportation service in the three phases (manufacturing, operation and end of life management of the vehicle):

- production of the vehicle and the battery,
- electricity production in different power plants,
- transmission of the electricity by the electricity grid,
- charging infrastructure,
- use of electric vehicle and

- end of life management via material recovery and/or energy generation.

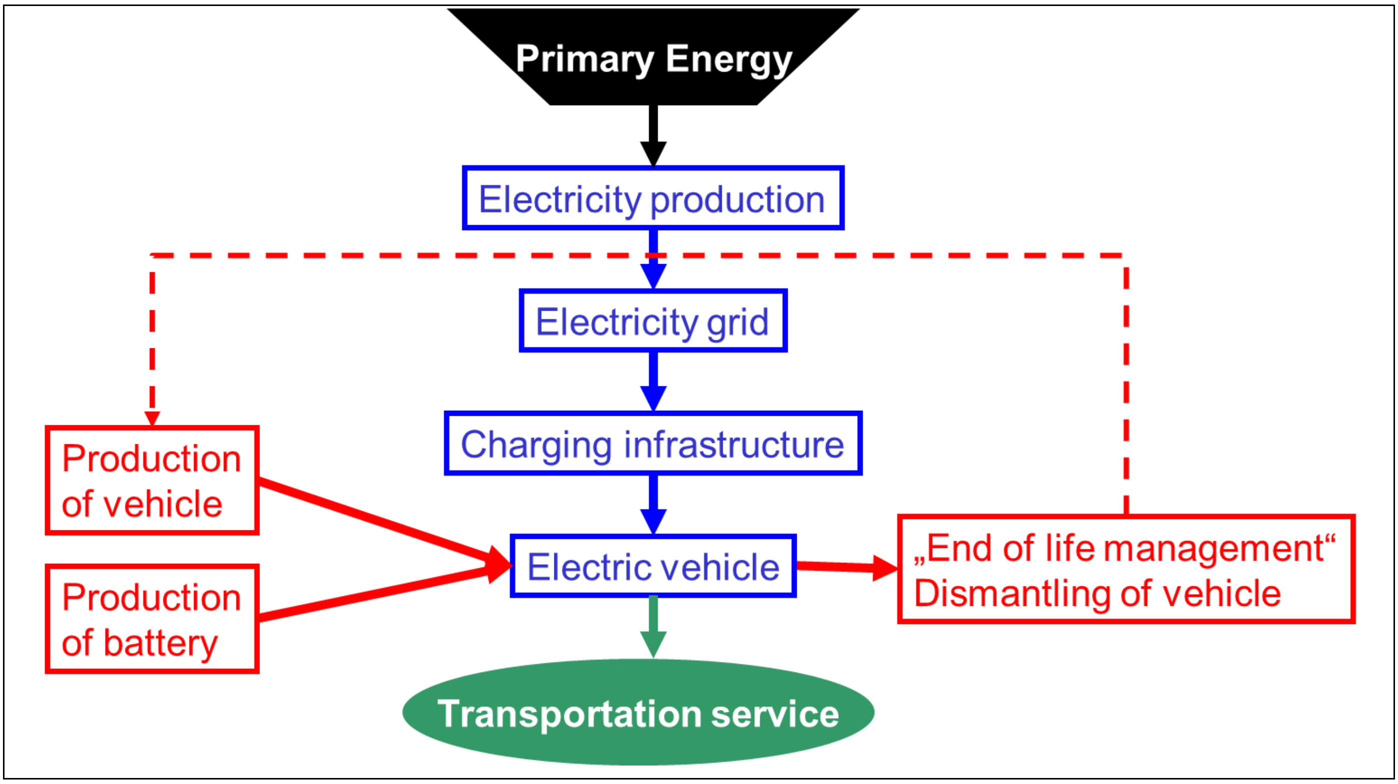


Figure 10: LCA system boundary

The analysis is done for each of the 38 countries separately from 2014 to 2018. The 38 countries are Austria, Australia, Belgium, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, India, Ireland, Italy, Japan, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Republic of Korea, Romania, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, and United States. Then the country specific results are added up to the global fleet of EVs, where two subgroups of countries are distinguished: the 18 "IEA HEV countries" (AT, BE; CA, CH, DE, DK, ES, FI, FR, IR, IT, KR, NL, NO, SE, TU, UK, US) and the 20 "Non IEA HEV countries".

In a so called "Country Factsheet on Estimated Environmental Impacts of Current EV-Fleet" the main data and results are summarized for each country:

- "Basic data" on electricity generation and size of electric vehicle fleet,
    - share of generation technologies supplying the national electricity grid,
    - estimated environmental effects of electricity at charging point,
    - current situation and future development of national electricity market (incl. import & export),
    - size of electric vehicle fleet: number of BEV and PHEV,
- "Estimation of LCA based environmental effects" by substituting conventional ICE,

- absolute annual change,
- relative annual change (referring to substituted ICE vehicles).

The international group of experts developed the methodology for the LCA of EV fleets in IEA HEV Task 30 "Environmental Effects of EVs" (since 2011). The LCA methodology is documented and published in [1-4]. An analysis of the possible future environmental effects of a growing fleet of EV, based on scenario analysis, is not considered in this work, as only the development and the existing EV fleet is considered.

2.7.2 Basic Data and Assumptions

There are approximately 5 million electric vehicles in 38 countries worldwide in 2018 [7, 8], of which

- 3.2 million are BEVs and 1.8 million are PHEVs
- 45% are located in China, 22% in the USA, 5% in Japan and 5% in Norway in 2018 (Figure 11).

It is expected that the EV fleet will grow further, but a scenario development of the global EV fleet under different conditions is not part of this activities in the IEA HEV Task 30.

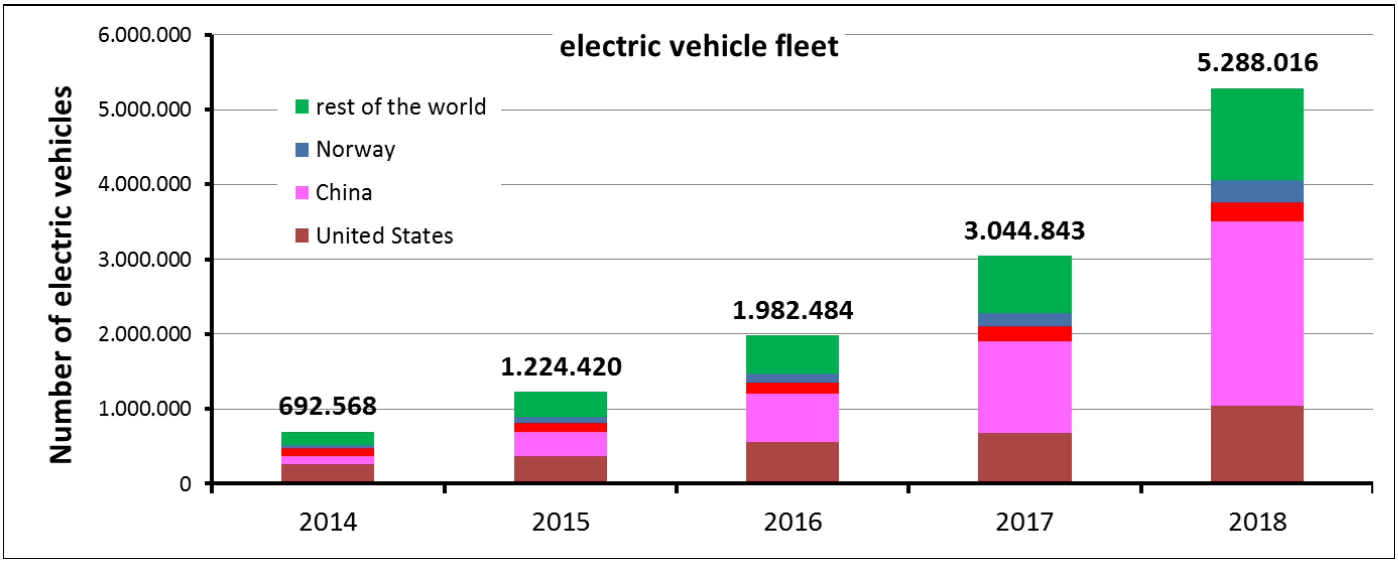


Figure 11: Vehicle fleet worldwide 2014 – 2018 [7, 8]

In Table 2 the main vehicle data used in the analysis are shown, where the energy consumption of the vehicle is given in a reasonable range, which is used in the calculation. In Table 3 the environmental data of the vehicles and in Table 4 the equivalent factors of environmental impacts are given.

Table 2: Main vehicle data

		BEV	PHEV	ICE	remark
consumption					
electricity	[kWh/km]	0.21 - 0.23	0.21 - 0.23	-	*1)*
fuel	[kWh/km]	-	0.44 - 0.49	0.49 - 0.54	*2), 3)*
annual kilometres					
electricity	[km/a]	14.000	9.100	-	*4), 5)*
fuel	[km/a]	-	4.900	14.000	

1) incl. 15% charging losses and aux. energy for heating/cooling
2) PHEV: in ICE-HEV mode 10% more efficient than ICE, in US and CA: 40%
3) ICE in USA and CA: 0.78 kWh/km (average)
4) annual kilometres USA and CA: 19,200 km/a
5) electric driven km of PHEV in USA&CA: 15,350 km/a; NL: 4,200 km/a

Table 3: Environmental data of vehicles

	emissions				primary energy				
	CO_2-eq.	SO_2-eq.	C_2H_4-eq	PM	fossil	renewable	nuclear	total	remark
	[g/km]	[g/km]	[g/km]	[g/km]	[kWh/km]	[kWh/km]	[kWh/km]	[kWh/km]	
EV (production&dismantling)	55 - 61	0.07 - 0.08	0.04 - 0.04	0.004 - 0.004	0.15 - 0.16	0.03 - 0.03	0.03 - 0.03	0.18 - 0.2	
ICE vehicle (production, operation&dismantling)	220 - 243	0.1 - 0.1	0.4 - 0.4	0 - 0	0.62 - 0.68	0.06 - 0.07	0.06 - 0.07	0.68 - 0.75	*1)*

1) ICE in USA and CA different, e.g. 290 g CO_2-eq/km

Table 4: Equivalent factors of environmental impacts

GWP	CO_2-eq	**Acidification**	SO_2-eq	**Ozon formation**	C_2H_4-eq
CO_2	1	SO_2	1	NMVOC	1
CH_4	34	NO_x	0.7	CH_4	0.014
N_2O	298			NO_x	1.22
				CO	0.11

The application of LCA to whole EV fleets must consider possible rebound effects to avoid an overestimation of the environmental benefits. Research on possible rebound effects of the broad introduction of EVs show that not each driven kilometre by an EV substitutes an ICE driven kilometre. The most relevant rebound effects identified are that EVs increase the global car fleet as EV become 2nd or 3rd vehicle in households and EVs substitute public transport, walking and cycling. The IEA task 30 analysed these possible rebound effects and estimated that, on average, an EV substitutes about 85% of ICE driven kilometres [6].

The main assumptions, derived from expert consultation and workshop discussions in the IEA HEV Task, in the LCA of EVs and ICE vehicles are:

- Grid losses: 5% - 7% from power plants to charging point.
- The average European electricity mix with 7% grid distribution losses is assumed for imported electricity in European countries.
- The charging energy losses are assumed to be 15%.
- Substitution rate: 85% of the ICE vehicle driven kilometres is substituted by electric driven kilometres (BEV and PHEV).
- The vehicles (ICE, BEV, and PHEV) are assumed to be generic middle-sized class vehicles (e.g. “VW Golf class”) for all considered countries (except USA and CA).
- The environmental effects of vehicle production and dismantling are generic for all countries; a differentiation based on the region where they are produced cannot be made.
- Lifetime for all vehicles (and battery for EVs) is 10 years.
- The GHG emissions of the battery production (incl. recycling of materials) are estimated between 35 – 50 g CO_2-eq/km-. However, further reductions are expected in future due to the increase of the global production volumes of automotive batteries realising economy of scale effects on energy efficiency and a higher share of renewable electricity use in the battery production in Europe and the USA.
- The electricity used for EV is based on the country’s specific annual average grid electricity generation mix, including imports and exports.
- The electricity generation mix for each country reflects generation in 2014 to 2018.
- The particulate emissions (< 10 µm) are only given in their total mass and not differentiated according to their size/toxicity.

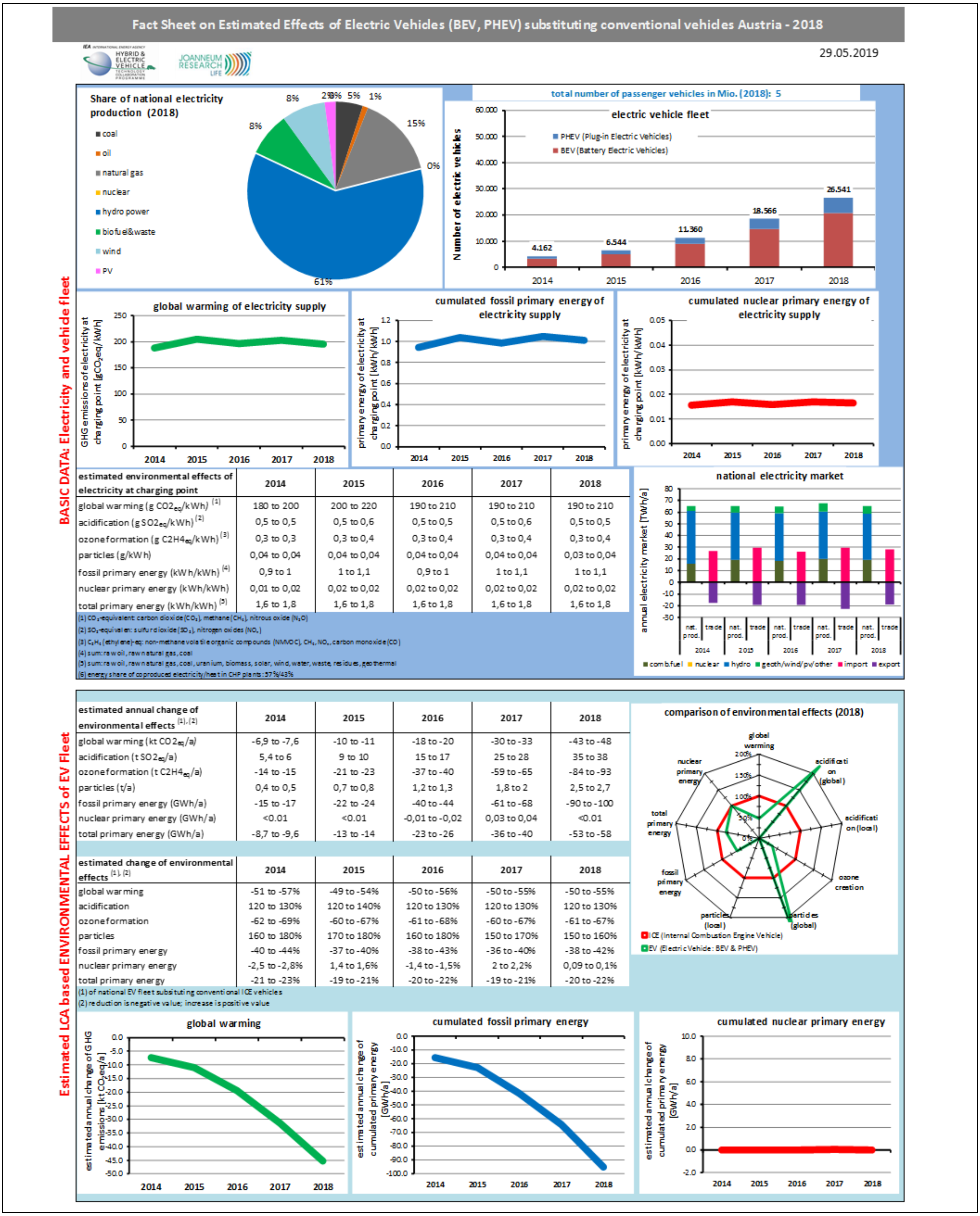
Due to these assumptions, the variation in the estimated impacts of electric vehicles between countries is due to variation in:

- emissions from national electricity production,
- average electricity consumption (kWh/km) by EV fleet in real world driving cycles,
- average fuel consumption of substituted conventional ICEs,
- emissions standards for vehicles and stationary power generation and
- travel behaviour (annual distance travelled by each vehicle technology).

2.7.3 Results

In Figure 12, an example (Austria) of the “Country Factsheets on Estimated Environmental Impacts of Current EV-Fleet” is shown, which contains all relevant data and results for the LCA for one country. It shows the development of the EV fleet, the electricity generation and the environmental effects of the electricity generation and of the EV fleet.

The range of environmental effects of the current national electricity supply (at the charging point) is shown for the IEA HEV countries in Figure 13 and Non IEA HEV countries in Figure 14 (example GHG emissions in g CO_2-eq per kWh at the charging point). The GHG emissions are close to 1,000 g CO_2-eq/kWh in countries with a high share of power plants using fossil fuels (e.g. SA, ID) and lower than 20 g CO_2-eq/kWh in countries with a high share of renewable and/or nuclear electricity generation (e.g. SE, NO). It is expected that the share of renewable electricity will further increase globally, while the amount of fossil based electricity will reduce. However, the scenario development of the global future electricity mix EV fleet under different conditions is not part of the activities of the IEA HEV Task 30.



estimated environmental effects of electricity at charging point	2014	2015	2016	2017	2018
global warming (g $CO2_{eq}$/kWh) (1)	180 to 200	200 to 220	190 to 210	190 to 210	190 to 210
acidification (g $SO2_{eq}$/kWh) (2)	0,5 to 0,5	0,5 to 0,6	0,5 to 0,5	0,5 to 0,6	0,5 to 0,5
ozone formation (g $C2H4_{eq}$/kWh) (3)	0,3 to 0,3	0,3 to 0,4	0,3 to 0,4	0,3 to 0,4	0,3 to 0,4
particles (g/kWh)	0,04 to 0,04	0,04 to 0,04	0,04 to 0,04	0,04 to 0,04	0,03 to 0,04
fossil primary energy (kWh/kWh) (4)	0,9 to 1	1 to 1,1	0,9 to 1	1 to 1,1	1 to 1,1
nuclear primary energy (kWh/kWh)	0,01 to 0,02	0,02 to 0,02	0,02 to 0,02	0,02 to 0,02	0,02 to 0,02
total primary energy (kWh/kWh) (5)	1,6 to 1,8	1,6 to 1,8	1,6 to 1,8	1,6 to 1,8	1,6 to 1,8

(1) CO_2-equivalent: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)
(2) SO_2-equivalen: sulfur dioxide (SO_2), nitrogen oxides (NO_x)
(3) C_2H_4 (ethylene)-eq: non-methane volatile organic compounds (NMVOC), CH_4, NO_x, carbon monoxide (CO)
(4) sum: raw oil, raw natural gas, coal
(5) sum: raw oil, raw natural gas, coal, uranium, biomass, solar, wind, water, waste, residues, geothermal
(6) energy share of coproduced electricity/heat in CHP plants: 57%/43%

estimated annual change of environmental effects (1), (2)	2014	2015	2016	2017	2018
global warming (kt $CO2_{eq}$/a)	-6,9 to -7,6	-10 to -11	-18 to -20	-30 to -33	-43 to -48
acidification (t $SO2_{eq}$/a)	5,4 to 6	9 to 10	15 to 17	25 to 28	35 to 38
ozone formation (t $C2H4_{eq}$/a)	-14 to -15	-21 to -23	-37 to -40	-59 to -65	-84 to -93
particles (t/a)	0,4 to 0,5	0,7 to 0,8	1,2 to 1,3	1,8 to 2	2,5 to 2,7
fossil primary energy (GWh/a)	-15 to -17	-22 to -24	-40 to -44	-61 to -68	-90 to -100
nuclear primary energy (GWh/a)	<0.01	<0.01	-0,01 to -0,02	0,03 to 0,04	<0.01
total primary energy (GWh/a)	-8,7 to -9,6	-13 to -14	-23 to -26	-36 to -40	-53 to -58

estimated change of environmental effects (1), (2)	2014	2015	2016	2017	2018
global warming	-51 to -57%	-49 to -54%	-50 to -56%	-50 to -55%	-50 to -55%
acidification	120 to 130%	120 to 140%	120 to 130%	120 to 130%	120 to 130%
ozone formation	-62 to -69%	-60 to -67%	-61 to -68%	-60 to -67%	-61 to -67%
particles	160 to 180%	170 to 180%	160 to 180%	150 to 170%	150 to 160%
fossil primary energy	-40 to -44%	-37 to -40%	-38 to -43%	-36 to -40%	-38 to -42%
nuclear primary energy	-2,5 to -2,8%	1,4 to 1,6%	-1,4 to -1,5%	2 to 2,2%	0,09 to 0,1%
total primary energy	-21 to -23%	-19 to -21%	-20 to -22%	-19 to -21%	-20 to -22%

(1) of national EV fleet subsituting conventional ICE vehicles
(2) reduction is negative value; increase is positive value

Figure 12: Country Factsheet on estimated environmental impacts of current EV-fleet – Example Austria

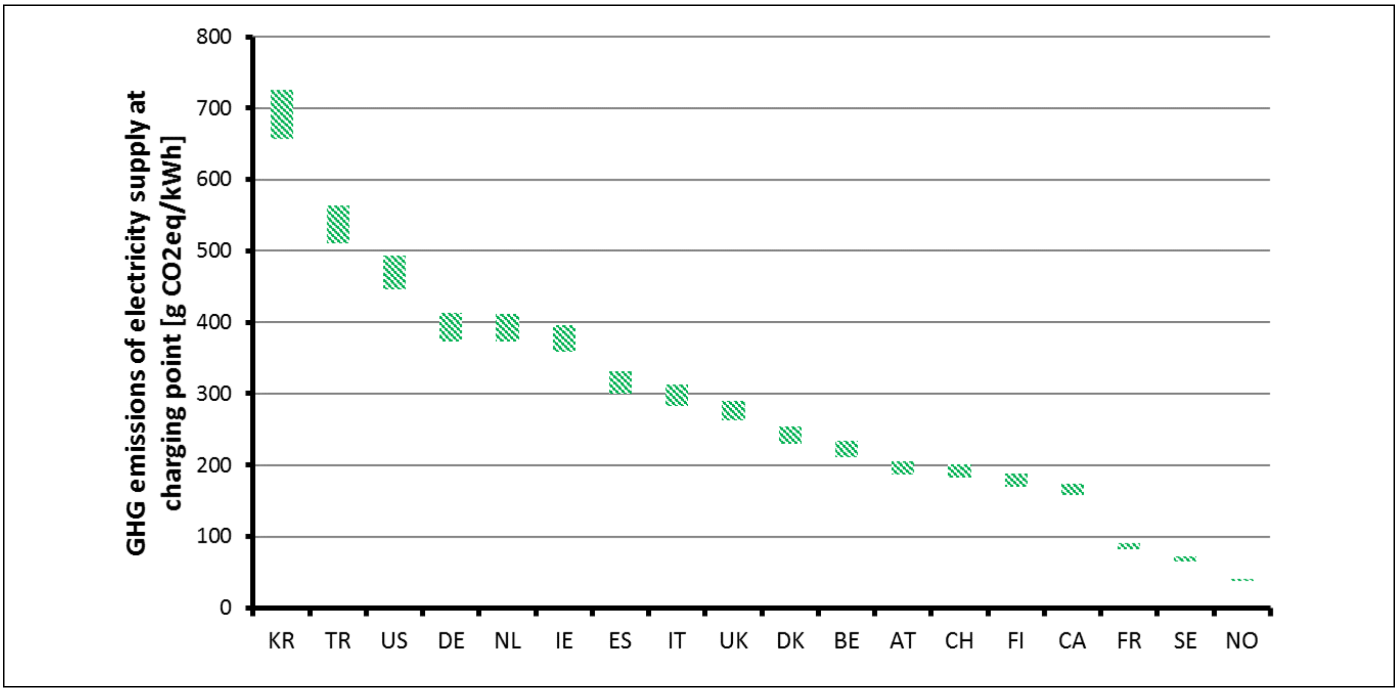


Figure 13: Estimated range of GHG emissions of electricity at charging point in IEA HEV countries in 2018

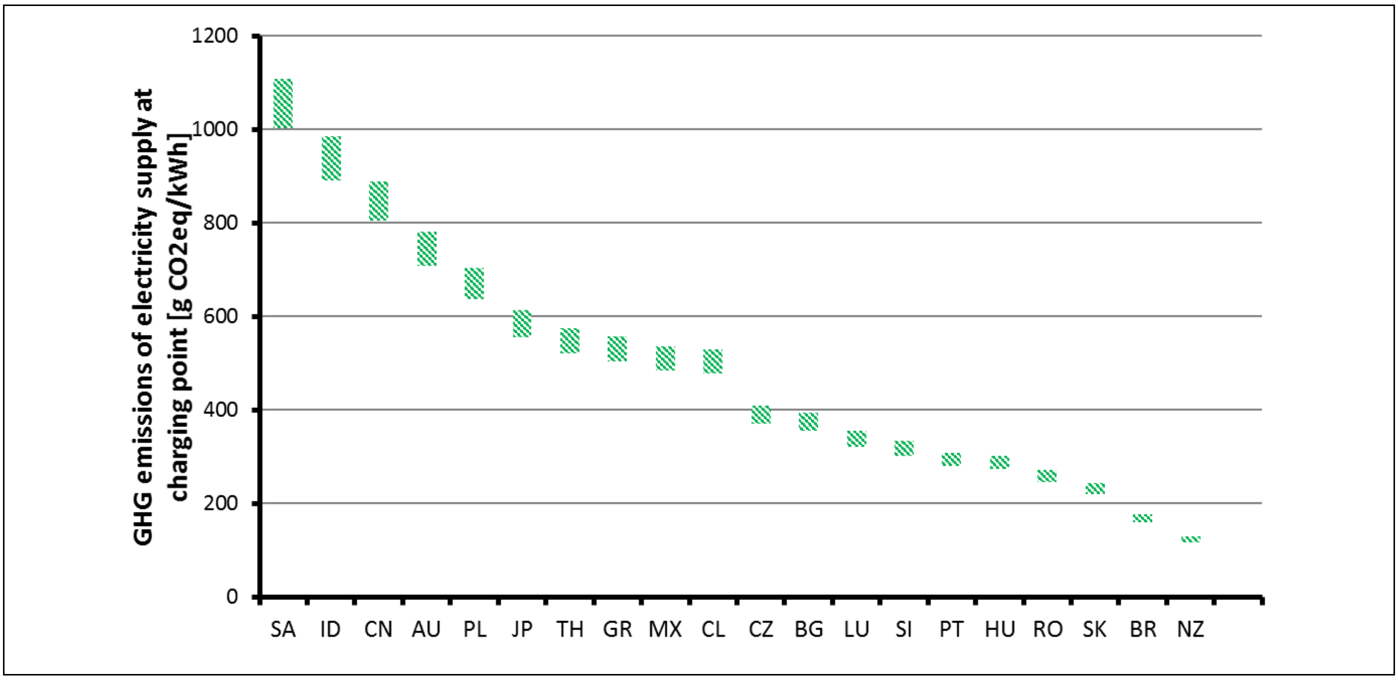


Figure 14: Estimated range of GHG emissions of electricity at charging point in Non IEA HEV countries in 2018

The estimated GHG change of EVs compared to ICE are shown in Figure 15 for the IEA HEV countries and in Figure 16 for the Non IEA HEV countries. In countries with a high share of renewable and/or nuclear electricity the GHG emissions reduction of the EVs is between 60 – 70%, whereas countries with a high share of fossil generated electricity have a low GHG emission reduction. If the GHG emission of the electricity at the charging point is > 600 g CO_2-eq per kWh electricity an increase of GHG emissions of the EVs compared to ICE is detected.

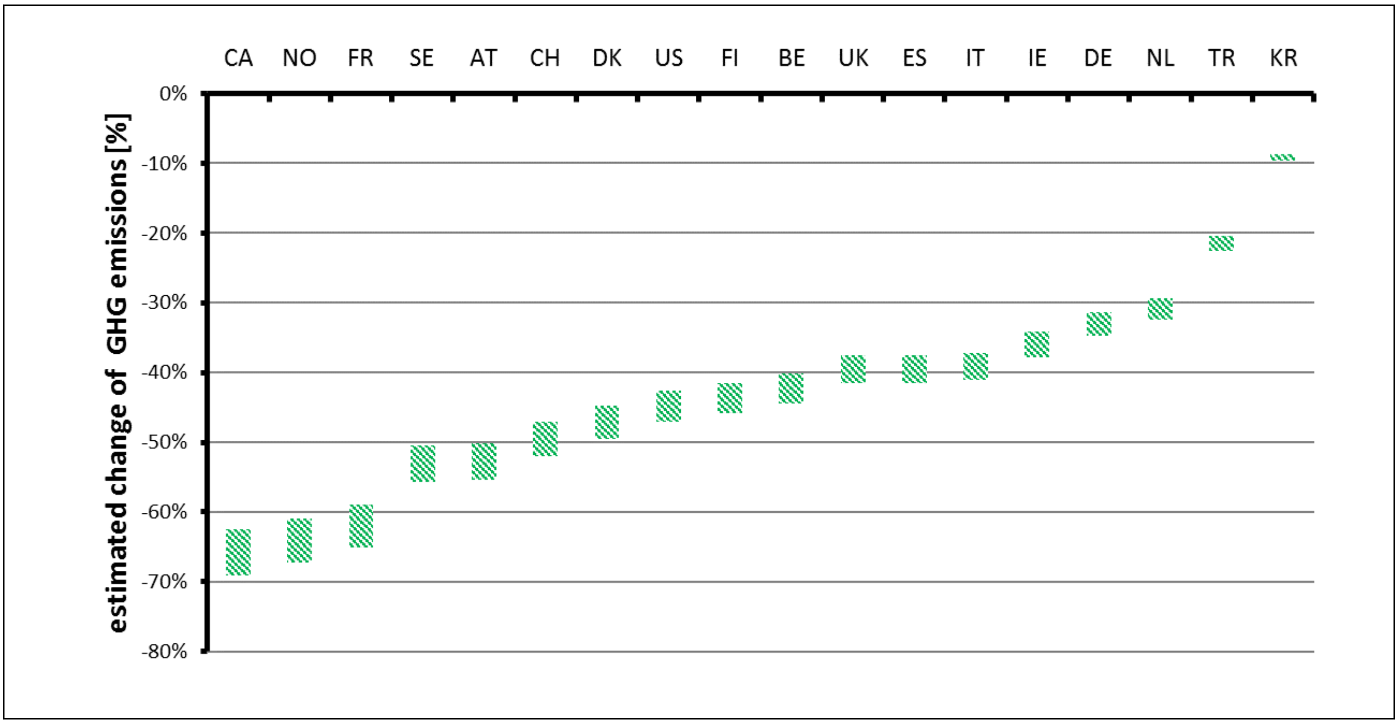


Figure 15: Estimated range of GHG emissions reduction of EVs substituting ICE vehicles in IEA HEV countries in 2018

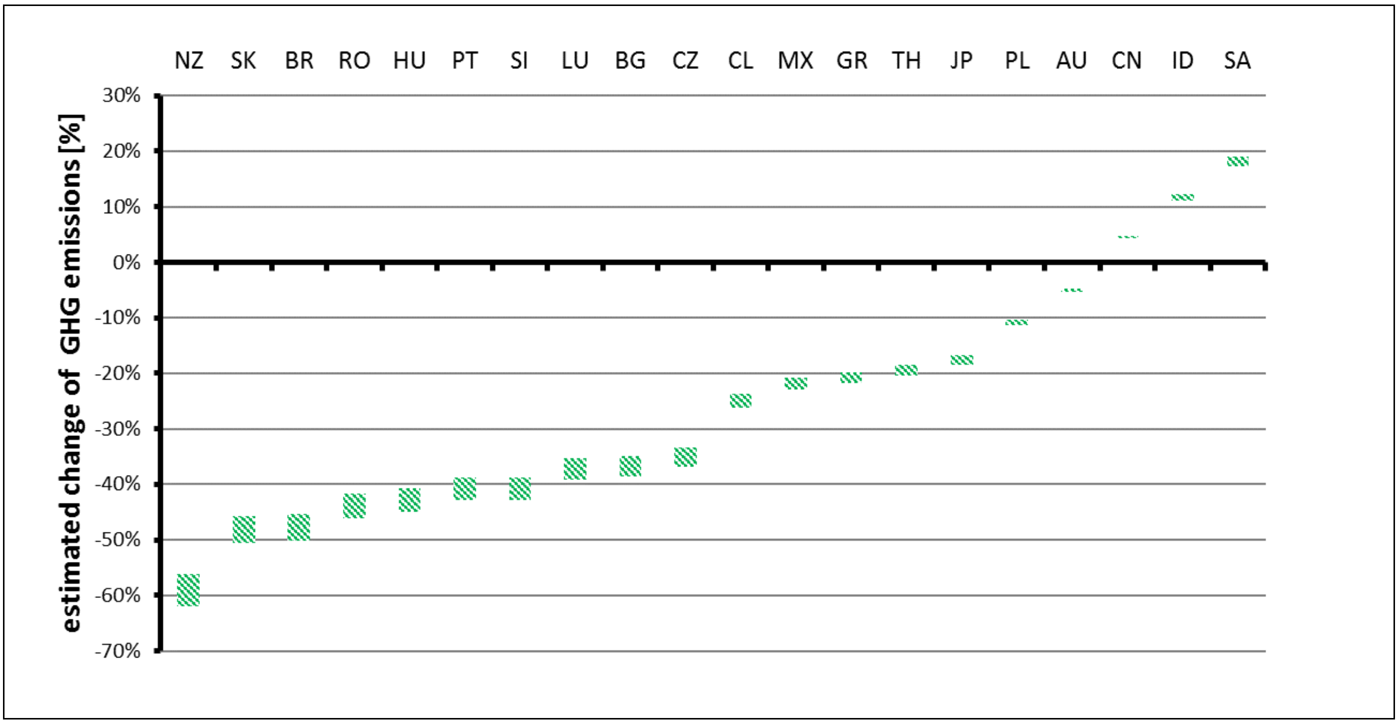


Figure 16: Estimated range of GHG emissions reduction of EVs substituting ICE vehicles in Non IEA HEV countries

Based on the country specific results the total global environmental effects in 2014 to 2018 of the globally increasing EV fleet are estimated. Figure 17 shows the total reduction of GHG emissions with a range between 4.6 – 5.1 Mt CO_2-eq in 2018, mainly resulting from the EVs fleet in IEA HEV countries, whereas the sum of the Non IEA HEV countries show nearly no effect in changing the GHG emissions. The estimated change of cumulative primary energy demand of the global EV fleet gives a reduction between 4,800 – 5,400 GWh/a, which is shown in Figure 18. The IEA HEV countries substantially contribute to this reduction, where the Non IEA HEV countries even result in an increase of cumulated primary energy demand.

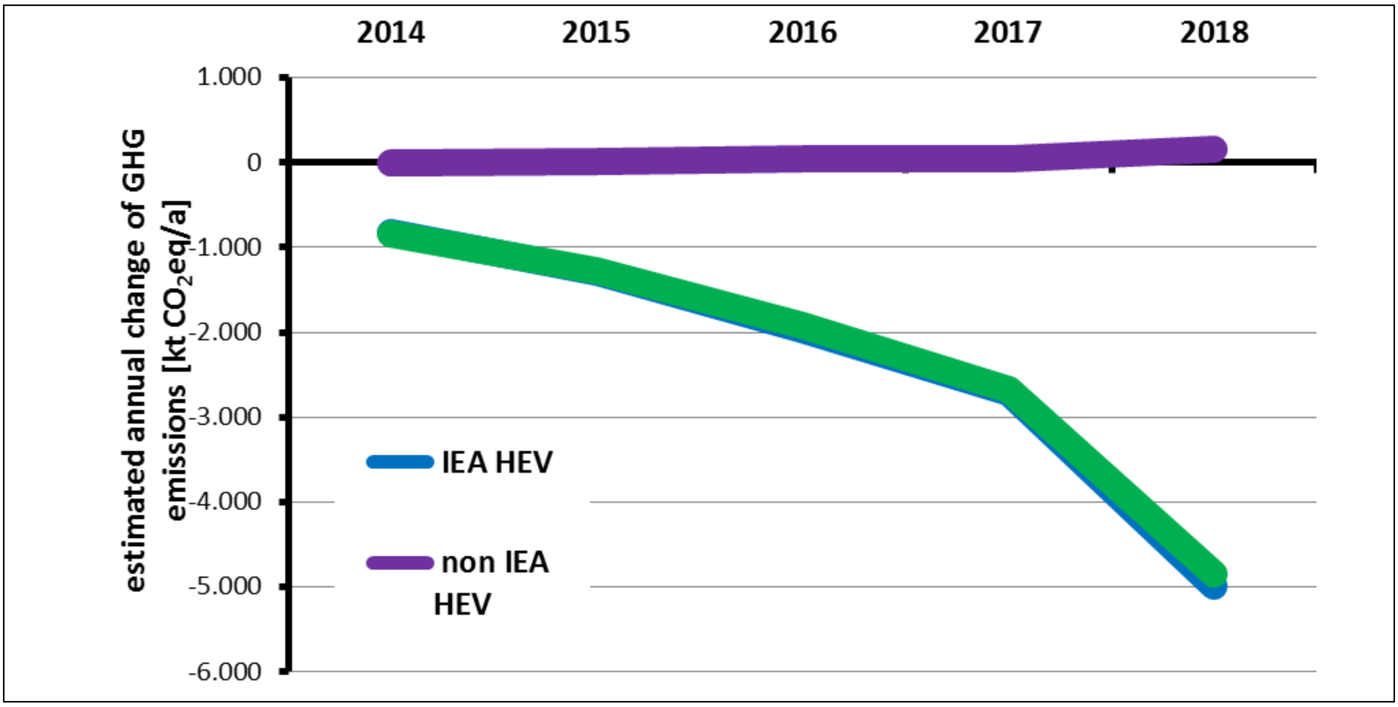


Figure 17: Estimated range of increasing GHG reduction of EVs substituting ICE vehicles globally (2014 – 2018)

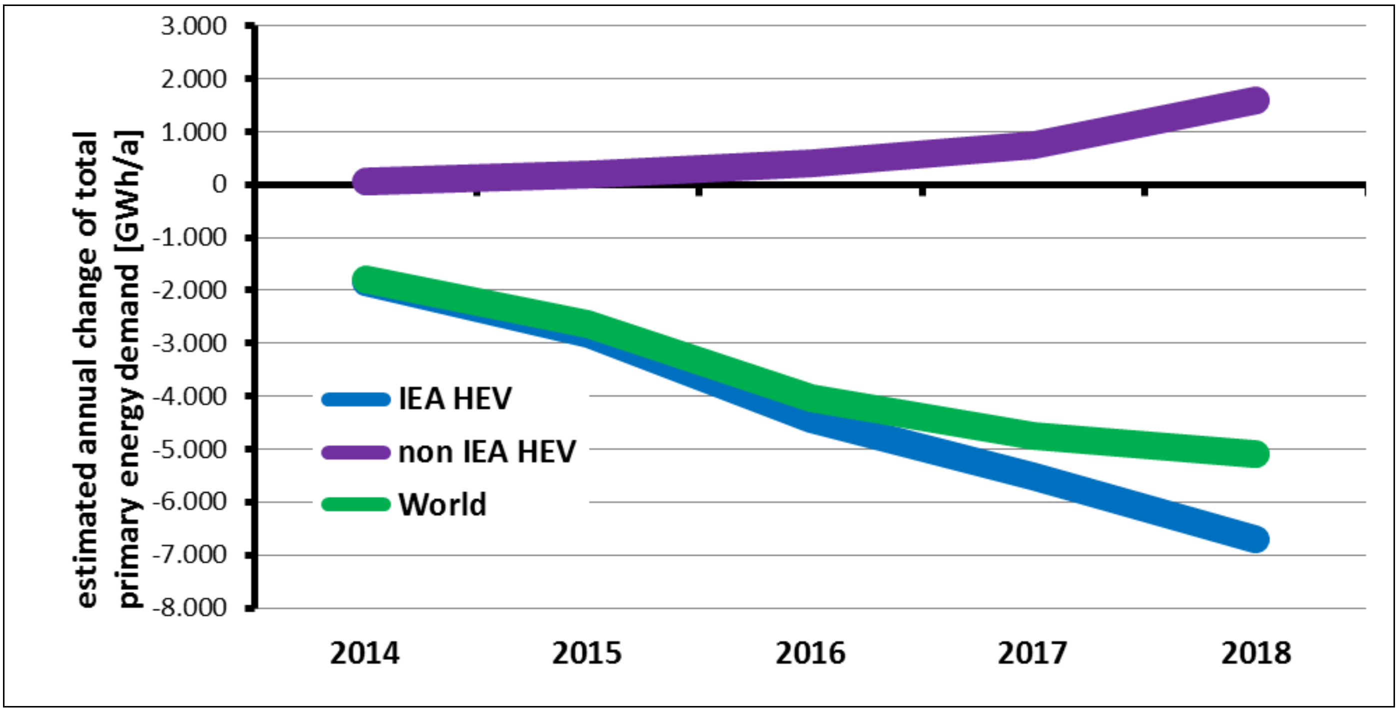


Figure 18: Estimated range of change in cumulative primary energy demand of EVs substituting ICE vehicles globally (2014 – 2018)

It is concluded that the share of electricity produced from fossil fuel has a substantial influence on the EV related emissions. A relatively large share of renewable or/and nuclear electricity contributes to substantial environmental benefits in the affected countries (e.g. NO, FR, AT), on the other side a relatively large share of fossil electricity contributed to an increase of impacts in the relevant countries (e.g. PL, CN).

Summarizing the estimated environmental effects of the global fleet of BEVs and PHEVs substituting for diesel and gasoline ICE vehicles shows for 2018 the following (Table 5):

- GHG-reduction: 23% to 26%,
- fossil primary energy reduction 23% to 25%,
- renewable primary energy increase 57% to 63%,
- nuclear primary energy increase 800% to 900% and
- total primary energy reduction 7.8% to 8.7%.

Table 5: Estimated change of environmental effects of global EV fleet in 2018

Environmental effect		**Change**			
Emissions					
	GWP	- 4.6 to - 5.1	[Mt/a]	- 23 to - 26	%
	Acidification	+ 23 to + 26	[kt/a]	+ 370 to + 400	%
	Ozone formation	- 9.0 to -10	[kt/a]	- 31 to - 34	%
	Particles	+ 3.1 to + 3.5	[kt/a]	+ 870 to + 960	%
Cumulated primary energy					
	fossil	- 13 to - 14	[TWh/a]	- 23 to - 25	%
	nuclear	+ 4.7 to + 5.2	[TWh/a]	+ 800 to + 900	%
	renewable	+ 3.2 to + 3.5	[TWh/a]	+ 57 to + 63	%
	total	- 4.8 to - 5.4	[TWh/a]	- 7.8 to - 8.7	%

The variation in the emissions of national electricity production, the electricity consumption of EVs at charging point and the fuel consumption of the substituted conventional ICEs mainly determine the estimated range of environmental effects.

The analyses shows that the environmental benefits strongly depend on the national framework condition, i.e. national grid mix of electricity generation. A significant reduction of GHG emissions (up to 80%), compared to conventional ICE vehicles, is reached in some countries due to a high share of renewable and non-fossil based electricity generation. Additional renewable electricity with synchronized charging will maximize the environmental benefits of EVs and adequate loading strategies are essential for further reductions.

There is strong evidence from the current data of EV fleet deployed in various countries that using a relevant share of renewable electricity in electric vehicles play a substantial role in the future of sustainable transportation, especially with the expected increase in renewable electricity generation.

2.7.4 Conclusions

Concluding on the environmental assessment of the global EV fleet based on Life Cycle Assessment compared to the substituted conventional ICE vehicles leads to the following key issues:

- The environmental effects depend on the national framework condition, e.g. national grid electricity generation mix.
- The broad ranges of possible environmental effects is caused by the:
  - emissions of the national electricity production and distribution,
  - electricity consumption of EVs at charging point and
  - fuel consumption of substituted conventional ICE vehicles-
- The highest environmental benefits can be reached by using additional installed renewable electricity, which is synchronized with the charging of the EVs.
- The adequate loading strategies for EVs to integrate additional renewable electricity effectively will create further significant environmental benefits.

This assessment shows the strong evidence that electric vehicle can contribute substantially to a sustainable future of the transportation sector in various countries if renewable electricity is used.

2.7.5 References

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2.8 Issues on Dynamic LCA of Vehicle Fleets

2.8.1 Introduction

Issues on dynamic LCA, e.g. annual environmental effects, become relevant for the rapidly increasing of EV-fleets combined with an additional generation of renewable electricity. For this, the Task identified the following relevant methodological aspects:

1) timing of environmental effects in the three lifecycle phases,
2) timing of environmental effects of increasing supply of renewable electricity,
3) timing of environmental effects of EVs using increasing supply of renewable electricity and
4) substitution effects and timing of environmental effects of EVs substituting ICE vehicles.

2.8.2 Methodological Aspects

The possible environmental effects of a system occur at different times during their lifetime. In LCA, the environmental effects are analysed for the three phases separately – production (for vehicles) or construction (for power plants), operation and end of life – over the whole lifetime of a system. Then the cumulated environmental effects over the lifetime are allocated to the service provided by the system during the operation phase, which is the functional unit in LCA, e.g. per kilometre driven for vehicles and kWh generated for power plants. Therefore, the functional unit gives the average environmental effects over lifetime by allocating the environmental effects for production and end of life over the lifetime to the service provided independent of the time when they occur.

Another approach considered in the Task is to reflect and keep the time depending course of the environmental effects in the life cycle and compare the absolute cumulated environmental effects in a dynamic LCA.

In Figure 19, the possible courses of the cumulated environmental effects of three systems in their lifetime are shown for the three phases – production, operation and end of life. All the three systems – A, B and C - have the same lifetime and provide the same service but the courses of the environmental effects are quite different. The system A has low environmental effects in the production/construction phase but high effects during the operation/use phase and again low effects in the end of life phase. While system B has very high effects in the production phase, very low further effects in the operation phase and declining environmental effects in the end of life phase due to the recycling of materials and a credit given for the supply of secondary materials for substituting primary material. The system C has lower effects in production/construction phase than system B and no further effects during the operation phase, but significantly declining environmental effects in the end of life phase, which is due to the reuse of certain parts, facilities or materials for other further purposes.

Considering the total cumulated environmental effects, system C has the lowest and system A the highest effects in their lifetime. However, additionally it can be analysed at which time in the lifecycle the system C has lower cumulated environmental effects compared to the other systems. At time t_1 system C has lower cumulated environmental effects than system B; at time t_2 system B has equal cumulated effects than system A.

This timing of the environmental effects becomes more relevant in future, when new innovative systems substitute conventional systems to reduce the overall environmental effects. However, it might take some time until the real reduction of environmental effects takes place by the new innovative system. This aspect becomes more and more relevant in the context e.g. of the global necessary reduction of GHG emissions with increasing energy efficiency and renewable energy. Therefore, in dynamic LCA the course of the cumulated environmental effects have to be considered and addressed more adequately.

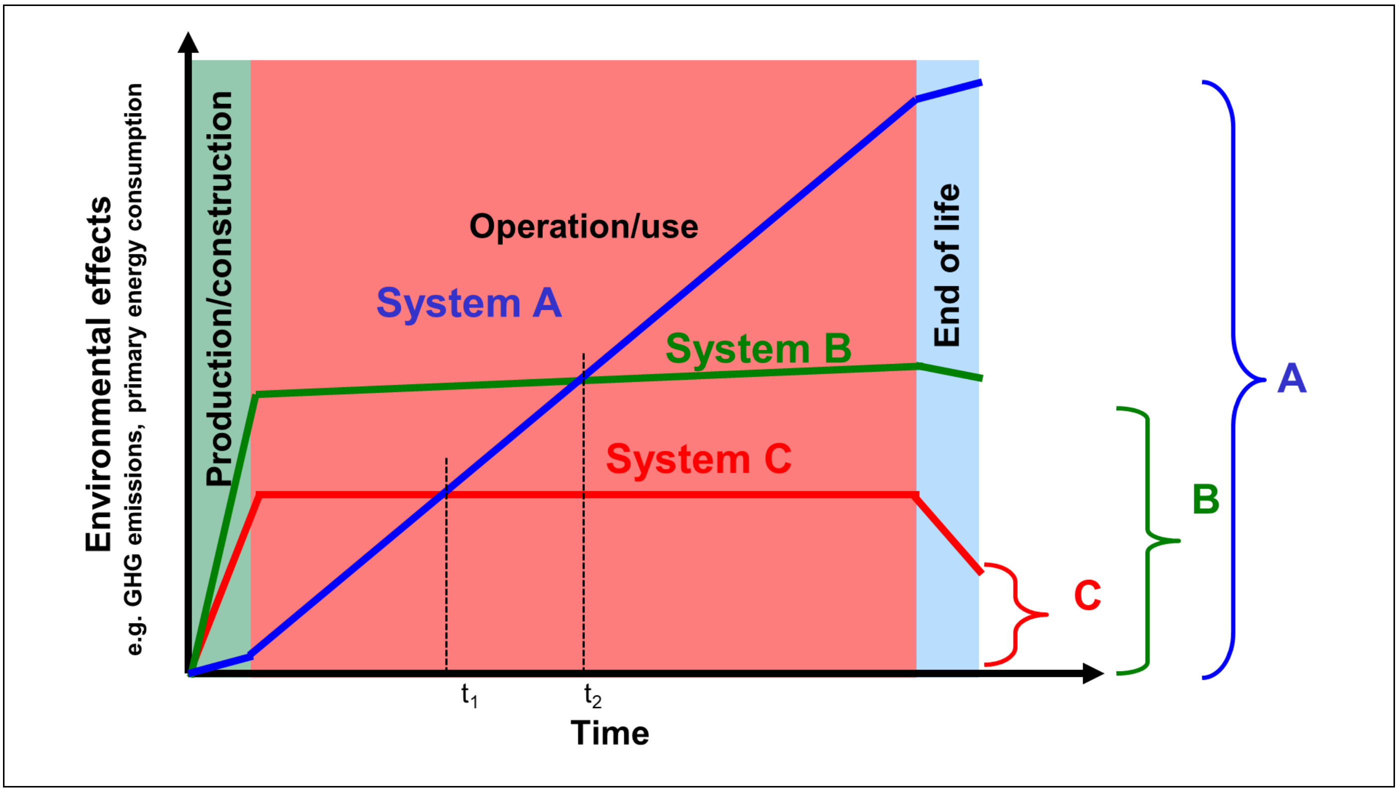

Figure 19: Timing of cumulated environmental effects of three systems with the same lifetime

In Figure 20, the timing of environmental effects of a BEV using renewable electricity substituting an ICE vehicle is shown. In total over the lifetime the BEV has lower environmental effects, e.g. GHG emissions than the ICE. Due to the higher environmental effects from production of the BEV, the environmental effects are higher in the beginning, but after about 3 years the environmental benefits of substituting ICE vehicles starts. An additional effect is that due to the rebound effect (further details see Task 30 working document) not each electric driven kilometre might substitute a fossil fuel driven kilometre. Therefore, the substitution rate might be lower than 100%. In the example below, the timing of environmental effects is shown for a substitution rate of 80% and 100%. Additionally, if the timing effects are analysed for a rapid annual increase of BEV the annual environmental effect might still be higher than the substituted ICE vehicles. So depending on the annual growing size of the BEV fleet it might take some time until the overall annual environmental effects decline by substitution of ICE vehicles.

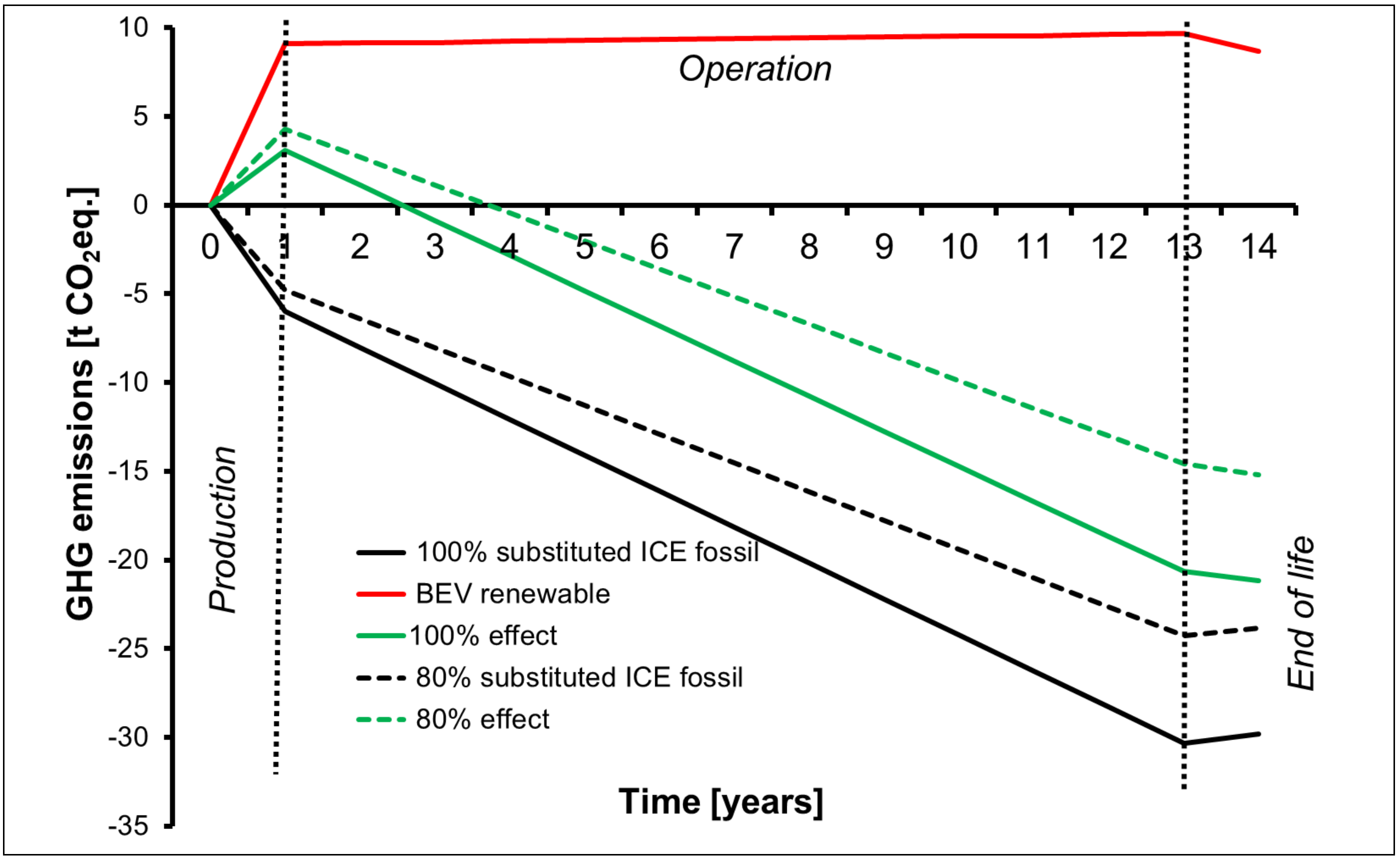

Figure 20: Timing of environmental effects of a BEV using renewable electricity substituting an ICE vehicle

2.8.3 LCA of Supplying Additional Renewable Electricity – Example Austria

It is relevant to analyse and assess the environmental effects of the increasing production of renewable electricity generation and its use, e.g. in BEV. The environmental effects, e.g. GHG emissions, of electricity from hydro, wind and solar power plants mainly occur in the construction and the end of life phases. In most countries, there are huge investments in new facilities to generate additional renewable electricity. Related to these investments significant environmental effects are taking place with these investments, but the substitution of conventional electricity generation will lead to a reduction of environmental effects in the coming years.

To illustrate the timing of the environmental effects in a dynamic LCA perspective the following example of Austria of increasing renewable electricity generation is described.

The additional renewable electricity generation in Austria increased between 0.2 up to 2.2 TWh per year from 2005 up to 2020. In Figure 21, the total renewable electricity generation in Austria is shown from 2005 to 2020. Already in 2004 about 40 TWh renewable electricity was generated mainly in hydro power plants. Over the years, the generation from renewable electricity increased from 41 TWh in 2005 up to

57 TWh in 2020 significantly. The share of renewable electricity in the Austrian grid mix (incl. imports) increased from about 60% in 2005 up to 75% in 2020.

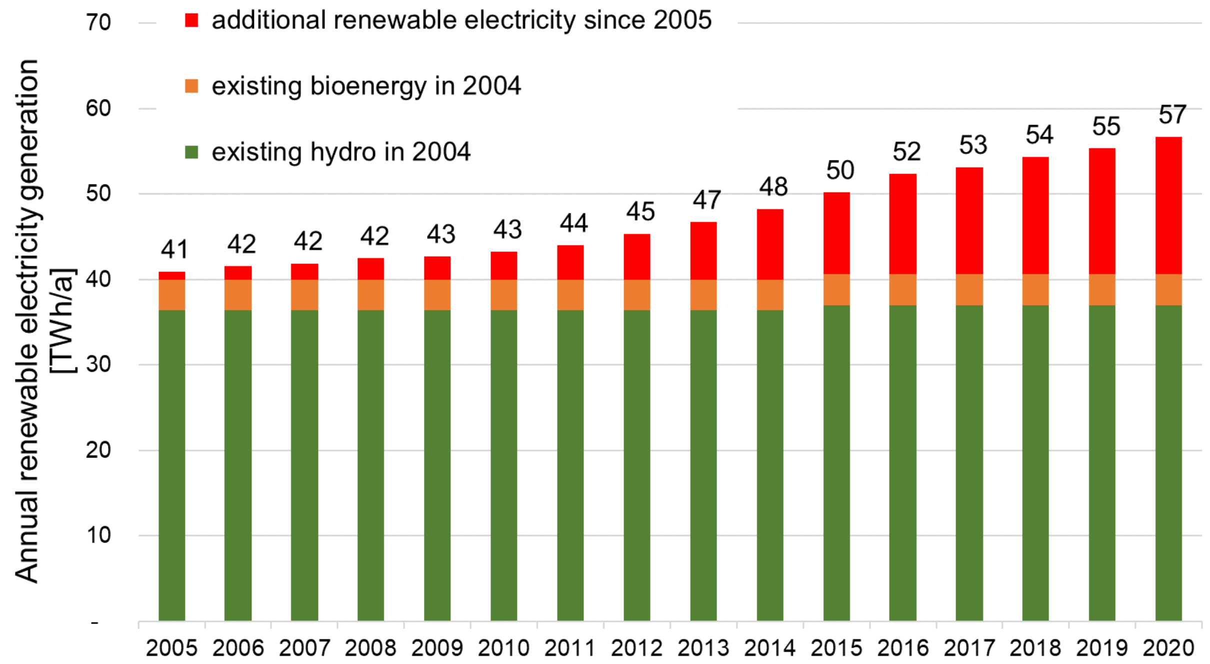

Figure 21: Renewable electricity generation in Austria (references are given in working document)

The annual GHG emissions due to the installation of new renewable electricity generation plants in Austria were between 100,000 up to 800,000 t CO_2-eq per from 2005 to 2020, depending on the annual installed generation capacity and the type of renewable energy. E.g. the installation of a PV power plant to generate 1 GWh annually with about 1,400 to 1,600 t CO_2-eq has significantly higher GHG emissions than a hydro or wind power plant with about 250 – 600 t CO_2-eq per 1 GWh anually.

The combination of the annual GHG emissions and the additional electricity generation gives the specific GHG emissions of renewable electricity generation in Austria (Figure 22), on one hand the GHG emissions of the additional installed renewable electricity generation and on the other hand the total renewable electricity mix in Austria. Due to the chosen dynamic LCA approach here, the GHG emissions of the construction of renewable electricity generation plants before 2005 are not considered in the years from 2005 onwards, only the relatively low GHG emissions of operating the plants for maintenance and the fuel supply for bioenergy are included. So the GHG emissions of renewable electricity generation in Austria in existing (before 2005) and newly installed power plants (since 2005) are in the range between 8 to 33 g CO_2-eq/kWh, whereas the GHG emissions of the additionally installed renewable electricity generation is between 31 and 250 CO_2-eq/kWh between 2005 and 2020.

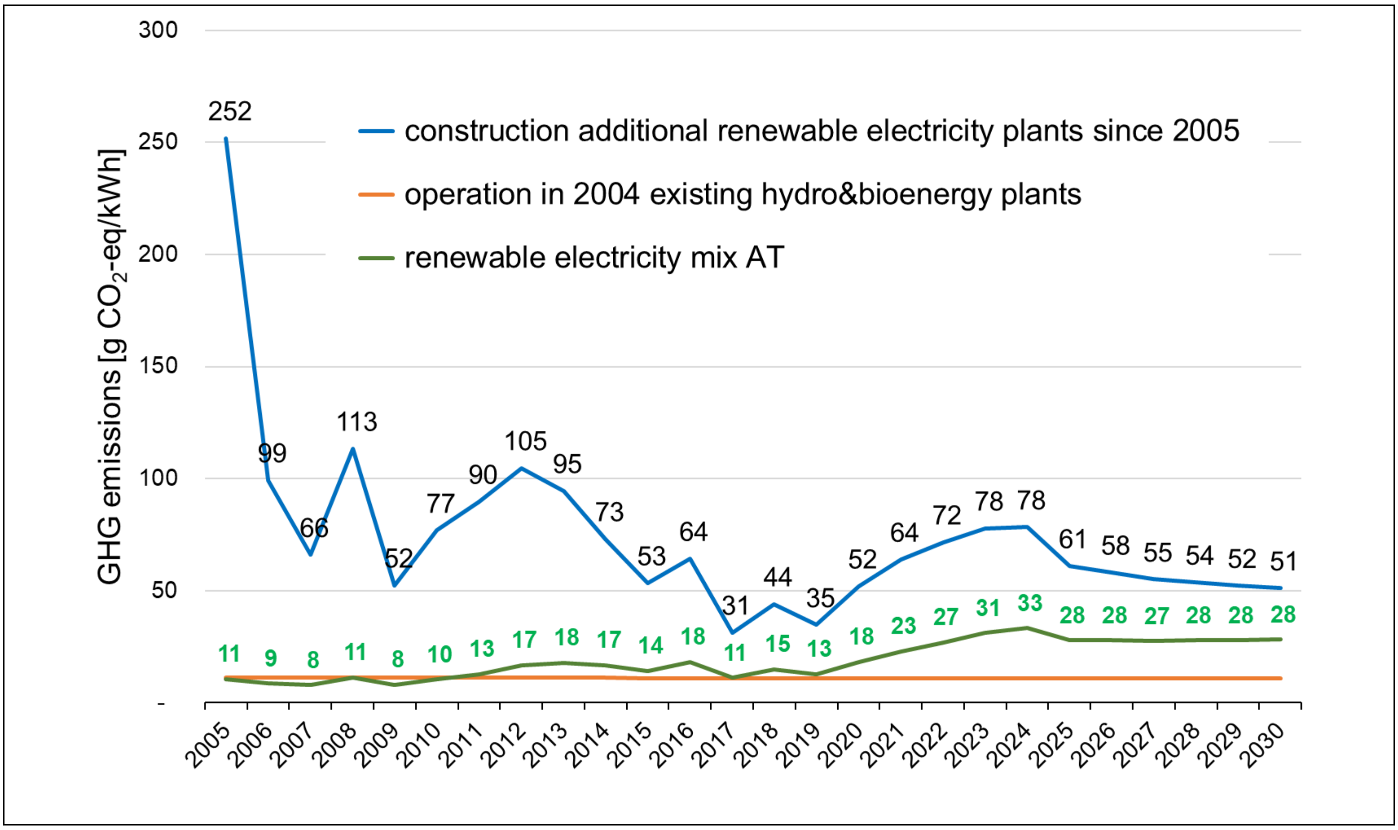

Figure 22: GHG emissions of renewable electricity generation in Austria

2.8.4 GHG Emissions of BEV Introduction in Austria

The environmental assessment of the global EV fleet based on LCA compared to the substituted conventional ICE vehicles leads to the following key issues:

- The environmental effects depend on the national framework condition, e.g. national grid electricity generation mix.
- The broad range of possible environmental effects is caused by the:
  - emissions of the national electricity production and distribution,
  - electricity consumption of EVs at charging point, and
  - fuel consumption of substituted conventional ICE vehicles.
- The highest environmental benefits can be reached by using additional installed renewable electricity, which is synchronized with the charging of the EVs.
- The adequate loading strategies for EVs to integrate additional renewable electricity effectively will create further significant environmental benefits.

Now this approach was further developed by taking the dynamic effects of introduction of BEV fleets and increasing supply of renewable electricity.

The introduction of BEV in Austria started in 2010. Additionally, also PHEV were introduced, which are not considered here. The annually registered BEV increased significantly and reached nearly 16,000 new BEVs in 2020. The BEV fleet increased up to about 46,000 BEVs in 2020. The rapid increase of the BEV fleet in Austria was stimulated by public funding of up to € 6,000 for the investment and the charging stations. If the supply of renewable electricity for the operation of the BEV is guaranteed by a corresponding electricity purchase contract.

Assuming an electricity demand of about 0.22 kWh/km (incl. heating, cooling and auxiliaries) and 10% grid and charging losses the additional renewable electricity demand for the operation of the BEV fleet increased from 0.3 GWh in 2010 up to 142 GWh in 2020. Considering the increased renewable electricity generation since 2010 in Austria the demand to operate the BEV fleet is in a range of 0.1 to 1.1% of the additional renewable electricity generated since 2010. Concluding, also in this system perspective it is evident that the Austrian BEV fleet is operated on renewable electricity, while the increasing demand for electricity is met with increasing supply of renewable electricity.

Considering the course of the annual GHG emissions of the renewable electricity generation in Austria, the GHG emissions of the operations of the BEV fleet in Austria are calculated using the GHG emission (2010 – 2020) between 10 to 18 g CO_2-eq/kWh. The GHG emissions of BEV fleet operation using the renewable electricity mix in Austria are in average between 2.5 to 4.5 g CO_2-eq/km without considering maintenance and spare parts. Therefore, in average between 2010 and 2020 the GHG emissions of a BEV operating in Austria are about 3.6 g CO_2-eq/km.

In addition, the GHG emissions from the production of the new registered BEV are calculated in an LCA perspective. The average GHG emissions of the global battery production has decreased from about 100 kg CO_2-eq per kWh battery capacity in 2010 to about 70 kg CO_2-eq/kWh. At the same time the battery capacity of a new BEV in Austria increase from about 30 kWh in 2010 to about 65 kWh in 2020 in average, due to the lower battery costs and the demand for higher driving ranges. Therefore, the production of a new BEV between 2010 and 2020 causes GHG emissions between 8.5 up to 10.5 t CO_2-eq. In comparison, the production of a conventional new ICE vehicle causes about 6 t CO_2-eq. However, the operation of a conventional substituted ICE vehicle has GHG emissions of about 145 g CO_2-eq/km with an average fuel consumption of about 0.52 kWh/km.

The GHG emissions of the BEV introduction since 2010 in Austria are calculated by considering the GHG emissions of the production from the annually new registered BEV and the operation of the BEV fleet by taking the substituted conventional ICE vehicles into account.
In Figure 23, the change of GHG emissions of the BEV fleet substituting an ICE fleet in Austria are shown. In 2020, the GHG emissions of the production of the newly registered 16,000 BEV are about 167,000 t CO_2-eq and the GHG emissions of the BEV fleet operation of about 45,000 vehicles with renewable electricity are about 3,000 t CO_2-eq.

Assuming each BEV substitutes for an ICE, about 16,000 newly registered conventional ICE vehicle were substituted in 2020 avoiding GHG emissions from their production of about 96,000 t CO_2-eq and avoiding GHG emissions of about 94,000 t CO_2-eq in the ICE fleet operation of about 45,000 conventional ICE vehicles. Therefore, in 2020 the BEV fleet in Austria emitted about 170,000 t CO_2-eq and avoided about 190,000 t CO_2-eq from substituting conventional ICE vehicles, which results in an overall GHG saving in 2020 of about 20,000 t CO_2-eq.

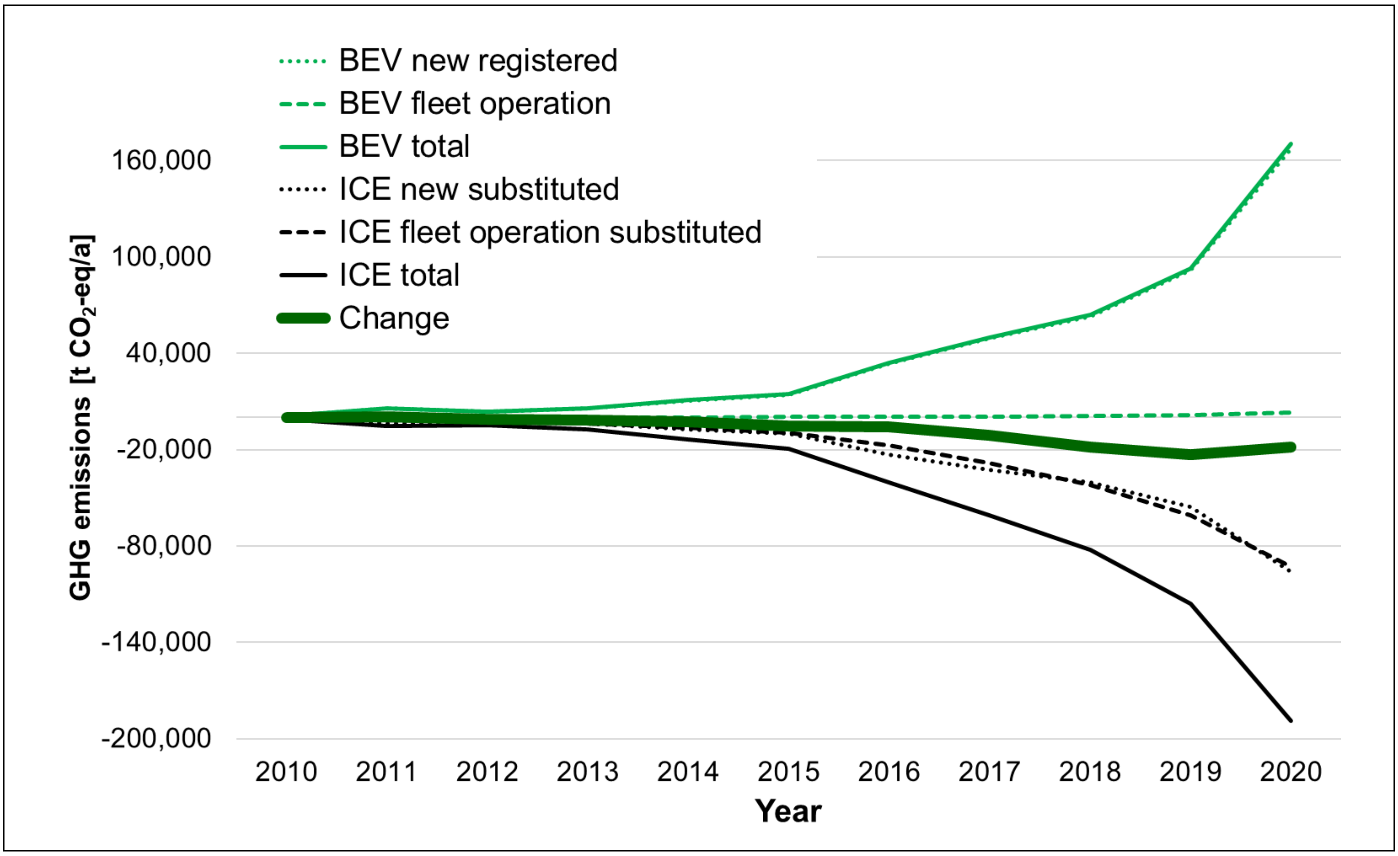

Figure 23: Change of GHG emissions of BEV fleet substituting ICE fleets in Austria

2.8.5 Scenarios for a Climate Neutral Passenger Vehicle Fleet in Austria 2040/2050

Based on the dynamic approach two scenarios for the "climate neutral" passenger vehicle fleet in Austria up to 2050 „BEV" and „e-Fuel" were developed.

The main characteristics of these two scenarios are:

- GHG reduction goals:
  - 2030: Austria about 55% reduction (based on 1990),
  - 2040: Austria „climate neutral" transportation sector,
  - 2050: EU and USA climate neutral,
  - 2060: Rest of the world climate neutral,
- Fleet modelling with NEMO (Network Emission Model) used for OLI (Österreichische Luftschadstoff-Inventur):
  - different shares of new registrations since 2021: BEV and ICE/PHEV,
  - only domestic passenger vehicles (without „tank tourism"),

  - vehicle fleet: remains constant,
  - total annual kilometres: constant since 2020,
- renewable electricity for BEV & e-Fuel generated in new power plants in Austria/abroad integrated in existing renewable electricity mix,
- CO_2-sources for e-Fuels:,
  - 50 – 100 kt/a from biomass (e.g. fermentation, combustion)
  - 100 kt/a from air,
- amount of biofuels for passenger vehicles remain constant since 2020 (about 250 kt).

This modelling was done in cooperation of:

- JOANNEUM RESEARCH (LCA & modelling),
- Graz University of Technology (vehicle fleet),
- IEA HEV Task 30 (methodology).

In Figure 24, the possible development of passenger vehicle fleet for climate neutrality 2050 is shown. In the BEV scenario, the vehicle fleet is renewed faster as nearly all newly registered vehicles have to be electric vehicles to reach the goal for 2030.

In Figure 25, the passenger vehicle energy consumption is shown. In the BEV-Scenario, the energy consumption is significantly less than in the e-Fuel-Scenario, as the electric vehicles are more efficient than the ICE vehicles using e-fuels. The peak of e-fuel demand is in 2030 to reach a 55% GHG reduction, after 2030 the number of ICE vehicles further decreases so less e-fuel is needed. Nevertheless, in both scenarios a significant increase of generating additional renewable electricity is necessary.

In Figure 26, the LCA based GHG-emissions of passenger vehicle fleet for climate neutrality 2050 are shown. In 2040, the GHG emission from vehicle operation are nearly zero, just some CH_4- and N_2O-emissions from the vehicle tail pipe remain. In 2050, due to the climate global neutrality the total GHG emissions are close to zero, a small amount still remains, as China and India claim to reach climate neutrality in 2060. The GHG emissions from vehicle end of life and vehicle export are negative, as “credits” are given for these effects.

In Figure 27, the LCA based total primary energy demand of passenger vehicle fleet for climate neutrality 2050 is shown. It becomes evident that the e-Fuel-Scenario needs much more primary energy than the BEV-Scenario as the energy conversion from renewable primary energy to transportation service is much lower with e-fuels. To cover the peak amount of e-fuels in 2030 a very strong increase of additional renewable power plants is necessary in a very short period of time, and the construction of these new power plants is the reason for the peak of primary energy in 2030.

In Figure 28, the cumulated results for 2020 – 2050 for the GHG emissions and the primary energy demand for both scenarios are shown. The cumulated GHG emissions and primary energy demand is lower in the BEV-Scenario, except the production? of more BEV has higher GHG emissions. Considering energy efficiency, it becomes evident that the BEV-Scenario needs significantly less cumulated renewable primary energy than the e-Fuel-Scenario.

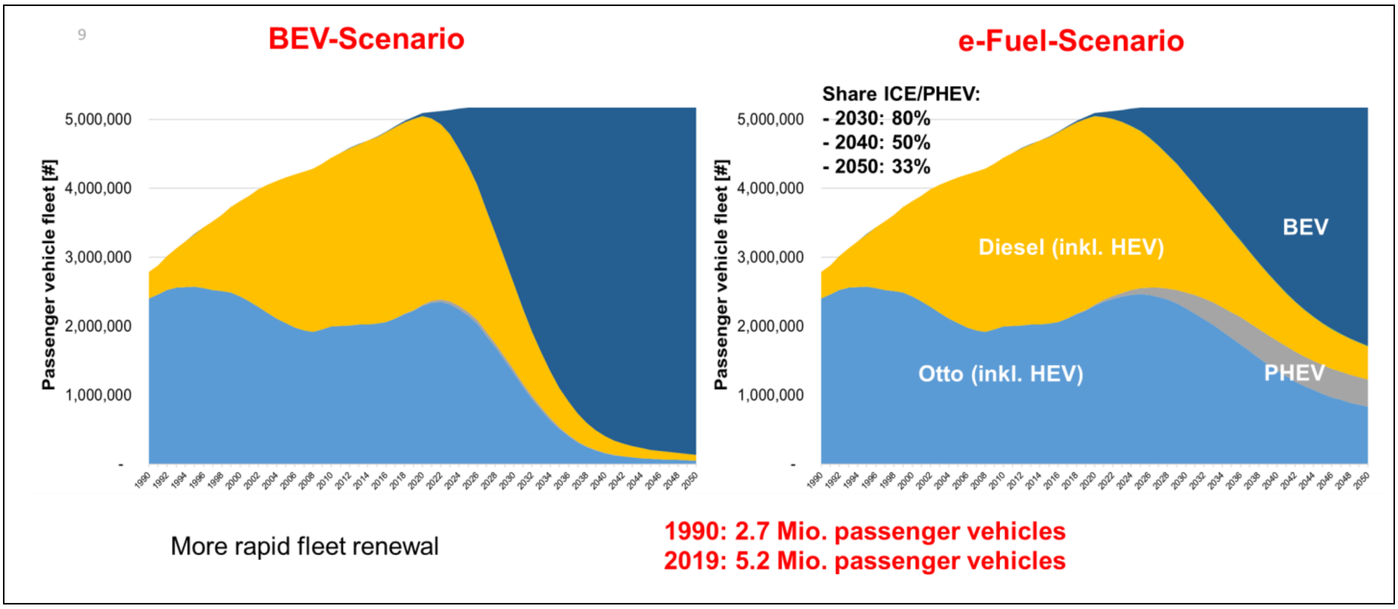

Figure 24: Development of passenger vehicle fleet for climate neutrality 2050

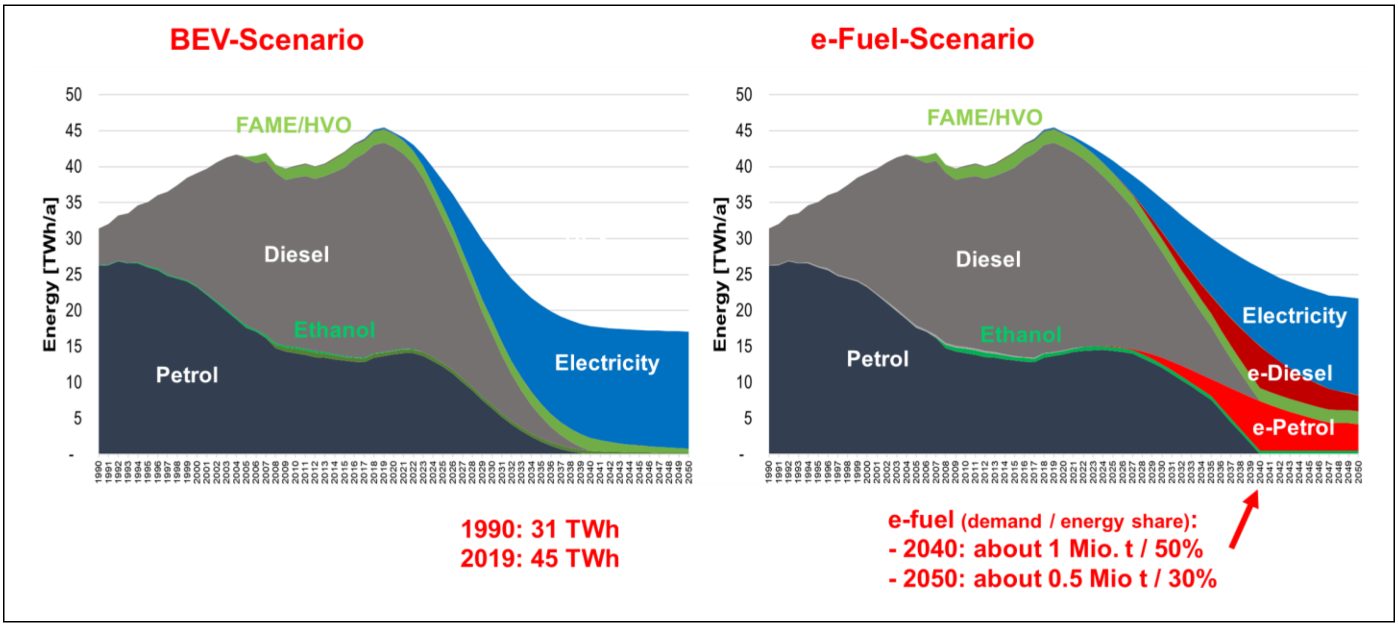

Figure 25: Passenger vehicle energy consumption

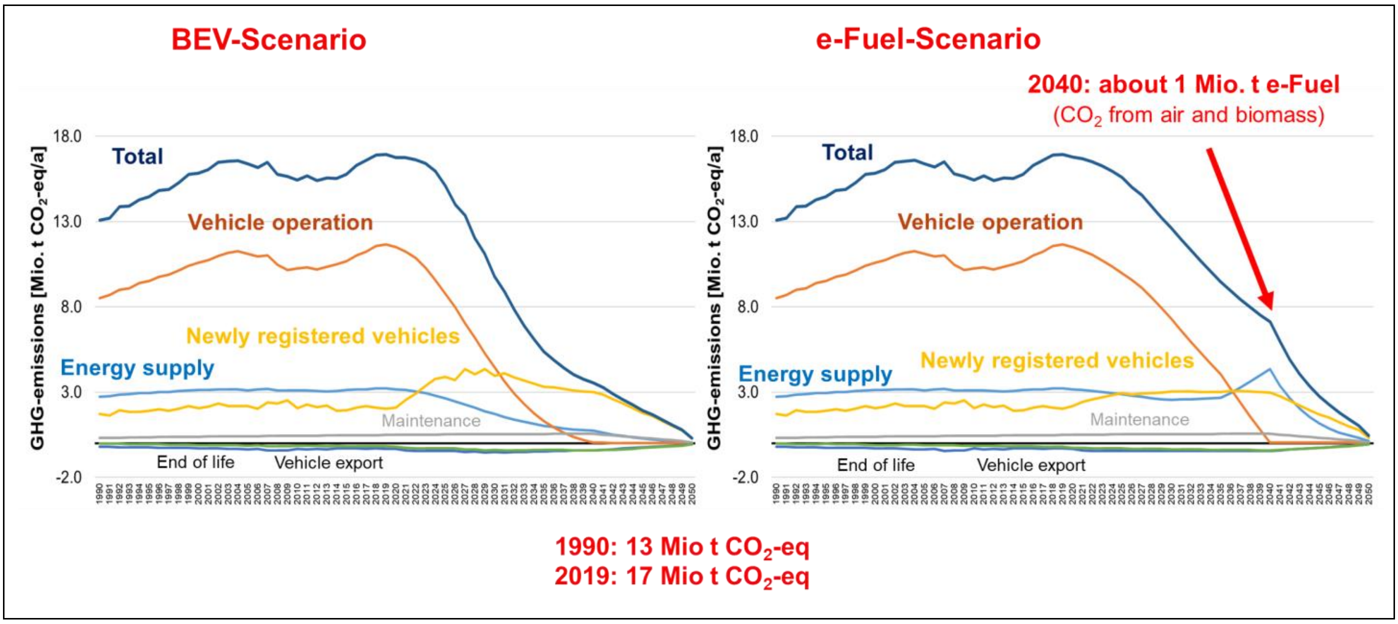

Figure 26: LCA based GHG-emissions of passenger vehicle fleet for climate neutrality 2050

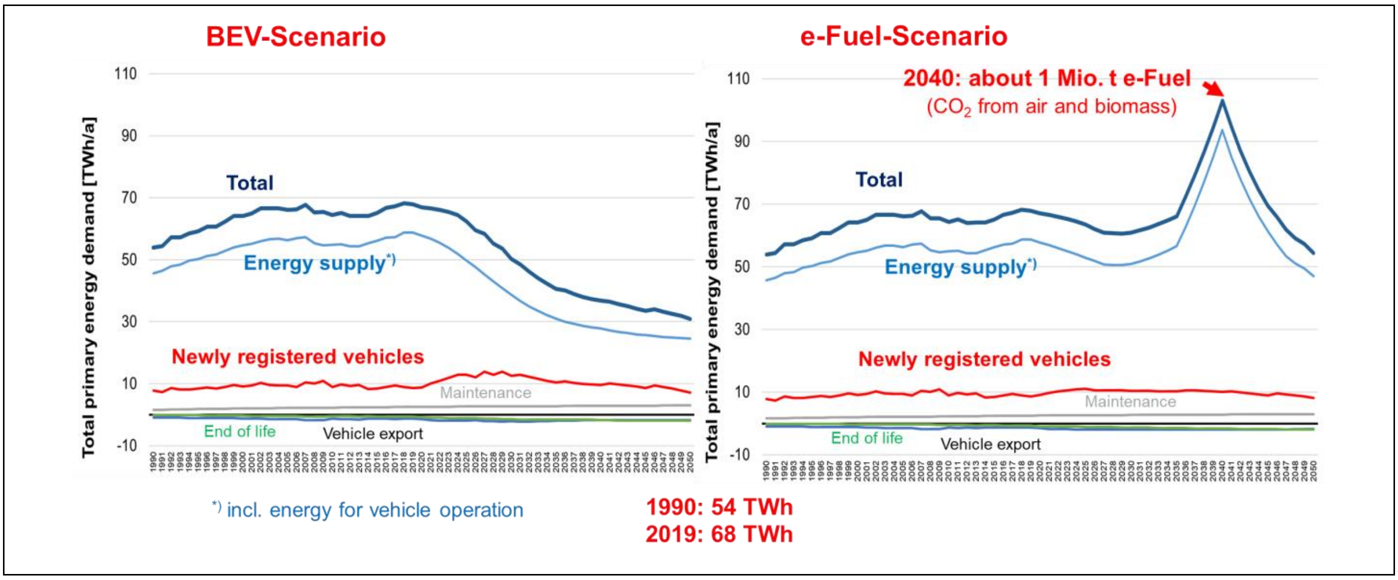

Figure 27: LCA based total primary energy demand of passenger vehicle fleet for climate neutrality 2050

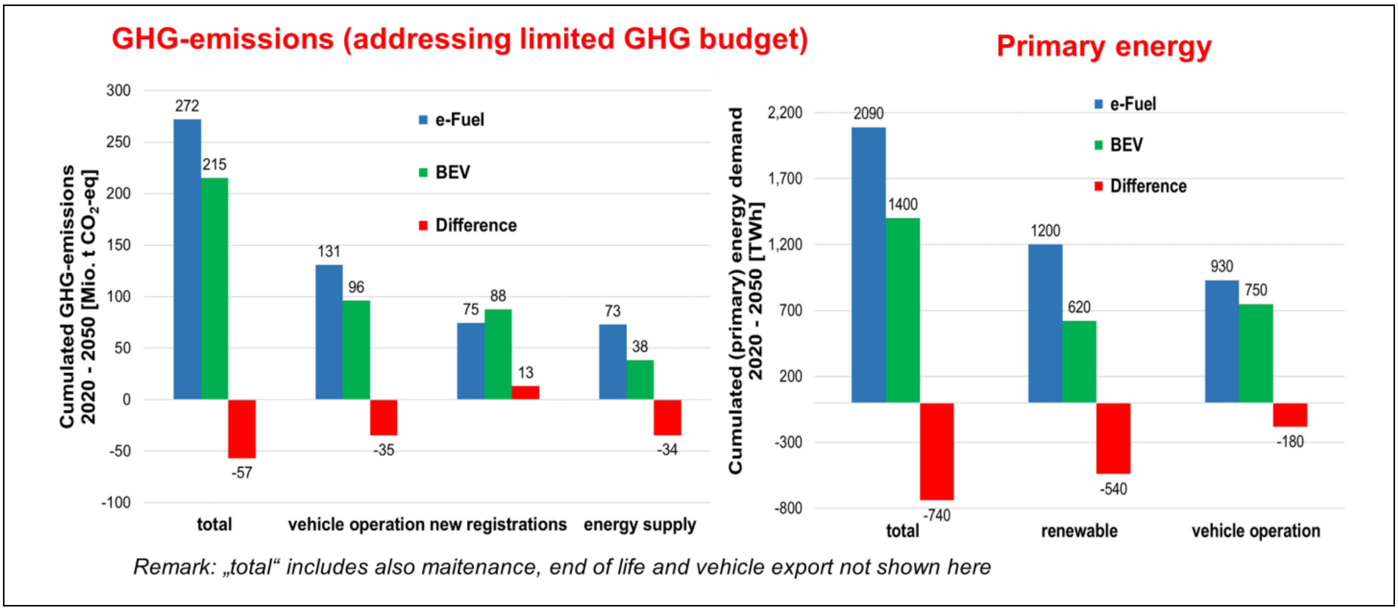

Figure 28: Cumulated results 2020 – 2050: BEV and e-Fuel-Scenario

The conclusions on dynamic LCA are:

- Timing of environmental effects in LCA of EVs production – operation - end of life phases becomes relevant in the transition time of:
  - strong BEV introduction in combination with a
  - strong increase of additional renewable electricity generation and
  - improvement of battery production technologies.
- Within the framework of LCA a methodology is developed and applied to the annual environmental effects of an increasing BEV fleet and substitution of ICE vehicles by considering the annual environmental effects of:
  - new vehicle production,
  - supply of renewable electricity from existing and new power plants,
  - substituted operation of ICE vehicles and
  - end of life of old vehicles.
- „Climate Neutrality“ with addressing the limited GHG budget for Paris Agreement is only possible on basis of dynamic LCA.

2.9 Dissemination Activities

The following dissemination and exploitation activities took place:

- Presentations:
  - *Experiences of in the IEA Collaboration Program on Hybrid and Electric Vehicles (HEV)*, EV2019 - Electric Vehicles International Conference & Show, October 3-4, 2019 in Bucuresti, Romania

- *Prüfstand „Lebenszyklusanalyse“: Klima- und Energiebilanz von Transportsystemen* (*Test Bench „Life Cycle Assessment“ – GHG and Energy Balance of Transportation Systems*), Symposium ZUKUNFT Gas-MOBILITÄT 2020; March 11 – 12, 2020
- *Most Climate-Friendly Propulsion with Renewable Fuel - Biofuel, Electricity, Hydrogen or e-Fuels*; ECO-Mobility – Virtual A3PS-Conference 2020
- *Climate Friendly Biofuels in Comparison to Other Fuels, Renewables in Transport*, Expert Talk, January 21, 2021, online
- *Climate Friendly Biofuels in Comparison to Other Fuels, Renewables in Transport*, Expert Talk, January 21, 2021, online
- *LCA Application to Growing EV-Fleets with Increasing Supply of Renewable Electricity – Methodological Aspects and Assessment for GHG Emissions of BEV Introduction in Austria*, IEA HEV Task 30 meeting, online, February 3, 2021
- *Greenhouse Gas and Energy Balance in the Life Cycle of Passenger Vehicles – Comparing E-Fuels and Electricity;* E-Fuels oder Verbrenner-Verbot?, Die Mobilitäts-Politik der EU am Scheideweg, 28.4.2021, online
- *GHG-Emissions of Additional Renewable Electricity in Austria and its Consequences on the Introduction of Electric Vehicles in a Dynamic LCA*, IEWT 2021, September 9 – 11, 2021, Vienna, Austria
- *Life Cycle Analysis of BEV and ICE, SEAI* National Energy Research & Policy Conference, November 25, 2021, Ireland
- *Scenarios for a Climate Neutral Vehicle Fleet in Austria Using Dynamic LCA*, 17. Symposium Energieinnovation, 16.-18. Februar 2022, Graz, Austria
- *Renewable Energy for Climate Friendly Lifestyles - Example Mobility Services with Battery Electric Vehicles*; for RENEWABLEMEET2022 - International Meet on Renewable and Sustainable Energy March 21-25, 2022, Dubai, UAE
- *Lesions Learnt in IEA HEV Task 30 - Recent Findings on the LCA of Electric Vehicles and its Possible Contributions to Climate Neutrality*, 4th Conference on Local E-mobility, April 13, Brno, Slovenija
- *Klimaneutrale Mobilität in Österreich – Methoden, Fakten und Mythen,* 5. Europäisches Forum Alpbach 2022, Session 7: Kreislauffähige und klimaneutrale Mobilität - Herausforderungen und Lösungen am Beispiel Fahrzeug, 26. August 2022

- Presentation & paper
  - *LCA Based Estimation of Environmental Effects of the Global Electric Vehicles Fleet - Facts&Figures from the IEA Technology Collaboration Program on Hybrid&Electric Vehicles*, Transport Research Arena TRA 2018 in Wien, 16-19 April 2018
  - *Water Issues and Electric Vehicles - Key Aspects and Examples in Life Cycle Assessment*, EVS31 – Electric Vehicle Symposium, Kobe, Japan, Sept. 30 – Oct 3, 2018

- *Time and Rebound Effects in the LCA of Electric Vehicles - Methodological Approach and Examples*, IEWT 2019, Vienna University of Technology, February 13 – 15, 2019
- *Evaluation of the Environmental Benefits of The Global EV-Fleet in 40 Countries – A LCA Based Estimation in IEA HEV*, EVS32 – Electric Vehicle Symposium Lyon, France, May. 19 – 22, 2019
- *Climate Neutrality of Growing Electric Vehicles Fleets (2010 - 2050) in a Dynamic LCA Considering Additional Renewable Electricity: Example Austria*; EVS35 Symposium Oslo, Norway, June 11-15, 2022

- Poster
  - *Environmental Effects of Electric Vehicles Globally - An Assessment in IEA HEV Task 30*, A3PS Conference 2018 "Future Propulsion Systems: Different Regions - Different Strategies - Different Solutions, November, 12 - 13 2018, Vienna, Austria
  - *Scenarios for a Climate Neutral Passenger Vehicle Fleet in Austria 2040 Using Dynamic LCA*, ECO-Mobility – A3PS-Conference 2021, November 18-19, 2021, Vienna, Austria
- Lecture:
  - *Electric Vehicle Lecture - Environmental Impacts of Electric Transport*, MSc Program "Renewable Energies" of Vienna University of Technology, online, February 13, 2021
- Presentation and working document:
  - *LCA Application to Growing EV-Fleets with Increasing Supply of Renewable Electricity – Methodological Aspects and Assessment for GHG Emissions of BEV Introduction in Austria*, IEA HEV Task 30 meeting, online, February 3, 2021
- Publications:
  - *An international dialogue about electric vehicle deployment to bring energy and greenhouse gas benefits through 2030 on a well-to-wheels basis*, Transportation Research Part D 74 (2019) 245–254
  - *Environmental Life Cycle Impacts of Automotive Batteries Based on a Literature Review*, Energies 2020, 13(23), 6345; https://doi.org/10.3390/en13236345
  - *GHG Emissions and Primary Energy Demand of Vehicle Fleets Based on Dynamic LCA Methodology – Introduction of Electric Vehicles in Austria 2010 – 2050*, 13th International Colloquium Fuels, September 15-16, 2021, Esslingen, Germany
- Working document of Task 30:
  - *Rebound Effects of Electric Vehicles and Possible Implication on Environmental Effects in LCA of Electric Vehicle*, status February 2021
  - *LCA Application to Growing EV-Fleets with Increasing Supply of Renewable Electricity – Methodological Aspects and Assessment for GHG Emissions of BEV Introduction in Austria*, status February 2021
- Contributions to the IEA HEV Annual Reports 2017, 2018, 2019, 2020, 2021 and 2022

- IEA HEV Newsletter
  - Contributions #1, #2 and #3 in 2021 and #1 in 2022
- Abstracts submitted
  - *Ökobilanz eines e-Bikes im Vergleich zum konventionellen Fahrrad*, 13. Österreichischer Radgipfel, 3. - 5. April 2022, Vienna, Austria; not accepted

3 Conclusions

3.1 Lesions Learnt

Based on the current trends the main challenges and R&D demand for electric vehicles are summarized and described.

3.1.1 Overview

The conclusion from the task work can briefly be summarized in the following 10 lessons learnt:

1. Methodology for Environmental Assessment: LCA not WtW,
2. System Boundary,
3. Systematic of Transportation Systems,
4. Main Factors Influencing LCA Results,
5. Possible Impacts and Impact Assessment Methodologies,
6. Minimum Requirements on Impact Assessment,
7. Main Water Issues in LCA of ICE and EV,
8. Recommendations for LCA of BEV, PHEV and ICE,
9. Potential Rebound Effects of EVs and
10. Dynamic LCA and Vehicle Fleets for Climate Neutrality 2050.

3.1.2 Methodology for Environmental Assessment: LCA not WtW

There is now an international consensus that the environmental effects of transportation systems can only be analysed and compared on the basis of LCA including the production, operation and the end of life treatment of the various facilities. Other methodologies like Well-to-wheel (WtW) or methodologies used in legislation, like in the Renewable Energy Directive in Europe, do only cover parts of the relevant stages in the lifecycle of a vehicle and its energy supply. These other methodologies exclude environmental effects from vehicle production and its end of life as well as the construction and dismantling of facilities to supply energy, e.g. electricity generation with wind and PV.

In Figure 29, the description of life cycle assessment is given, which must follow at least the guidelines given in ISO 14,044 with the phases of an LCA:

1) Goal and Scope Definition,

2) Inventory Analysis,

3) Impact Assessment and

4) Interpretation.

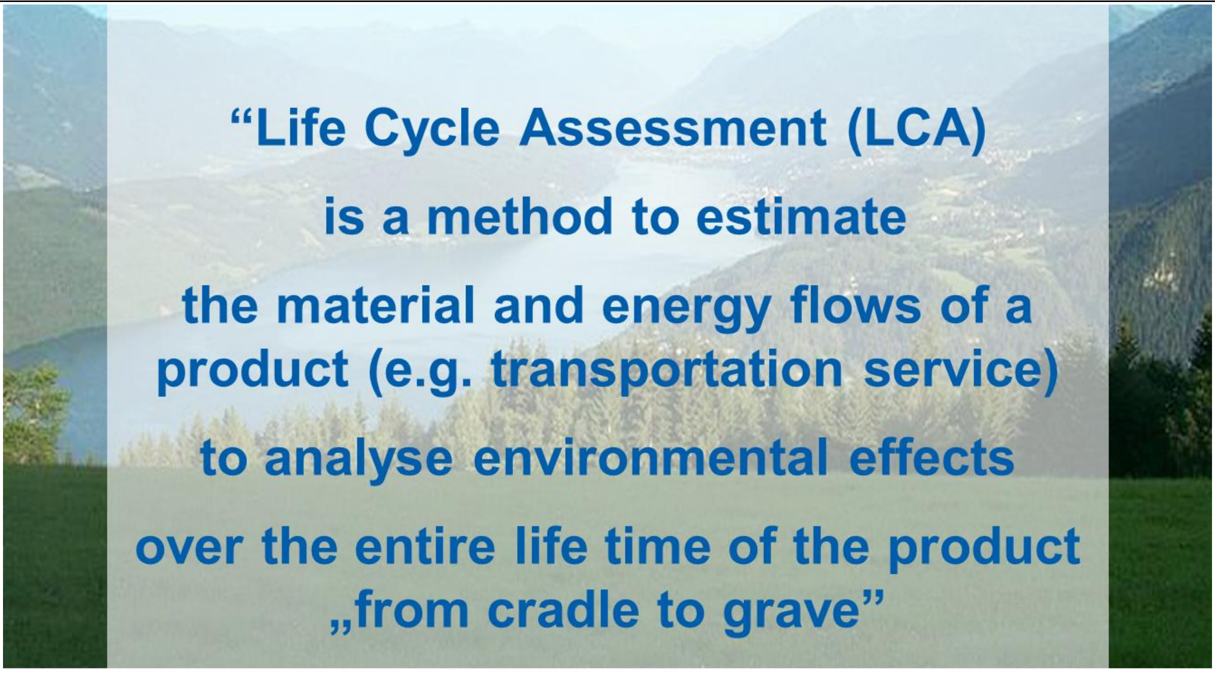

Figure 29: Lesson learnt #1: LCA is the only methodology for Environmental Assessment of EVs

3.1.3 System Boundary

The LCA of EVs and ICEs must cover the three phases in their life cycle:

1. production phase
2. operation phase and
3. end of life phase.

In the production phase, all components of the vehicle are relevant and for EVs especially the battery production is relevant. The operation phase covers the energy fuel supply, the maintenance, the auxiliary materials (e.g. add blue, lubricant oil) and spare parts. The end of life phase covers all recycling and use activities to provide secondary material and/or energy. All the energy and material inputs are based on their process chain starting with the natural resources.

In Figure 30, the system boundaries for an LCA of EVs is given, starting with natural resources for electricity generation (e.g. hydro, raw oil, coal) and ending with the supply of a transportation service. The main processes are:

- power plant (incl. coproduct heat from CHP power plants),
- electricity grid,
- storage system to balance - if necessary - the electricity supply and the electricity demand for charging,
- the charging station and
- the vehicle.

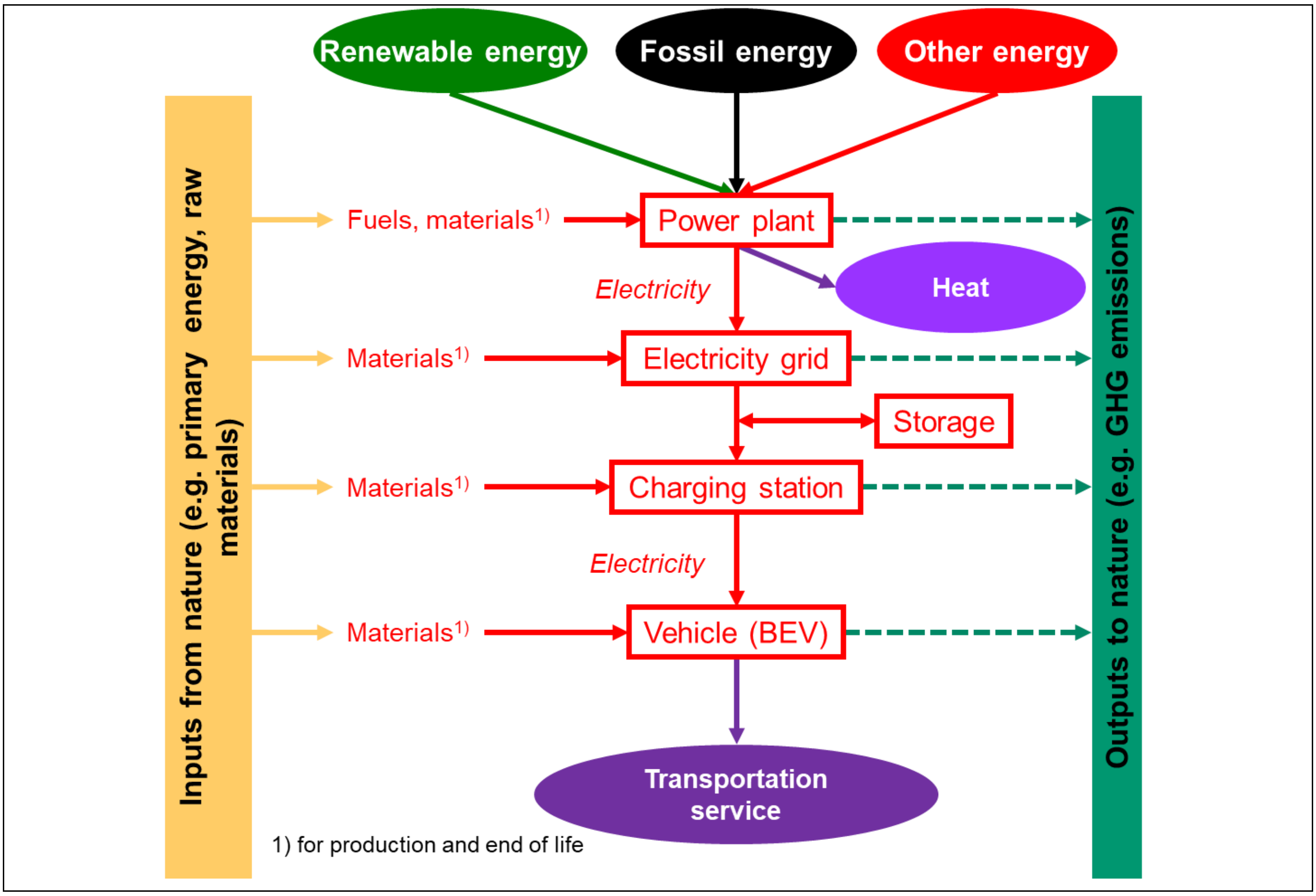

Figure 30: Lesson learnt #2: System boundaries

3.1.4 Systematic of Transportation Systems

The transportation system analysed must be characterised exactly be the following 6 criteria (Figure 31):

- type of vehicle,

- propulsion system,
- fuel/energy carrier,
- type of primary energy,
- state of technology and
- country.

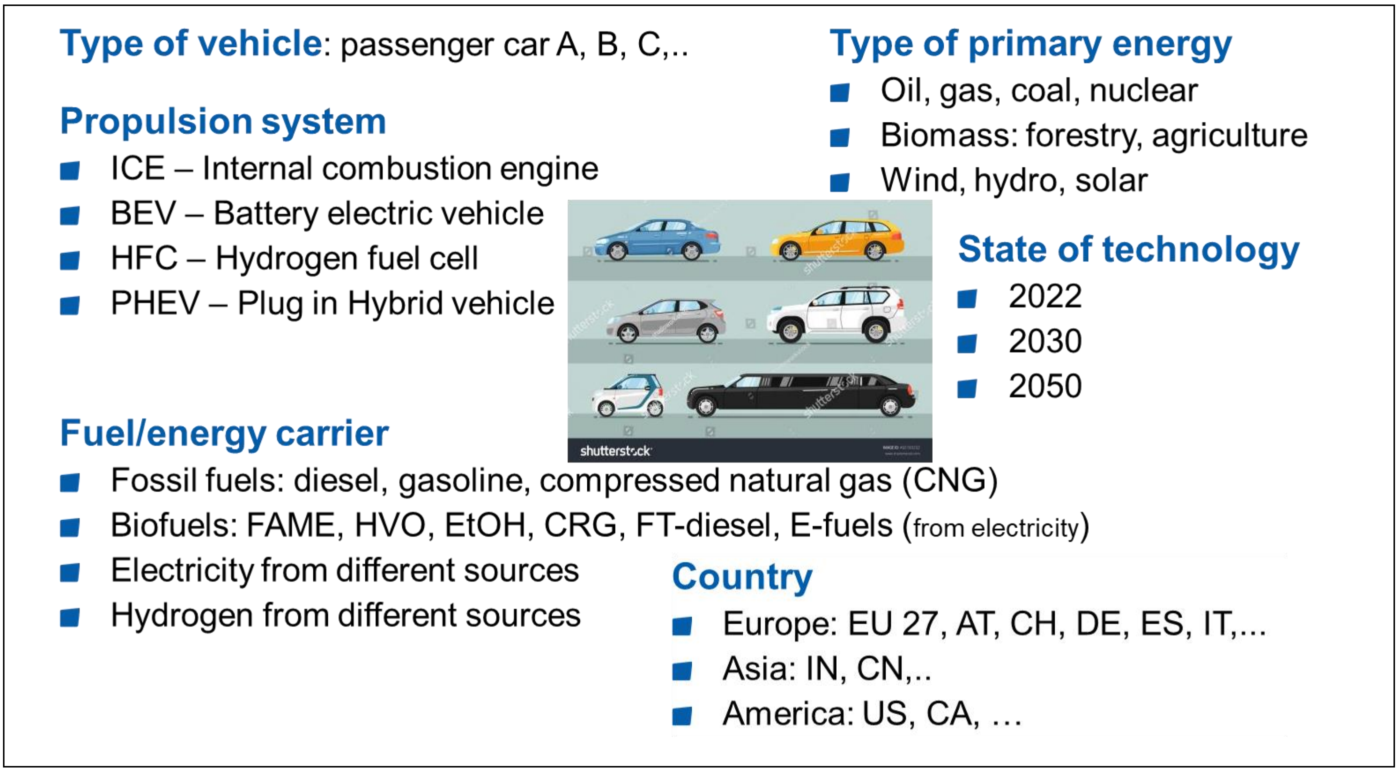

Figure 31: Lesson learnt #3: Systematic of transportation systems

3.1.5 Main Factors Influencing LCA Results

The main influencing factors in LCA of vehicles are:

- source of electricity generation and its future development up to 2030/2050,
- lifetime mileage,
- energy consumption of vehicle (incl. heating, cooling, auxiliaries) and electric share for PHEV,
- battery:
  - production: country, production capacity, source of electricity,
  - battery capacity,
  - end of life (material recycling or reuse in 2nd life),

- biofuels:
  - direct land use effects (dLUC),
  - indirect land use effects (iLUC),
  - type of feedstock (e.g. from agriculture, forestry or industrial residues),
- e-fuels:
  - source of CO_2,
  - „carbon neutral" only using CO_2 from air and sustainable biomass.

3.1.6 Possible Impacts and Impact Assessment Methodologies

The way from Inventory Analysis to Impact Assessment is via mid- and end-point indicators. With regard to the geographical scope of the different impacts, the mid-point indicators are grouped for global, regional and local impacts. The mid-point indicators on these geographical scopes are:

- global:
  - climate change,
  - ozone depletion,
  - primary energy use (consumption) (fossil and renewable),
  - resource use, minerals and metals,
  - water footprint (based on inventory level method),
  - land use (focus on inventory data),
- regional:
  - acidification,
  - photochemical ozone formation,
  - smog formation,
  - eutrophication, terrestrial, freshwater and marine,
  - ionising radiation,
- local:
  - human toxicity, cancer and non-cancer,
  - particulate matter,
  - land use,
  - water scarcity,
  - biodiversity and
  - ecotoxicity, fresh water aquatic, marine aquatic and terrestrial.

Water and land use were allocated to the global and to the regional level, whereas on global level mainly results from inventory analysis are relevant, whereas on local level a very distinctive methodology might be applied for local impact assessment based on very localized data.

The end-point indicators, which are always assessed on global scale, are:

- protection areas:

  - human health,
  - ecosystem health,
  - resource availability and
- external costs.

Due to the methodological complexity and uncertainty, the practical addressing and calculation of "end-point indicators" are not recommended for LCA of EVs and conventional vehicles.

The main relevant impacts with current state of impact assessment methodologies using available and robust inventory data in LCA are mainly for global impact categories.

These main global impact categories for transportation systems are:

- climate change,
- primary energy use (consumption) (fossil and renewable),
- resource use minerals and metals,
- water footprint (inventory level),
- ozone depletion and
- land use (inventory level).

3.1.7 Minimum Requirements on Impact Assessment

The minimum requirements in the impact assessment to compare different vehicles are the:

- GHG emissions in CO_2-equivalent with its share of CO_2, CH_4 and N_2O and
- primary energy demand in e.g. MJ with its share of fossil or renewable energy.

To illustrate these minimum requirements the LCA results are shown using wind electricity to provide transportation service with different propulsion and fuel systems (H2 fuel cell, BEV and ICE with e-fuel) in comparison to petrol and diesel in Figure 32. Of course, the GHG emissions are lower if renewable energy is used, but the primary energy demand gives information about the vehicle with the highest energy efficiency from primary energy to transportation service, e.g. BEV are most energy efficient.

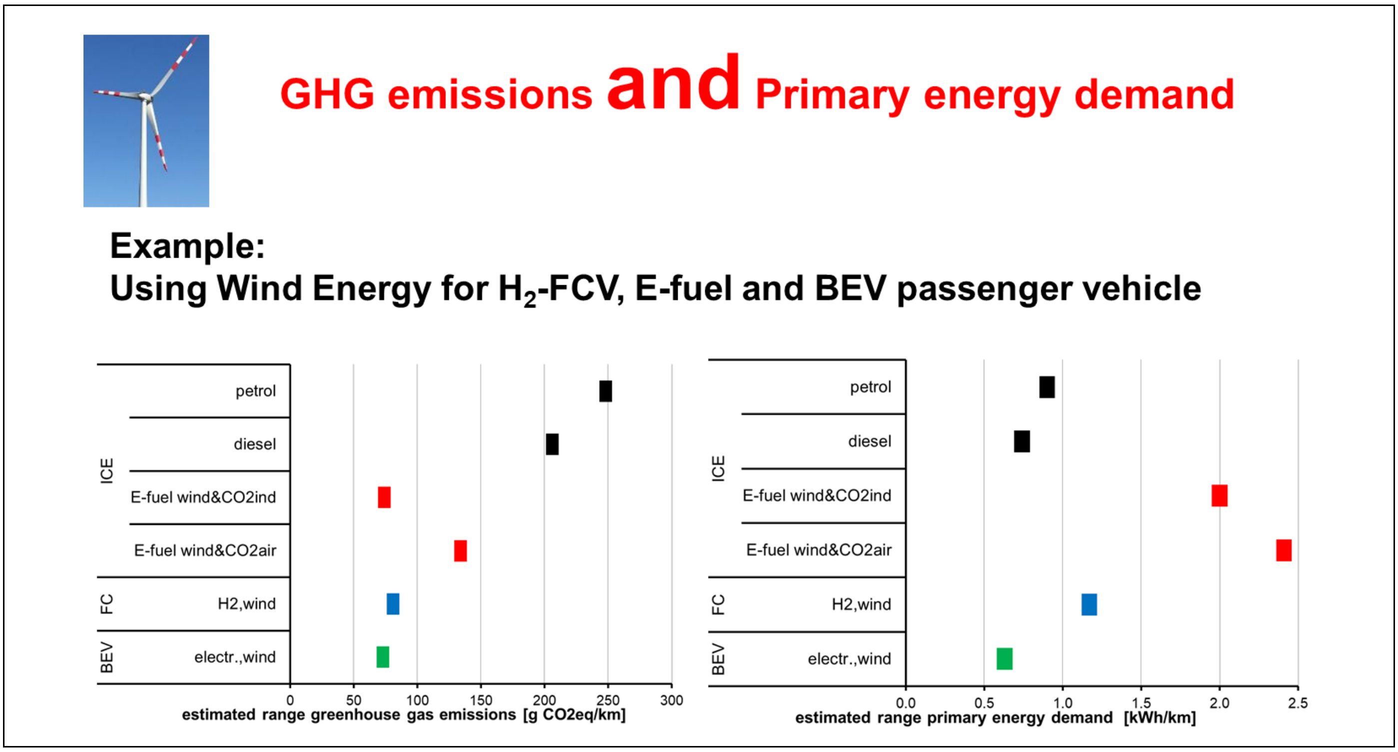

Figure 32: Lesson learnt #5: GHG emissions and primary energy demand as minimum requirements in impact assessment

3.1.8 Main Water Issues in LCA of ICE and EV

The main water issues in LCA of ICE and EV identified so far are:

- ICE (incl. blending of biofuels):
  - fossil fuel extraction and refining,
  - cultivation of feedstock for biofuels, e.g. for biodiesel (B5), bioethanol (E10),
  - vehicle production,
- EV (BEV and PHEV):
  - electricity generation (e.g. thermal open/closed cycle, hydro power),
  - battery production and
  - vehicle production.

3.1.9 Recommendations for LCA of BEV, PHEV and ICE

The main global impacts should be addressed (in future) (Figure 33):

- climate change,

- primary energy use (fossil and renewable),
- resource use minerals and metals,
- water footprint (inventory level),
- land use (inventory level).

For EVs (incl. batteries) and renewable electricity generation the type and amount of material used in the construction phase becomes more relevant than for conventional vehicles using raw oil. Therefore, the impact category of "Resource use, mineral and metals" becomes a more relevant global impact category. Concluding, an advanced requirement for LCA should be to calculate the amount of material in the inventory analysis especially for the most relevant materials like Cu, Li, Co, Ni, Mn and others. Based on the inventory the resource use should be assessed based on kg Sb-eq and giving the main contributions from single minerals or metals.

Water issues are also relevant, especially for mining activities, lithium extraction and hydro power. So on global scale the Water Footprint using the inventory based methodology should be assessed in future LCA of EVs and ICEs.

In addition, land use aspects are relevant for mining of raw materials as well as for renewable electricity production. As a next step in LCA of EVs the amount of land or land occupation over time should be analysed in the inventory phase by at least differentiation on the type of land: agriculture, forestry, infrastructure, industrial area or any other type of land.

The results on the considered global impact categories should be documented and communicated not only for the total value but also for the three main phases in the life cycle of a transportation system:

- production:
  - Vehicle,
  - energy/battery storage,
- operation:
  - fuel/energy supply,
  - fuel use,
  - maintenance,
- end of life:
  - recycling and/or reuse and
  - substitution of secondary material.

The main influencing parameters on the global impacts should be identified and described.

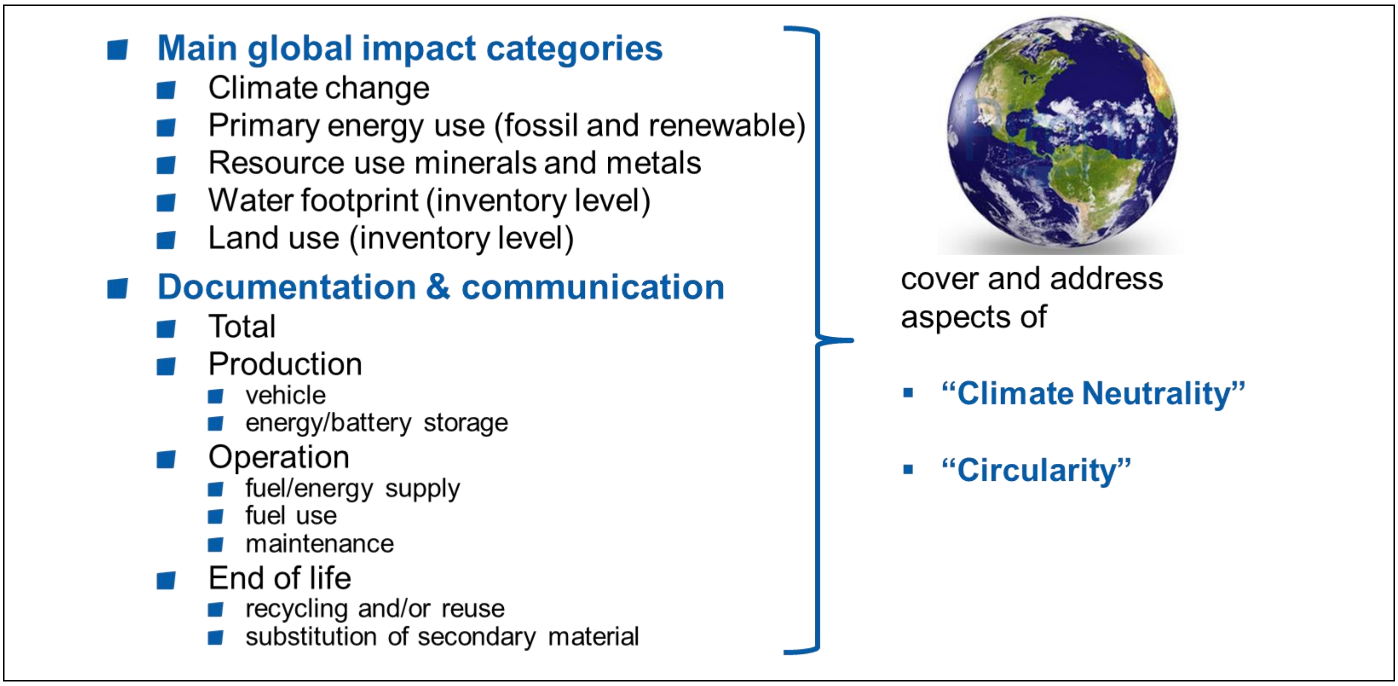

Figure 33: Lesson learnt #8: Main global impacts and documentation requirements

3.1.10 Potential Rebound Effects of EVs

In LCA of EVs and conventional ICE vehicles the environmental effects are given for the functional unit of 1 driven kilometre, in comparison to other transportation modes like buses, trains and trams the functional unit is often per passenger kilometre. Depending on the goal and scope of the LCA, also the annual environmental effects or the cumulated effects over the lifetime are relevant.

LCA methodology according to ISO 14,040 defines the functional unit as the basis for comparison of environmental effects of different systems, which provide the same service or function. Therefore, in the comparison based on LCA it is assumed that the functional unit or service of a system can be provided and substituted by another system. However, due to possible rebound effects, it is possible that a system A cannot substitute a system B for 100%. That is why in LCA of EVs especially for EV fleets it must be proven that no rebound effects are possible, or rebound effects have to be considered.

The possible rebound effect can be considered in LCA by the definition of the functional unit and the substitution rate. In reflecting possible rebound effects in comparing the environmental effects of EVs with conventional ICE vehicles the following issues are relevant and have to be analysed and described referring to possible different uses of the vehicles:

- number of substituted ICE vehicles,
- substituted other transportation modes e.g. public transport, walking,
- different annual mileage,
- vehicle lifetime and

- driving distance with one charging or refill.

These aspects must be considered carefully by defining the functional unit. The possible conclusion might be that the substitution rate is not 100%, it could be in most cases less than 100% but in specific cases also more than 100%, saying that 1 electric driven kilometre substitutes more than 1 fossil ICE driven kilometre.

The analysis of these issues should be documented in LCA to argue for the chosen substitution rate.

Current experiences in considering rebound effects in LCA show that these are most relevant by considering environmental effects of whole vehicle fleets over time and future scenarios for the development of environmental benefits of EVs in scenarios for transportation services and or mobility systems. In these cases, the influence of possible rebound effects have to be reflected in LCA. A recommendation for practical application is to make sensitivity analyses on various substitution rates to identify the order of magnitude on the final results.

3.1.11 Dynamic LCA and Vehicle Fleets for Climate Neutrality 2050

Issues on dynamic LCA, e.g. annual environmental effects, become relevant for the rapidly increasing of EV fleets combined with an additional generation of renewable electricity. Therefore, the Task identified the following relevant methodological aspects:

- timing of environmental effects in the three lifecycle phases,
- timing of environmental effects of increasing supply of renewable electricity,
- timing of environmental effects of EVs using increasing supply of renewable electricity and
- substitution effects and timing of environmental effects of EVs substituting for ICE vehicles.

All environmental effects based on LCA should be calculated and should be shown over time, e.g. a new BEV in 2022 charges changing electricity mix in the years during its life time. Due to climate goals, the electricity mix might change rapidly in future, this must be reflected in the dynamic LCA.

3.2 Outlook

The described global indicators also cover and address aspects of the two most relevant environmental aspects currently under public and political agenda e.g. within the GreenDeal:

- “Climate neutrality” and
- “Circularity”.

However, as these aspects are relevant in a dynamic system perspective, e.g. recycling to secondary material, further methodological developments are necessary to integrate them in LCA.

Considering current international LCAs on EVs in comparison to ICE, it becomes obvious that Global Warming and Primary Energy Demand are a minimum requirement and state of the art in impact assessment. LCAs disregarding one of these two impacts are too limited or misleading in their conclusions and interpretations.

It is expected, that the other global impacts - Resource Use, Water Footprint and Land Use – will be analysed and assessed in LCA of EVs in future more often, using the rapid international progress made for inventory data.

Considering the local and regional impact categories in LCA, further methodological developments, better inventory data and general acceptance are necessary. Alternatively, these environmental impacts (e.g. biodiversity) will be addressed with other methodologies than LCA more adequate in future.

The new IEA HEV TCP Task 46 (2022 – 2024) "LCA of electric Trucks, Buses, 2-Wheelers and other Vehicles" will address these global impact categories further and intends to develop and discuss new approaches to address "Climate Neutrality" and "Circularity" of transportation system in (dynamic) LCA.

Annex 1: Expert Workshop on Water Issues

Annex 2: Expert Workshop on Effects on Air

Annex 3: Expert Workshop on Resources, Waste and Land Use (incl. LCA Autonomous Vehicles)

Annex 4: Expert Workshop on Impact Assessment