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Der vorliegende Bericht dokumentiert die Ergebnisse eines Projekts im Rahmen der IEA Forschungskooperation. Es wurde vom Bundesministerium für Innovation, Mobilität und Infrastruktur (BMIMI) initiiert, um österreichische Forschungsbeiträge zu den Kooperationsprojekten der Internationalen Energieagentur (IEA) zu unterstützen.

Die IEA Forschungskooperationen umfassen eine breite Palette an Energiethemen mit dem Ziel Energiesysteme, Städte, Mobilitäts- und Industriesysteme fit für eine nachhaltige Zukunft bis 2050 zu machen. Auch Themen wie Gendergerechtigkeit oder Ressourcen- und Kreislaufwirtschaftsaspekte werden berücksichtigt.

Dank des überdurchschnittlichen Engagements der beteiligten Forschungseinrichtungen und Unternehmen ist Österreich erfolgreich in der IEA verankert. Durch die vielen IEA-Projekte entstanden bereits wertvolle Inputs für europäische und nationale Energieinnovationen und neue internationale Standards. Auch in der Marktumsetzung konnten richtungsweisende Ergebnisse erzielt werden.

Ein wichtiges Anliegen ist es, die Projektergebnisse einer interessierten Öffentlichkeit zugänglich zu machen. Daher werden alle Berichte nach dem Open Access Prinzip in der Schriftenreihe des BMIMI über die Plattform nachhaltigwirtschaften.at veröffentlicht.

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1 Kurzfassung

Motivation und Forschungsfrage

Das Technology Collaboration Program (TCP) der Internationalen Energieagentur (IEA) on Electric Vehicles (EV) hat das Ziel, ausgewogene und objektive Informationen über zukunftsweisende Elektrofahrzeuge zu schaffen und diese Informationen für staatliche Institutionen und lokale Entscheidungsträger zusammenzutragen. Das Ziel dieser F&E-Dienstleistung ist die Teilnahme an der Task 46 „*LCA of Electric Trucks, Buses, other Vehicles and V2X-Services" (Lebenszyklusanalyse von elektrischen Lkws, Bussen, anderen Fahrzeugen und V2X-Dienstleistungen),* um zu den international vereinbarten Themen beizutragen und die Leitung der Task 46 als Task Manager.

Es besteht ein internationaler Konsens darüber, dass die Umweltwirkungen von Elektrofahrzeugen im Vergleich zu anderen Antriebssystemen und Energieträgern nur auf der Grundlage einer Lebenszyklusanalyse (LCA) bewertet werden können. Dies umfasst die Produktion des Fahrzeugs und der notwendigen Infrastruktur, den Betrieb der Fahrzeuge einschließlich der Bereitstellung der Energieträger und die Verwertung am Ende der Lebenszeit des Fahrzeugs und seiner Komponenten. Aus diesem Grund hatte das EV TCP seit 2011 Task-Aktivitäten zu LCA, die in Task 46 fortgesetzt werden.

Ausgangssituation/Status Quo

Die Task 46 baut auf den vorangegangenen Tasks „*Assessment of Environmental Effects of Electric Vehicles*" (2016 - 2021) auf und weitet ihren Fokus von Pkw auf weitere UNECE-Klassen wie Busse, Schwer- und Lieferwagen und andere Arbeitsmaschinen mit der notwendigen Ladeinfrastruktur aus. Der Schwerpunkt der international vereinbarten Themen liegt auf der Erarbeitung eines gemeinsamen LCA-Ansatzes mit Fokus auf Klimaneutralität und Zirkularität für diese Fahrzeugklassen unter den teilnehmenden Ländern. Dieser gemeinsame Ansatz wird sowohl der IEA als Organisation als auch den teilnehmenden Partnerländern einen besseren, faktenbasierten Vergleich der Umweltauswirkungen elektrisch betriebener Antriebssysteme, d. h. batterieelektrischer Fahrzeuge, Wasserstoff-Brennstoffzellenfahrzeuge und E-Fuel-Fahrzeuge mit Verbrennungsmotor, im Vergleich zu herkömmlichen Kraftstoffen ermöglichen. Die LCA-Ergebnisse werden in Fallstudien für unterschiedliche Fahrzeugklassen dokumentiert.

Projekt-Inhalte und Zielsetzungen

Task 46 konzentriert sich auf die Bewertung von Zirkularität und Klimaneutralität mithilfe dynamischer LCAs, die auf der Expertise der Mitglieder aus den 13 Mitgliedsländern – Österreich, Australien (Observer), Kanada, Europäische Kommission, Deutschland, Niederlande, Norwegen, Republik Korea, Spanien, Schweiz, Türkei (Observer), Großbritannien und USA – basieren. Der Task 46 analysiert verschiedene Umwelteffekte mittels LCA von strombasierten Antriebssystemen – batterieelektrisch, Wasserstoff-Brennstoffzelle und E-Fuels – im Vergleich zu fossilen Kraftstoffen. Neben der Identifizierung der relevantesten methodischen Fragestellungen, notwendigen Grunddaten und Wirkungskategorien werden neue Ansätze zur Bewertung von "Klimaneutralität" und "Zirkularität" aus der LCA-Perspektive entwickelt und in Fallstudien angewendet. Die Fallstudien beziehen

sich auf Lkw, Busse, V2X-Dienste, Leichtelektrofahrzeuge und Spezialfahrzeuge für Bergbau und Feuerwehr.

Methodische Vorgehensweise

Die methodische Vorgehensweise umfasst:

- Klimaneutralitätspotenzial und Zirkularitätspotenzial werden definiert und in einer dynamischen LCA bewertet.
- Die wichtigsten zu berücksichtigenden Umweltauswirkungen werden untersucht: Treibhausgas(THG)-Emissionen (inkl. direkte H_2-Emissionen), (nicht-)erneuerbare Primärenergie, (nicht-)zirkuläre Masse, Klimaneutralitätspotenzial und Zirkularitätspotenzial.
- Es werden verschiedene LCA-Fallstudien durchgeführt: Lkws, Stadtbusse, Feuerwehrautos, SUVs, LEV, Bergbaufahrzeuge, V2X-Dienstleistungen mit neu installierten Kraftwerken für erneuerbaren Strom im Vergleich zu Benzin, Diesel und Wasserstoff & E-Fuel mit erneuerbarem Strom.

Ergebnisse und Schlussfolgerungen

Im Rahmen der LCA wird eine Definition von Klimaneutralität und Zirkularität entwickelt: *„Ein Produkt oder eine Dienstleistung ist „klimaneutral" und „zirkulär", wenn im gesamten Lebenszyklus - Produktion, Betrieb und Verwertung am Ende der Lebensdauer - nur wiederverwendete Komponenten, Sekundär-/Recyclingmaterial und erneuerbare Energie verwendet werden und kein Abfall und keine Treibhausgasemissionen verursacht werden".*

Die wichtigsten Ergebnisse sind:

- Batterieelektrische Fahrzeuge, die mit erneuerbarem Strom betrieben werden, haben im Vergleich zu anderen Transportsystemen die geringsten Umweltauswirkungen.
- Die Haupteinflüsse auf die Umweltauswirkungen der elektrischen Fahrzeuge sind
  - Energiebedarf des Fahrzeugs,
  - Stromquelle,
  - Batteriekapazität,
  - Lebensdauer und jährliche Betriebsstunden.
- Bedeutung von Klimaneutralitätspotenzial & Zirkularitätspotenzial
  - Möglicherweise sind das zwei zusätzliche weitere Umweltauswirkungen in der LCA, die bisher bei den Umweltauswirkungen nicht abgedeckt werden.
  - Nur Systeme, die erneuerbare Energien nutzen, haben das Potenzial in Richtung Klimaneutralität und Zirkularität.
  - 100% Klimaneutralität ist nur in Kombination mit Carbon Capture & Storage (CCS) möglich.

Ausblick

Die Ergebnisse werden breit für die relevanten Stakeholder verbreitet und zugänglich gemacht. Im Team wurde eine neue Task 52 „*Electric Vehicles and Circularity*" entwickelt und im Jahr 2025 im EV TCP gestartet.

2 Abstract

Motivation and research question

The Technology Collaboration Program (TCP) of the International Energy Agency (IEA) on Electric Vehicles (EV) has the aim to create balanced and objective information on forward-looking electric-vehicles and to compile this information for governmental institutions and local decision makers. The objective of this R&D service is the participation in Task 46 *"LCA of Electric Trucks, Buses, other Vehicles and V2X-Services",* to contribute to the internationally agreed topics and the leading of the Task 46 as Task Manager.

There is an international consensus that the environmental effects of electric vehicles in comparison to other propulsion systems and energy carriers can only be assessed based on Life Cycle Assessment (LCA); this covers the production of the vehicle and its necessary infrastructure, the operation of the vehicles including the supply of the energy carriers and the end-of-life of the vehicle and its components. For that reason, the EV TCP had tasks dealing with LCA since 2011, which is continued in Task 46.

Initial situation/status quo

The Task 46 is based on the previous EV tasks 30 *"Assessment of Environmental Effects of Electric Vehicles"* (2016 - 2021) and expands its focus from passenger vehicles to further UNECE-classes like bus, heavy and delivery trucks, and other working machines with its necessary charging infrastructure. The main emphasis of the internationally agreed topics is the elaboration of a common LCA approach with a focus on Climate Neutrality and Circularity for these vehicle classes among the participating countries. This common approach will give the IEA as organisation as well as the participating partner countries a better, fact-based comparison of environmental effects of propulsion systems based on electricity, which are battery electric vehicles, hydrogen fuel cell vehicles and e-fuel vehicles with an internal combustion engine in comparison to conventional fuels. The LCA results are documented in case studies for different vehicles.

Project contents and objectives

Task 46 focuses on assessing Circularity and Climate Neutrality using dynamic LCA based on the expertise of the members from the 13 member countries – Austria, Australia (observer), Canada, European Commission, Germany, Norway, Republic of Korea, Spain, Switzerland, The Netherlands, Turkey (observer), UK, USA. The Task 46 analysis different environmental effects using LCA of electricity-based propulsion systems – battery electric, hydrogen fuel cell and e-fuels - in comparison to fossil fuels. In addition to the identification of the most relevant methodological issues, necessary inventory data and impact categories, new approaches for assessing "climate neutrality" and "circularity" in a LCA perspective are developed and applied in case studies. The case studies are on trucks, buses, V2X-services, light electric vehicles and on special vehicles for mining and fire department.

Methodical procedure

The methodological developments are:

- Climate Neutrality Potential & Circularity Potential are defined and assessed in dynamic LCA.

- The key impacts considered are: GHG emissions (incl. direct H_2-emissions), (non-)renewable primary energy, (non-)circular mass, Climate Neutrality Potential & Circularity Potential.
- Various LCA case studies are performed: trucks, city bus, fire truck, SUV, LEV, mining haul, V2X-services using newly installed renewable electricity plants in comparison to petrol, diesel, and hydrogen & e-fuel using renewable electricity.

Results and conclusions

In the context of LCA a definition of Climate Neutrality and Circularity is developed: *"A product or service is "climate neutral" and "circular", if its whole life cycle - production, operation and end-of-life - uses only reused components, secondary/recycled material, renewable energy and makes zero waste and zero GHG emissions"*.

The key results are:

- Battery electric vehicles using renewable electricity have best environmental performance compared to others.
- Main influences on impacts of electric vehicles are
  - Energy demand of vehicle,
  - Source of electricity,
  - Battery capacity,
  - Lifetime and annual operating hours.
- Climate Neutrality Potential & Circularity Potential
  - Both might be two additional impact categories in LCA.
  - Only systems using renewable energy have the potential towards Climate Neutrality & Circularity.
  - 100% Climate Neutrality is only possible in combination with Carbon Capture & Storage (CCS).

Outlook

The results are broadly disseminated and among the team a new Task 52 *"Electric Vehicles and Circularity*" was developed and started in the EV TCP in 2025.

3 Background

Electric vehicles have the potential to substitute conventional vehicles to contribute to a sustainable development of the transportation sector worldwide, for example, in the reduction of greenhouse gas (GHG) and particulate emissions.

The EV TCP has the aim to create balanced and objective information on forward-looking electric, hybrid and fuel cell vehicles and to compile this information for governmental institutions and local decision makers.

The working program of the EV TCP includes a broad information exchange of programs and technologies in each of its member countries, studies on energetic and environmental impacts of electric vehicles and an analysis of necessary infrastructure and storage technologies. Moreover, trends and technological requirements of future hybrid vehicles are analysed.

There is international consensus that the improvement of the sustainability of electric vehicles can only be analysed based on life cycle assessment (LCA), which includes the production, operation, and the end-of-life treatment of the vehicles and the energy/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 materials are used to produce new vehicles or other products.

The main activities influencing the environmental impacts of electric vehicles on a life cycle basis are:

1. Production and lifetime of the battery,
2. Electricity consumption of the vehicle in the operation phase, incl. e.g. energy demand for heating,
3. Source of the electricity, only additional renewable electricity maximizes the environmental benefits and
4. End of life treatment of the vehicle and its battery (e.g. reuse, material recycling).

Since 2011, the Technology Collaboration Program (TCP) on “Electric Vehicle (EV)” of the International Energy Agency (IEA) is operating tasks dealing with various aspects of LCA of different vehicles. In recent Tasks 19 and 30, there was a strong focus on LCA of passenger vehicles and its comparison to gasoline and diesel vehicles. However, due to the strong development and market introduction of other battery electric vehicles this Task 46 focuses on LCA of other battery electric vehicles (BEV) than passenger cars and also compares the environmental impacts to other fuels

made from electricity like hydrogen and e-fuels. These are hydrogen fuel cell vehicles (H_2-FCV) and internal combustion engines using e-fuels (e-fuel ICE).

The objective of this R&D service is the participation in Task 46 *"LCA of Electric Trucks, Buses, Two-Wheelers and V2X-Services"* by working on the internationally agreed topics and the leading of the task as Task Manager.

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4 Objectives of the Task

4.1 Motivation

The Task 46 is based on the previous EV tasks 30 *"Assessment of Environmental Effects of Electric Vehicles"* (2016 - 2021) and expands its focus on passenger vehicles (M1) to further UNECE-classes like two-wheelers, bus, heavy and delivery trucks, and other working machines (L, M, N) with its necessary charging infrastructure. The main emphasis of the internationally agreed topics is the elaboration of a common LCA approach for this vehicle classes among the participating countries. This common approach gives the IEA as organisation as well as the participating partner countries a better, fact-based comparison of environmental effects of propulsion systems based on electricity, which are battery electric vehicles, hydrogen fuel cell vehicles and e-fuel vehicles with an internal combustion engine in comparison to conventional fuels. The LCA results are documented in case studies for the considered different vehicles.

4.2 Goal and Scope

The main objectives of the task are:

1. Elaboration and deepening of a common approach to LCA methodology of the considered vehicle classes within the participating countries and the IEA, in which a focus is put on the assessment on "climate neutrality" and "circularity" in a life cycle perspective.
2. Elaborate LCA case studies on urban buses, trucks (last mile and long distance) and V2X-services including the necessary charging infrastructure, which are based on technology and system descriptions established in cooperation with other EV tasks, e.g. Task 50 "Leight Electric Vehicles".
3. Organisation and execution of at least three international expert workshops.

The developed approaches on Climate Neutrality and Circularity Assessments are applied in six LCA case studies on

1. Trucks (N1, N2 and N3)
2. Fire trucks
3. Mining haul truck
4. City buses
5. Light Electric Vehicles (LEV) and
6. V2X-services.

Finally, also the necessary further R&D demand is identified. All activities are in close interaction and exchange with stakeholders and broad dissemination activities are established with various distribution pathways.

Austria takes over the role of the Task Manger in order to lead and coordinate the task. The Austrian Task Manager also fulfils the report obligations to the ExCo and the Technical Committee for the annual task assessment.

4.3 Approach

The approach includes the following four main activities of Task 46 (Figure 1)

1. Technology and system description with vehicle and infrastructure data, relevant issues and LCA data on buses, trucks, other vehicles and V2X services with different fuel/propulsion systems
2. LCA cases studies to apply new approach to assess Climate Neutrality and Circularity
3. Expert workshops and stakeholder involvement
4. Documentation and dissemination

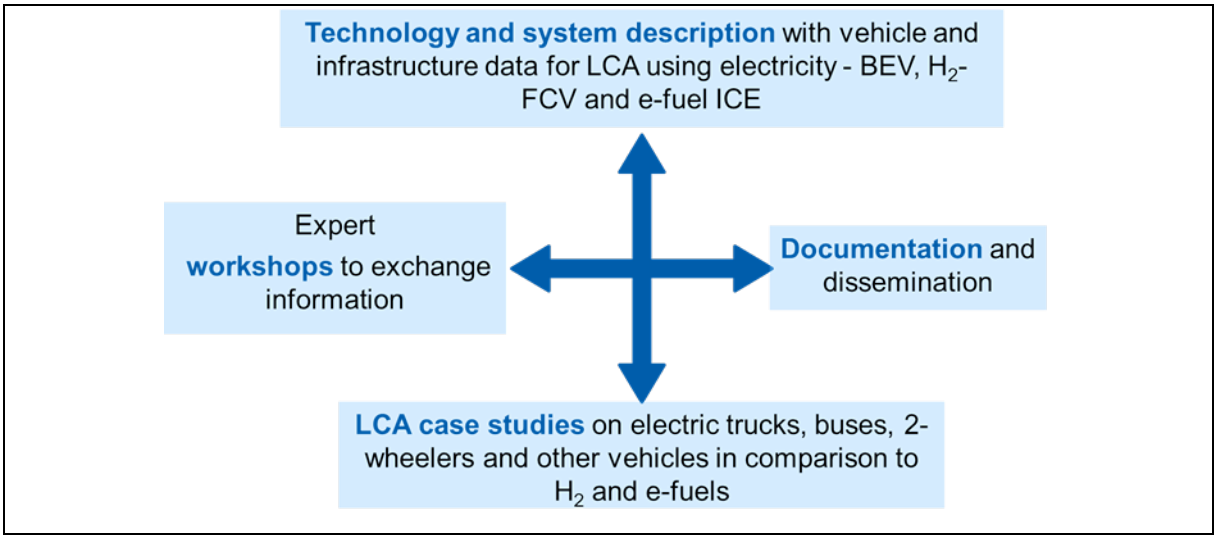


Figure 1: Main objectives of Task 46 (JOANNEUM RESEARCH)

In the six LCA case studies the electric vehicles are compared to vehicles with conventional fuels (diesel, petrol and natural gas), with hydrogen fuel cell and e-fuel ICE vehicles. The electricity for the EVs is produced from renewable sources; the hydrogen and e-fuel are also made from renewable electricity. The e-fuels use CO_2 from air by direct air capture. The overall considered systems are shown in Figure 2, where the whole life cycle is covered – from taking resources and energy from nature to provide transportation services by considering possible co-products.

The following systems are considered

- Internal combustion engine (ICE) using fossil fuels (diesel, petrol, natural gas)
- Battery (BEV) and catenary electric vehicles using renewable electricity
- Hydrogen (H_2) fuel cell (FC) vehicles using renewable hydrogen from electrolysis and
- Internal combustion engine using e-fuels with CO_2 from Direct Air Capture (DAC) and renewable hydrogen.

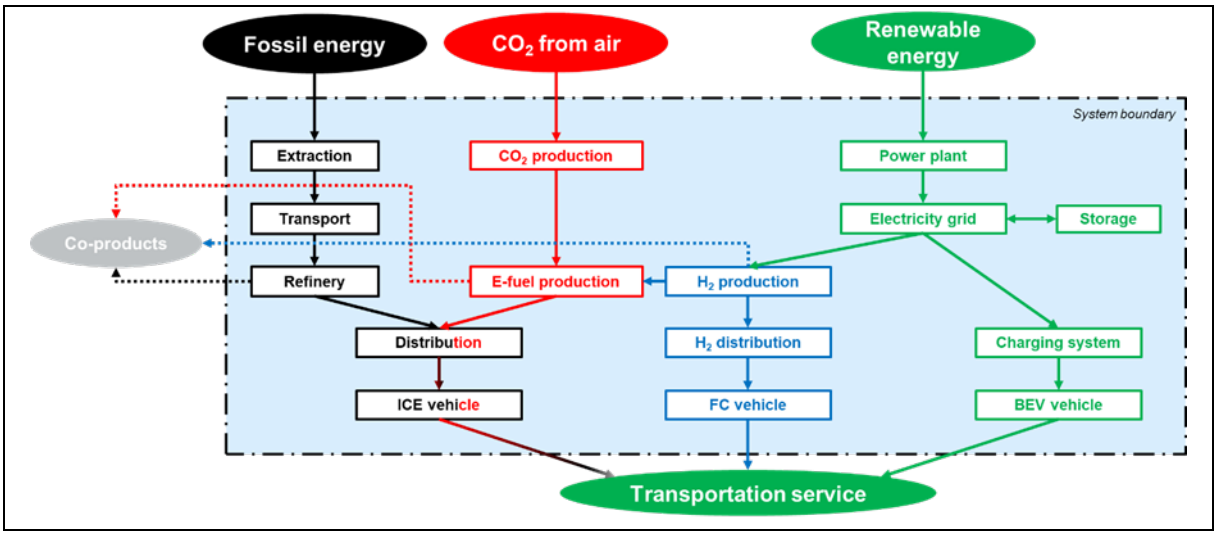


Figure 2: LCA comparison of renewable hydrogen, e-fuel systems and conventional fuels (Comment: distribution and ICE vehicle can be used for fossil fuel and e-fuel) (JOANNEUM RESEARCH)

4.4 Cooperations and Partners

The cooperations and partners are described in this section.

4.4.1 IEA EV TCP

The Electric Vehicle Technology Collaboration Programme (EV 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 electric vehicles – Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV).

The EV 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).

EV TCP is now in its seventh five-year term of operation that runs from March 2025 until March 2030. An annual report is published each year, which details work completed under the EV TCP and news from member countries.

4.4.2 Membership to the EV TCP

The EV 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 EV TCP's primary work is conducted through tasks.

The 18 active Contracting Parties (member countries) are Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Ireland, Italy, Luxembourg, Norway, Republic of Korea, Spain, Sweden, Switzerland, United Kingdom, and the United States. (status: November 2025)

4.4.3 Governance and Management

The work of EV 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 EV TCP ExCo meets twice a year to discuss and plan the working programme.

4.4.4 Tasks in EV TCP

The actual work of the EV 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 a Task Manager (TM). The work plan of a new Task is prepared by an interim TM, either on the TM's own initiative or on request of the ExCo, and the work plan is then submitted for approval to the EV TCP ExCo. To date, 40 tasks have been completed, and 12 tasks are ongoing. (status: November 2025). Further details on the tasks are available on https://evtcp.org/tasks/.

4.4.5 Partners in Task 46

The 11 partners in Task 46 were

- Argonne (US): Jarod Kelly,
- DLR (DE): Simone Ehrenberger, Janna Ferdouse,
- European Commission: Guido Sacchetto (DG R&I), Dina Silina (DG CLIMA), Carlo de Grandis (DG R&I),
- Government of The Netherlands (NL): Wilco Fiechter, Yvonne Boesten,

- IREC (ES): Víctor José Ferreira Ferreira,
- JOANNEUM RESEARCH (AT): Gerfried Jungmeier, Maria Hingsamer
- University of Waterloo (CA): XiaoYu Wu,
- Norwegian Centre for Transport Research (NO): Linda Ager-Wick Ellingsen,
- Ricardo Energy & Environment (UK): Nikolas Hill, Marco Raugei,
- PSI (CH): Christian Bauer,
- University of Ulsam (KR): Ocktaeck Lim.

The two observing partners were

- Sabanci Universitesi (TR): Tugce Yuksel,
- Transport Energy/Emission Research (AUS): Robin Smit.

A cooperation for e-fuels with the TCP AMF Task 64 *"E-fuels and End-use Perspective"* (Task Manager: Zoe Stadler) was established and finished in 2024 *(https://iea-amf.org/content/projects/map_projects/64*).

The Task Managers were

- Gerfried Jungmeier, JOANNEUM RESEARCH,
- Simone Ehrenberger, DLR (vice).

In Figure 3 the logos of the partners are shown.



Figure 3: Logos of the partners

4.4.6 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 aims of this board are

- to inform exchange/networking of mobility relevant IEA TCPs:
    - AFC: Advanced Fuel Cells,
    - AMF: Advanced Motor Fuels,
    - AMT: Advanced Materials for Transportation,
    - Bioenergy: Bioenergy,
    - EV: Electric Vehicles,
- to provide information on international activities and Austrian contributions,
- to give strategic support and expert advice, as well as support in the transfer of project content and results, and
- to meet once a year.

The National Project Advisory Board is managed by JOANNEUM RESEARCH. The further details of the National Project Advisory Board are described in chapter 6.7.

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5 Results

In this chapter the following results are described:

- Circularity and Climate Neutrality methodology,
- LCA expert workshops and
- LCA case studies.

5.1 Circularity and Climate Neutrality

The definition and the assessment methodology for Climate Neutrality and Circularity are described.

5.1.1 Definitions

Climate Neutrality and Circularity can be assessed in dynamic LCA based on the GHG emissions and the mass flows over the lifetime. Therefore, LCA based definitions of Climate Neutrality and Circularity are necessary, which are given in the following. To keep the wording appropriate to LCA nomenclature, in the impact assessment a “Climate Neutrality Potential (CNP)” and a “Circularity Potential (CPO)” are defined and applied. These definitions are initially developed in IEA EV Task 46 based on the expertise at JOANNEUM RESEARCH and applied for the first time in these LCA case studies on different vehicle types.

A product or service is “climate neutral“ and “circular“, if its whole life cycle - production, operation and end-of-life - uses only

- reused components (reuse index),
- secondary/recycled material (recycled content),
- renewable energy,

and makes

- zero waste and
- zero GHG emissions.

In Figure 4, this definition is shown for supplying a 100% circular transportation service with its closed material cycle, which is driven by renewable energy. A mobility demand is satisfied by transportation services that are provided by a closed material cycle using renewable energy.

In Figure 5 the wording and relations between “GHG reductions”, “zero GHG emissions” and “(towards) Climate Neutrality (radiative forcing)” is shown. It shows the relevance of the timing of the GHG emissions in the lifecycle and its influence on the radiative forcing. Initially GHG emissions are reduced until the GHG emissions become zero. Even if the GHG emissions are zero, still there is radiative forcing from the previously emitted GHG emissions.

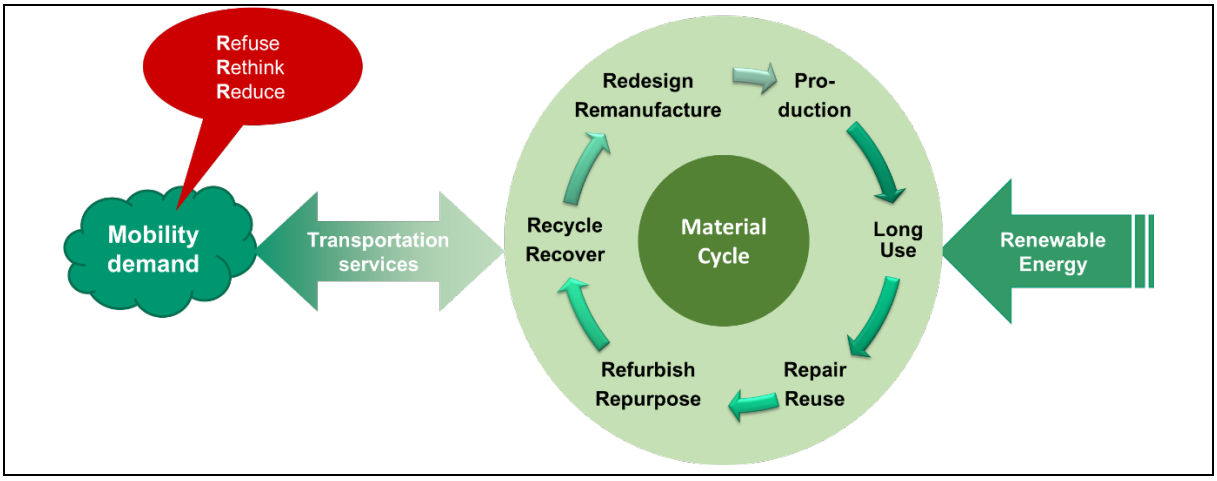


Figure 4: Circularity and Climate Neutrality for transportation services (JOANNEUM RESEARCH)

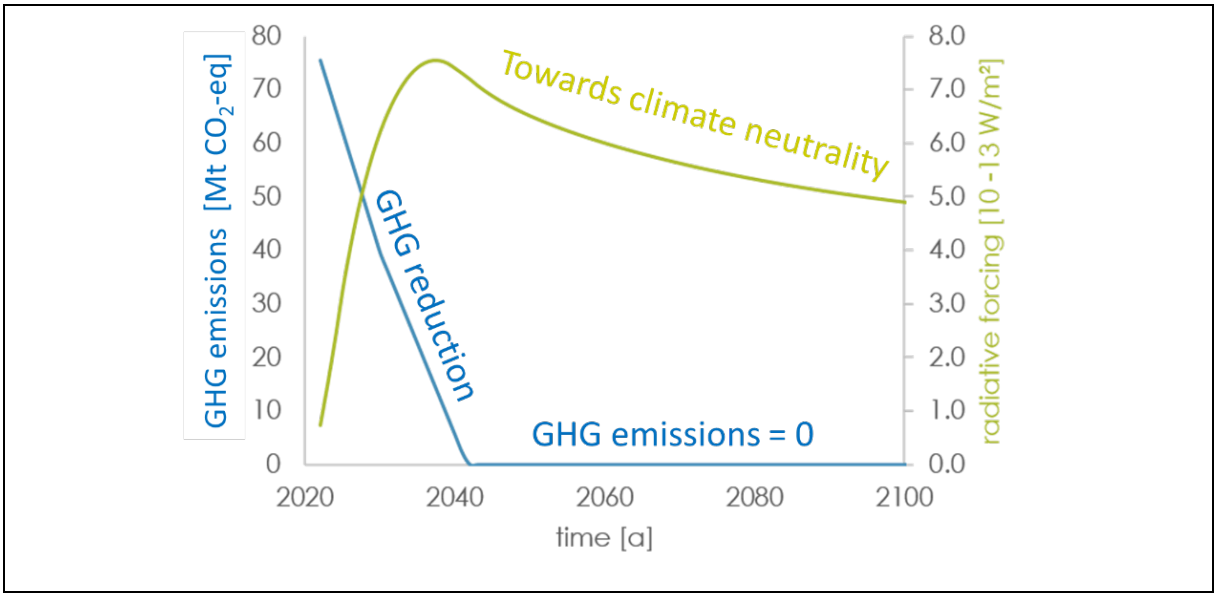


Figure 5: Relations between GHG reduction, zero GHG emissions and Climate Neutrality (radiative forcing) (JOANNEUM RESEARCH)

The indicators for the assessment in the LCA are

- Circularity Potential (CPO),

- Based on data of Inventory Analysis: mass flows in and out of the considered systems,
- Material Circularity Index (MCI) based on mass flows over lifetime: 1 = circular (whereas: 0.1 = linear) (MacArthur 2019),
  - Linear Flow Index of materials ($LFI_{material}$),
  - Utility Factor of product ($UF_{product}$): Utility = lifetime * intensity of use,
  - MCI = $LFI_{materials}$ * $UF_{product}$,

- Climate Neutrality Potential (CNP),
  - Based on GHG emissions for the impact assessment,
  - Physical measure is the total top-of-atmosphere radiative forcing based on GHG emissions over lifetime: $RF = 0\ \mathrm{W/m^2}$,
  - Every GHG emission increases the CNP, so Climate Neutrality is a visionary target, at least the assessment helps to see if the systems is on a path "towards climate neutrality" aiming for
    - Zero GHG emissions in operation phase: e.g. 0 kg CO_2-eq/a,
    - Small change in radiative forcing after system´s lifetime in 2050: $\Delta RF_{2050} = 0\ \mathrm{W/m^2}$.

The calculation of the MCI is based on the methodology developed by the Ellen MacArthur Foundation (MacArthur 2019), which is shown in Figure 6. The basis are the mass flows in and out of the system, whilst the most relevant factors are the amount of primary material used and the amount of non-recoverable waste that determines the LFI of a material and the MCI of a product.

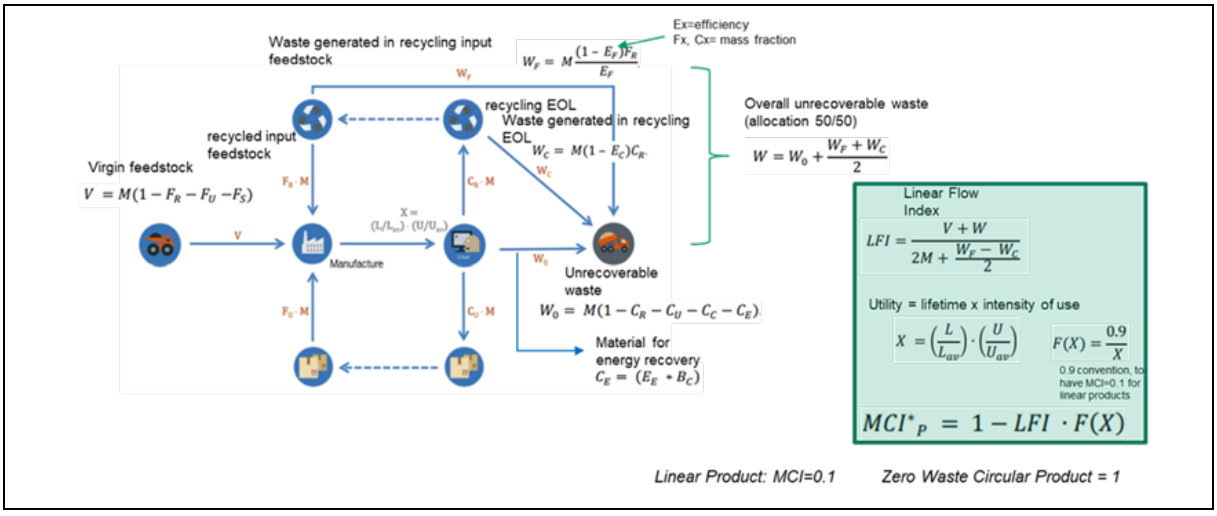


Figure 6: Calculation of the LFI of materials and the MCI of products (MacArthur 2019)

Considering these definitions, it can be concluded that Climate Neutrality and Circularity are visionary and long-term targets. In any case, all future products and services must be developed and assessed “towards” their Climate Neutrality Potential and Circularity Potential to address the global challenges. Also electric vehicles – even using renewable electricity - are not circular and not climate neutral today, but there are many challenges and possibilities for further developments to realise the technical opportunities towards circularity and towards Climate Neutrality.

5.1.2 Assessment with a Dynamic LCA Approach

According to the definitions on Climate Neutrality and Circularity it becomes clear that the approach of a dynamic LCA must be applied, in which the annual GHG emissions and the annual material demand is analysed during the whole lifetime of the transportation systems. (see Jungmeier et al. 2022).

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 passenger kilometre driven. 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. The 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 7, 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. By contrast, system B has average effects in the production phase, very low further effects in the operation phase and finally increasing environmental effects in the end-of-life phase due to the recycling of materials. The system C has highest effects in production/construction phase, but during the operation phase, the annual additional environmental effects decrease, and the cumulated effects become more or less stable, e.g., an electric vehicle consumes more and more renewable electricity during its lifetime as the electricity mix is becoming more renewable. In the end-of-life phase, the environmental effects significantly decline, which is due to the reuse of certain parts, facilities or materials for other further purposes. Therefore, with these effects, the system C sets initial possibilities *towards* Climate Neutrality. Additionally, if system C will be combined with a Carbon Capture and Storage (CCS) facility, that capture the GHG emissions from system C at the same time as they are emitted, the total system C with CCSU will be “100% Climate Neutral”.

In a dynamic LCA the Climate Neutrality Potential and Circularity Potential can be assessed based on the GHG emissions and the mass flows including primary energy over the lifetime of the transportation system.

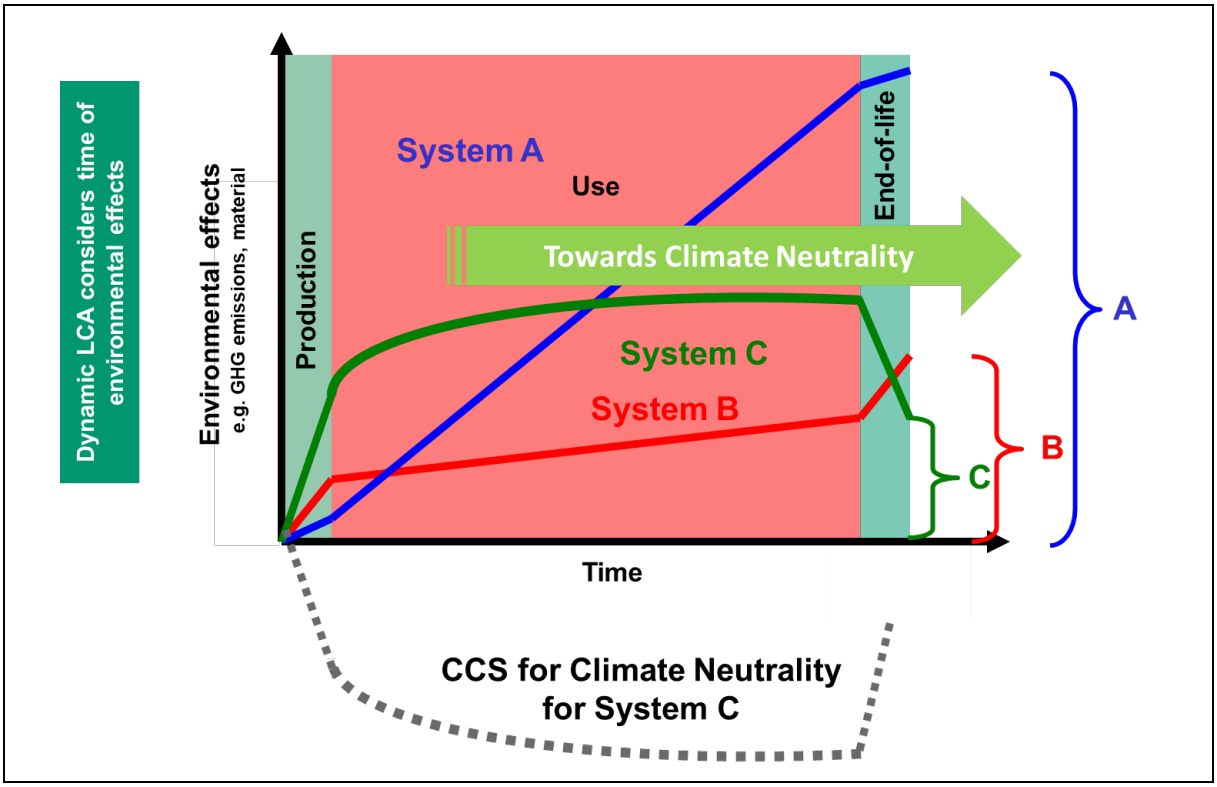


Figure 7: Timing of cumulated GHG emissions of three systems with the same lifetime and service (JOANNEUM RESEARCH)

5.1.3 Circularity Potential

The starting point to calculate the Circularity Potential is based on the Material Circularity Index (MCI) of Ellen MacArthur (MacArthur 2019)

- Linear Flow Index ($LFI_{material}$): material specific,
- Utility Factor ($UF_{product}$): utilisation specific, e.g. lifetime,
- Material Circularity Index (MCI): MCI = $LFI_{materials}$ * $UF_{product}$.

The further development towards the Circularity Potential (CPO) in Task 46 covered the following

- The CPO is based on MCI but normalised F(x) = 1/x [%] (instead of 0.9/x):
  - 0% - linear,
  - 100% - circular,

- System boundaries like dynamic LCA,
- Calculated over entire lifetime covering,
    - Production,
    - Operation and,
    - End-of-Life (EoL),
    - Total.
- Primary fossil energy of production, operation & EoL is included ($MCI_{fossil\ energy} = 0$): fossil cumulated primary energy taken from LCA,
- Circular and non-circular mass, e.g. g/km.

The following aspects are relevant in this approach:

- Air, CO_2 and water are excluded as natural inputs (main focus on technical cycles).
- Quality of recycled material is not considered ($Q_{virgin\ material} \neq Q_{recycled\ material}$), only useable mass of open and closed loop recycling.

5.1.4 Climate Neutrality Potential

GHGs increase the light absorption in the atmosphere, which causes a warming effect. The increased heat can be expressed in Watt per square metre [W/m²]. It depends strongly on the decay behaviour of the individual gases; consequently, the consideration of time effects is recommended. The common metric for assessing climate impacts is the global warming potential, which normalises the radiative forcing of arbitrary GHGs on a standard emission of carbon dioxide, both in time spans of 20, 100 or 500 years. This aggregates the time information of the different gases. As an alternative, the radiative forcing can be used directly and dynamically. To this end, the emission profile of each gas is convolved with its radiative efficiency and its characteristic impulse response function (Cherubini et al. 2012, Myhre et al 2013). The radiative efficiency is a value for the individual warming activity after an impulse emission. The impulse response function describes the declining warming effect of the decaying gas. In contrast to the global warming potential, the dynamic additional radiative forcing avoids now the aggregation of warming effects over time and allows the time differentiated representation of effects of individual greenhouse gases.

The Climate Neutrality Potential is calculated in W/m^2 at the end-of-life of the transportation system.

5.2 LCA Expert Workshops

Four LCA workshops were organized, which are described in the following chapters. The results are also available on the webpage (https://evtcp.org/task/task-46/).

5.2.1 Environmental Effects of Trucks – Towards Climate Neutrality and Circularity

The aim of the online expert workshop in October 13 - 14, 2022 was to analyse, assess and discuss the environmental effects of trucks with different propulsion systems based on LCA.

The results on the key issues in LCA of trucks are:

- Key parameters determining LCA
  - Lifetime of battery and truck,
  - Battery capacity and range,
  - Battery production,
  - Energy demand for different driving cycles with different loads,
  - Size of truck and specification,
  - Type of electricity: additional renewable electricity needed,
  - Functional units used: per t-km, per km and per total lifetime,
  - Recycling/reuse of batteries,
  - Charging strategies.
- Generalized current LCA results
  - Electric trucks have lower impacts if renewable electricity is used than H_2-fuel cell, ICE with e-fuels and ICE (with diesel and CNG) trucks due to the high overall energy efficiency,
  - Catenary battery electric vehicles (BEV) might have the lowest impacts,
  - Relative advantages in the LCA of the BEV decrease with increasing vehicle (and battery) size,
  - Urban delivery with e-trucks creates significant environmental benefits,
  - Currently the main focus in LCAs is on GHG emissions and primary energy demand.
- Further needs
  - Improved datasets on key raw materials: virgin/primary and recycled/secondary.
  - How might further improvements to upstream processes/raw materials production contribute?,
  - Improvements to the assessment of novel low-carbon fuels/production pathways, especially e-fuels,
  - Methodological considerations for contributions by LCA to assess climate neutrality and circularity.

These results were used for the LCA case study on trucks that was performed by the Task 46 (see chapter 5.3.2). In the workshop, there was a focus in group works on the following issues, which results were finally used for the Task 46 activities and case studies:

- LCA and climate neutrality,
- LCA and circularity,
- LCA and e-fuels.

5.2.2 Environmental Impacts of Buses – Aspects of Climate Neutrality and Circularity

The aim of the online expert workshop in January 16 – 17, 2024 was to analyse, assess and discuss the environmental effects of buses with different propulsion systems based on LCA. The main topics were

- Methodological aspects of LCA,
- LCA application to buses,
- Identification of key issues on LCA of buses,
- Assessing circularity in LCA.

The results on the key issues in LCA of buses are:

- Generalized current LCA results
    - Electric buses have lower GHG emissions and primary energy demand if renewable electricity is used compared to H_2-fuel cell, ICE with e-fuels and ICE with diesel buses,
    - Climate neutrality is only possible with Carbon Capture & Storage (CCS),
    - Other impacts show different results, e.g. NO_x, resource use Sb-eq mainly driven by battery production and fossil energy use for electricity,
    - Relative advantages in the LCA of the BEV decrease with increasing vehicle (and battery) size,
    - Currently the main focus in LCAs is on GHG emissions and primary energy demand
    - ISO standards set framework for LCA standardisation, but very generic and documentations must be improved.
- Key parameters determining LCA
    - Specification of system essential (e.g. single bus or fleet operation): technology and economy first, and afterwards the environment assessment,
    - Functional units: per bus-km, per passenger-capacity-km and per total bus lifetime
    - Sensitivity analysis mandatory,
    - Battery: lifetime in years and total lifetime mileage, capacity, chemistry and location of production,
    - Charging strategy: overnight depot charging and opportunity charging: pantograph and wireless,
    - Energy demand: driving cycle and heating/cooling demand,
    - Type of electricity used incl. projection over lifetime of the bus,
    - Particle matter (PM) emission from brakes and tires to be considered: BEV lower due to recuperative breaking up to 80%,
    - Recycling/reuse of batteries: allocation for secondary material/use and/or credits for secondary material/use.
- Further needs

- Improved datasets on key raw materials: virgin/primary and recycled/secondary,
- How might further improvements to upstream processes/raw materials production contribute? E.g. battery replacement,
- Methodology for End-of Life to be further developed/discussed,
- Methodological considerations for contributions by LCA to assess climate neutrality and circularity.

These results were used for the LCA case study on buses that was performed by the Task 46 (see chapter 5.3.5).

5.2.3 LCA of Automotive Batteries – Exchange Knowledge and Identify Common Issues

The online workshop took place on April 14, 2024. The aim of the workshop was to analyse, assess and discuss the environmental effects in the life cycle of automotive batteries. The participation in the workshop was by invitation only.

After external keynote speakers, the partners of Task 46 presented their LCA activities on automotive batteries, e.g. modelling, data base, literature search, and presented recent results on the environmental impacts, e.g. kg CO_2-eq/kWh, $kWh_{primary\ energy}$/kWh of automotive batteries.

The participants discussed the presentations to describe the current state-of-the-art of LCA of batteries and to identify common issues for further developments and draw key conclusions.

The results of the workshop are summarized in the two topics

- Current state-of-the-art of battery LCAs and
- Issues and future R&D demand on battery LCAs

<u>Current state-of-the-art of battery LCAs</u>

- Observed GHG emissions of automotive batteries in the year 2024 are between 45 – 110 kg CO_2-eq/kWh_battery capacity,
- Functional unit: per kWh of battery capacity (if characteristics of battery are equal also per kg of battery),
- Indicators presented
    - Main currently used indicator: GHG emissions,
    - Other used indicators:
        - Primary energy demand,
        - Material demand,
        - Circularity and Climate Neutrality Potential,

        - Mineral resource scarcity kg Cu-eq,
- Significant improvements of impacts of batteries in the previous five years,
- Cell production and its materials most relevant part of overall impacts,
- Location of battery cell production and assembly relevant in LCA,
- Supply chain data will be more available in future due to regulation, e.g. EU battery regulation,
- GREET is a relevant public data source for batteries; GREET includes is material cycle from raw material to disposal,
- Availability of materials (e.g. copper, cobalt etc.) is not the problem, it is the economics of making them available at the right amount at the right time.

Issues and future R&D demand on battery LCAs

- LCA aspects of battery use phase, e.g. energy losses, maintenance, degradation etc.,
- End-of-life:
    - LCA methodology adaption to batteries and harmonization,
    - LCA modelling to be further developed,
    - Substitution in dynamic LCA approach to be reconsidered,
- Development and further testing of dynamic LCA,
- Further development of approach to address the "Climate Neutrality Potential",
- Further definitions of circularity: e.g. balance between different impact categories,
- Further development of "Circularity Potential" in LCA: e.g. criticality of materials,
- LCA results in ranges to reflect uncertainties, variation etc. and communicate them, especially in comparing batteries,
- Materials for clean energy economy: critically, strategic, social/ethic effects, supply risk,
- Integration of costing and LCA,
- LCA in roadmaps for further reduction of battery´s impacts.

5.2.4 Life Cycle Assessment of Electric Vehicles - Steps Towards Circularity & Climate Neutrality

The in-person expert workshop took place on May 15 – 16, 2025 in Vienna/Austria. Based on the context of Climate Neutrality and Circularity, the aim of the expert workshop was to analyse, assess and discuss the environmental effects of electric vehicles, the scientific assessment approach and its practical relevance for industry, government and consumers.

The main topics of the workshop were

- Relevance of LCA for politics, industry and consumers,
- Methodological aspects of LCA,
- Approaches to assess Climate Neutrality and Circularity,

- LCA results of electric vehicles in comparison to other fuels,
- Results of IEA EV Task 46,
- Stakeholder information exchange and
- Further R&D demand.

In addition, possibilities for an intensive exchange between/with experts and stakeholders in breaks and interactive formats were there. The format of the workshop included presentations, discussions and interactive group work.

The workshop is summarized in following areas

- Results of IEA EV Task 46 "LCA of Trucks, Buses, other Vehicles and V2X-Services",
- LCA of Electric Vehicles - Modelling, Database & Results,
- Carbon Capture and Storage - Global perspectives and challenges for implementation,
- Circularity in Public Transport – A System Approach,
- Identification of R&D demand in LCA,
- New IEA EV Task 52 "EVs and Circularity" (2025 – 2027).

Further details on the workshop are available on https://evtcp.org/task/task-46/.

<u>Results of IEA EV Task 46 "LCA of Trucks, Buses, other Vehicles and V2X-Services"</u>

The main findings of the common activities of the 12 countries in Task 46 are:

- Definitions of "Climate Neutrality (Potential)" and "Circularity (Potential)": A product or service is "climate neutral" and "circular", if whole life cycle - production, operation & end-of-life
    - Uses only
        - Reused components,
        - Recycled material,
        - Renewable energy,
    - Makes
        - Zero waste and
        - Zero GHG emissions,
- Indicators for assessment
    - Circularity Potential
        - Based on mass balance in lifetime,
        - Between 0% = linear and 100% = circular,
    - Climate Neutrality Potential
        - Based on GHG emissions in lifetime,
        - Total radiative forcing at top-of atmosphere of GHG emissions: $W_{year}/m^2 = 0$,
        - "Towards Climate Neutrality": zero GHG emissions in operation phase,

- Concluding
    - Climate Neutrality and Circularity are visionary and long-term targets,
    - But: future products and services must be developed and assessed towards Climate Neutrality and Circularity,
- The task assessed Climate Neutrality Potential & Circularity Potential in dynamic LCA.
- Key impacts considered:
    - GHG emissions (incl. H_2),
    - (Non-)renewable primary energy,
    - (Non-)circular mass,
    - Climate Neutrality Potential and
    - Circularity Potential.
- Various LCA case studies of different vehicles were performed including newly installed renewable electricity plants in comparison to petrol, diesel, and hydrogen & e-fuel with CO_2 from air using renewable electricity:
    - Trucks,
    - City buses,
    - Fire trucks,
    - SUVs,
    - Mining hauls and
    - V2X-services.
- Key results
    - Battery electric vehicles using renewable electricity have best environmental performance compared to others,
    - Main influences
        - Energy demand of vehicles,
        - Source of electricity,
        - Battery capacity,
        - Lifetime and annual operating hours.
- Climate Neutrality Potential & Circularity Potential
    - Might be two additional impact categories in LCA not covered in the current impact categories,
    - Only systems using renewable energy have the potential towards Climate Neutrality & Circularity,
    - 100% Climate Neutrality: Only possible in combination with Carbon Capture & Storage (CCS.

The key issues of the LCA case studies are:

- Apply dynamic LCA,
- Testing and learning Circularity and Climate Neutrality assessment,
- Include construction of new power plants for renewable electricity in production phase,
- Consider GWP of direct H_2-emissions for H_2-system and e-fuels, as direct H_2-emissions might contribute to Global Warming (see e.g. Warwick et al. 2022),

- Different charging strategies for BEV: depot charging, opportunity charging, wireless charging, catenary systems,
- Additional services for BEV: V2X-Services,
- Allocation for V2X-Service,s
- Considering change of batteries and fuel cells,
- Definition and communication of estimated ranges of results for significant differences,
- Different types of vehicles,
- Discussion: “Zero emission vehicle”,
- Lifetime: different and same lifetime for vehicles and renewable power plants,
- EoL methodology comparison: avoided burden approach and cut-off.

LCA of Electric Vehicles - Modelling, Database & Results

- Appropriate modelling requires vehicle comparisons that meet the same technical criteria
    - Physics-based tools (e.g. such as *Autonomie)* are ideal for this,
    - Provide modelling results for energy and materials.
- Inventory choices should be locational relevant
    - R&D GREET has broad energy and material coverage,
    - Temporal variation should also be included.
- Modelling analysis shows that “Cradle-to-Grave” GHG reduction of the Small SUV is possible
    - Powertrain advancement is critical to achievement,
    - Significant reductions require lower-emitting energy pathways,
    - All investigated powertrains indicate significant emission reduction when combining powertrain and energy pathway progressions.

Carbon Capture and Storage - Global perspectives and challenges for implementation

The Q&A of key issues were:

- Are there global perspectives and challenges for implementation? - Yes. Operational risks can be handled according to modern standards.
- Is CCS an attractive business model for storage operators in 2025? - No. Mostly due to unclear or negative regulatory framework.
- Are we well on track to meet mid- and long-term CCS goals? - No. Challenges of accelerating CCS development are vastly underestimated.

Circularity in Public Transport – A System Approach

The Dutch government has set an ambitious goal to be 100% circular by 2050. To translate this into action, a national agreement for the public transport sector is currently being developed in the form of a covenant. A Reflection of these activities and the presented approach was done in the group work on circularity of the workshop. The following questions were addressed:

1. What are your main takeaways and insights from this sector-wide study?

2. How is this relevant to your work, and what challenges do you encounter with measuring circularity?

The results of the group work are:

- Group 1 elaborated the limits of Material Flow Analysis (MFA):
    - Energy is not taken into consideration.
    - Traceability of the flow? It is a calculation of stock = inventory. But: how are flows connected?
    - How to reduce the input and waste, based on the MFA?
    - MFA is a powerful tool to feed the LCA inventory phase.
    - Functional unit and delivered service is not considered.
- Group 2 provided feedback on the preliminary study results:
    - Make note on what is missing in the study (blind spots).
    - Safety, liability associated with second life, reuse, etc.
    - Front end design of suppliers and the impact on costs.
    - Could this repress innovation in tech from a methodological perspective?
    - How to manage lifetimes across vehicles (bus, tram, road, train).
    - Energy and maintenance are blind spots.
    - How to treat common goods (roads etc.).
    - How to ensure method generality (i.e. for other localities).
    - Where do you get the needed data and how to do a plausibility check?
    - Data and transparency are limited, needs to be improved.
    - Front end versus back end for circularity – a lot of auto steel is re-used elsewhere.
- Group 3 discussed challenges for measuring circularity:
    - Considering reuse and lifetime extension in circularity measurements.
    - Include more 'R's' other than recycling.
    - Gap between the availability of secondary materials and recycled material requirements.
    - Gap in material quality.
    - Potential conflicts with other targets (e.g. CO_2 and energy).
- Group 4 considered the broader system impacts:
    - Difference in regarding one bus versus analysing a whole system or sector?
    - MFA without LCA?
    - Input to sector analysis including time (dynamic analysis).
    - What does the relative goal (50% reduction in 2030) lead to?
    - Theoretically: perfect maintenance = no change to the system.
    - Include fossil energy for operation.
    - How does circularity really connect to sustainability?
    - Is there enough secondary material?
    - Reaching the target in the NL can lead to displacement from other use cases or regions. Increasing availability of recycled material needed.
- Statements on predefined questions:

- *It is a realistic goal to reduce primary material use in the public transport sector with 50% by 2030?*
  - Of what? Stocks or flows.
  - Percentage of annual replacements.
  - A goal that just focuses on circularity is not enough. You will need LCA, which helps with decisions on when to replace the buses and to what extent.
- *In circular impact assessment, carbon emissions (CO_{2eq}) are the most important metric for LCA?*
  - In general, CO_2eq is the most important and widely recognized.
  - For circularity it is not the only measure:
    - Depletion/scarcity,
    - Raw material extraction,
    - Biodiversity,
    - Water,
    - Material re-use/recycling,
    - Product design/eco-design and
    - Sufficiency.
- *Fuel/energy consumption during the use phase should always be included in the systems approach for measuring circularity.*
  - First, the group decided on a clear 'Yes'; fuel energy consumption during the use phase should be included in circular studies. Throughout the discussion, it became a 'no', acknowledging the complexity of a larger scope.
  - The word "fossil" should be added before "fuel/energy" in the statement.
- *Strategic and Critical Raw Materials require separate sub-targets, beyond primary material use reduction*
  - Yes!
  - Design for the 10 R-strategies.
  - Focus on how frequently the equipment is used.

<u>Identification of R&D Demand in LCA</u>

The identification of the R&D demand in LCA are summarized in three areas that are described in the following:

1. LCA and Mode Shift between Different Transportation Modes,
2. Relevance of other Impacts and
3. Circularity Issues.

LCA and Mode Shift between Different Transportation Modes

Mode shift or modal shift seem to be popular terms nowadays that are sometimes loosely mentioned as a decarbonization measure or potential policy focus. However, it appears that most LCA

studies have focused on road transport so far, suggesting a current gap in knowledge. It is clear that assessing the impact of mode shift will require location and mode-specific modelling, taking into account different energy consumption profiles but also mode specific issues such as "moving media" (e.g. ocean current, wind fields) and non-CO_2 radiative forcing impacts for aircraft. This is shown in a recent mode shift well to wheel (WTW) study (*https://www.accscience.com/journal/EER/1/1/10.36922/eer.3470, https://www.accscience.com/journal/EER/1/1/10.36922/eer.3471*), but this was not a full LCA. It is often assumed that non-road transport (rail, shipping, aircraft) has higher mileage or service hours and therefore the full LCA may be less relevant - however this needs further research and confirmation.

During the workshop a number of interesting issues were raised and discussed by the subgroups

- Including mode shift in LCA may be seen as a logical next step where the LCA is applied to "transport as a service". It is clear that a split between freight and personal travel is required.
- Many non-road transport sectors need to develop decarbonization policies - the question is are they done following the LCA approach? It was mentioned that MAERSK in Denmark is currently developing a method.
- Moreover, without a higher level solid LCA approach current policies may be less cost-effective as they may affect mode shift and therefore unintended impacts.
- It was questioned whether France's prohibition of short distance flights was based on an LCA study.
- Some LCA studies are available looking at car sharing and use of public transport, as well as micro-mobility (still road).
- It appears that a high quality, consistent, transparent and locally appropriate and open database of emission factors and electricity consumption factors is not yet available, but this would be quite relevant for reliable LCA studies.
- It could be useful to look for specific use cases (e.g. supply chains, logistics).
- When looking between modes specific aspects such as different service delivery (e.g. travel time) and customer satisfaction may become relevant considerations in mode shift LCAs. Related to that is an assessment of realistic mode shift potential.
- There are several interesting applications of quality multi-mode LCA data, such as for instance, the opportunity for consumers to select different delivery times of online products and reducing LCA emission impacts.

Relevance of other Impacts

Other relevant impacts – beside the ones presented & discussed during the workshop are.

- Resource dissipation,
- All locally relevant indicators/impacts,
- Biodiversity incl. Land use Change on specific location and its effects over time,
- Absolute environmental sustainability: connecting indicators to planetary boundaries,

- Particulate matters: further characterization by type, size, specifics, toxic, human health. Possible pathway from emission to impact,
- Social LCA and indicators and
- Links of LCA to sustainability reporting and vice versa.

Circularity Issues

First, some topics are identified that are of interest for discussion:

- How should we combine LCA & Circularity?
- What are important aspects from policy and from consumer perspective?
- What are good metrics for assessing recycling, secondary materials, transport applications etc.? How to address the different R-Principles of circular economy?
- How to incorporate the economic part of circular economy into product design?

Then the most important issues for these aspects are identified:

- Design phase / product development issues:
    - Extending the lifetime of vehicles is a key factor,
    - (electric) Vehicles face a digital security problem when thinking of designing them more circular, updates are difficult after some years,
    - Current vehicles and components often lack compatibility after a few years due to new technologies available, packaging problems etc.
- Methodological aspects:
    - Product category rules are needed for a better specification of how to apply circularity metrics,
    - LCA can serve as a toolbox for supporting circularity strategy decisions in the design phase, but also in the end-of-life,
    - Scope 4 emissions (avoided emissions) are in discussion and could help to reveal benefits of circular approaches.
- Economic aspects:
    - Without a business case there is no Circular Economy possible!
    - The product-as-a-service approach can be helpful for the vehicle markets (can also help to extend the vehicle lifetime).
    - Alternative ownership strategies can be created, e.g. a vehicle can go through several leasing stages
- Consumer aspects
    - Circularity should be a criterion to consumers,
    - This might also change with younger generations,
    - It should be made clear what the benefits of more circular vehicles for the individual consumers are to increase acceptance.
- Policy issues (EU)
    - It's important to have the end-of-life responsibilities clarified,

- A regulation on circular vehicles is in progress --> LCA could support here or somehow be incorporated,
- Consumer rights that address "R"-aspects are needed, e.g. the right to repair (like smartphone rules),
- A new corporate sustainability reporting directive that is coming up will address social, ecological and also circularity aspects; such information can help further assessments.

5.3 LCA Case Studies

The LCA case studies are described in this section.

5.3.1 Introduction

Task 46 performed LCA case studies on the following vehicles:

- Trucks (N1, N2 and N3),
- Fire trucks,
- Mining haul trucks
- City buses,
- V2X-services and
- Light Electric Vehicles (LEV) and SUVs.

The main aim of these LCA case studies was to develop and apply the methodologies to assess Climate Neutrality Potential and the Circularity Potential. The main impact categories calculated are:

- GHG emissions,
- Climate Neutrality Potential,
- Primary energy demand and
- Circularity Potential

The new LCA aspects developed in Task 46 and applied in the LCA case studies were

- Apply dynamic LCA,
- Testing and learning Circularity and Climate Neutrality assessment,
- Include construction of new power plants for renewable electricity in production phase,
- Consider GWP of direct H_2-emissions for H_2-system and e-fuels,
- Different charging strategies for BEV: depot charging, opportunity charging, wireless charging, catenary systems,
- Additional services for BEV: V2X-Services,

- Allocation for V2X-Services,
- Considering change of battery and fuel cell due to possible lifetime limitations,
- Definition and communication of estimated ranges of results for significant differences,
- Different types of vehicles,
- Discussion: “Zero emission vehicle”,
- Lifetime: different and same lifetime for vehicle(s) and renewable power plants,
- EoL methodology comparison: “avoided burden approach” and “cut-off”,
- Interaction, discussion and dissemination of draft findings: LCA workshop on trucks and buses.

In the LCA case studies of the different electric vehicles with different charging strategies and technologies are compared to

- Diesel and natural gas ICE vehicles,
- Hydrogen fuel cell vehicles (with hydrogen from renewable electricity) and
- E-fuel ICE vehicles using CO_2 from direct air capture (DAC) and renewable hydrogen.

The system boundaries of the compared transportation systems are shown

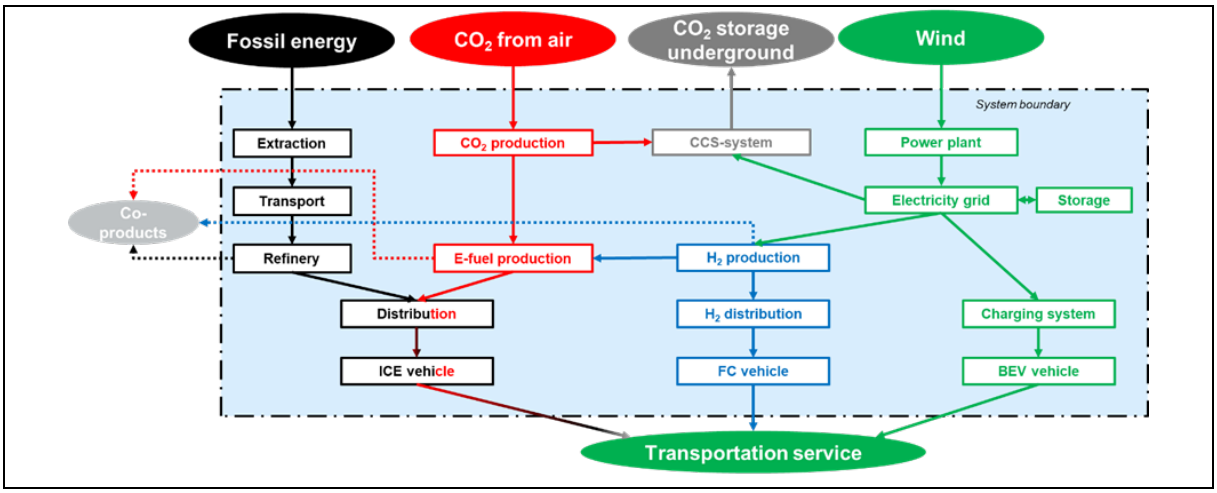


Figure 8: System boundaries for LCA case studies (Comment: distribution and ICE vehicle can be used for fossil fuel and e-fuel) (JOANNEUM RESEARCH)

In the following chapters the different LCA case studies are described with their specific findings, key data and results. All the detailed results of the LCA case studies are made available for the Task 46 participant as slide shows.

5.3.2 N1, N2 and N3 Trucks

The goal of this LCA case study is to identify significant differences of environmental effects of trucks with different propulsion systems/fuels for current technology (base year 2023). The applied methodology is a dynamic LCA using generic global production data for materials considering the cumulative environmental effects over the lifetime of the truck. The specification of technology and systems are different trucks: N1 (< 3.5 t), N2 (3.5 t > 12 t) and N3 (< 16 t). Here in the final report the focus is on N3 trucks, for which typical driving cycles as weighting of urban rural and highway driving are considered.

The following transportation systems are analysed:

- Diesel with ICE (Internal Combustion Engine),
- E-diesel from renewable electricity mix and CO_2 from air with ICE,
- H_2 with FC (Fuel Cell) from renewable electricity mix: GH_2 @ 700 bar and LH_2 (gaseous/liquid H_2),
- electricity for BEV and catenary truck: additional renewable electricity mix: 50% wind, 25% hydro and 25% PV,
- CNG (Compressed Natural Gas) with ICE,
- E-CNG with ICE and
- E-MeOH (methanol) with FC.

The functional units are

- Per truck-km and
- Per t-km due to the different payloads.

The GWP_{100} of direct H_2-emissions is 10.9 kg CO_2eq per kg of hydrogen (range: 6.5- 15 kg CO_2eq/kg_{H2}) (based on Ilissa et al. 2022 and Warwick et al. 2022).

The database for the LCA was developed to represent adequately the technical, geographical and timely framework condition to fulfil the goal and the scope of the case study. The foreground data for the trucks are listed in Table 1 and the Linear Flow Index (LFI) of the relevant materials is shown in Figure 9, where H_2 and e-fuels have a LFI of 0. The background data for the materials for truck components and the material composition are from GREET 2022, the battery data are based on LCA Battery Model of JOANNEUM, and the electricity & fuel supply are from the internal LCA database of JOANNEUM RESEARCH. The total lifetime mileage is 1.2 Mio. km in 12 years.

Table 1: Foreground data for N3 trucks (Task 46 et al. 2024)

Truck type class		N3								
Propulsion		ICE	ICE	ICE	ICE	BEV	BEV	FC	FC	FC
Fuel		diesel	e-diesel	CNG	e-CNG	electricity	catenary	GH2@700	LH2	e-MeOH
Weight	[kg]	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Powertrain System (including BOP)	[kg]	1,045	1,045	941	941	-	-	318	318	500
Transmission System	[kg]	547	547	547	547	273	273	273	273	273
Chassis (w/o battery)	[kg]	10,200	10,200	10,200	10,200	10,200	10,500	10,200	10,200	10,200
Traction Motor	[kg]	-	-	-	-	279	279	279	279	279
Generator	[kg]	-	-	-	-	-	-	-	-	-
Electronic Controller	[kg]	-	-	-	-	147	147	147	147	147
Hydrogen Tank Onboard Storage	[kg]	-	-	100	100	-	-	1,451	2,000	200
Van/Box	[kg]	-	-	-	-	-	-	-	-	-
Body: including BIW, interior, exterior, and glass	[kg]	3,750	3,750	3,750	3,750	3,750	3,750	3,750	3,750	3,750
Lift-gates	[kg]	-	-	-	-	-	-	-	-	-
Battery	[kg]	120	120	120	120	7,216	1,223	500	500	500
Total w/h battery	[kg]	15,542	15,542	15,537	15,537	14,649	14,949	16,418	16,967	15,349
Total	[kg]	15,662	15,662	15,657	15,657	21,865	16,172	16,918	17,467	15,849
Payload	[kg]	24,338	24,338	24,343	24,343	18,135	23,828	23,082	22,533	24,151
Battery capacity	[kWh]	0	0	0	0	1059	179	54	54	54
Energy demand *)	[kWh/km]	2.94	2.94	3.34	3.34	1.89	1.74	2.72	2.72	3.20
CH4 emissions *)	[g/km]	0.0008	0.0008	0.008	0.008	0	0	0	0	0.00002
N2O-emissions *)	[g/km]	0.05	0.05	0.025	0.025	0	0	0	0	0.002
H2 emissions **)	[g/km]	0	0	0	0	0	0	0.64	1.28	0
NOx emissions *)	[g/km]	0.2	0.2	0	0	0	0	0	0	0
PM-emissions *)	[g/km]	0.003	0.003	0	0	0	0	0	0	0
Urea/AdBlue *)	[l/100 km]	1.20	1.20	0	0	0	0	0	0	0
Engine oil	[kg/100 km]	0.016	0.016	0.016	0.016	0	0	0	0	0
Driving range per charging	[km]					503	93			

*) average driving cycle
**) H2 losses/emissions

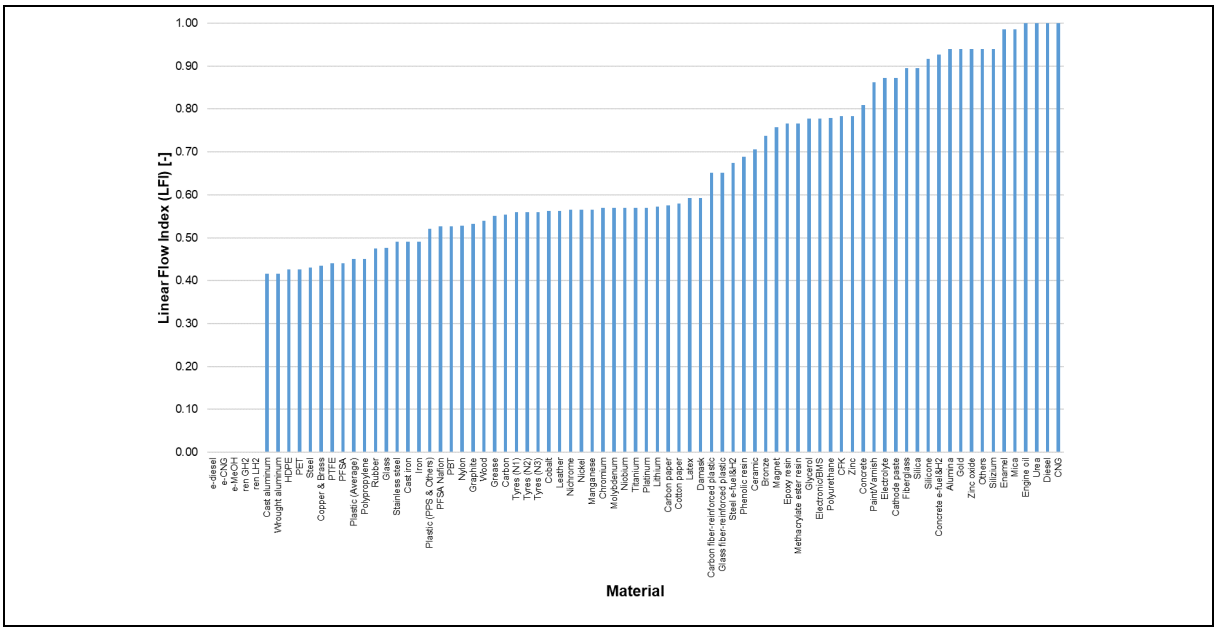


Figure 9: Foreground data on LFI of relevant materials (Task 46 et al. 2024)

Based on the LCI of all relevant materials the Circularity Potential for the truck, energy supply system and the operation material were calculated. The following remarks are relevant for the calculation of the Circularity Potential of the total system:

- The total Circularity Potential of the systems is calculated based on the mass flow distribution over lifetime.
- The Circularity Potential considers the
  - different payloads of the considered trucks (see Table 1) and

    - different lifetimes of truck (12 years) and energy supply (20 – 40 years).
- The fossil fuels - diesel, CNG - and the operational materials - urea, engine oil - are non-circular (LCI=1 and MCI=0) following the definition for fossil fuels and are initially considered for operation phase.
- E-fuels, CO_2 from air and H_2 are not considered in the mass flows. Hydrogen is made from a sustainable water source.
- Additionally, a reduced availability of secondary material is assumed for the construction of power plants for H_2 and e-fuel production. This is because much more additional power plants are needed, compared to the electricity required by electric trucks.
- For the catenary truck, it was assumed that 1 km of catenary is built.
- It is assumed that both the production phase and the end-of-life phase last at least one year.

In Figure 10 the global warming potential of the GHG emissions over time for the N3 trucks are shown in t CO_2eq per t payload and kilometre. The increase of GHG emissions during the construction phase is due to the construction of the truck and the power plants. As the electricity demand for e-fuel and H_2 is higher than for electric trucks, the GHG emissions are significantly higher. The systems using renewable electricity have nearly no additional GHG emissions during operation except from spare parts and maintenance. In comparison, the GHG emissions of diesel and CNG rise significantly during operation due to the combustion of fossil fuel. The decrease of the GHG emissions in the EoL phase is on one hand due to the supply with secondary material from recycling of the truck for any other product. On the other hand, the lifetime of the electricity and fuel supply (20 – 40 years) is longer than for the trucks (12 years). The energy supply systems can be used for other purposes and are therefore only partly allocated to the transport system with trucks. Thus, all systems using renewable electricity have the potential towards climate neutrality in the operation phase, but the GHG emissions are significantly higher during the whole lifetime of e-fuel and H_2 compared to electric trucks.

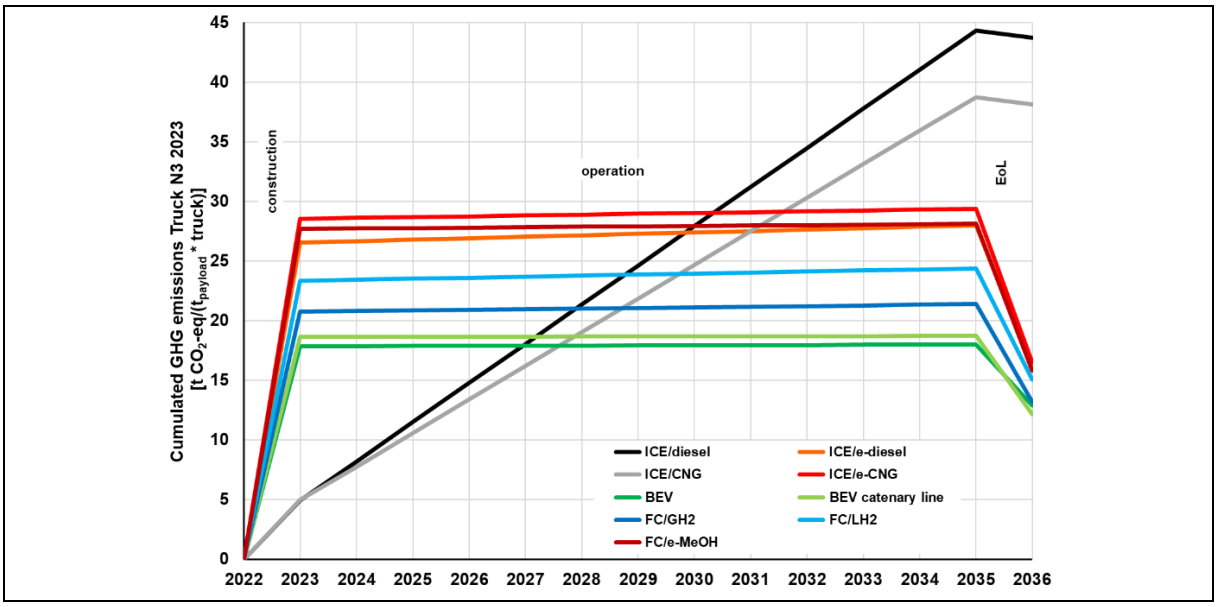


Figure 10: Global Warming Potential of the GHG emissions over time for the N3 trucks (JOANNEUM RESEARCH)

In Figure 11 the Climate Neutrality Potential of the radiative forcing over time for the N3 trucks is shown. It can be seen that due to the GHG emissions over time the BEV has the lowest radiative forcing in the year 2100 although the GHG emissions of the BEV catenary system are lower in 2036. Therefore, the Climate Neutrality Potential in 2100 delivers additional assessment information compared to the GHG emissions over time.

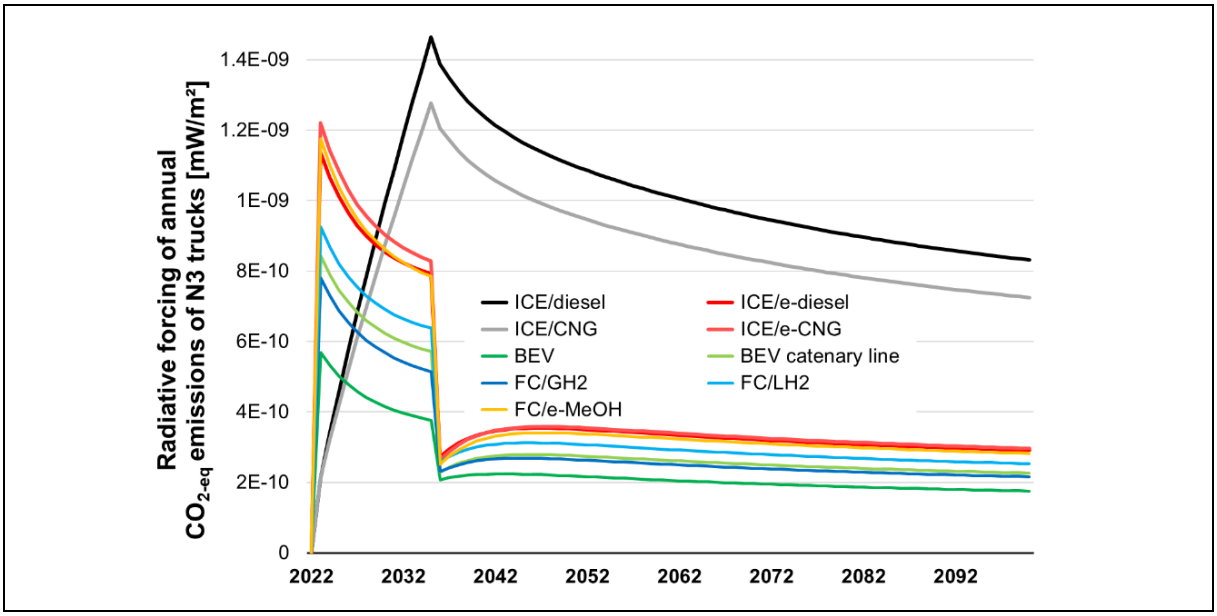


Figure 11: Climate Neutrality Potential of the radiative forcing over time for the N3 trucks until year 2100 (JOANNEUM RESEARCH)

Figure 12 shows the total and renewable primary energy demand over time for the N3 trucks in MWh per t payload and kilometre. The increase of total primary demand during the construction phase is due to the construction of the truck and the power plants. As the electricity demand for e-fuel and H_2 is higher than for electric trucks, the primary energy demand is significantly higher. The systems using renewable electricity have a strong increase in the renewable primary energy demand in the operation phase, which can even be higher than for the trucks using fossil fuels. The decrease of the primary energy demand in the EoL phase is on one hand due to the supply with secondary material from recycling of the truck for any other product. On the other hand, the lifetime of the electricity and fuel supply (20 – 40 a) is longer than for the trucks (12 a). The energy supply systems can be used for other purposes and therefore are only partly allocated to the transport system with trucks, as described above as well.

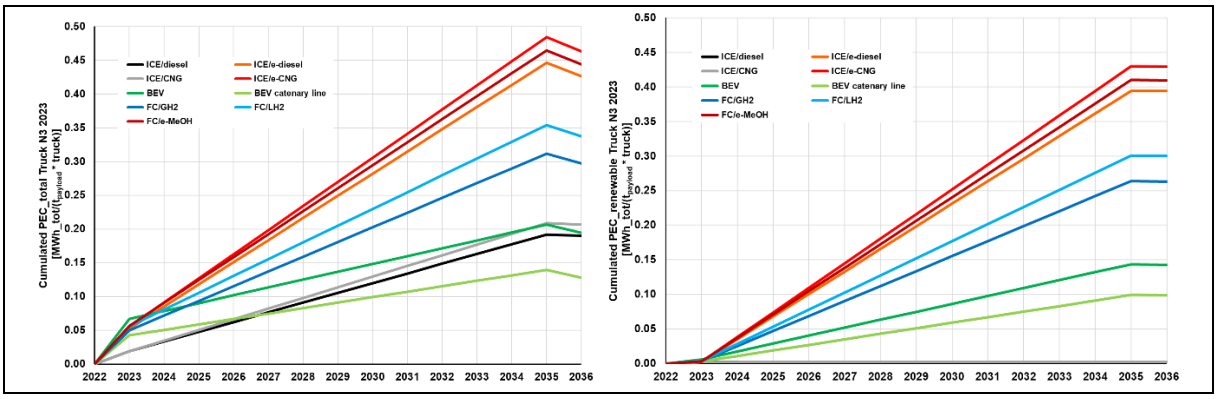


Figure 12: Total and renewable primary energy demand over time for the N3 trucks (PEC: Primary Energy Consumption is equal to PED: Primary Energy Demand) (JOANNEUM RESEARCH)

As the basis for the calculation of the MCI, the total material demand in the lifetime of the N3 trucks is shown in Figure 13. In all systems, the mass of the truck is significantly lower than the mass of the used fossil fuel and the mass needed for construction of renewable power plants as well as the catenary system.

In Figure 14, the Circularity Potential of the total system for the N3 trucks is shown. Due to the use of fossil fuels, the Circularity Potential of the ICE with diesel and CNG are far the lowest (3.5 – 4.0%), whereas most of the other systems using renewable electricity are between 59% to 63%. The catenary system has with 70% the highest Circularity Potential, due to the small battery and the longer lifetime of the catenary system.

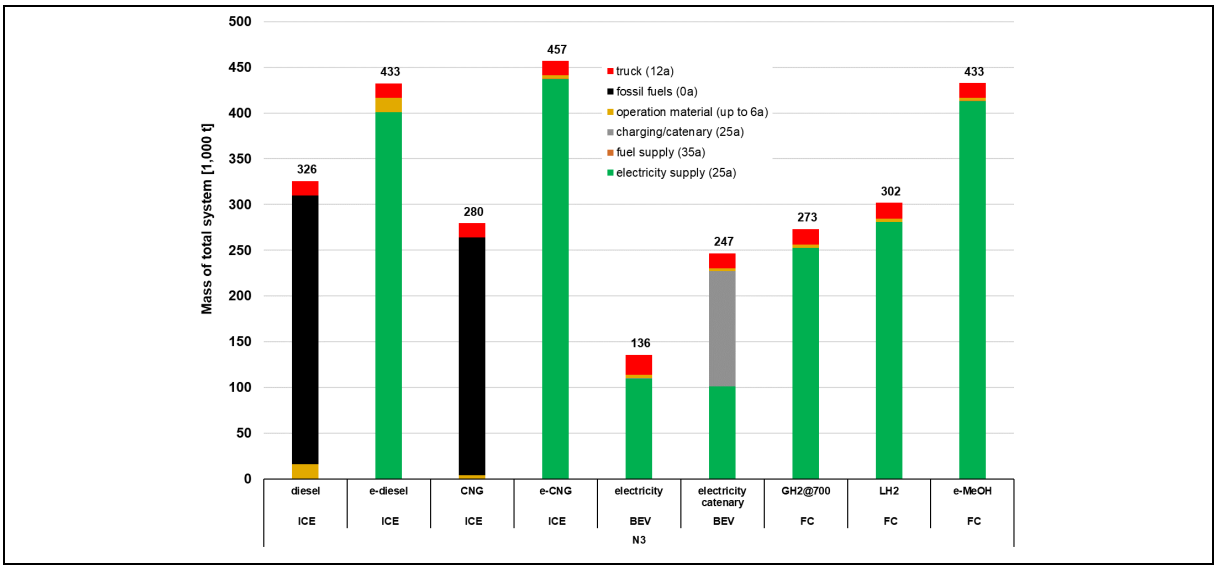


Figure 13: Total material demand for the N3 trucks (JOANNEUM RESEARCH)

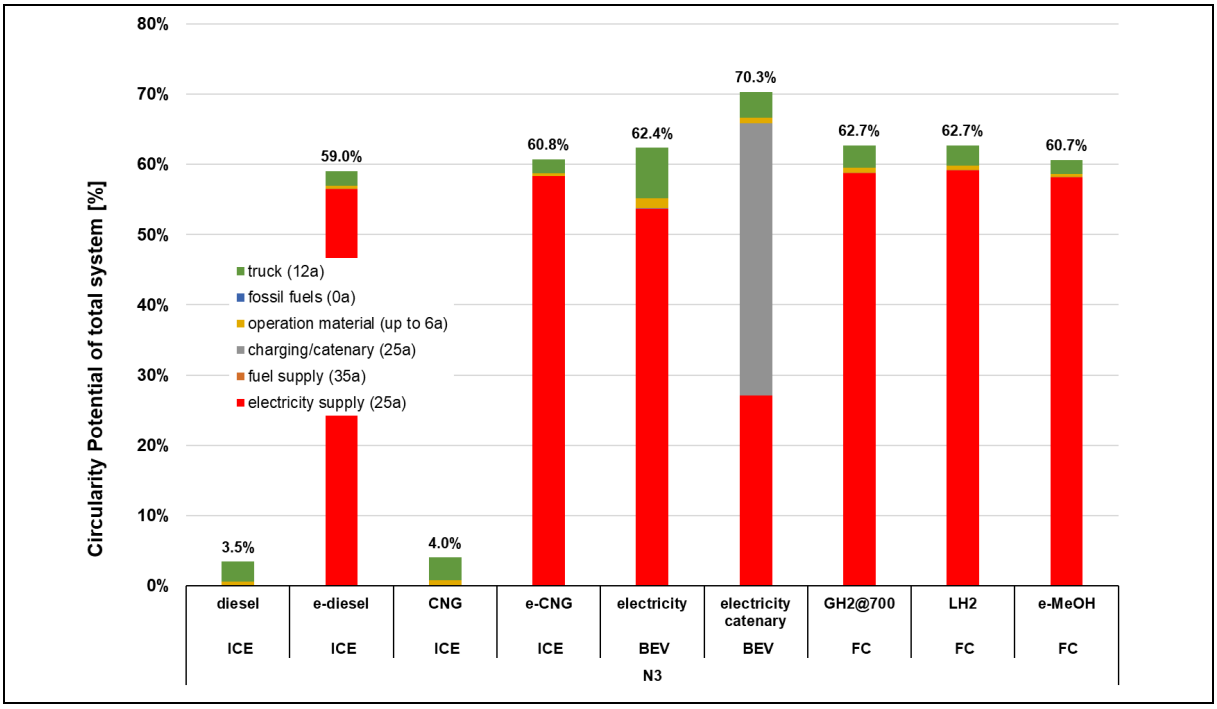


Figure 14: Circularity Potential of the total system for the N3 trucks (fossil energy only for operation phase) (JOANNEUM RESEARCH)

In Figure 15 the Circularity Potential over time for the N3 trucks is shown. All systems start in nature with a Circularity Potential of 100% before the construction phase. During the construction, phase the Circularity Potential decreases significantly, again for e-fuel and H_2 more than for electric trucks due to the higher demand of renewable power plants. In the operation phase the Circularity Potential for systems, using renewable electricity nearly remains constant beside a small influence due to the spare parts and maintenance. For systems, using fossil energy the Circularity

Potential is drastically reduced in the operation phase due to the non-circularity of fossil fuel combustion. In the EoL phase the Circularity Potential increases significantly due to the longer lifetime of the renewable power plants that can be used for other purposes outside the system boundary of the truck systems.

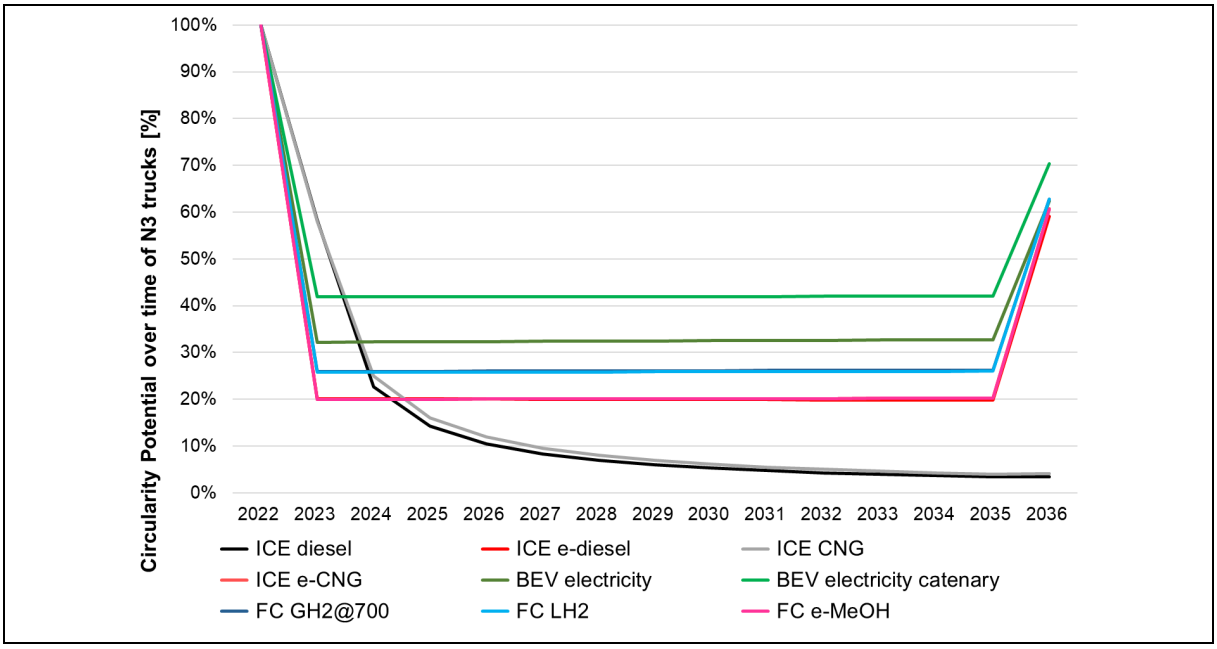


Figure 15: Circularity Potential over time for the N3 trucks (JOANNEUM RESEARCH)

Figure 16 shows the overall assessment of the different environmental effects of the N3 trucks. In this overall summary, the reference is the diesel/ICE, which is set to 100%. The Circularity Potential is given in 1/CPO. One can observe that the Climate Neutrality Potential - measured in radiative forcing in the year 2100 – delivers different results than the GHG emissions. Additional to well established categories in life cycle-based assessment, the Circularity Potential as well as the Climate Neutrality Potential in 2100 delivers information covered neither in the primary energy demand nor in the GHG emissions.

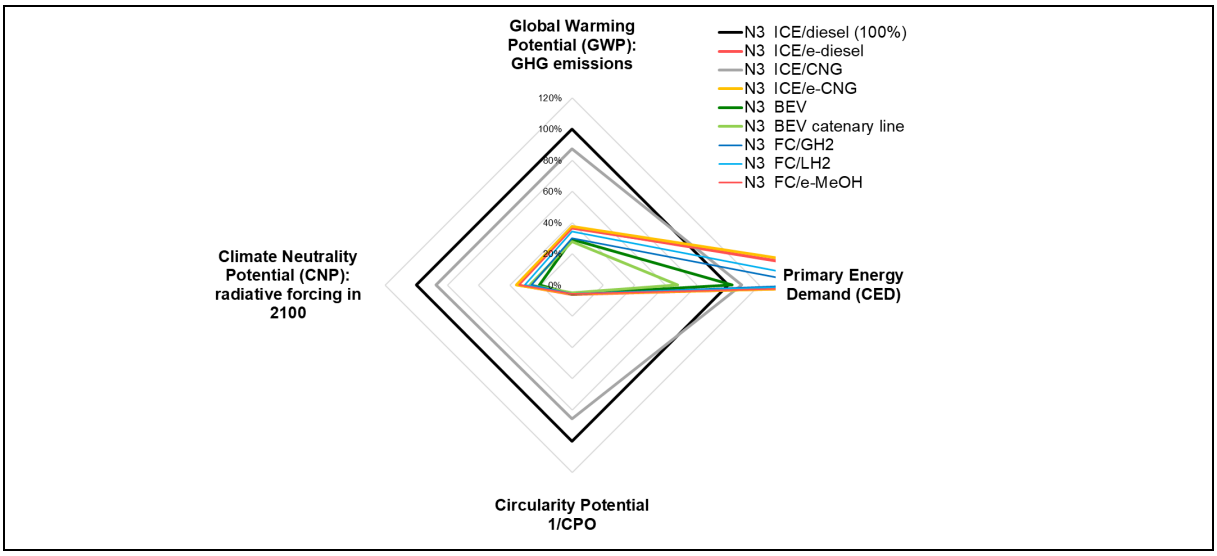


Figure 16: Overall assessment and comparison of the N3 trucks with diesel ICE = 100% (JO-ANNEUM RESEARCH)

The conclusions and observations are:

- Climate Neutrality Potential and Circularity Potential describe additional environmental effects not covered yet in the different LCA assessment categories.
- The Climate Neutrality Potential measures the radiative forcing in W/m² in the year 2100. Thus, the timing of the GHG emissions during the lifetime of the system is relevant.
- The Circularity Potential is based on the MCI and is between 0% (linear) and 100% (circular). It is mainly determined by the amount of primary material (incl. fossil fuels) and the non-recoverable waste.
- Systems using renewable energy have the potential to direct towards Climate Neutrality and Circularity.
- The assessment of Circularity Potential using MCI shows that material circularity is significantly determined by the amount and type of material used.
- The amount of material for the renewable electricity power plants is significantly higher than the amount of material used in the truck.
- Observations on Circularity Potential of trucks using diesel, CNG, e-fuels, H_2 and electricity
    - The Circularity Potential of systems using renewable electricity is determined by renewable power plants,
    - The Circularity Potential of using fossil fuels is mainly determined by the fossil fuels used for truck operation,
    - The Circularity Potential of the truck body is mainly determined by steel,
    - The Circularity Potential of batteries and H_2 tank are significantly lower than for the rest of the truck.
- The Circularity Potential considering fossil energy for the operation phase only shows
    - Battery truck has lowest Circularity Potential with 44% - 53%,
    - Renewable supply infrastructure has a Circularity Potential of 52% - 76%,

- The total system with diesel truck has lowest Circularity Potential (3 – 5%) and electric trucks highest Circularity Potential (62% - 70%).

Further details of this LCA case study were published at EVS 37 (Jungmeier et al. 2024).

5.3.3 Fire Trucks

The goal of this LCA is to identify significant differences of environmental effects of an electric fire truck with a range extender (based on diesel ICE) and a diesel fire truck. This LCA was done in close cooperation with Rosenbauer/Austria, a global producer of fire trucks. Task 46 wanted to test with this LCA case study, if the newly developed approach for circularity and Climate Neutrality is also relevant for the industry.

The applied methodology is a dynamic LCA using generic global production data for materials considering the cumulative effects over the lifetime of an urban fire truck, for which typical fire-fighting and rescue services were defined.

The following fire trucks are analyzed:

- diesel fire truck with ICE (Internal Combustion Engine),
- battery electric fire trucks electricity with range extender (REX with diesel ICE).

The functional unit is defined per hour of mission for firefighting or rescue services, which is defined in cooperation with Rosenbauer based on an evaluation of the use of the electric fire truck in a German city. The base case has 1,200 hours per year of mission in a typical urban fire department. Due to the very different use cases, a detailed analysis for the electric fire truck was done:

- Case 1: 1,100 h/a,
- Case 2: 1,500 h/a,
- Case 3: 1,200 h/a,
- Average: 1,200 h/a and
- Extreme 1,600 h/a.

Figure 17 shows the system boundary for LCA case study of fire trucks.

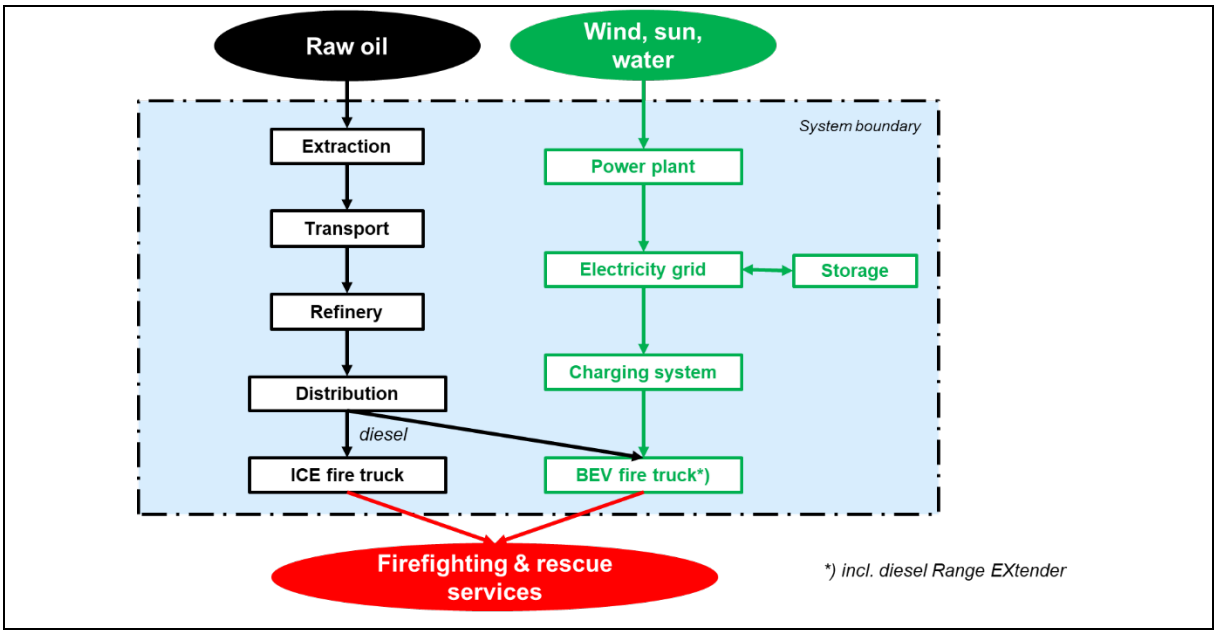


Figure 17: System boundary for LCA case study of fire trucks (JOANNEUM RESEARCH)

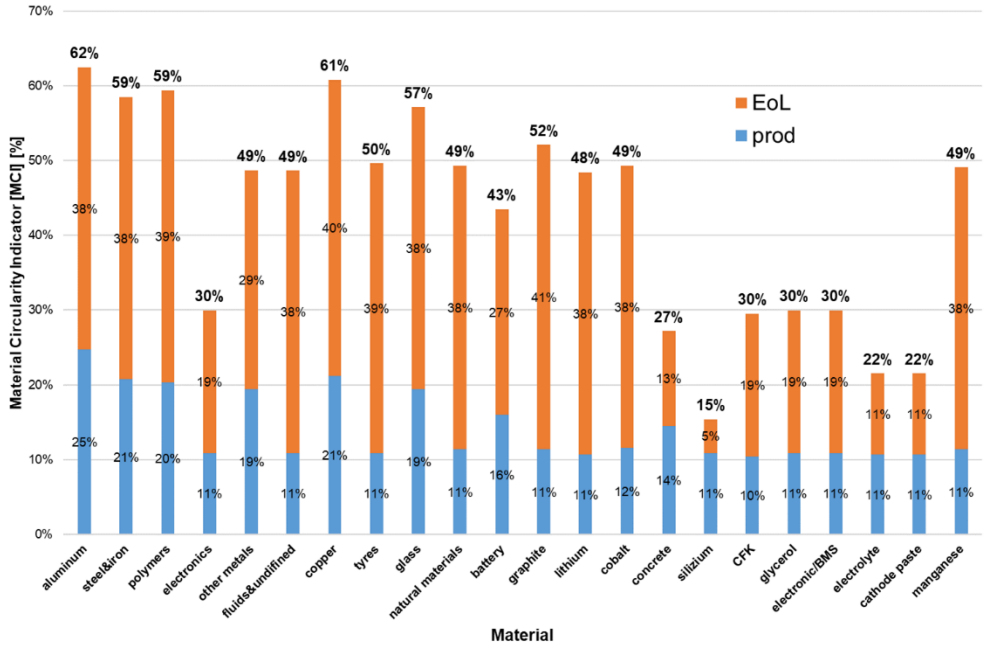
Renewable electricity is generated in all cases in new power plants for renewable electricity, which are considered in the production phase of the total system incl. fire truck and infrastructure for charging.

The database for the LCA was developed to represent adequately the technical, geographical and timely framework condition to fulfil the goal and the scope of the case study. The foreground data for the fire trucks were mainly provided by Rosenbauer (Rosenbauer 2025) and are given in Table 2. The background data for the materials for truck components and the material composition are from GREET 2022, the battery data are based on LCA Battery Model of JOANNEUM, and the electricity & fuel supply are from the internal LCA database of JOANNEUM RESEARCH. The total lifetime of the fire trucks is assumed with 15 years.

In Figure 18 the foreground data for the MCI of the relevant materials are shown.

Table 2: Foreground data for fire trucks (Rosenbauer 2025)

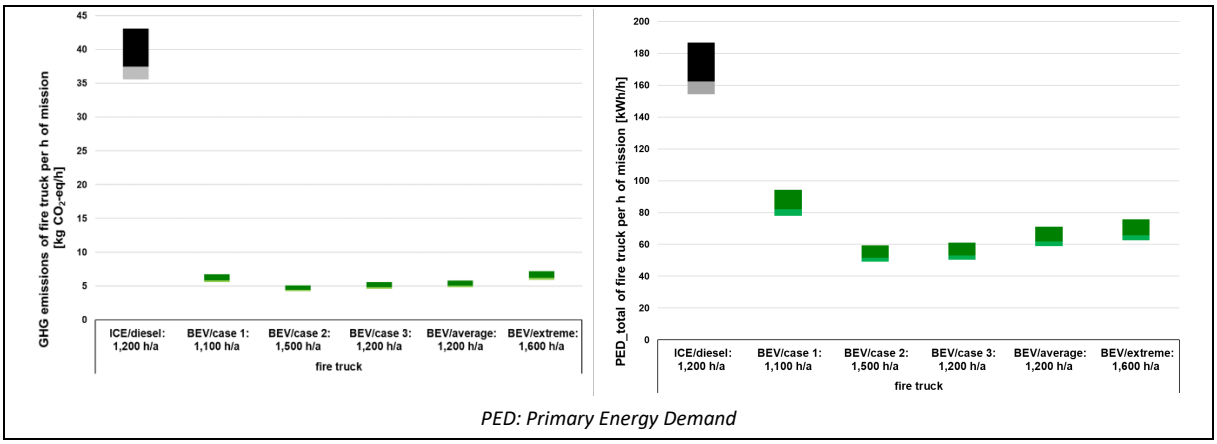
Characteristics	Unit	ICE LHF	eLHF				
		diesel: 1,200 h/a	case 1: 1,000 h/a	case 2: 1,500 h/a	case 3: 1,200 h/a	average: 1,200 h/a	extreme: 1,600 h/a
Case #		0	1	2	3	4	5
weight	t	9.0	12.8	12.8	12.8	12.8	12.8
max weight	t	16.0	16.0	16.0	16.0	16.0	16.0
battery capacity	kWh	20	264	264	264	264	264
lifetime	a	15	15	15	15	15	15
missions							
days	d	365	365	365	365	365	365
annual missions	1/a	2,200	1,900	2,600	2,000	2,200	2,500
annual operating hours	h/a	1,200	1,000	1,500	1,200	1,200	1,600
km for missions	km	14,100	11,300	17,900	13,200	14,100	20,000
km total	km	21,800	15,400	22,500	27,500	21,800	25,000
electricity per mission	kWh	-	27.2	20.8	20.5	22.8	30.0
diesel per mission	kWh	80.0	0.05	1.5	1.0	0.9	5.9
annual REX used	h/a	0	2	126	128	81	950
annual diesel	l/a	15,700	9	404	201	204	1,493
annual electricity	kWh/a	0	52,700	44,360	34,570	43,870	57,600
total energy	kWh/a	154,000	52,790	48,320	36,540	45,870	72,230
share electricity	%	0%	99.8%	92%	95%	96%	80%



prod: production phase and EoL: End-of-Life phase

Figure 18: Foreground data for MCI of materials (JOANNEUM RESEARCH)

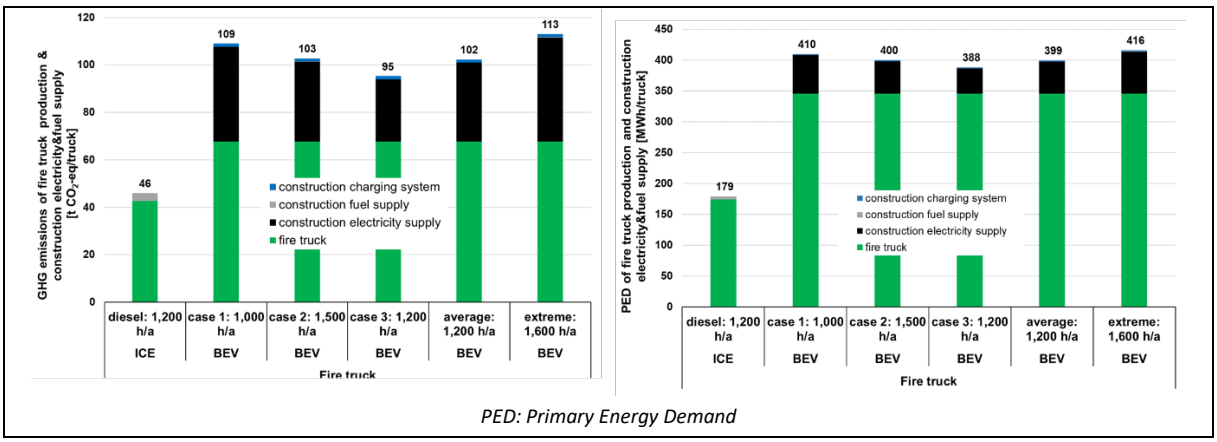
In Figure 19 the GHG emissions and the primary energy demand per mission hour for the fire trucks are shown, where the diesel fire truck has significant higher GHG emissions than the electric fire trucks. The ranges are due to sensitivity analysis on energy demand, electricity supply and battery.



PED: Primary Energy Demand

Figure 19: GHG emissions (left) and primary energy demand (right) of fire trucks per hour of missions in total life cycle (JOANNEUM RESEARCH)

In Figure 20 the GHG emissions and primary energy demand of fire truck production and power plant construction are shown. The electric fire trucks have, due to the battery, higher GHG emissions in the production phase. And the construction of the renewable power plants has a significant contribution to the total GHG emission in the construction phase.



PED: Primary Energy Demand

Figure 20: GHG emissions (left) and primary energy demand (right) of fire trucks production and power plant construction (JOANNEUM RESEARCH)

In Figure 21 the GHG emissions and the Climate Neutrality potential over the lifetime for the fire trucks are shown. In Figure 22 the total and the renewable primary energy demand of the fire trucks are shown.

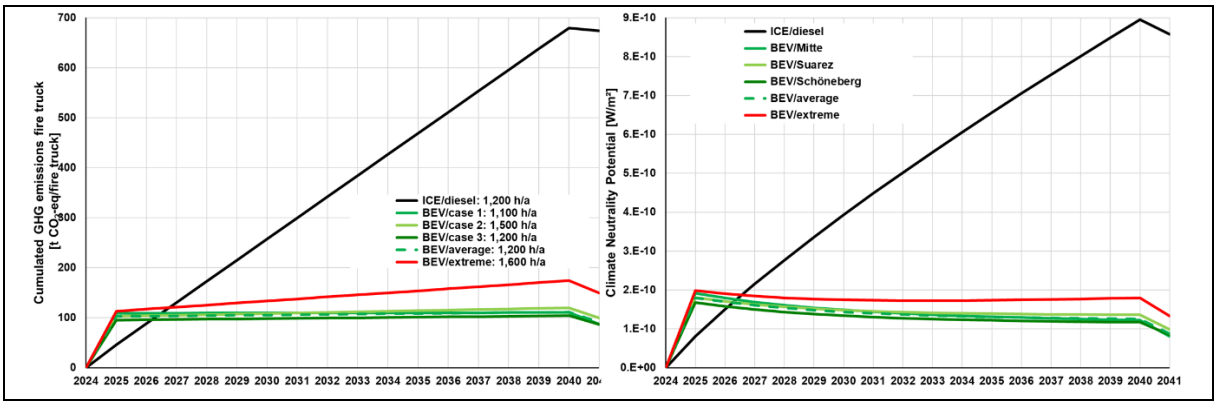


Figure 21: Global Warming Potential of the GHG emissions (left) and Climate Neutrality Potential (right) over time for the fire trucks (JOANNEUM RESEARCH)

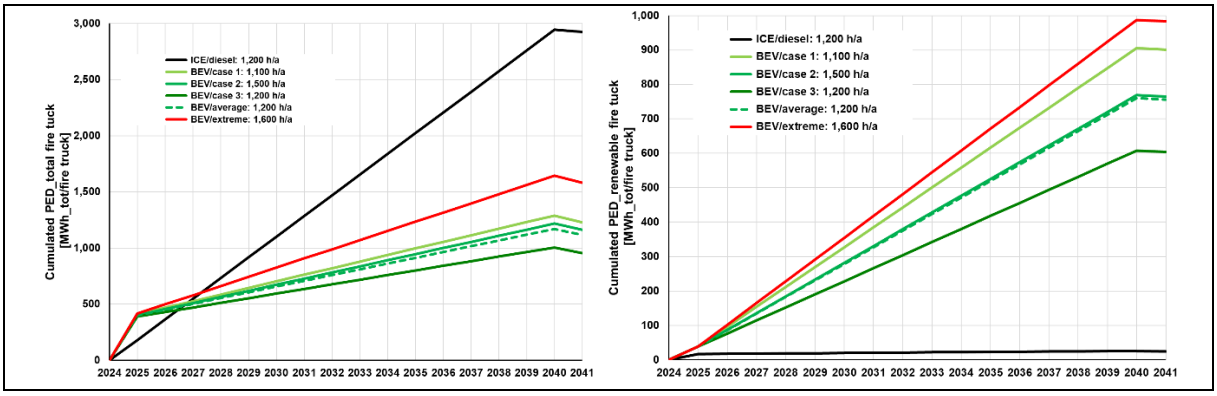


Figure 22: Total (left) and renewable primary energy demand (right) of fire trucks (JOANNEUM RESEARCH)

Figure 23 shows the Circularity Potential of the fire trucks (left) and the total system (right). As the basis for the calculation of the Circularity Potential, the total material demand in the lifetime of the fire trucks is calculated and shown in Figure 24 (left). In Figure 24 (right) the Circularity Potential over time for the fire trucks is shown. All systems start in nature with a Circularity Potential of 100% before the construction phase. Using the mass and the Circularity Potential the circular and non-circular mass is calculated and shown in Figure 25.

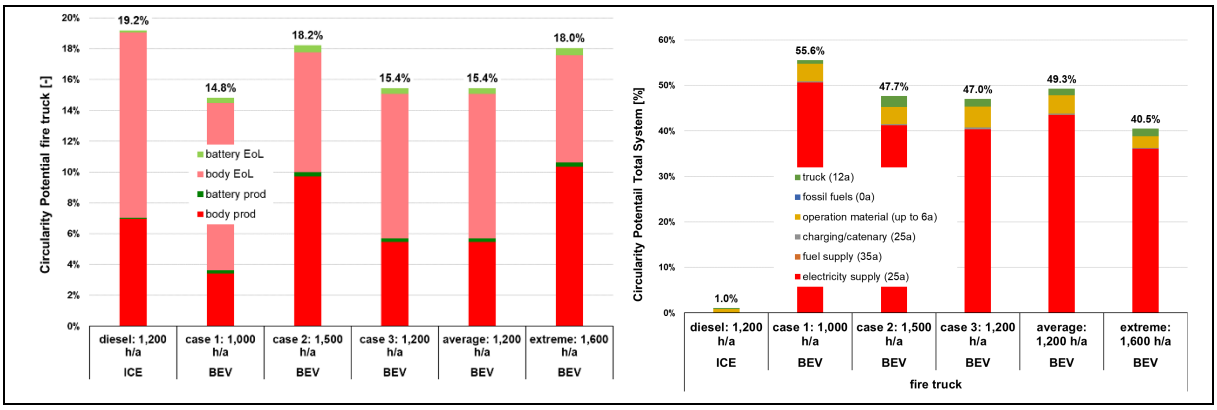


Figure 23: Circularity Potential of the fire trucks (left) and the total system (right) (JOANNEUM RESEARCH)

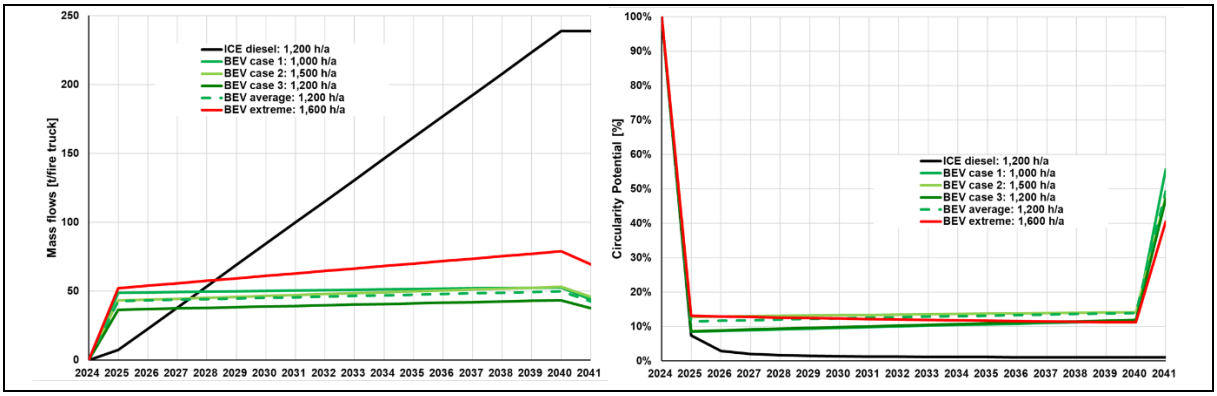


Figure 24: Mass flow (left) and Circularity Potential (right) in the lifetime of the fire trucks (JOANNEUM RESEARCH)

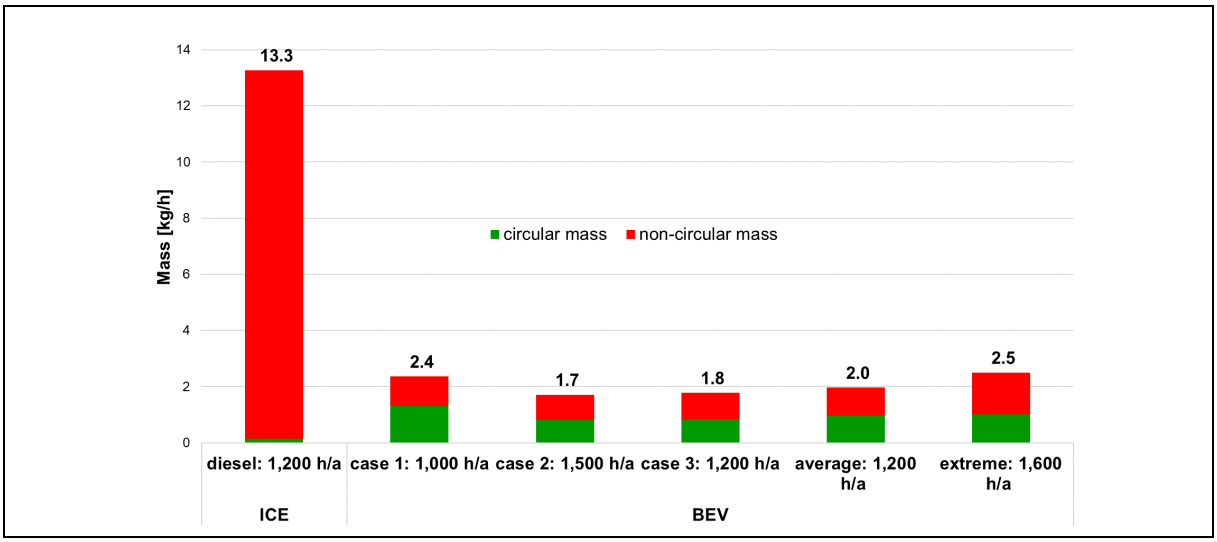


Figure 25: Circular and non-circular mass of the fire trucks (JOANNEUM RESEARCH)

Figure 26 shows the overall assessment of the different environmental effects of the fire trucks. In this overall summary, the reference is the diesel/ICE, which is set to 100%. The Circularity Potential is given in 1/CPO. One can observe that the Climate Neutrality Potential - measured in radiative forcing in the year 2050 – delivers different results than the GHG emissions. Additional to well established categories in life cycle-based assessment, the Circularity Potential as well as the Climate Neutrality Potential in 2050 delivers information covered neither in the primary energy demand nor in the GHG emissions.

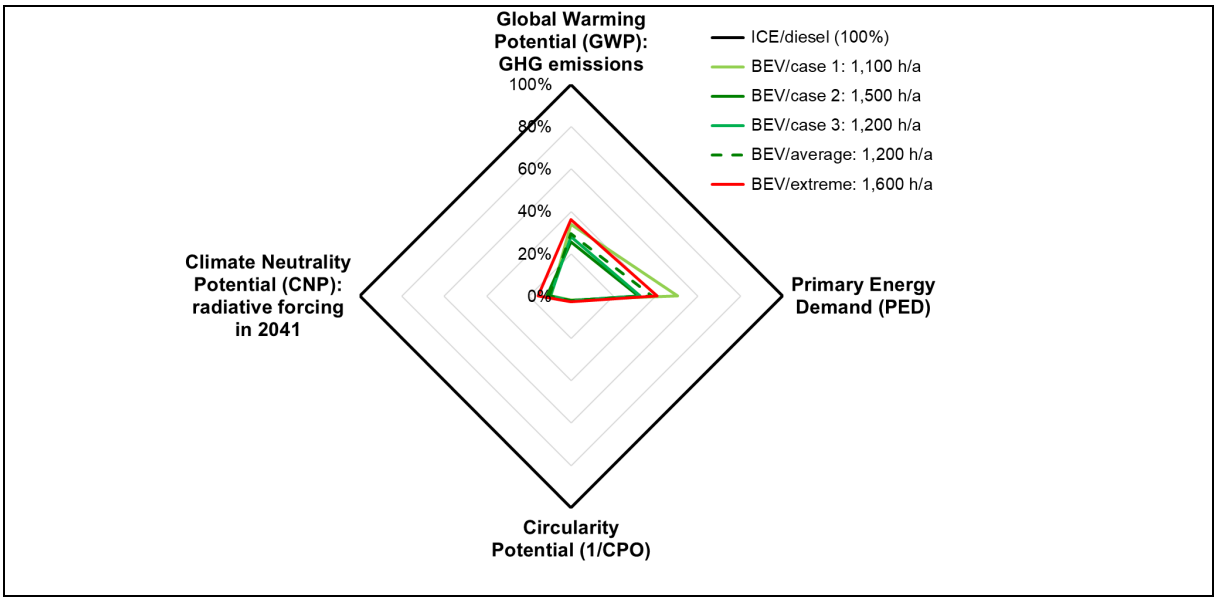


Figure 26: Overall assessment and comparison of the fire trucks, diesel ICE = 100% (JOANNEUM RESEARCH)

The following conclusions and observations are drawn:

- The electric fire truck using renewable electricity has significant lower environmental impacts than diesel fire truck:
    - GHG emissions: 66 – 74% reduction,
    - Climate Neutrality Potential: 98% higher but not zero,
    - Primary energy demand: 50 – 68% reduction,
    - Circularity Potential: 84 – 91% higher but not 100% circular!
- Main influences
    - Energy demand of truck,
    - Source of electricity,
    - Battery capacity,
    - Use of a range extender (REX with a diesel ICE,)
    - Lifetime and annual operating hours.
- Further R&D demand
    - Detailing of further typical missions for different activities e.g. driving, pumping etc.,
    - Measuring the CH_4 & N_2O emission of ICE and REX,
    - Further detailing of fire truck production at Rosenbauer,
    - Electricity from natural gas and electricity mix for different countries,
    - Information material for clients, e.g. Carbon Footprint, LCA,
    - Further improvement of environmental impacts of (electric)fire truck and
    - Framework/concept for “100% climate neutral fire truck”.

5.3.4 Mining Trucks

The goal of this LCA case study is to identify significant differences of environmental effects of an electric mining haul truck (MHT) with other propulsion systems. The applied methodology is a dynamic LCA using generic global production data for materials considering the cumulative effects over the lifetime of a mining haul truck. The following MHTs are analyzed:

- Systems
    - Internal combustion engine (ICE),
    - Hybrid electric ICE (HYB),
    - Battery electric truck (BEV),
    - Opportunity charging,
    - Catenary line,
    - Fuel cell (FC) with liquid hydrogen (LH_2).
- Energy carriers
    - Diesel,
    - E-diesel from renewable electricity mix and CO_2 from air,
    - Liquid hydrogen (LH_2) from renewable electricity mix,
    - Renewable electricity for BEV, e-diesel and LH_2: mix: 50% wind, 25% hydro, 25% PV.

The functional unit is defined per operation hour.

The database for the LCA was developed to represent adequately the technical, geographical and timely framework condition to fulfil the goal and the scope of the case study. The foreground data for the MHTs were taken from literature and the Task 46 partners and are given in Table 3. The background data for the materials for tuck components and the material composition are from GREET 2022, the battery data are based on LCA Battery Model of JOANNEUM, and the electricity & fuel supply are from the internal LCA database of JOANNEUM RESEARCH. The total lifetime of the mining haul trucks is assumed to be 15 years with 7,300 annual operating hours.

Table 3: Foreground data for mining haul trucks

truck type class		MHT						
propulsion		ICE		HYB		BEV		FC
fuel		diesel	e-diesel	diesel	e-diesel	electricity	catenary	LH2
weight	[kg]	413,000	413,000	413,000	413,000	413,000	413,000	413,000
Powertrain System (including BOP)	[kg]	1,000	1,000	1,000	1,000	-	-	1,000
Transmission System	[kg]	200	200	200	200	150	150	150
Chassis (w/o battery)	[kg]	174,420	174,420	179,946	179,946	167,525	167,525	185,468
Traction Motor	[kg]	-	-	100	100	500	500	-
Generator	[kg]	-	-	100	100	200	200	-
Electronic Controller	[kg]	30	30	100	100	250	250	100
Hydrogen Tank Onboard Storage	[kg]	-	-	-	-	-	-	4,000
Body: including BIW, interior, exterior, and glass	[kg]	1,200	1,200	1,200	1,200	1,200	1,200	1,200
Lift-gates	[kg]	-	-	-	-	-	-	-
Battery	[kg]	150	150	800	800	14,000	800	800
total w/h battery	[kg]	176,850	176,850	182,646	182,646	169,825	169,825	191,918
total	[kg]	177,000	177,000	183,446	183,446	183,825	170,625	192,718
payload	[kg]	236,000	236,000	229,554	229,554	229,175	242,375	220,282
battery capacity	[kWh]	0	0	200	200	3,500	200	200
energy demand *)	[kWh/h]	1,488	1,488	1,356	1,356	538	538	1,184
CH4 emissions *)	[g/h]	0.04	0.04	0.04	0.04	0	0	0
N2O-emissions *)	[g/h]	2.5	2.5	2.3	2.3	0.0	0.0	0.0
H2 emissions **)	[g/h]	0	0	0	0	0	0	370
NOx emissions *)	[g/h]	0.2	0.2	0	0	0	0	0
PM-emissions *)	[g/h]	0.003	0.003	0	0	0	0	0
urea/AdBlue *)	[l/100 h]	100	100	91	91	0	0	0
engine oil	[kg/100 h]	0.78	0.78	0.71	0.71	0	0	0
*) average driving cycle								
**) H2 losses/emissions								

To show the relevance of direct H_2-emissions for global warming, the Figure 27 shows the contribution of direct H_2-emissions to the GHG emissions from stack (left) and energy supply and operational material (right) of mining haul trucks per operating hour. For the trucks, using H_2 and e-fuel the contribution of H_2 to GWP is significant from the H_2 supply due to the H_2–losses. The GWP_{100} of hydrogen is 10.9 kg CO_2-eq per kg of hydrogen (range: 6.5- 15 kg CO_2-eq/kg_{H2}) (based on Ilissa et al. 2022 and Warwick et al. 2022). The direct H_2-emissions are assumed the following (UC Davis 2023)

- GH_2 losses: 4.3% (2.6% - 5.9%) and
- LH_2 losses: 9.2% (6.4% - 12.0%).

In Figure 27 it can be seen that only electric vehicles have zero GHG emissions in the operation phase, whereas ICE and FC have emissions due to diesel combustion or the combustion of engine oil and urea as a well as direct H_2-emissions due to losses.

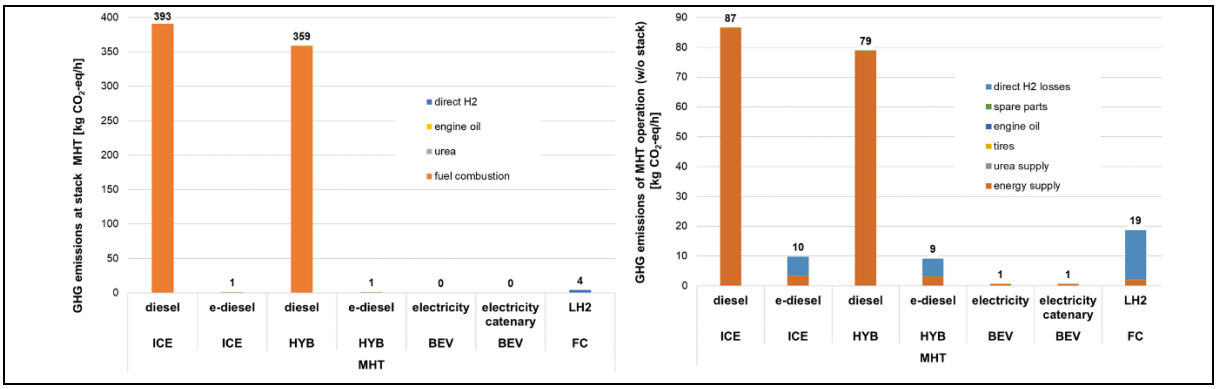


Figure 27: GHG emissions from stack (left) and energy supply & operational material (right) MHT per operating hour with direct H_2-emissions (JOANNEUM RESEARCH)

In Figure 28 the GHG emissions (left) and the primary energy demand (right) per mission hour for the MHTs are shown, where the diesel mining truck has significant higher GHG emissions than the electric MTH. The ranges are due to sensitivity analysis on energy demand, annual operating hours, electricity supply and battery.

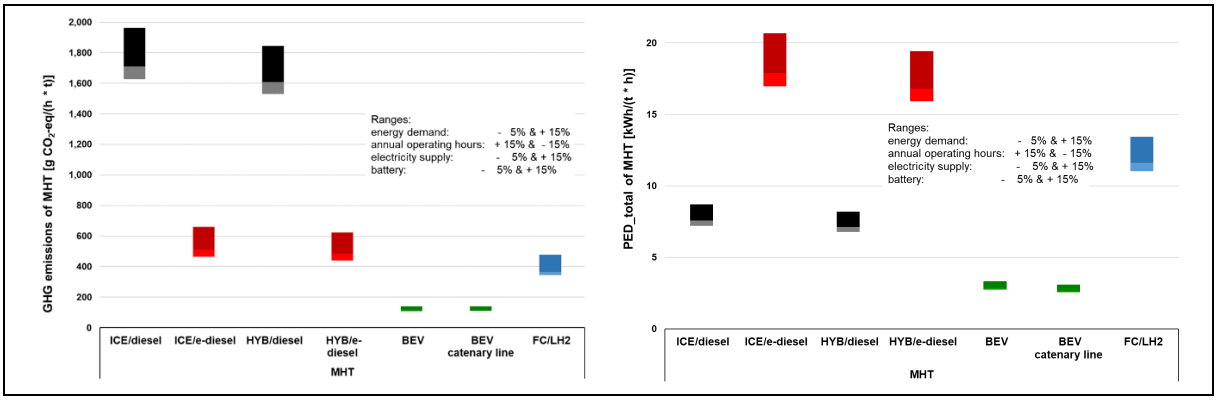


Figure 28: GHG emissions (left) and primary energy demand (right) of MHT per hour of missions in total life cycle (JOANNEUM RESEARCH)

In Figure 29 the Global Warming Potential of the GHG emissions and the Climate Neutrality Potential over the lifetime for the MHT are shown. In Figure 30 the total and renewable primary energy demands of the MHT are shown.

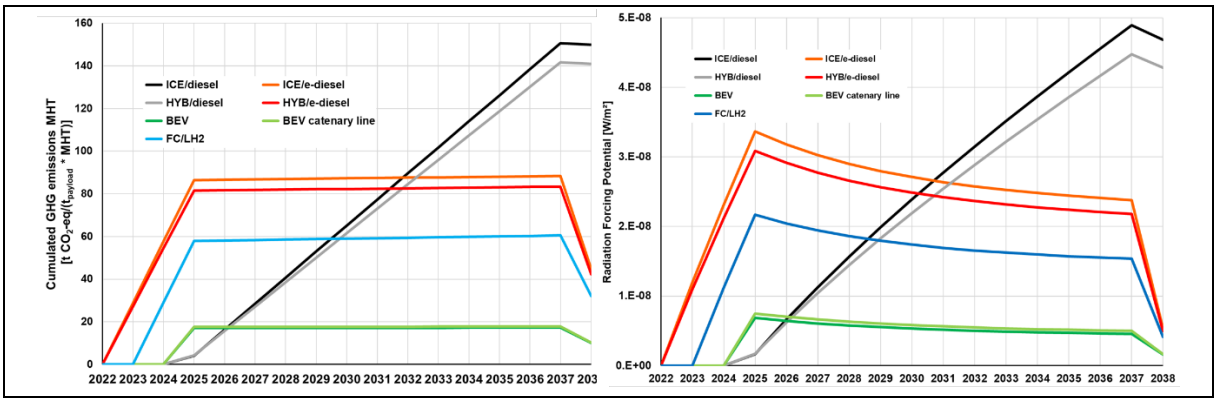


Figure 29: Global Warming Potential of the GHG emissions (left) and Climate Neutrality Potential (right) over time for the MHT (JOANNEUM RESEARCH)

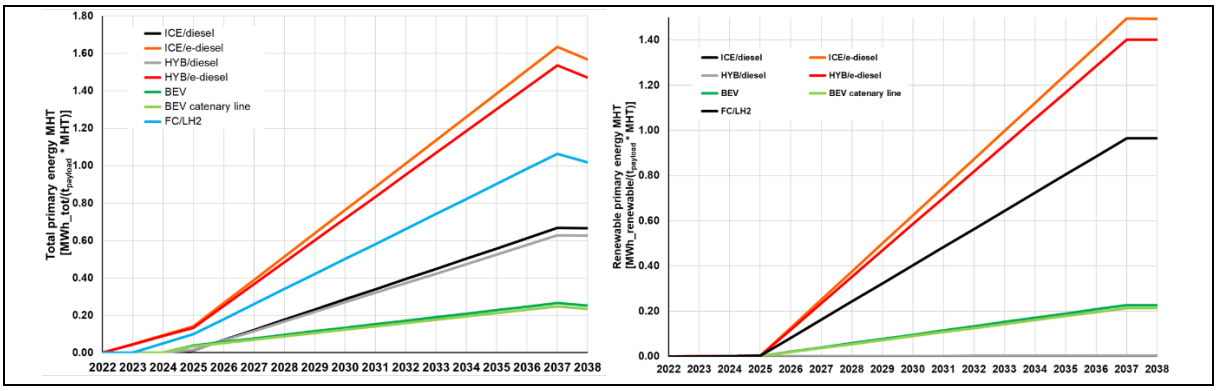


Figure 30: Total (left) and renewable primary energy demand (right) of mining haul truck (JOANNEUM RESEARCH)

Figure 31 shows the Circularity Potential of the MHT (left) and the total system (right). As the basis for the calculation of the Circularity Potential, the total material demand in the lifetime of the MHT is calculated and shown in Figure 32 (left). In Figure 32 (right) the Circularity Potential over time for the MHT is shown. All systems start in nature with a Circularity Potential of 100% before the construction phase. Using the mass and the Circularity Potential the circular and non-circular mass is calculated and shown in Figure 33.

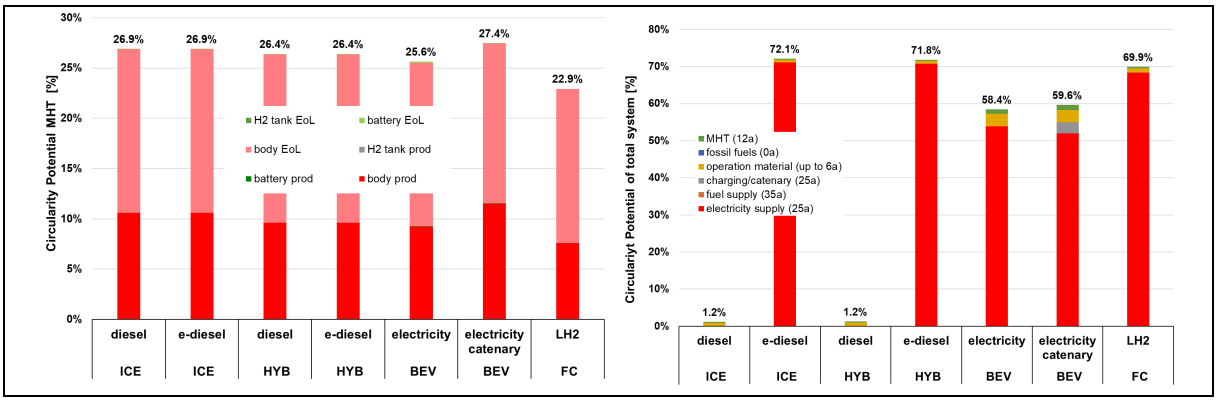


Figure 31: Circularity Potential of the mining haul truck only (left) and the total system (right) (JOANNEUM RESEARCH)

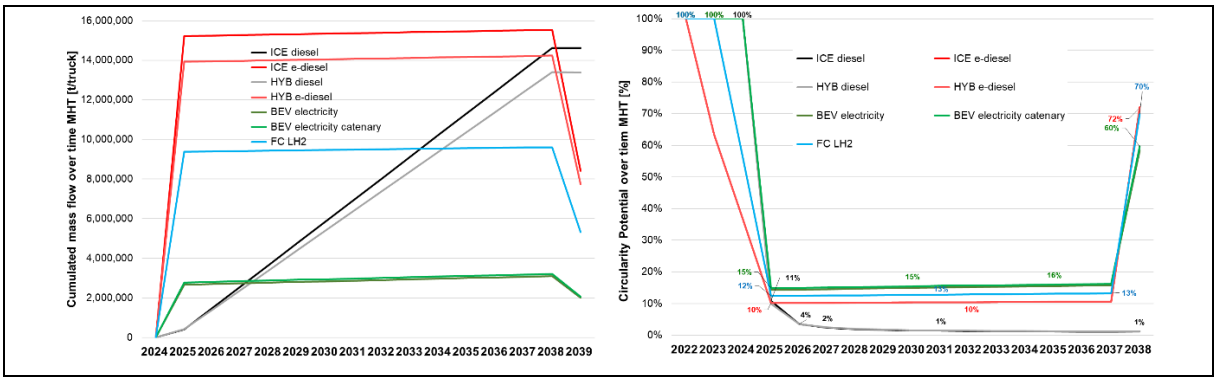


Figure 32: Mass flow (left) and Circularity Potential (right) in the lifetime of the MHT (JOANNEUM RESEARCH)

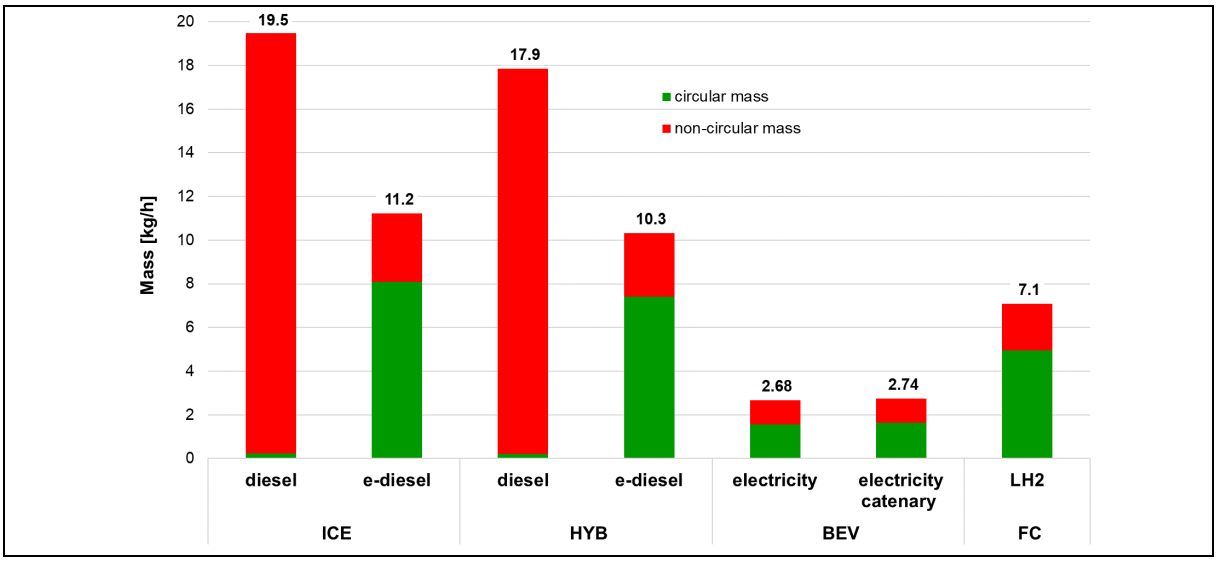


Figure 33: Circular and non-circular mass of the MHT (JOANNEUM RESEARCH)

Figure 34 shows the overall assessment of the different environmental effects of the mining haul truck. In this overall summary, the reference is the diesel/ICE, which is set to 100%. The Circularity Potential is given in 1/CPO. One can observe that the Climate Neutrality Potential - measured in radiative forcing in the year 2039 – delivers different results than the GHG emissions. Additional to the well-established categories in life cycle-based assessment, the Circularity Potential as well as the Climate Neutrality Potential in 2039 delivers information covered neither in the primary energy demand nor in the GHG emissions.

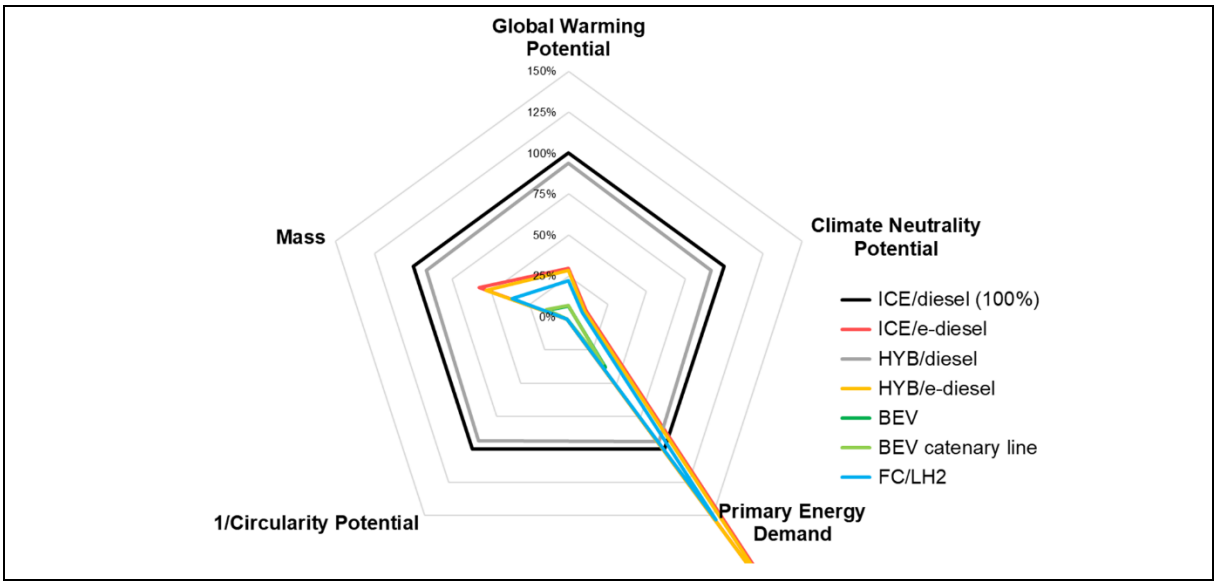


Figure 34: Overall assessment and comparison of the MHT, diesel ICE = 100% (JOANNEUM RESEARCH)

The following conclusions and observations are drawn:

- The electric mining truck using renewable electricity has significant lower environmental impacts than diesel mining truck:
  - Electric MHTs using renewable electricity have significant lower environmental impacts than other systems,
  - GHG emissions: 93% reduction,
  - Climate Neutrality Potential: 96 - 97% higher but not zero,
  - Primary energy demand: 62 - 65% reduction,
  - Circularity Potential: 98% higher but not 100% circular,
  - Mass: 86% reduction.
- Main influences
  - Energy demand of truck,
  - Source of electricity,
  - Battery capacity,
  - Lifetime and annual operating hours,
  - Direct H_2 emissions mainly relevant from LH_2 supply.

5.3.5 City Buses

The goal of this LCA case study is to identify significant differences of environmental effects of city buses with different propulsion systems/fuels for current and future technology (2024 and 2036) based on the conclusions of a workshop on LCA of buses (see chapter 5.2.2). The applied method-

ology is a dynamic LCA using generic global production data for materials considering the cumulative effects over the lifetime of the city buses, for which typical urban driving cycles are considered.

The following transportation systems are analyzed:

- Diesel with ICE (Internal Combustion Engine),
- E-diesel from wind electricity and CO_2 from air with ICE,
- Electricity for BEV with depot (DC), opportunity (OC) and wireless charging (WC) with wind electricity,
- H_2 with FC (Fuel Cell) from wind electricity: GH_2 @ 700 bar.

The functional unit is per passenger kilometer (P-km) due to the different passenger capacities of the city buses. Renewable electricity is generated in all cases in new wind power plants, which are considered in the production phase of the total system incl. city bus, and infrastructure for charging.

The further specifications are

- Battery and fuel cell change after 6 years,
- Consideration over lifetime of two buses for 24 years, same lifetime as wind power plant,
- Duration of system construction: e-fuel= 3 years, H_2 = 2 years and BEV = 1 year,
- "Climate Neutrality" of all systems
    - In combination with CCS of CO_2 from air with wind power,
    - Calculated based on CO_2eq also covering CH_4 and N_2O,
    - CCS simplified with static LCA (no timing of GHG emissions, mainly relevant for construction phase).

The database for the LCA was developed to represent adequately the technical, geographical and timely framework condition to fulfil the goal and the scope of the case study. The foreground data for the city buses are in Table 4. The background data for the materials for city bus components and the material composition are from GREET 2022, the battery data are based on LCA Battery Model of JOANNEUM, and the electricity and fuel supply are from the internal LCA database of JOANNEUM RESEARCH. The total lifetime mileage is 1.4 Mio. km in 24 years.

Table 4: Foreground data for city buses (Task 46 et al. 2024)

type class		city bus					
propulsion	[name]	ICE	ICE	BEV	BEV	BEV	FC
fuel	[name]	diesel	e-diesel	DC	OC	WC	GH2@700
weight	[kg]	19,500	19,500	19,500	19,500	19,500	19,500
Powertrain System (including BOP) ***)	[kg]	69	69	-	-	-	215
Transmission System	[kg]	677	677	338	338	338	338
Chassis (w/o battery)	[kg]	7,500	7,500	7,500	7,500	7,500	7,500
Traction Motor	[kg]	793	793	190	190	190	190
Generator	[kg]	-	-	-	-	-	-
Electronic Controller	[kg]	20	20	145	145	145	145
Hydrogen Tank Onboard Storage	[kg]	-	-	-	-	-	612
Van/Box	[kg]	-	-	-	-	-	-
Body: including BIW, interior, exterior, and glass	[kg]	3,500	3,500	3,500	3,500	3,500	3,500
Lift-gates	[kg]	-	-	-	-	-	-
Battery ***)	[kg]	100	100	3,000	1,100	850	900
total w/h battery	[kg]	12,559	12,559	11,673	11,673	11,673	12,500
total	[kg]	12,659	12,659	14,673	12,773	12,523	13,400
passenger capacity	[#]	105	105	84	95	101	100
payload	[%]	35%	35%	25%	34%	36%	31%
battery capacity	[kWh]	5.0	5.0	450.0	200.0	150.0	35.0
energy demand H2 without upstream losses	[kWh/km]						2.920
energy demand *)	[kWh/km]	5.050	5.050	1.900	1.700	1.680	3.044
CH4 emissions *)	[g/km]	0.001	0.001				
N2O-emissions *)	[g/km]	0.018	0.018				
H2 emissions **)	[g/km]						0.69
NOx emissions *)	[g/km]	0.084	0.084				
PM-emissions *)	[g/km]	0.002	0.002				
urea/AdBlue *)	[l/100 km]	2.061	2.061				
engine oil	[kg/100 km]	0.016	0.016				
driving range per charging (max SOC 90%)	[km]			213	106	80	

**) average driving cycle*

***) H_2 losses/emissions*

****) 2nd battery/fuel cell 10% less*

In Figure 35 the GHG emissions per passenger capacity kilometre for the buses 2024 are shown, where the diesel bus has the highest and the electricity buses have the lowest emissions. The ranges are due to sensitivity analysis on energy demand, annual mileage, electricity supply and battery.

In Figure 36 the Global Warming Potential of the GHG emissions over time for the city buses – bus 1: 2024 – 2035 and bus 2: 2036 – 2047 - are shown in t CO_2eq over the total lifetime. The GHG emissions increase during the construction phase is due to the construction of the city buses and the power plants. The GHG emissions start in different years for the considered systems due to different assumed construction time. As the electricity demand for e-fuel and H_2 is higher than for electric city buses, the GHG emission are significantly higher, mainly in the construction phase. The systems using renewable electricity have nearly no additional GHG emissions during operation except from spare parts and maintenance. In comparison, the GHG emissions of diesel rise significantly during operation due to the combustion of fossil fuel. The decrease of the GHG emissions in the EoL phase is due to the supply of secondary material from recycling of the city buses and the wind power plants for any other product. The changing of the fuel cell and the batteries after 6 years are visible but not significant in the total life cycle. Thus, all systems using renewable electricity have the potential to become climate neutral, but the GHG emissions are significantly higher during the whole lifetime of e-fuel and H_2 compared to electric city bus.

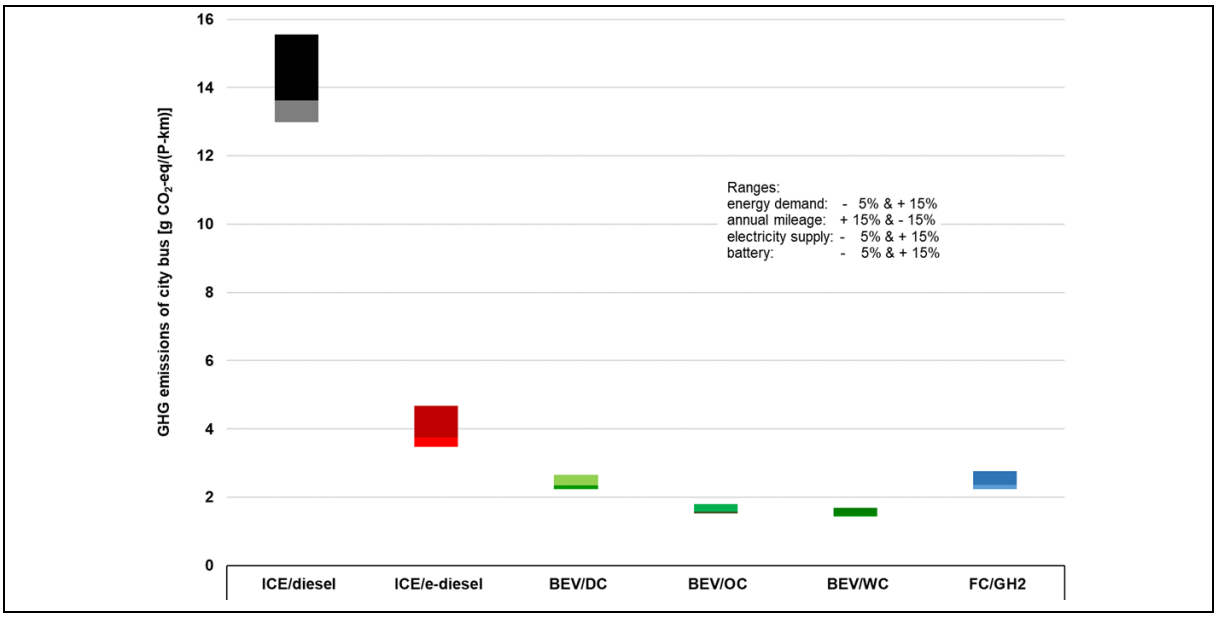


Figure 35: GHG emissions of the city buses in the year 2024 (JOANNEUM RESEARCH)

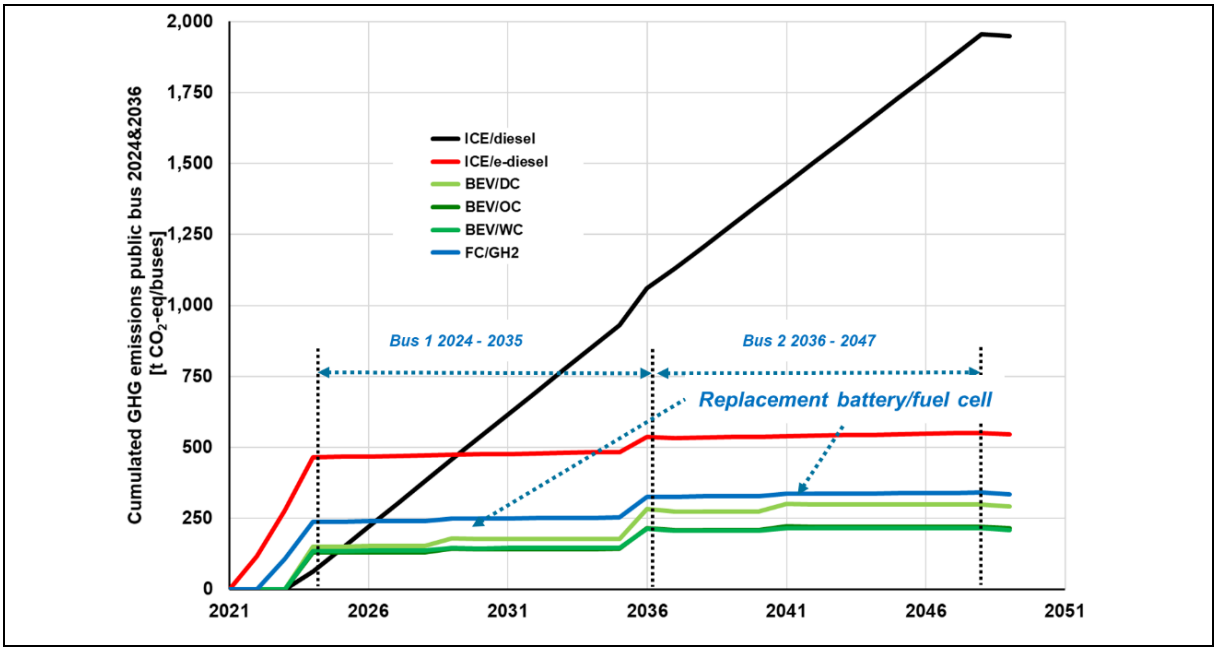


Figure 36: Global Warming Potential of the GHG emissions over time for the two city buses (bus 1 and bus 2) (JOANNEUM RESEARCH)

In Figure 37 the Climate Neutrality Potential of the radiative forcing over time for the city buses is shown. It can be seen that due to the GHG emissions over time the electric buses have the lowest radiative forcing at the end of its lifetime. The Climate Neutrality Potential in 2050 delivers additional assessment information compared to the GHG emission over time.

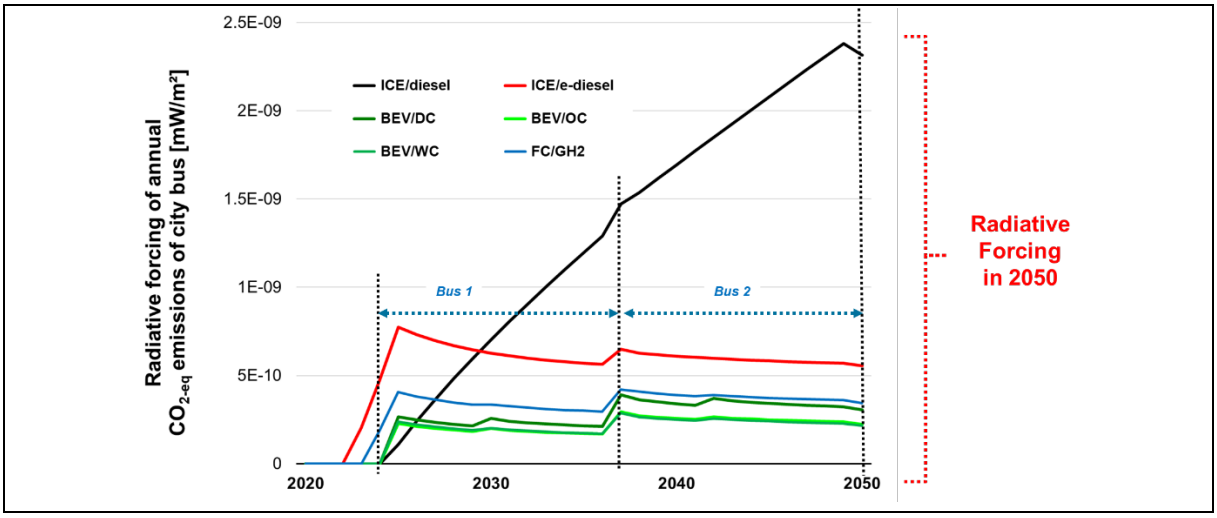


Figure 37: Climate Neutrality Potential of the radiative forcing over time for the city buses (JOANNEUM RESEARCH)

Figure 38 shows the total and renewable primary energy demand over time for the city buses in MWh of the total lifetime without CCS, and in Figure 39 with CCS for the "100% climate neutral city buses". The total primary energy increase during the construction phase is due to the construction of the city bus and the power plants. As the electricity demand for e-fuel and H_2 is higher than for electric city buses, the primary energy demand is significantly higher. The primary energy demand of the diesel ICE-bus is about the same as for the H_2 FC-bus. The systems using renewable electricity have a strong increase in the renewable primary energy demand in the operation phase, which can even be higher than for the city buses using fossil fuels. The decrease of the primary energy demand in the EoL phase is due to the supply with secondary material from recycling of the city bus and the wind power plants for any other product.

The amount of renewable electricity for the "100% climate neutral" city bus with diesel is about the same as for the "100% climate neutral" electric buses, whereas for H_2 and e-diesel it is significantly higher. It might be concluded that if CCS is technically and economically feasible in the future, significantly less additional renewable electricity would be needed for a "100% climate neutral" diesel bus than for a "100% climate neutral" e-diesel or H_2 bus.

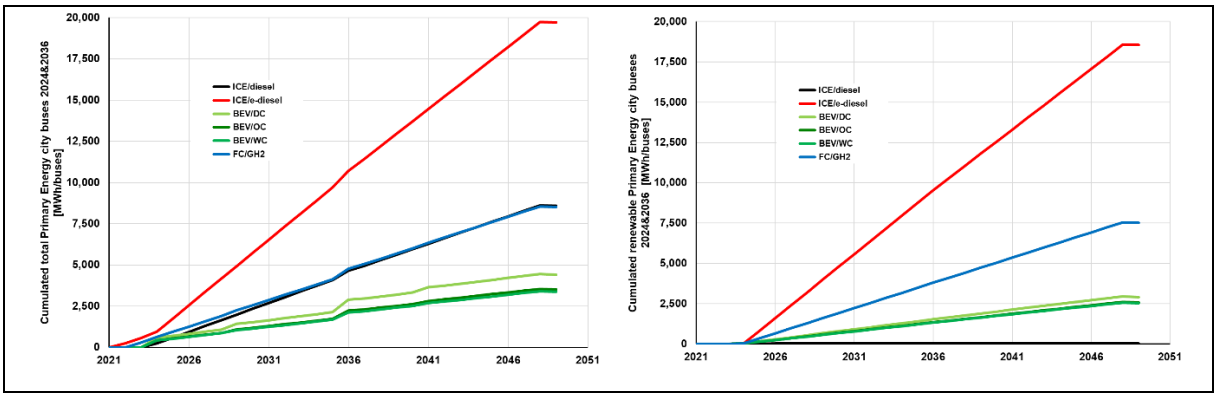


Figure 38: Total (left) and renewable (right) primary energy demand over time for the city buses without CCS (JOANNEUM RESEARCH)

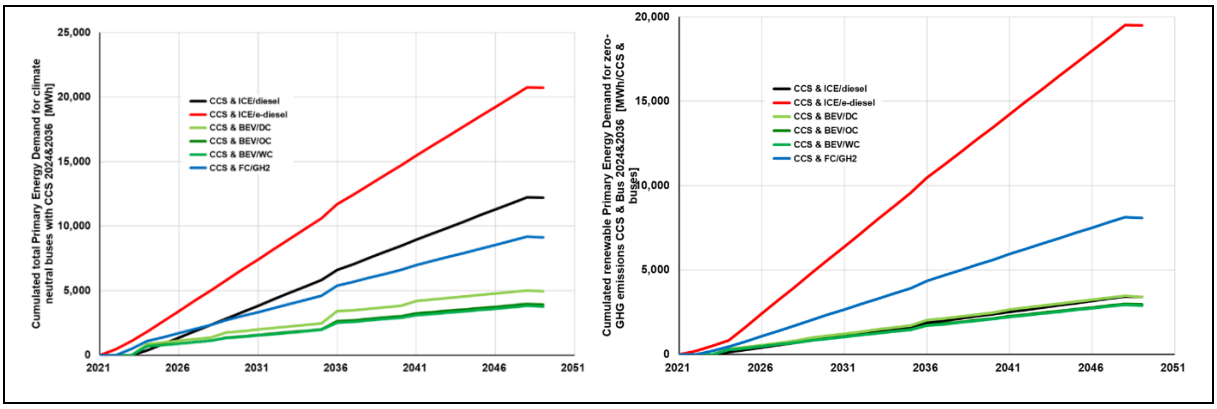


Figure 39: Total (left) and renewable (right) primary energy demand over time for the “100% climate neutral” city buses with CCS (JOANNEUM RESEARCH)

As the basis for the calculation of the Circularity Potential, the total material demand in the lifetime of the city buses is calculated. In all systems, the mass of the city bus is significantly lower than the mass of the used fossil fuel and the mass needed for construction of renewable power plants as well as the catenary system.

In Figure 15 the Circularity Potential over time for the city buses is shown. All systems start in nature with a Circularity Potential of 100% before the construction phase. During the construction, phase the Circularity Potential decreases significantly, again for e-fuel and H_2 more than for electric city buses due to the higher demand of renewable power plants. In the operation phase the Circularity Potential for systems, using renewable electricity nearly remains constant beside a small influence due to the spare parts and maintenance. For systems, using fossil energy the Circularity Potential is drastically reduced in the operation phase due to the non-circularity of fossil fuel combustion.

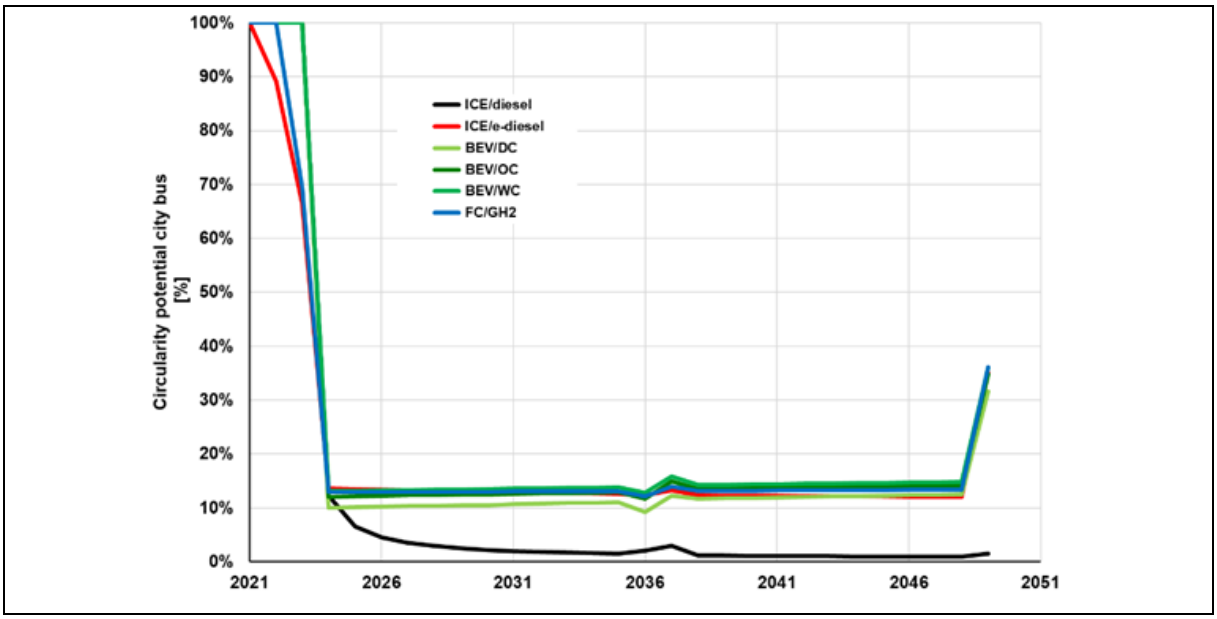


Figure 40: Circularity Potential over time for the city buses (JOANNEUM RESEARCH)

Figure 41 shows the overall assessment of the different environmental effects of the city buses without CCS and "100% climate neutral" with CCS. In this overall summary, the reference is the diesel/ICE, which is set to 100%. The Circularity Potential is given in 1/CPO. One can observe that the Climate Neutrality Potential - measured in radiative forcing in the year 2050 – delivers different results than the GHG emissions. Additional to the well-established categories in life cycle-based assessment, the Circularity Potential as well as the Climate Neutrality Potential in 2050 delivers information covered neither in the primary energy demand nor in the GHG emissions.

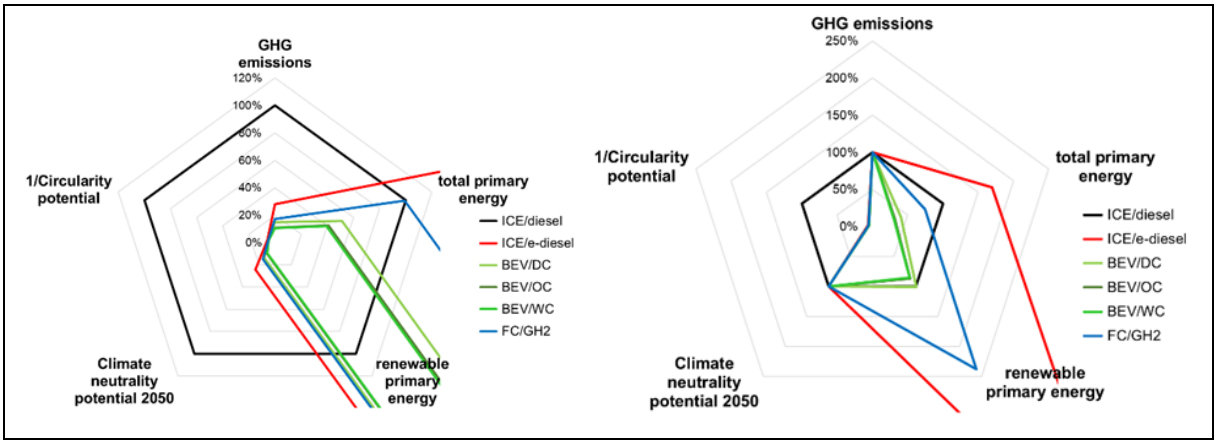


Figure 41: Overall assessment and comparison of the city buses without (right) / with CCS (left), diesel ICE = 100% (JOANNEUM RESEARCH)

The following conclusions and observations can be drawn:

- Climate Neutrality Potential and Circularity Potential describe additional environmental effects not covered yet in the different LCA assessment categories.
- The Climate Neutrality Potential measures the radiative forcing in mW/m² in the year 2050. Thus, the timing of the GHG emissions during the lifetime of the system is relevant.
- The Circularity Potential is measured with the Material Circularity Index, which is between 0% (linear) and 100% (circular), which is mainly determined by the amount of primary material (incl. fossil fuels) and the non-recoverable waste.
- Systems using renewable energy have the potential to direct towards Climate Neutrality and Circularity.
- The assessment of circularity using CPO shows that material circularity is significantly determined by the amount and type of material used.
- The amount of material required for the renewable electricity power plants is significantly higher than the amount of material used in the city bus.
- Additional wind power: relevant in dynamic LCA to assess Circularity and Climate neutrality
- Further development of the approach for "Climate Neutrality Potential" and "Circularity Potential": works well
- Battery and fuel cell change after 6 years: no significant influence on results
- Consideration over lifetime of two buses for 24 years: gives a better picture of circularity index at EoL
- Duration of system production: e-fuel= 3 years, H_2 = 2 years and BEV = 1 year: initially considered assessed to raise also these issues for further discussion
- "Climate Neutrality" with CCS of all systems:
    - More wind power needed,
    - ICE/diesel needs about the same amount of electricity as for BEV systems,
    - "It needs less additional renewable electricity to use fossil diesel with CCS than making e-diesel".
- Further issues
    - Reconsider methodology on recycling: e.g. GHG credits,
    - Including criticality of materials in circularity assessment
- Battery electric city buses have the lowest environmental effects in all environmental impacts.
- Due to the higher necessary battery capacity of the depot charging strategy, the city bus using depot charging has little higher environmental impacts than the city buses using (wireless) opportunity charging.
- The e-diesel bus has the highest GHG emissions and the highest primary energy demand.
- The Circularity Potential of the electric, hydrogen and e-diesel bus a quite similar (31 – 36%). Due to the use of fossil diesel in the operation phase, the Circularity Potential of the diesel bus is below 1.5%.
- In combination with CCS, all city buses can have zero GHG emissions and can be climate neutral throughout the total lifetime.
- The additional primary energy for CCS needed is
    - 30% for diesel bus and the absolute amount is the same as the electric bus needs in total,
    - 5% for e-diesel bus,
    - 10% for electric buses and the absolute amount is the lowest compared to all other buses and
    - 7% for hydrogen bus.

Further details of this LCA case study were published at EVS 37 (Jungmeier et al. 2025) and REMADE 2025 (Jungmeier et al. 2025a).

5.3.6 V2X-Services with Passenger Vehicle

The aims of this LCA case study were

- Assessment of environmental effects of electric vehicles using different V2X-functionalities,
- Identification of V2X cases relevant for LCA methodology,
- Analysing and discussing methodological aspects of V2X functionalities,
- Influence of battery: material recycling and 2nd stationary life e.g. for PV,
- Usage of electricity from new built renewable power production plants (generic data: 25% PV, 25% hydro, 50% wind).

The key issues on the applied methodology were

- Dynamic LCA using generic global LCA data,
- Allocation of V2X functionalities,
- Detailing circularity assessment on production and EoL,
- EoL phase: cut off approach.

The considered systems are passenger vehicles (based on year 2024) (based on Volvo 2024)

- Petrol ICE as reference (based on Volvo XC90 MHEV),
- BEV (based on Volvo EX90) with different V2X use cases

Initially, the most interesting and possible cases for V2X-servcies were identified by considering the following aspects:

- Usages
    - Driving
        - Direct charging (charging when plugged),
        - Smart charging (availability of renewable electricity; using price signals),
        - Bidirectional charging (balancing renewable electricity; charge with low/discharge with high prices).
    - V2X
        - V2D (energy storage for device, e.g. barbeque, light),
        - V2G (energy storage for grid),
        - V2H (energy storage for house),
        - V2G&H (energy storage grid/house),

    - Frequency services (for grid).
- EoL battery
    - Material recycling,
    - 2nd life (reuse) as stationary battery e.g. PV.

Based on these aspects the following eight BEV cases for the LCA were selected (Table 5 and Figure 42):

- 1_recycling (BEV base case).
- 2_2nd life energy storage.
- 3_smart charging.
- 4_smart charging V2D.
- 5_bidirectional charging V2H.
- 6_bidirectional charging V2G.
- 7_bidirectional charging V2G&H and
- 8_frequency service.

Additional also a case "0_petrol ICE" is considered to show also the key differences to conventional vehicles.

In Figure 43 the system boundaries for the V2X use cases are shown. For the cases without smart or bidirectional charging an additional electricity storage in the grid is considered.

Table 5: Main characteristics of the eight cases of V2X-services (JOANNEUM RESEARCH)

Electricity	Usages								EoL battery		Acronym
renewable mix	driving			V2X					material recycling	2nd life	
	direct charging	smart charging	bidirectional charging	energy storage				frequency services			
				V2D	V2H	V2G	V2G&H				
ICE petrol											0_petrol ICE (reference)
BEV 1	+								+		1_recycling (BEV base case)
BEV 2	+									+	2_2nd life energy storage
BEV 3		+							+		3_smart charging
BEV 4				+					+		4_smart charging V2D
BEV 5			+		+				+		5_bidirectional charging V2H
BEV 6			+			+			+		6_bidirectional charging V2G
BEV 7			+				+		+		7_bidirectional charging V2H&G
BEV 8			+					+	+		8_frequency service
BEV 9											9_PV for BEV
BEV 10											10_PV for PV&home

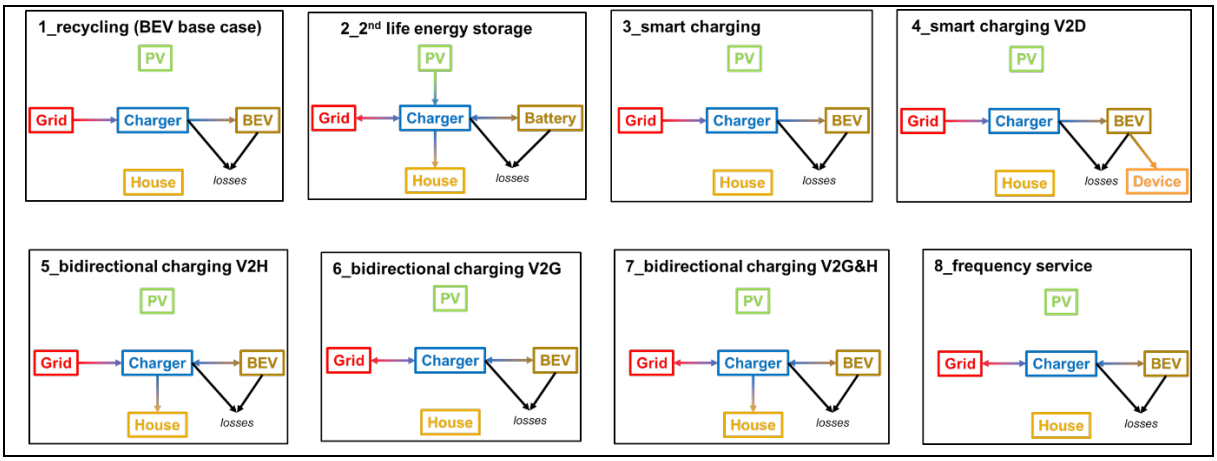


Figure 42: The eight analysed case (PV only relevant for 2nd life of battery as stationary electricity storage) (JOANNEUM RESEARCH)

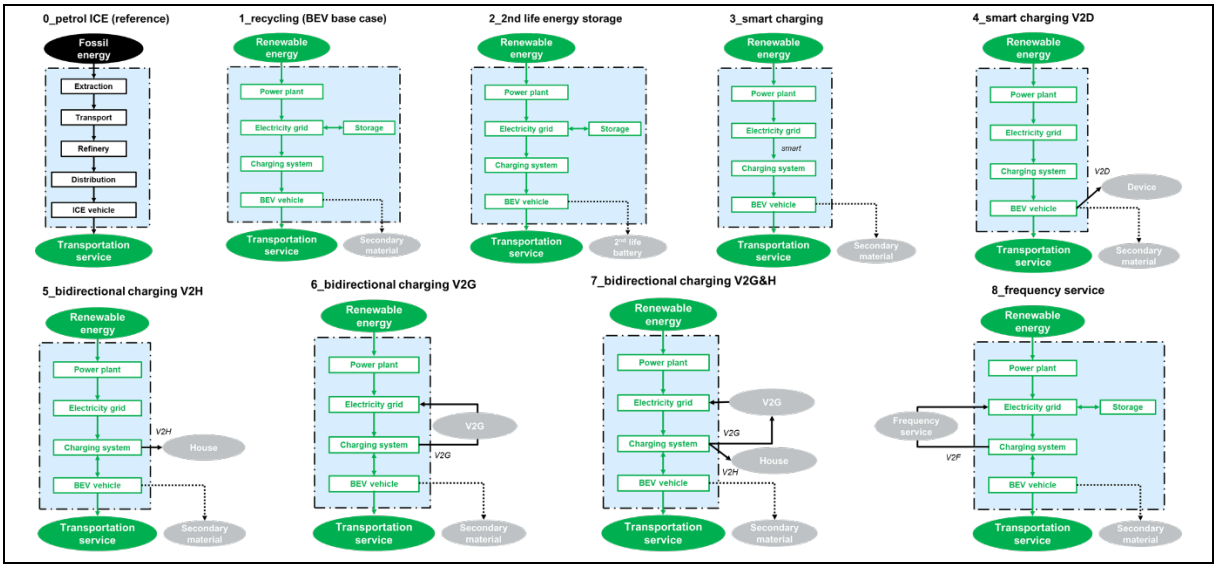


Figure 43: System boundaries for the eight analysed cases and the petrol ICE as reference (JOANNEUM RESEARCH)

One key methodological issue was the allocation of the battery, the charging infrastructure and the rest of the vehicle to the transportation services and the V2X-services (Figure 44). The allocation is done based on the annual electricity throughput of the charger and the battery (Figure 45). Additional it was recognized that also the rest of the vehicle is somehow relevant for the V2X-services, e.g., offering a casing for the energy storage for PV electricity, and must therefore also partly allocated to the V2X-services and the driving. For this, a combined allocation of mass and energy for the rest of the vehicle was developed and is described in Figure 46.

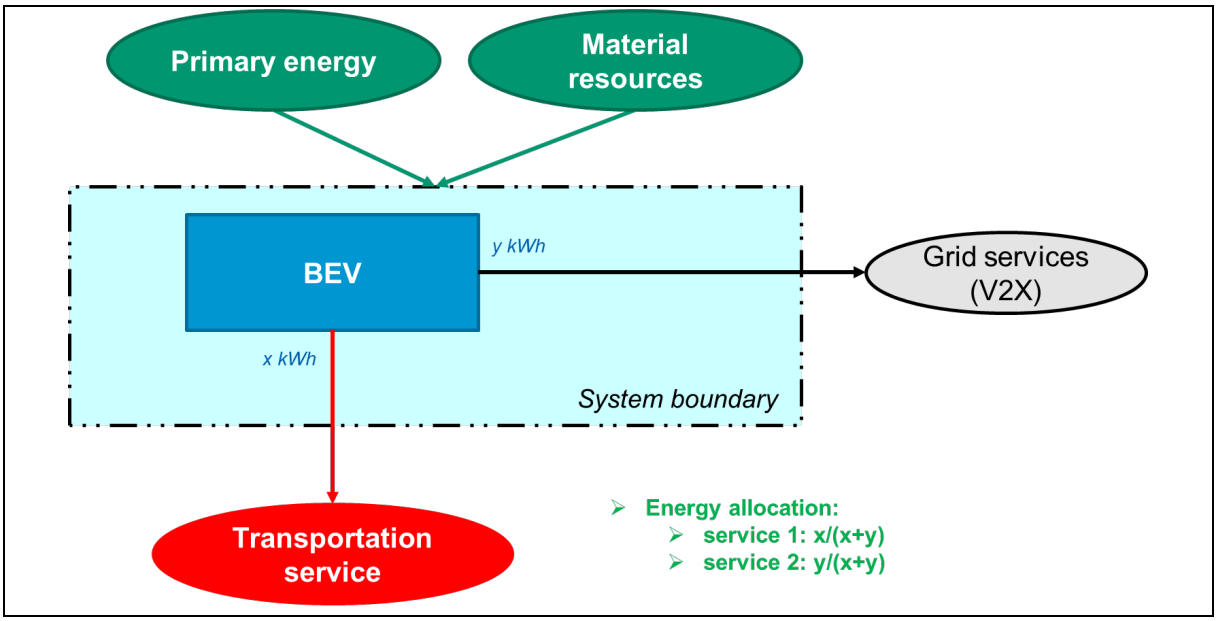


Figure 44: Allocation issue for transportation and V2X-services (JOANNEUM RESEARCH)

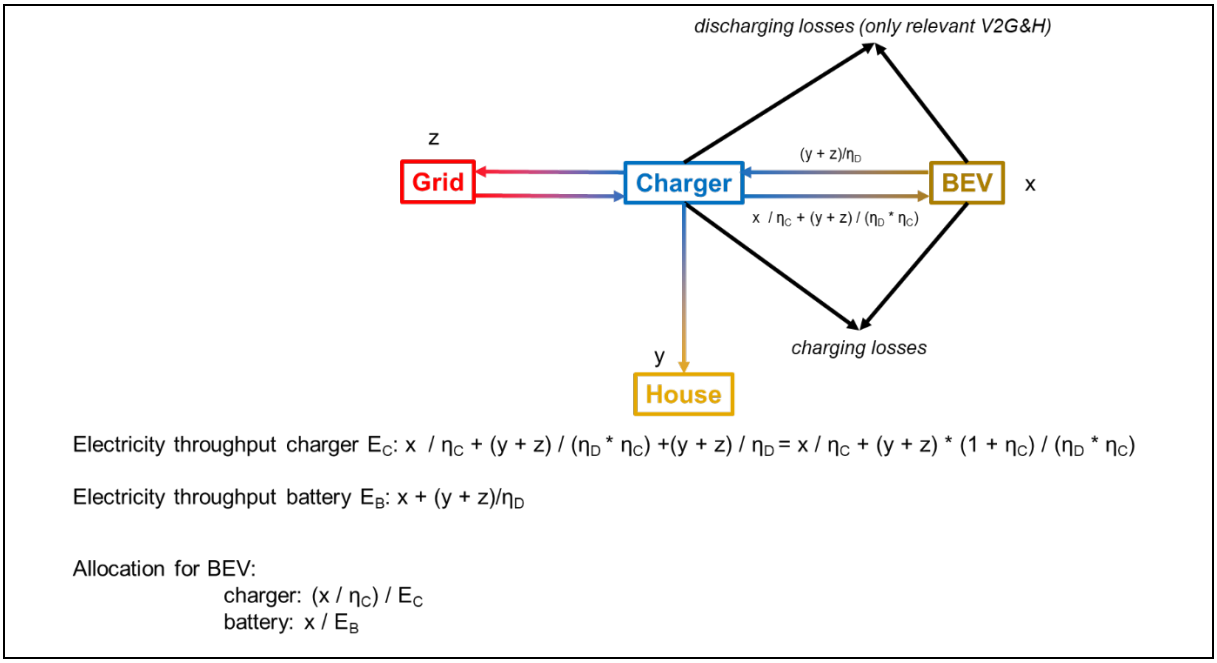


Figure 45: Energy allocation for the charger and battery based on the annual electricity throughput (JOANNEUM RESEARCH)

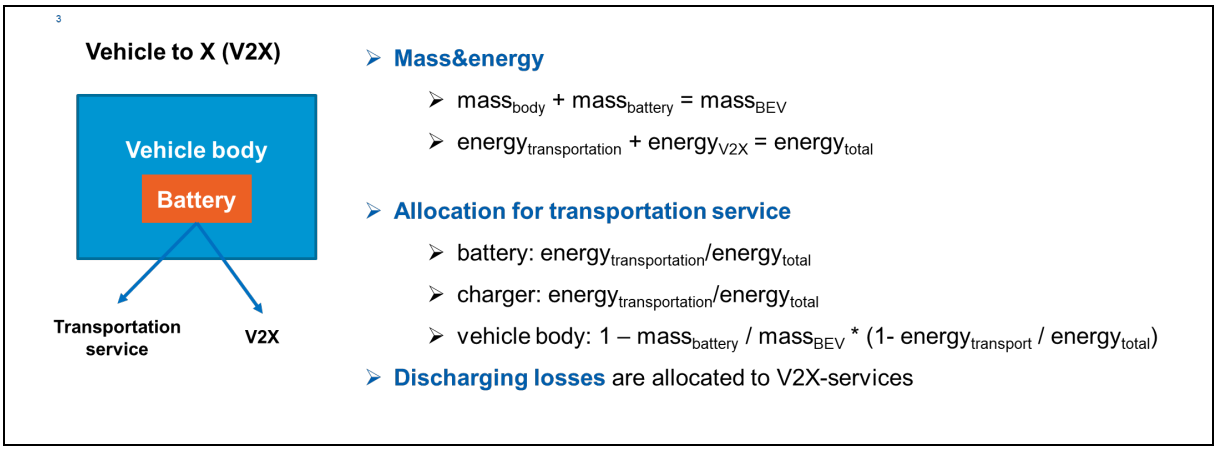


Figure 46: Allocations of BEV with V2X-services for driving (JOANNEUM RESEARCH)

The main influencing parameters on allocations are

- 1_recycling (BEV base case)
  - Share of renewable electricity mix (wind, PV & hydro) to be stored due to mis-match of supply and demand,
  - Efficiency of energy storage.
- 2_2nd life energy storage
  - Amount of stationary stored electricity in 2nd life,
  - Energy allocation: share of electricity for driving / stationary stored electricity,
  - EoL: reduction for battery production used for stationary storage.
- 3_smart charging
  - Efficiency of (partial load) charging,
  - Discharge losses all allocated to V2X-services.
- 4_smart charging V2D
  - Share of electricity for device and BEV,
  - Energy allocation for charger and battery,
  - Mass and energy allocation for BEV body.
- 5_bidirectional charging V2H
  - Share of electricity for house and BEV.
  - Allocation like “4_smart charging V2D”.
- 6_bidirectional charging V2G
  - Share of electricity for grid and BEV,
  - Allocation like “4_smart charging V2D”.
- 7_bidirectional charging V2H&G
  - Share of electricity for grid, house and BEV,
  - Allocation like “4_smart charging V2D”.
- 8_frequency service
  - Share of battery capacity for frequency services and annual hours,
  - Allocation like “4_smart charging V2D”.

The foreground data for the V2X-services are documented in Table 6, whereas the most relevant foreground data are the annual electricity demands for the transportation services in relation to the V2X-services. Based on the battery of the considered vehicle with about 110 kWh capacity also the battery aging was considered by defining the use cases of V2X-services.

Table 6: Foreground data of the eight cases of V2X-services (JOANNEUM RESEARCH)

Use Case	Electricity								Allocation for EV		
	household/device	vehicle	usefull electricity	losses	total to grid/h	total from grid	througput charger	battery	vehicle*)	battery **)	charger**)
	MWh/a										
1_recycling (BEV base case)		3.48	3.48	0.24		3.73	3.75	3.48	100%	100%	100%
2_2nd life energy storage		3.48	6.96	1.86	3.48	5.35	3.75	3.48	100%	50%	100%
3_smart charging		3.48	3.48	0.45		3.94	4.00	3.48	100%	100%	100%
4_smart charging V2D	0.11	3.48	3.60	0.48		3.96	4.28	3.66	99%	95%	94%
5_bidirectional charging V2H	0.70	3.48	4.18	0.64		4.82	5.81	4.56	96%	76%	71%
6_bidirectional charging V2G	-	3.48	4.53	0.76	1.05	5.29	6.91	5.38	94%	65%	59%
7_bidirectional charging V2H&G	1.25	3.48	5.57	1.15	0.84	6.73	9.45	6.97	92%	50%	43%
8_frequency service	-	3.48	4.01	0.68	0.52	4.69	5.59	4.53	97%	85%	85%
*) mass&energy allocation											
**) energy allocation											

These are the main foreground data for the vehicles:

- Driving
  - 200,000 km total mileage
  - 12 a lifetime
  - 16,667 km/a
- BEV (based on Volvo EC90)
  - 111 kWh NMC811
  - 20% reserve
  - 88.8 kWh battery capacity
  - 20.9 kWh/100km
  - 0.209 kWh/km
  - 425 km driving range
  - 471 full loading cycles
  - 2,500 max loading cycles
  - 2,029 remaining cycles
  - 2,748 kg total weight
  - 467 kg battery weight
  - 2,281 kg body weight
- Battery specific
  - 4.21 kg/kWh
  - 0.19 kWh/kg
- Bidirectional/smart charging
  - 10 kg extra weight
- ICE (based on Volvo XC90 MHEV petrol)
  - 2,143 kg weight
  - 9.1 l/100km (82.1 kWh/100 km)
- GHG emissions taken from Volvo (Volvo 2024)

With these foreground data the results of the allocation of the vehicle, battery and charging system to the transportation service are shown in Figure 47.

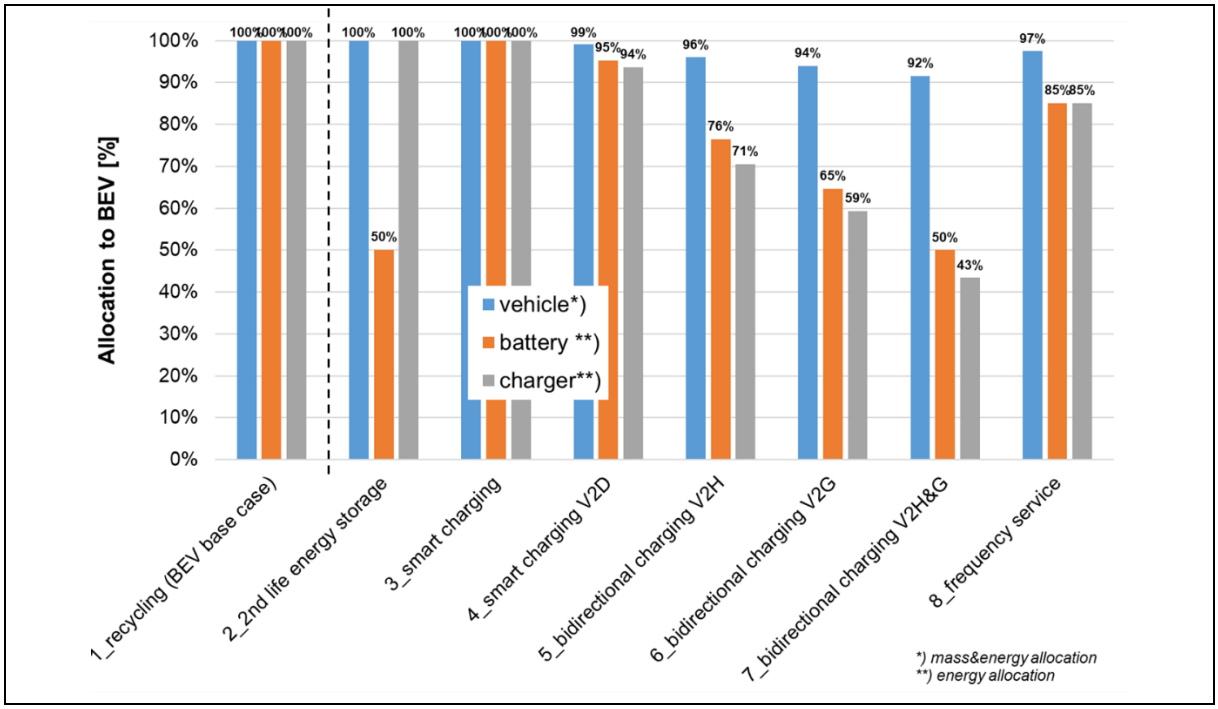


Figure 47: Allocations of BEV with V2X-services in the considered use cases (JOANNEUM RESEARCH)

Figure 48 shows the GHG emissions (left) and primary energy demand (right) per kilometre for the considered cases. The ranges are due to sensitivity parameters of the foreground data. As expected, the ICE petrol has far off the highest GHG emissions and the transportation services also providing V2X-services leads to lower GHG emissions and lower primary energy demand as the BEV in the base case. The main influencing parameter is the amount of electricity used for driving in relation to the amount of electricity for V2X-services. In addition, Figure 49 shows the relation of GHG emissions and primary energy demand of the transportation service per km with the V2X use cases. The smart charging has higher GHG emissions than the base case due to the lower energy efficiency of smart charging in comparison to uncontrolled full power charging in the base case.

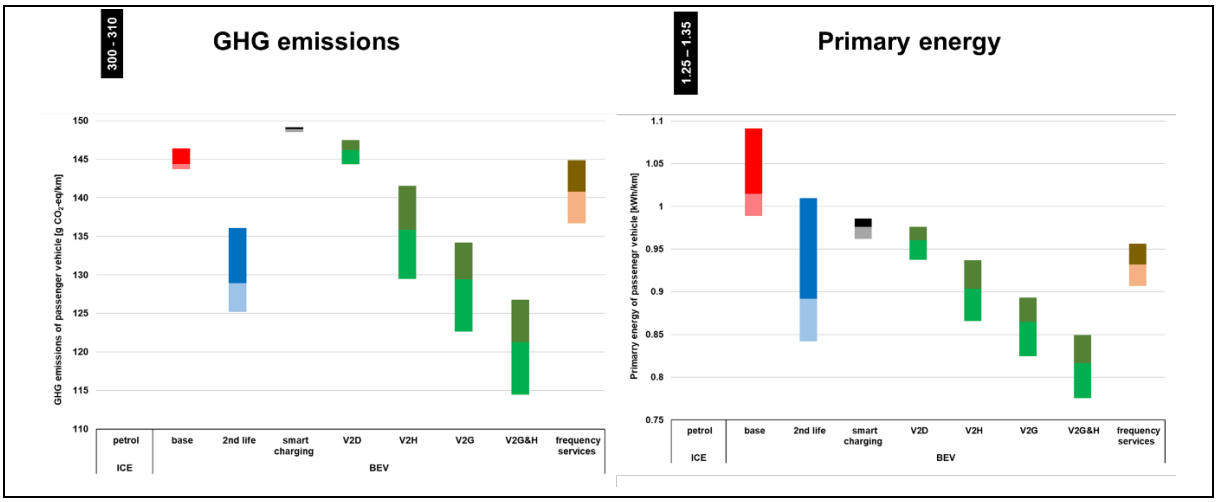


Figure 48: GHG emissions (left) and primary energy demand (right) per kilometre, ranges are due to sensitivity of the foreground data (JOANNEUM RESEARCH)

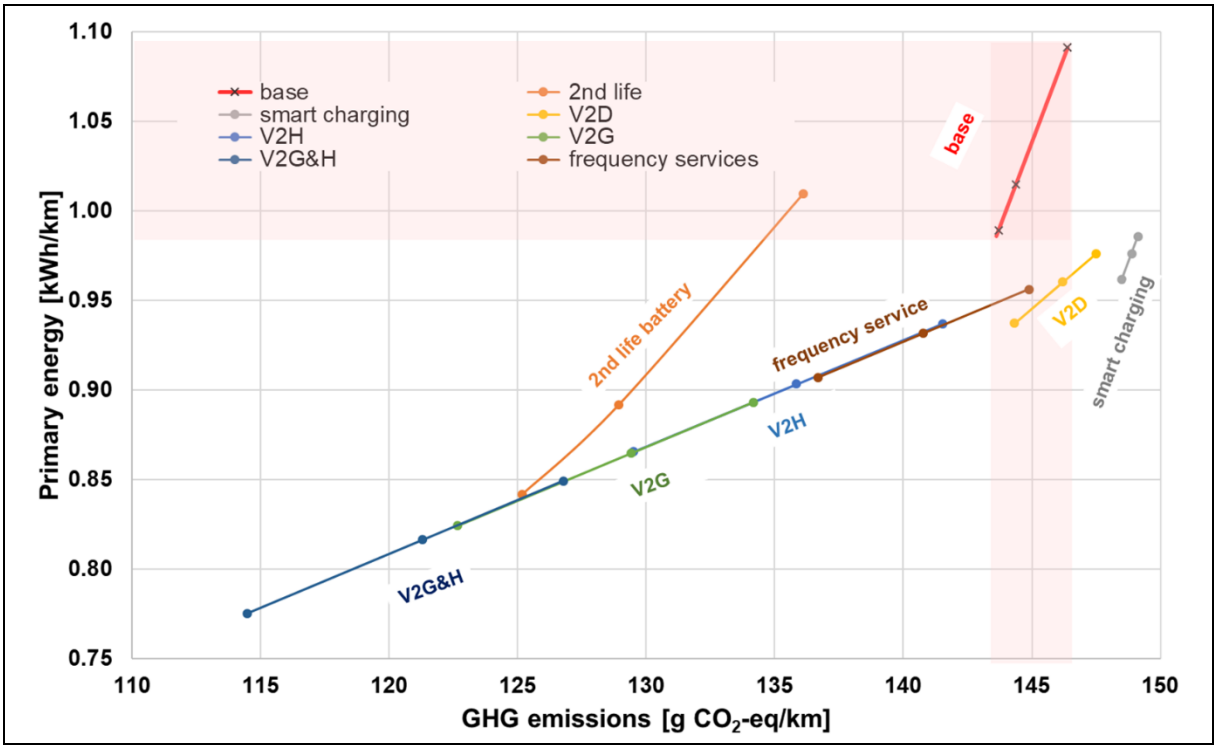


Figure 49: Relation of GHG emissions and primary energy demand of the transportation service per km with the V2X use cases (JOANNEUM RESEARCH)

Figure 50 shows the Circularity Potential of vehicle (left) and of the total system (right). The Circularity Potential of the ICE vehicles is higher than for the BEV as the battery with its lower Circularity Potential. Nevertheless, the Circularity Potential of the total system is significantly higher with the BEV and even higher with the V2X-servcies than with the ICE vehicle, as the petrol use in the operation phase significantly reduces the total circularity.

Figure 51 shows the overall assessment of the V2X use cases, where the BEV without V2X-services is the reference (=100%) and scale between 80% and 105%. There are no benefits for smart charging compared to full load uncontrolled charging, as the efficiency is lower with smart charging temporarily with partial loads. However, the BEV also providing V2X-services have significantly lower environmental impacts, as the battery, the vehicle and the charging station are used more intensively.

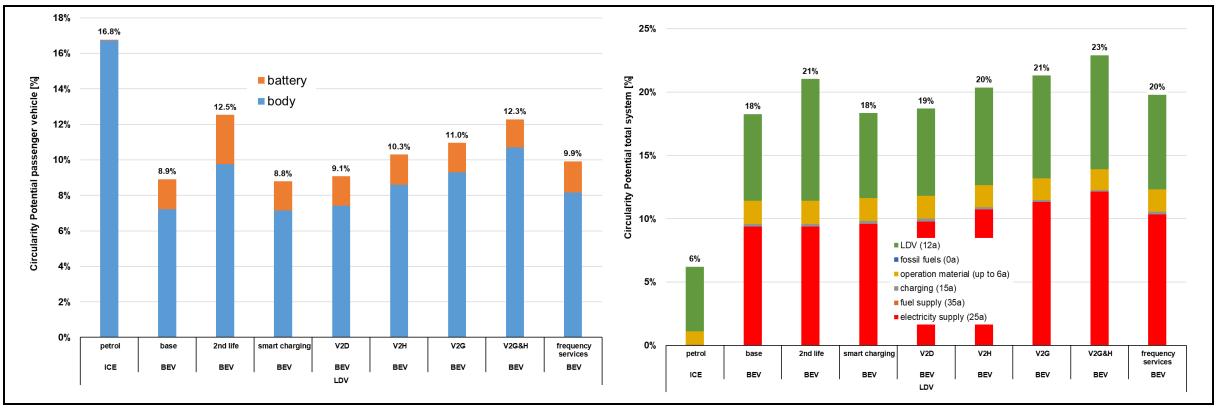


Figure 50: Circularity Potential of vehicle (left) and total system (right) (JOANNEUM RESEARCH)

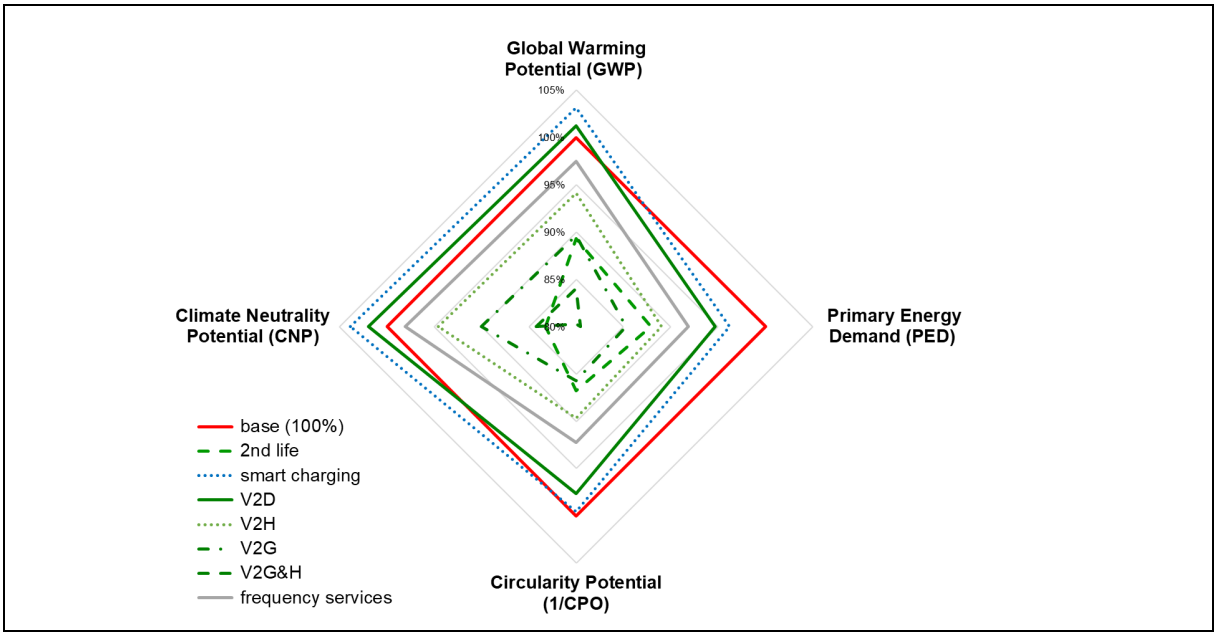


Figure 51: Overall assessment of the V2X use cases, BEV without V2X = 100% (JOANNEUM RESEARCH)

The main conclusions of the LCA case study on V2X-services are:

- Fossil energy in all three phases and materials of facilities (e.g. electricity generation, vehicle) are relevant for circularity,
- Relation of energy used for transportation service and V2X-service is relevant for impacts,
- EoL-methodology: “cut-off approach” is applicable, reasonable & practicable for V2X-services,
- Allocation of impacts to transportation service and V2X-services is essential
    - Allocation based on annual energy throughput (energy allocation),
    - Relevant parts for allocation:
        - Battery (incl. battery management system -BMS),
        - Vehicle body,
        - Charger (incl. charging components in vehicle).
- Frequency services: substitution approach reasonable too,
- Results: V2X-services
    - Reduce GHG emissions and primary energy demand,
    - Increase Circularity Potential,
    - Increase Climate Neutrality Potential,
    - 2nd life of battery has lowest impacts,
    - Smart charging reduces mainly primary energy demand.
- Climate Neutrality Potential (CNP) and Circularity Potential (CPO)
    - Are two new impact categories in LCA,
    - Consideration in dynamic LCA over time is relevant.

5.3.7 Light Electric Vehicles (LEV)

The aims of the LCA case study on Light Electric Vehicles (LEV) in comparison to SUVs are

- Substitution of transportation services of SUV by LEV,
- Influence of V2X-services,
- Usage of electricity from newly built renewable power production plants (generic data: 25% PV, 25% hydro, 50% wind).

The key issues on the methodology are

- Dynamic LCA using generic global LCA data,
- Allocation of V2X functionalities,
- Detailing circularity assessment on production and EoL,
- EoL: cut off approach.

The systems considered are passenger vehicles (2024):

- Petrol ICE as reference (based on Volvo XC90 MHEV),

- BEV (based on Volvo EX90) with V2X-services,
- LEV: three different vehicles: 45 km/h, 90 km/h and 125 km/h,

The functional units are

- per km,
- per lifetime,
- considering a high V2X-services: 3.5 more electricity than for driving (significantly more than in the LCA case study on V2X-services (Chapter 5.3.6).

The LCA case study is done in cooperation with IEA EV Task 50 “Light Electric Vehicles” that provided the information on the LEV (https://evtcp.org/task/task-50/). Table 7 shows the foreground data for the SUV and LEV.

Table 7: Foreground data for the SUVs and LEVs (Volvo 2024, IEA EV Task 46 and 50)

propulsion		ICE	BEV			
vehicle		SUV petrol	SUV	LEV 45	LEV 90	LEV 125
aluminum	[kg]	317	551	96	114	68
steel&iron	[kg]	1,131	989	173	204	122
polymers	[kg]	399	412	72	85	51
electronics	[kg]	7	14	2	3	2
other metals	[kg]	36	52	9	11	6
fluids&undifined	[kg]	86	63	11	13	8
copper	[kg]	34	71	12	15	9
rubber	[kg]	62	60	11	12	7
glass	[kg]	56	63	11	13	8
natural materials	[kg]	7	4	1	1	1
battery	[kg]	8	467	42	100	173
total w/h battery	[kg]	2,135	2,281	398	471	281
total	[kg]	2,143	2,748	440	571	454
battery capacity	[kWh]	0	111	6.1	14.4	25.0
energy demand *)	[kWh/km]	0.82	0.21	0.06	0.07	0.10
CH4 emissions *)	[g/km]	0.014	0	0	0	0
N2O-emissions *)	[g/km]	0.014	0	0	0	0
urea/AdBlue *)	[l/100 km]	0.00	0	0	0	0
engine oil	[kg/100 km]	0.013	0	0	0	0
Technical electr. range (nomin.)	[km]	1000	531	111	200	250
Lifetime	[a]	12	12	12	12	12
Lifetime milleage	[km]	240,000	240,000	80,000	160,000	160,000
Passenger capacity	[P]	5	5	2	2	3
Lifetime milleage factor **)	[-]	1	1	0.33	0.67	0.67
Passenger capacity factor **)	[-]	1	1	0.40	0.40	0.60
*) average driving cycle						
**) based on SUV						

As the lifetime and the passenger capacity of the SUV and the LEVs is different, a reasonable functional unit was defined. In dynamic LCA the same lifetime in years (assumed: 12 years) and the same passenger-kilometres defines the functional unit. The different person capacity of the considered vehicles

- SUV: 5 persons,

- LEV 45 & 95: 2 persons,
- LEV 125: 3 persons.

makes it necessary to define the same service in total lifetime of 337,000 passenger-km. For this a total mileage of the SUV of 240,000 vehicle-km and 1.4 person(P)/SUV was assumed. So, the functional unit is per km of SUV substituted by LEV (Figure 52). Therefore, 240,000 km of SUV are substituted by

- 258,000 km of LEV 45&95,
- 244,000 km of LEV 125,
- 254,500 km of LEV mix.

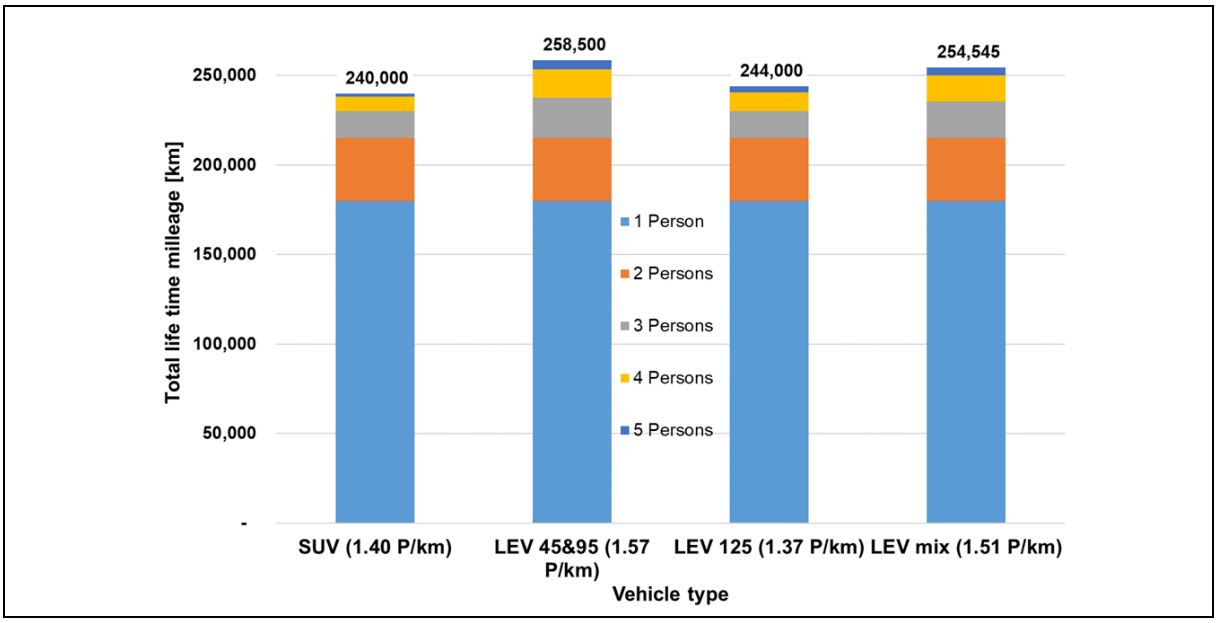


Figure 52: Vehicle kilometre per SUV and LEVs to provide 337,000 passenger-km in the total lifetime. (JOANNEUM RESEARCH)

To take the different lifetimes and the different passenger capacities of the SUV and the LEVs into account, a “Lifetime factor” and a “Capacity factor” are defined and applied.

- Lifetime factor for mileage: 240,000 km in 12 years
  - 1 SUV: 240,000 km in 12 years
  - 3 LEV 45: 3 x 80,000 km
  - 1.5 LEV 90: 1.5 x 160.000 km
  - 1.5 LEV 125: 1.5 x 160.000 km
  - 1 mix LEV - 1.2x45, 0.6x90, 0.3x125:
    - 40% LEV 45: 96,000 km with 1.2 LEV 45
    - 40% LEV 95: 96,000 km with 0.6 LEV 90
    - 20% LEV 125: 48,000 km with 0.3 LEV 125

- Capacity factor for passenger-kilometres 337,000 P-km
    - 1 SUV: capacity for 5 persons
    - 1.08 LEV 45&95: capacity for 2 persons
    - 1.02 LEV 125: capacity for 3 persons
    - 1.06 LEV mix: capacity for 2.2 persons
- Total = lifetime factor x capacity factors
    - 1 SUV
    - LEV 45
    - 1.62 LEV 95
    - 1.53 LEV 125
    - 1.06 Mix LEV

Simplified this means that more LEVs are needed to substitute the same passenger capacity kilometres of one SUV.

Figure 53 shows the GHG emissions and the Climate Neutrality Potential of SUV and LEV. The petrol ICE has the highest GHG emissions, and the LEV have significant lower GHG emissions. Also, the effect of reducing GHG emissions of the SUV with V2G&H services is obvious. The electric vehicles are systems that can be classified “towards Climate Neutrality” as in the operation phase nearly no additional GHG emissions occur except for maintenance and spare parts. Again, it is obvious that the Climate Neutrality Potential gives additional information about the timing of the GHG emissions and their effect on Global Warming.

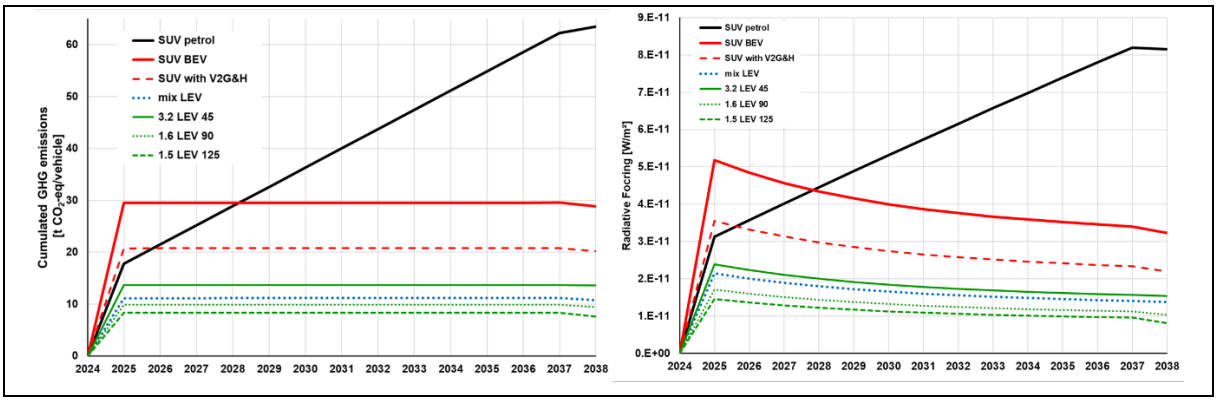


Figure 53: GHG emissions and Climate Neutrality Potential of SUV and LEV (JOANNEUM RESEARCH)

Figure 54 gives the mass and Circularity Potential over the total lifetime of the SUV and LEV. The mass of the petrol ICE and the SUV is significantly higher than of the LEV. The decrease in the EoL phase is due to the further use of the renewable power plants that have a longer lifetime than the electric vehicles. The Circularity Potential starts with 100% in nature and decreased rapidly in the production phase due to the extraction of virgin material and fossil energy. The Circularity Potential for the petrol ICE decreases during the operation phase due to the use of fossil fuel, whereas

for the electric vehicles it remains more or less constant as renewable energy is used. In the EoL phase, the Circularity Potential increase to its final value as secondary material is provided for other products or services. The SUV with V2G&H-services has the highest Circularity Potential as the battery is used more efficient that in the other electric vehicles.

Figure 55 shows the circular and non-circular mass of SUV and LEV, which is calculated based on the mass and Circularity Potential. The petrol ICE has the highest mass and highest non-circular mass, where the LEVs have the smallest mass. The non-circular mass is mainly determined by the amount of virgin material in the production phase and the use of fossil energy for production, operation and EoL.

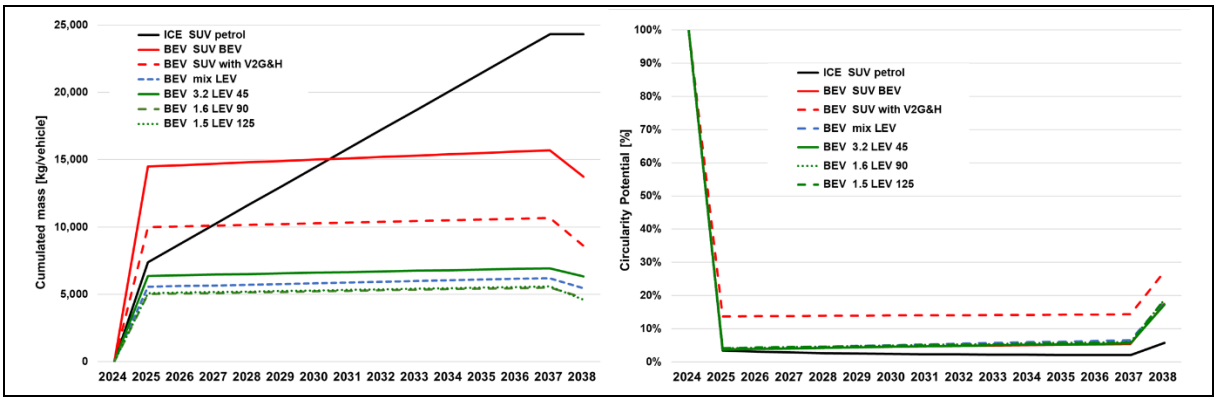


Figure 54: Mass and Circularity Potential of SUV and LEV over lifetime (JOANNEUM RESEARCH)

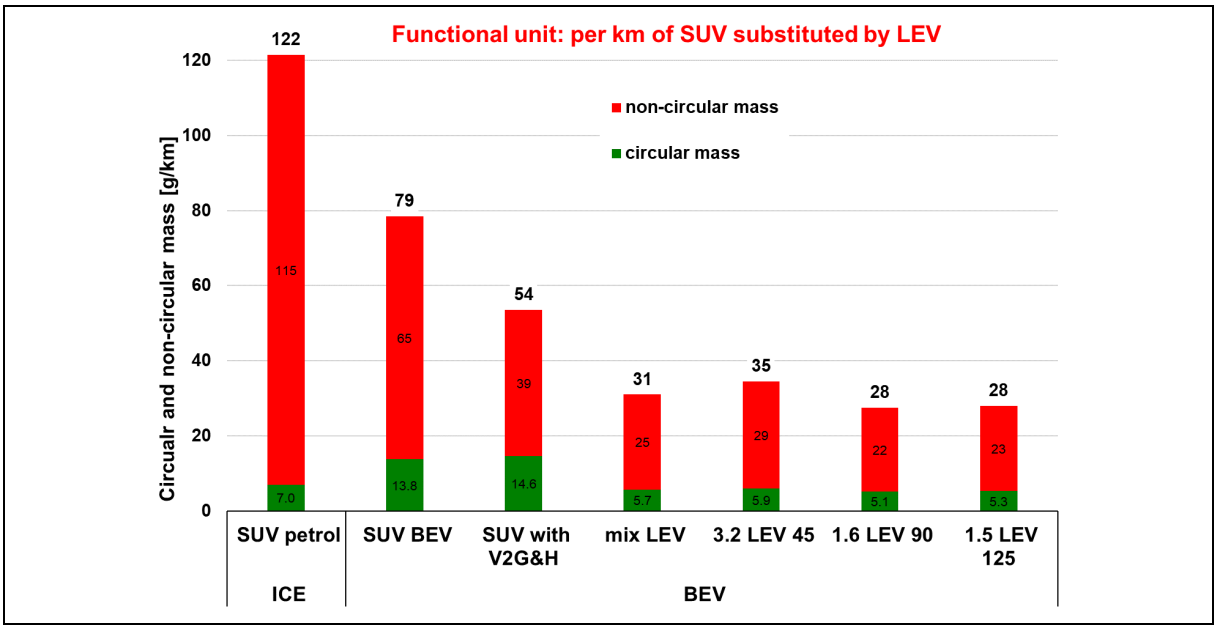


Figure 55: Circular and non-circular mass of SUV and LEV (JOANNEUM RESEARCH)

Figure 56 shows the overall environmental assessment of the LCA case study on SUV and LEV (petrol ICE = 100%). All electric vehicles using renewable electricity have lower environmental impacts. The LEVs are significantly more beneficial for the environment that the SUV, except the SUV with V2G&H-services has a higher Circularity Potential, even when more LEVs are needed to substitute for one SUV. Main reasons for the environmental benefits of the LEVs is the lower energy consumption for operation, the smaller battery and the lower weight.

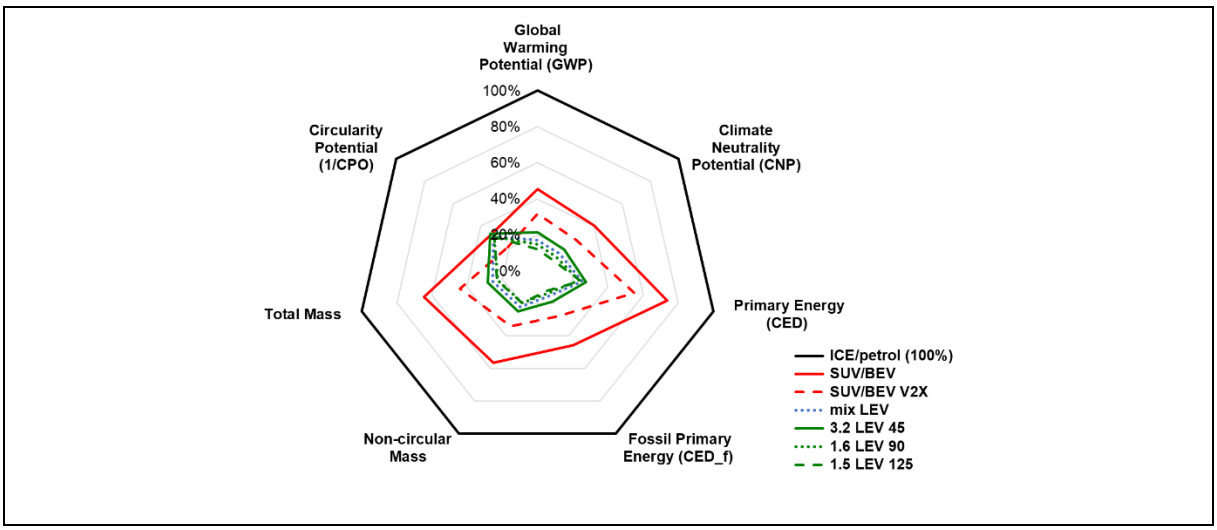


Figure 56: Overall assessment of the LCA case study on SUV and LEV (petrol ICE = 100%) (JOANNEUM RESEARCH)

The main conclusions of this LCA case study are:

- Functional unit
    - Same lifetime in years (lifetime factor),
    - Same passenger-kilometre (capacity factor),
    - Needs more LEV with more mileage than SUVs for same functional unit.
- LEV compared to SUV significantly
    - Reduce GHG emissions and primary energy,
    - Increase Circularity Potential,
    - Decrease (non-)circular mass,
    - Increase Climate Neutrality Potential.
- V2X-services with SUV reduce environmental impacts but still higher than LEV,
- ICE using fossil fuel has highest environmental impacts,
- Climate Neutrality Potential (CNP) and Circularity Potential (CPO)
    - Are two new impact categories in LCA,
    - Consideration in dynamic LCA over time relevant,
    - Developed by JOANNEUM with IEA EV Task 46 “LCA of Trucks, Buses, other Vehicles and V2X-Services”.
- Electric vehicles using renewable electricity have the potential to become climate neutral and circular,
- Currently EVs using additional renewable electricity are a step towards climate neutrality and circularity,
- Smaller EVs are significantly more beneficial for the environment than SUVs.

Further details of this LCA case study were published at the EV Task 50 Workshop “Light Electric Vehicles – Ecological aspects” (Jungmeier 2025).

5.3.8 Key Findings

- Climate Neutrality Potential and Circularity Potential are assessed with dynamic LCA.
- Key impacts considered: GHG emissions (incl. H2), (non-)renewable primary energy, (non-)circular mass, Climate Neutrality Potential and Circularity Potential.
- Various LCA Case Studies: trucks, city buses, fire trucks, SUV and LEV???, mining haul trucks, V2X-services using newly installed renewable electricity plants in comparison to petrol, diesel, and hydrogen & e-fuel using renewable electricity.
- Battery electric vehicles using renewable electricity have best environmental performance compared to others.
- Main influences
    - Energy demand of vehicle,
    - Source of electricity,
    - Battery capacity,
    - Lifetime and annual operating hours.
- Climate Neutrality Potential and Circularity Potential

- Might be two additional impact categories is LCA,
- Only systems using renewable energy have the potential towards Climate Neutrality & Circularity,
- 100% Climate Neutrality: Only possible in combination with Carbon Capture & Storage (CCS).

6 Dissemination

6.1 Introduction

The aim of the dissemination activities was to reach different stakeholders and to provide them relevant information and results from Task 46. Beside the internal information exchange between the project partners and LCA experts, a very relevant stakeholder group was the national ExCo-members, as they needed environmental information for their national activities related to electric vehicles.

A focus of the dissemination activities was to present actual results from the Task at (inter)national relevant conferences, e.g. EVS, IEWT with a targeted audience of LCA experts on vehicles, batteries and electricity generation. Additional it was possible to present the Task 46 results to industry and to a broader interested audience.

The dissemination activities were structured in the following areas:

- Presentation and papers,
- Webinars,
- Internal and ExCo meeting,
- Annual reports and Newsletter from the EV TCP,
- National Austrian IEA annual Networking meeting and
- National Project Advisory Board.

In addition, the LCA expert workshops were a very relevant element of the dissemination activities, which were already described in chapter 5.2.

Key focus of all dissemination activities was to communicate the methodology of dynamic LCA applied to different types of electric vehicles and to high-lighten the key parameters to maximize the environmental benefits of electric vehicles. The key developments of Task 46 on climate neutrality and circularity were communicated, and its applications were shown in the various case studies (see chapter 5.3).

6.2 Presentations and Papers

- *Renewable Energy for Climate Friendly Lifestyles - Example Mobility Services with Battery Electric Vehicles*; RENEWABLEMEET2022 - International Meet on Renewable and Sustainable Energy March 21-23, 2022, Dubai, UAE (online)

- *Scenarios for a Climate Neutral Vehicle Fleet in Austria Using Dynamic LCA*, 17. Symposium Energieinnovation, February 16-18 2022, Graz, Austria
- *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
- *Diesel, Wasserstoff, Strom oder doch E-Fuels? – Umweltbewertung von PKWs im Lebenszyklus*, 15. Münchner Gespräche, July 21 2022
- *Klimaneutrale Mobilität in Österreich – Methoden, Fakten und Mythen; 5. Europäisches Forum Alpbach 2022*, Kreislauffähige und klimaneutrale Mobilität - Herausforderungen und Lösungen am Beispiel Fahrzeug, Alpbach/Austria, August 26 2022
- *How Ecological Electric Vehicles Really Are? - Lesions Learnt in IEA EV Task 30 & 46*, 9th Symposium E-mobility, October 18 – 20, 2022, Belgrade
- *LCA Approaches and Circular Economy to Enhance Sustainability of Mobility Solutions, including Tendering Process*, Strategic Session 4.1 – TRA2022, November 14-17, 2022, Lisbon, Portugal
- *Towards Climate Neutrality and Circularity – The Case of e-Trucks in Austria 2040+*; A3PS ecomobility conference, November 24 – 25, 2022, Vienna, Austria
- *The Possible Role of Electricity and Biofuels in A Climate Neutral Transportation Sector in Austria*, Central European Biomass Conference, January 18 – 20, 2023, Graz, Austria
- *Klimafreundliche Lebensstile - Beispiel Mobilität*, Jan. 26, 2023, Steyr, Austria
- *Klimaneutralität und Kreislaufwirtschaft – Stand des Wissens und Zukunftsperspektiven am Beispiel Elektrofahrzeug*, IEWT2023, February 15-17 2023, Vienna, Austria
- *Battery Ecology from Birth to Death - Life Cycle Assessment (LCA) of Automotive Batteries*, 1st Battery Conference, March 23, 2023, Belgrade, Serbia
- *Klimaneutralität - Methode der dynamischen LCA und Anwendung für den österreichischen Verkehrssektor 2040*, CCCA-Klimatag 2023,April 11–13 2023, Leoben, Austria
- *Towards Assessing Climate Neutrality and Circularity Using Dynamic LCA - Examples on Electric Vehicles*, Advanced Materials for Transportation AMT-TCP ExCo, June 29, 2023, Vienna, AUSTRIA
- *Methodological Framework to Assess Climate Neutrality and Circularity with Dynamic LCA - case study e-Trucks*, World Resource Forum, September 4 – 6, 2023, Geneva, CH
- *Klimaneutralität und Kreislauffähigkeit – Lebenszyklusanalysen von elektrischen Fahrzeugen in IEA EV Task 46*, Austrian IEA Network Meeting in Vienna/September 26, 2023
- *Addressing Climate Neutrality and Circularity with LCA – Possible Approaches and three Examples*, ARGONNE LCA Seminar, Chicago, October 2023
- *Umweltbilanz und Kreislauffähigkeit im Lebenszyklus von Autobatterien*, Informationsabend „Autobatterien Quo Vadis“, Kooperationsveranstaltung von ATTC & Bev, Wien, November 8, 2023
- *An initial Approach to Assess Climate Neutrality and Circularity – A LCA case study on Trucks in IEA EV Task 46*, General Assembly of EU project TranSensus LCA, Darmstadt, Germany, January 2024

- *Der ökologische Fußabdruck von Autos – Wie schädlich sind sie wirklich?*, Tea Time Sciencetalk, WELIOS, Wels, Austria; February 2024
- *Eine kreislauffähige und klimaneutrale Fahrzeugflotte in Österreich 2050 – Wie das gehen könnte*! EnInov 2024 18. Symposium Energieinnovation, Graz, Austria, February 2024
- *Die Kreislauffähigkeit der Mobilität messbar machen – Grundlagen, Beispiele und Handlungsfelder*, Circularity Forum, St. Pölten, Austria; March 2024
- *Dynamic LCA to Assess Climate Neutrality and Circularity - Case Study e-Trucks of IEA EV Task 46*, EVS37 Symposium, EVS 37, Seoul, April 2024
- *Fahrzeuge mit unterschiedlichen Antrieben am Weg zur Klimaneutralität & Kreislauffähigkeit*, Triple N-Talks, May 16, 2024, Leoben, Austria
- *Klimaneutralität und Kreislauffähigkeit im Fokus der Nachhaltigkeit*, ACstyria Business Frühstück - ESG im Fokus: Nachhaltigkeit in Finanzierung & Förderung, October 1, 2024, Graz, Austria
- *Klimaneutralität und Kreislauffähigkeit bewertet im Lebenszyklus*, Ich tu's Energy Lunch # 64 "Energiezukunft Steiermark: Szenarien, Strategien und Maßnahmen", October 3, 2024, Graz, Austria
- *Are Climate Neutrality Potential and Circularity Potential New Impact Categories in LCA? - A case study on Trucks*, SETAC LCA Conference, October 21 – 23, 2024; Gothenburg, Sweden
- *Circularity and Climate Neutrality Potentials in the LCA of Vehicles*, 19th A3PS Conference Eco-Mobility 2024, November 14-15, 2024, Vienna, Austria
- *Assessing Climate Neutrality and Circularity in LCA – Methodology and Application in a Case Study*, Recy & DepoTech 2024, November 13-15, 2024, Leoben, Austria
- Climate Neutrality and Circularity – case study for a 100% Climate Neutral City Bus, IEWT 2025, February 26–28, 2025, Vienna, Austria
- *Klimaneutralität und Kreislauffähigkeit: Herausforderungen und Lösungen fürs Automobil*, FORUM JOANNEUM | Zukunft der Mobilität – Teil 1: Automobil, February 25, 2025; Graz, Austria
- *EV Task 46 "LCA of Trucks, Buses, V2X-Services and other Vehicles"*, Projektbeirat „Öster. Mitarbeit in IEA Tasks/Annexes in EV, AMF, AMC, AMT und Bioenergy", April 2, 2025, Vienna
- *Assessing the Circularity Potential in LCA as a New Impact Category – A case study on Buses, REMADE*, April 2025, Washington, USA (reviewed paper)
- *LCA for 100% Climate Neutral Buses – An Approach in IEA EV Task 46*, EVS38 Gothenborg, Sweden, June 15-18, 2025
- *Assessing Climate Neutrality and Circularity Potentials - A LCA case study on City Buses*, Resource Efficient Vehicles, September 23 – 25, 2025, Graz, Austria

6.3 Webinars

Together with IEA EV Task 1 “Information Exchange”, two webinars were organized. There were about 100 participants at each webinar? with very different background and some LCA newcomers.

The webinars are available on the webpage (https://evtcp.org/task/task-46/). The two webinars addressed the following questions to inform the participants about the basics of LCA on vehicles:

- What is LCA?
- How to set the system boundary?
- How to compare BEV and ICE?
- What impacts are relevant?
- Where is the electricity coming from?
- What about impacts of battery production?
- What are examples of comparing BEV with other vehicles in Europe, AUS and US (incl. some works on PEV)?
- What are the key influencing factors?
- What is necessary from LCA point of view to maximize benefits and minimize impacts from EVs?
- What is climate neutrality and how can it be addressed?
- How is circularity addressed by LCA today?

The programs of the two webinars were:

Webinar 1: “LCA of BEV – Basics”: November 21, 2024 3 – 4 pm (CET)

- Introduction: *IEA EV and Task 46* (Gerfried Jungmeier – JOANNEUM RESEARCH, AT)
- *LCA Methodology & Application for Electric Vehicles* (Jarod Kelly - ARGONNE, US and Nikolas Hill - Ricardo, UK)
- *Q&A* via chat with audience

Webinar 2: “LCA of BEV – Developments” January 21, 2025; 2 – 3 pm (CET)

- Introduction: *IEA EV and Task 46* (Gerfried Jungmeier – JOANNEUM RESEARCH, AT)
- *Climate Neutrality & Circularity Assessment of EVs – Results of Task 46* (Gerfried Jungmeier – JOANNEUM RESEARCH, AT)
- *Specialities of BEV-LCA* (Robin Smit - Transport Energy/Emission Research, AUS)
- *Q&A* via chat with audience

6.4 Internal and ExCo meetings

The Task Manager Gerfried Jungmeier participated in eight ExCo meetings (55th – 62th meeting) and presented the ongoing activities in Task 46. The report of the task activities in the ExCo meetings was recognized as a very efficient dissemination activity due to the high interest of the ExCo members and the other Task Managers.

The Task 46 had 19 internal online task meetings.

6.5 Newsletter and Annual Reports

Task 46 contributed to the

- IEA EV Annual Reports 2022, 2023, 2024, 2025 and 2026: https://evtcp.org/publications/?e-filter-ea2ff63-publication-type=annual-report
- IEA EV Newsletter between 2022 and 2025: https://evtcp.org/latest/

6.6 National Austrian IEA Annual Networking Meeting

The Task Manager participated in the National IEA Vernetzungstreffen to network and exchange with other members of the Austrian IEA Technology Cooperation programme.

6.7 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 (2022, 2023, 2024 and 2025) during the working period of Task 46. The Task Manager of Task 46 managed the National Advisory Board.

The following activities of the National Project Advisory Board are established to stimulate an active information exchange in Austria:

- The Task Manager 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 TCPs
    - EV – Electric Vehicle,

- AMF – Alternative Motor Fuels,
- AFC – Advanced Fuel Cells,
- Bioenergy and
- AMT - Advanced Materials for Transportation.

The members of the National Project Advisory Board are:

- KLIEN – Climate and Energy Fund,
- FFG – Forschungs-Förderungsgesellschaft,
- BMINI – Federal Ministry Innovation, Mobility and Infrastructure,
- Energy Agency Austria,
- JOANNEUM RESEARCH,
- BEST - Bioenergy and Sustainable Technologies,
- HyCentA – Hydrogen Centre Austria,
- University of Technology Vienna,
- IRIS – Industrial Risk and Safety Solutions,
- AIT – Austrian Institute of Technology,
- LEC – Large Combustion Engine Centre.

The following IEA tasks/annexes of the TCPs were represented by these members and they are part of the national information exchange on transport relevant TCP activities:

- EV Task 46 *"LCA of Trucks, Buses, V2X-Services and other Vehicles",*
- EV Task 49 *"Fire Safety",*
- EV Task 52 *"EVs and Circularity",*
- EV Task 53 *"Interoperability of Bidirectional Charging (INBID)",*
- AFC Annex 34 *"Hydrogen and Fuel Cells for Transportation",*
- Bioenergy Task 39 *"Biofuels to Decarbonise Transport",*
- AMF Task 66 *"Recent Progress in SAF Research",*
- AMF Tasks *"TCP EATS: Exhaust Gas Aftertreatment Systems",*
- AMF Task 65: *"Non-Road Mobile Machinery – NRMM",*
- AMT Annex XII: *"Tailored Engineered Surfaces for energy efficiency",*
- AMT Task: *"Tire and Brake Emissions".*

7 Conclusions, Outlook and Recommendations

7.1 Conclusions

The main conclusions of Task 46 are:

- Task 46 is a cooperation of 12 countries on LCA of electric vehicles.
- Climate Neutrality Potential and Circularity Potential can be assessed in dynamic Life Cycle Assessment (LCA).
- The definition of Climate Neutrality and Circularity is
    - A product or service is “climate neutral“ and “circular“, if its whole life cycle - production, operation and end-of-life - uses only
        - reused components (reuse index),
        - secondary/recycled material (recycled content),
        - renewable energy.
    - and makes
        - zero waste and
        - zero GHG emissions.
- An assessment methodology for Climate Neutrality and Circularity was developed, tested in case studies and widely discussed with various stakeholders from research industry and government.
- The key environmental impacts to be considered are:
    - GHG emissions (incl. direct H_2-emissions),
    - (non-)renewable primary energy,
    - (non-)circular mass,
    - Climate Neutrality Potential and
    - Circularity Potential.
- Various LCA case studies: trucks, city buses, fire trucks, LEVs and SUVs, mining haul trucks, V2X-services using newly installed renewable electricity plants in comparison to petrol, diesel, and hydrogen & e-fuel using renewable electricity.
- Key results
    - Battery electric vehicles using renewable electricity have best environmental performance compared to others.
    - Main influences
        - Energy demand of vehicle,
        - Source of electricity,
        - Battery capacity,

        - Lifetime and annual operating hours.
    - In comparison to vehicles using renewable hydrogen in fuel cells and e-fuel using CO_2 from air and renewable hydrogen in ICE, the electric vehicles have significantly lower environmental impacts especially a lower primary energy demand.
- Climate Neutrality Potential & Circularity Potential
    - Both might be two additional impact categories in LCA.
    - Only systems using renewable energy have the potential towards Climate Neutrality and Circularity,
    - 100% Climate Neutrality: Only possible in combination with Carbon Capture & Storage (CCS).

7.2 Outlook

The results of Task 46 are disseminated among various stakeholders.

The team of Task 46 also developed a new Task *"Electric Vehicles and Circularity"*, which has started in 2025. The topic of this new task is on further developing the assessment method for the Circularity Potential e.g. critical raw materials, and industrial case studies for EVs and its components (https://evtcp.org/task/task-52/).

7.3 Recommendations

The recommendations from Task 46 are

- Environmental impacts of electric vehicles can only be analysed based on LCA, covering the production, use and end-of-life phase of the total vehicle.
- The assessment of the "Circularity Potential" and the "Climate Neutrality Potential" is possible with dynamic LCA, where the timing of the GHG emission and the materials flows is considered over the total lifetime.
- "Circularity Potential" and "Climate Neutrality Potential" are two possible new impact categories not yet covered in LCA but show high relevance for future developments.
- The most relevant impact categories that should be covered in LCA of vehicles are:
    - GHG emissions (incl. direct H_2-emissions),
    - (non-)renewable primary energy,
    - (non-)circular mass,
    - Climate Neutrality Potential and
    - Circularity Potential.
- A transparent documentation of the LCA is mandatory and the key foreground data must be documented explicitly.

- Finally, it becomes obvious that electric vehicles in different applications have the best environmental performance, if additional renewable electricity is used. Vehicles running on hydrogen fuel cell or e-fuels internal combustion engine have a significant higher energy demand; and therefore, should only be used for applications that cannot be electrified.
- A 100% Climate Neutral and 100% Circular transportation system is not possible today and even not in near term future. A 100% Climate Neutral transportation system is only possible in combination with Carbon Capture and Storage (CCS) using Direct Air Capture (DAC) for the CO_2. But electric vehicles using renewable electricity have already now the highest Climate Neutrality Potential and Circularity Potential, compared to all other systems. There are many new technology developments in the pipe to further improve electric vehicles, the renewable energy generation and charging strategies that EVs will improve their environmental performance in future significantly.

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Abbreviations

BEV	Battery Electric Vehicle
BMS	Battery Management System
CNP	Climate Neutrality Potential
COP	Circularity Potential
DAC	Direct Air Capture
EV	Electric Vehicle
ExCo	Executive Committee
FC	Fuel Cell
GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
H_2	Hydrogen
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine

IEA	International Energy Agency
LCA	Life Cycle Assessment
LEV	Light Electric Vehicle
LFI	Linear Flow Index
MCI	Material Circularity Index
SUV	Sport Utility Vehicle
TCP	Technology Collaboration Programme
PED	Primary Energy Demand (equivalent to Cumulated Energy Consumption - PEC)
PHEV	Plug-In Hybrid Vehicle
V2X	Vehicle to X-services: X might be: Home (V2H), Grid (V2G), Device (V2D)