Contents of Work Package **4-WP04:** Life Cycle Analysis in Mobility Systems

4-WP04: Life Cycle Analysis in Mobility Systems

Coordinator of the WP

Czech Technical University in Prague – Faculty of Mechanical Engineering, Ing. Miroslav Žilka, Ph.D.

Participants of the WP

- you are invited (3 – WP13 – 001 - Energy-Tender)

Main Goal of the WP

Creation of environmental models and subsequent processing of analyzes of the life cycle of the mobility system and its key components in the environment of the Czech Republic as a basis for quantifying environmental benefits, supporting decision-making at the level of policy formulation and innovation processes.

Partial Goals for the Current Period

Creation of Database of LCA studies focused on the mobility system

Creation of a report summarizing findings from available LCA studies and directions for future development in the area

Development of an individual LCA study focused on the mobility system in the Czech Republic

Identification and realisation of suitable case studies of LC (Life Cycle) analyses in the field of mobility

Contents of Work Package **4-WP04:** Life Cycle Analysis in Mobility Systems

4-WP04: Life Cycle Analysis in Mobility Systems

Official 4-WP04 Deliverables:

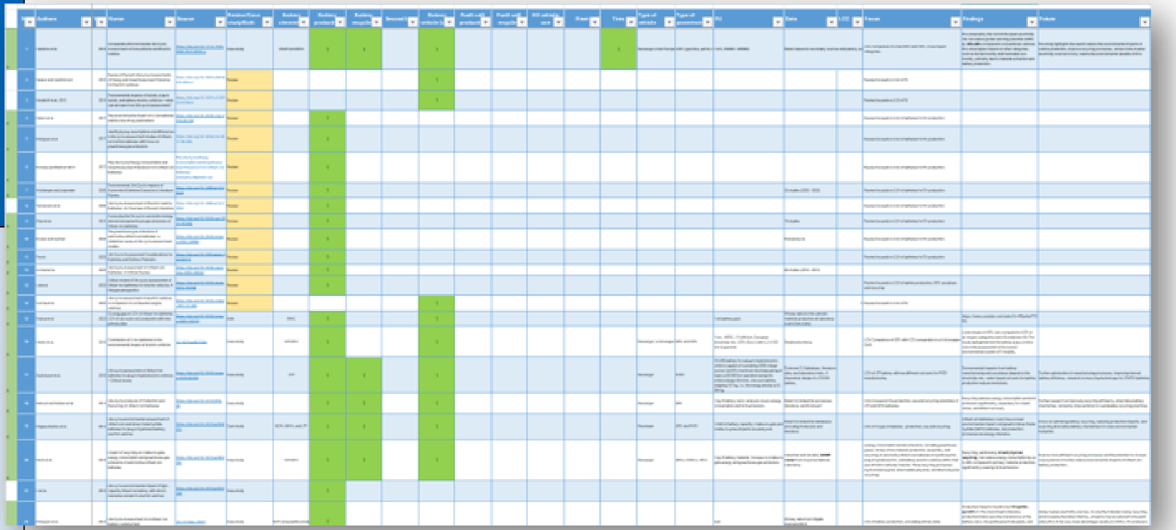
- 4-WP04-001 | **Quantitative Life Cycle Analysis of the Sustainability of the Mobility Systems and its Selected Partial Elements**, VI./2026, CTU 1.0

Activities in **4-WP04:** Life Cycle Analysis in Mobility Systems

Activity	**Knowledge Base of LC Inputs of Key Elements of the Mobility System**
Time of realization	04/2023 – 12/2024
Output	**4-WP04-001 (O):** Quantitative Life Cycle Analysis of the Sustainability of the Mobility Systems and its Selected Partial Elements (FS ČVUT) **6/2026**

Activity outputs:

1. Structuralized database of relevant information sources
2. Report summarizing main findings and insights from the review



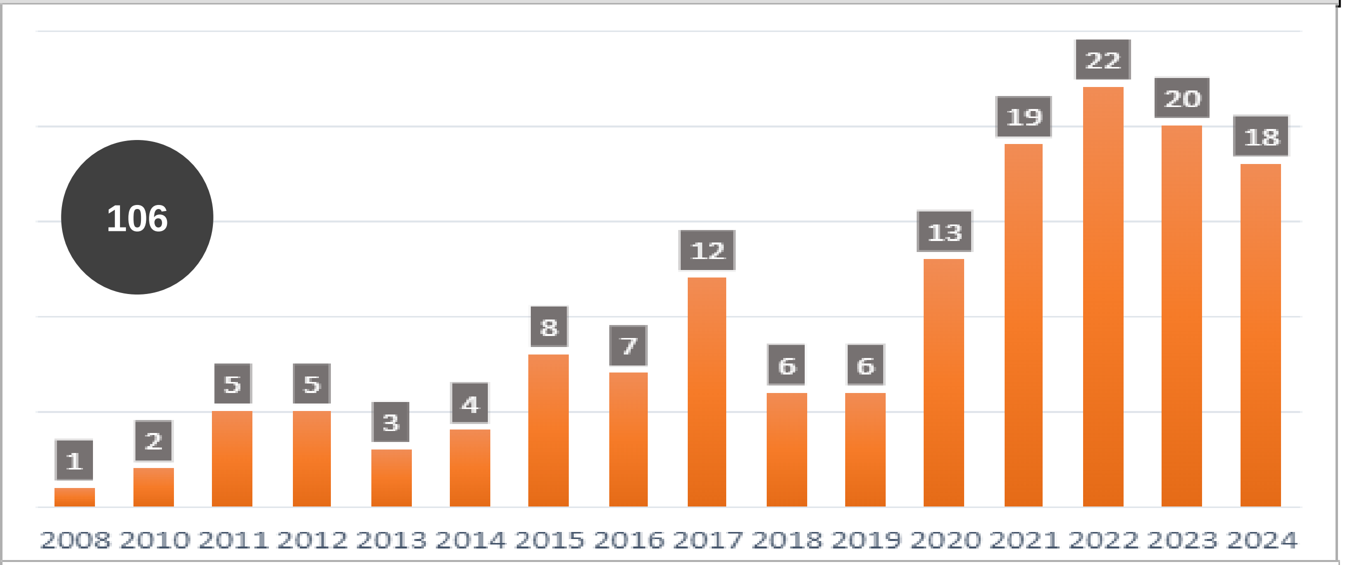
Why?

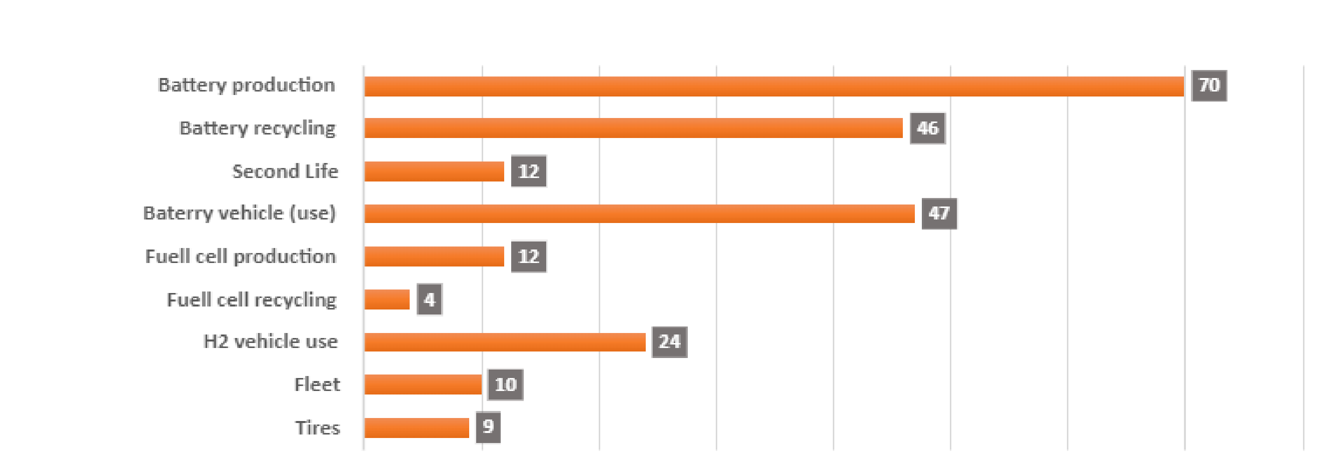
- Capturing the current state of knowledge in the field of LCA analyzes of key elements of the mobility system
- Obtaining inputs for LC modelling
- Building a knowledge base for the consortium

Activities in **4-WP04:** Life Cycle Analysis in Mobility Systems

Database structure

- *Authors, Year of publication , Title, Doi*
- *Review or case study type*
- *Battery chemistries analysed*
- *Battery production phase is envisaged*
- *Battery recycling phase is envisaged*
- *Second life of batteries is envisaged*
- *Battery vehicle use is envisaged*
- *Fuel cell production is envisaged*
- *Recycling of the fuel cell is envisaged*
- *Use phase of fuel cell vehicle is envisaged*
- *Type of vehicle*
- *Type of powertrain*
- *If the fleets are envisaged or only individual cars*
- *If tires are envisaged*
- *Function unit*
- *Data source*
- *LCC*
- *Focus*
- *Main findings*
- *Future steps*

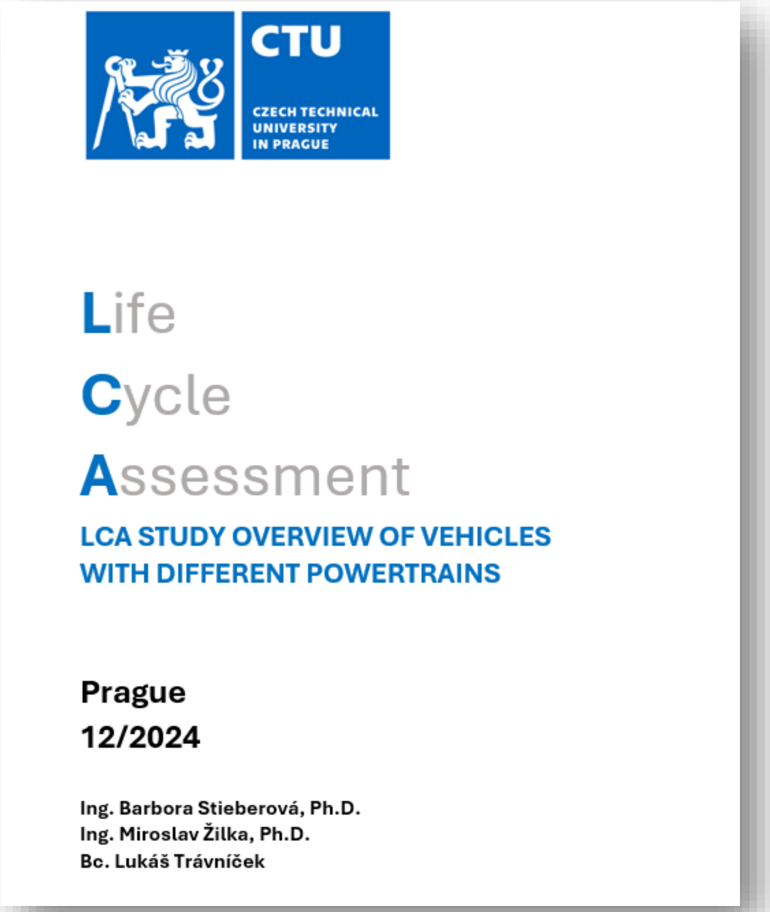




Activities in **4-WP04:** Life Cycle Analysis in Mobility Systems

Report structure

- *Introduction*
- *LCA methodology description focused on the vehicles*
- *LCA focused on batteries and BEV cars*
  - *LCA results of battery production*
  - *LCA results of BEV vehicles*
  - *LCA of future batteries and battery vehicles*
  - *LCA focused on recycling of batteries*
  - *LCA focused on second life of batteries*
- *LCA focused on hydrogen car*
- *LCA focused on fleets*
- *LCA focused on tires*


CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

Life
Cycle
Assessment

LCA STUDY OVERVIEW OF VEHICLES WITH DIFFERENT POWERTRAINS

Prague
12/2024

Ing. Barbora Stieberová, Ph.D.
Ing. Miroslav Žilka, Ph.D.
Bc. Lukáš Trávníček

Main findings in appendix.

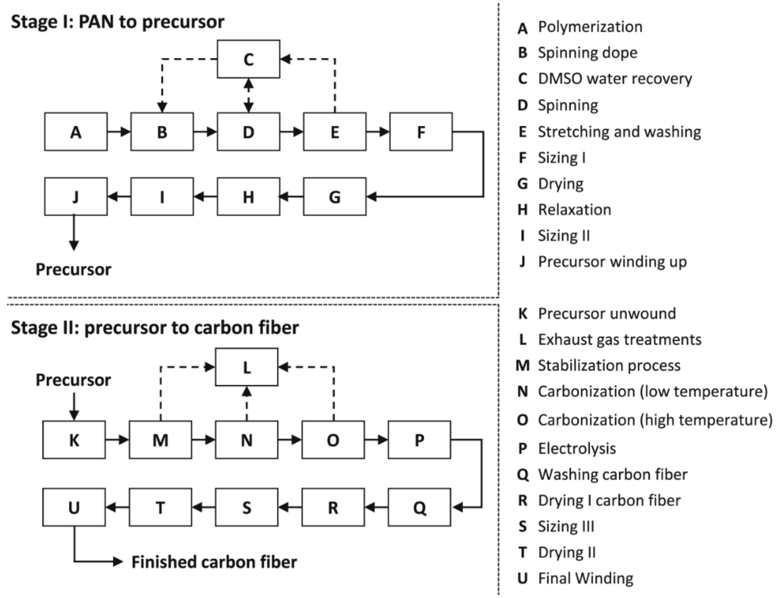
Activities in **4-WP04:** Life Cycle Analysis in Mobility Systems

Activity	LCA study focused on the mobility system in the Czech Republic
Time of realization	08/2024 – 12/2025
Output	**4-WP04-001 (O):** Quantitative Life Cycle Analysis of the Sustainability of the Mobility Systems and its Selected Partial Elements (FS ČVUT) **6/2026**

Activity outputs:
Current – 2030 – 2035 –2050 – Fleet LCA in the Czech Republic, different powertrains FCV included

Current and future activities

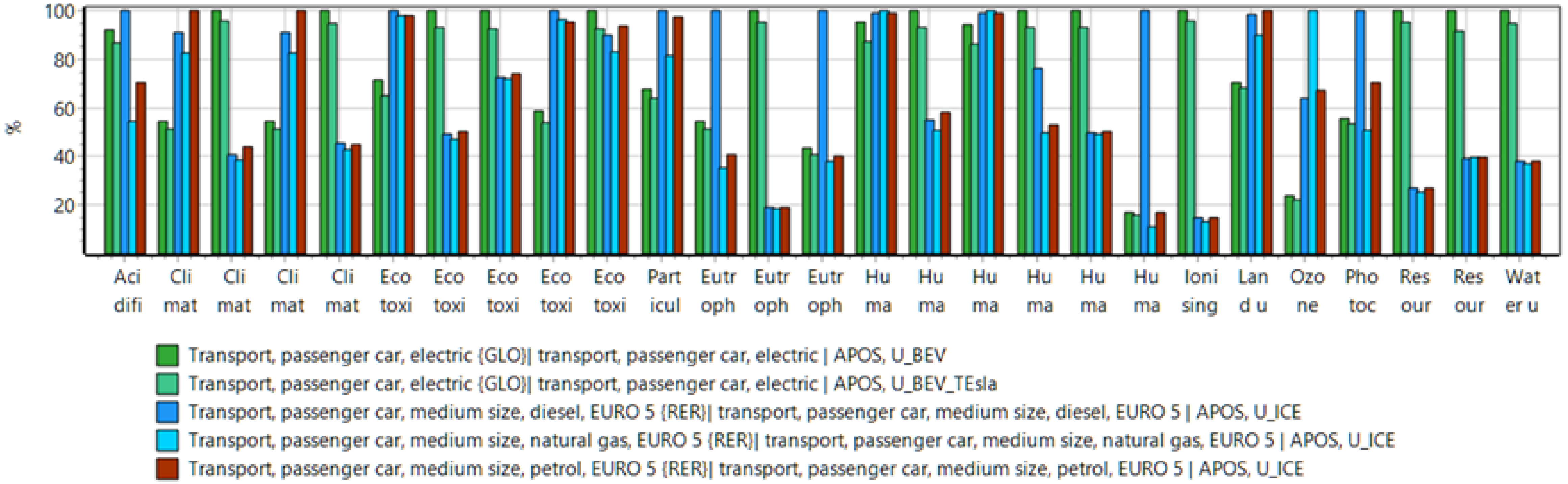
- Gathering data (LCA data for different cars and fuels, fleet forcast,………), using the Ecoinvent database and literature
- Modeling of hydrogen tank and fuel cells in Simapro based on the scientific literature



Carbon fibre manufacturing (Benitez et al. 2021)

Activities in **4-WP04:** Life Cycle Analysis in Mobility Systems

Initial results – current electricity mix



Method: Environmental Footprint 3.1 (adapted) V1.00 / EF 3.1 normalization and weighting set / Characterization

Comparing processes;

Activities in **4-WP04:** Life Cycle Analysis in Mobility Systems

Activity	**Economic model for Energy tender**
Time of realization	04/2024 – 12/2025
Output	**4-WP04-001 (O):** Quantitative Life Cycle Analysis of the Sustainability of the Mobility Systems and its Selected Partial Elements (FS ČVUT) **6/2026**

Activity outputs:
Economic comparison of diesel and electric locomotive
(Potentialy including environmental comparison)

Realised activities
- Initial parameterization for partner consultation

Planned activities
- Parameter verification
- Model adjustments and scenario modelling.
- Potential environmental assessment

Current status – initial parameterization for consultation with partners
- **3 technical elements of the system:**
  - **Diesel locomotive series 75x**
  - **Electric locomotive series 36x**
  - **Energy tender**
- **2 model routes:**
- **Passenger - express train Berounka - Prague/Žel. Ruda**
- **Freight - Freight train Plzeň/Žatec/Most**

↓↓↓

- **Evaluation sheet – comparison**
  - **Current status (362 + 754)**
  - **Tender on part of the route**
  - **Tender the whole route**

Activities in **4-WP04:** Life Cycle Analysis in Mobility Systems

Initial model

Locomotive

Train route

Comparison

Activities in **4-WP04:** Life Cycle Analysis in Mobility Systems

Activity	**LCA – urban cargo logistics**
Time of realization	11/2024 – 12/2025
Output	**4-WP04-001 (O):** Quantitative Life Cycle Analysis of the Sustainability of the Mobility Systems and its Selected Partial Elements (FS ČVUT) **6/2026**

Activity outputs:
LCA analysis of urban cargo logistics

Realised activities
- Initial contact and establishment of partnership

Planning activities
- Data collection
- LCA analysis and interpretation of results

URBAN CARGO LOGISTICS

- ***Exclusive logistic partner for IKEA***
- ***55 electric delivery vans***
- ***Possibility to compare with conventional delivery vehicles***

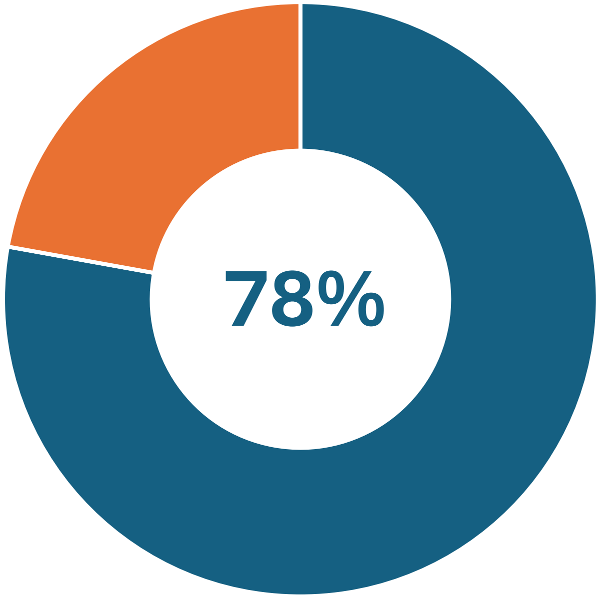
Current contribution of **4-WP04:** Life Cycle Analysis in Mobility Systems

Assessment of the Contribution of Deliverables

- Building a structured knowledge base in the field of LC studies of mobility systems and its sub-elements for the use of consortium members.
- Presentation of benefits and data structure of LC analyses, identification of suitable case studies within the consortium.

Current contribution of **4-WP04:** Life Cycle Analysis in Mobility Systems

Assessment of the Formal/Administrative Goals of the Work Package

Finances	Commercialisation	Deliverables
BUDGET CONSUMPTION 04-09 2024 	Analytical tasks Not relevant	OK

Current contribution of **4-WP04:** Life Cycle Analysis in Mobility Systems

Acknowledgment

This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Centres II, project # TN02000054 Božek Vehicle Engineering National Center of Competence (BOVENAC).

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report - findings*

- *There has been a growing number of Life Cycle Assessment (LCA) studies focused on vehicles with different powertrains in recent years and reviewing papers as well as.*
- *LCA studies vary in terms of different* ***system boundaries for example:***
  - *only production of components (batteries, FCs): (Ellingsen et al. 2014; Dai 2019)*
  - *only production of components (batteries, FCs) and its recycling potential: (e.g. Sun et al. 2020, Lotrič et al. 2020, Mohr et al. 2020; Jiang et al. 2022; Rosenberg et al, 2023)*
  - *only WTW (Well to wheel): (e.g. Wang et al., 2020; He et al. 2021; Qian et al., 2023)*
  - *production, WTW (Pinto and Bautista et al. 2024; Chen-Glasser et al., 2023; Zackrisson et al. 2010; Majeau-Bettez et al. (2011); Erakca et al., 2023)*
  - *production, WTW, recycling (e.g. Ciez and Whitacre, 2019)*
  - *production, WTW, secondary use (e.g. Ahmadi, 2017; Genikomsakis et al. in 2013)*
  - *production, WTW, secondary use, recycling (e.g. Koroma et al. 2022; Quan et al. 2022)*
  - *production, secondary use, (e.g. Kamath et al. 2020)*
  - *production, secondary use, recycling (e.g. Bobba et al. 2018)*
  - *LCA of fleets in certain locations (e.g. Candelaresi et al. 2023, Tarabay et al. 2023)*
  - *One step of recycling (e.g. Adhikari et al 2023)*

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report - findings*

Data for LCA analysis

- ***Ecoinvent database** – for example: data for battery cell and pack production based on Dai et al. 2017, 2018, 2019, Patents and Battery management system for Li-ion batteries on Ellingsen et al. (2014)*
- ***Greet software** developed by the Argonne National Laboratory (ANL) in the USA*
- *Primary data from different literature sources*

***Find the inventories in articles which enable the reproduction of analysis is challenging. For example Mandala et al., 2023** reviewed 6 LCA study focused on LCA analyses of emerging solide state batteries and stated that "**inventory datasets provided by the studies are not sufficient to reproduce results**".*

*Peters et al., 2017 **analysed** the environmental impact of Li-Ion batteries and the role of key parameters, they analysed **113 studies** (2000 and 2016) and they found that only **11 contributed** original life cycle inventory) as it is stated in Dai et al, 2019. Up to Dai study (2019) among the main sources for inventories for articles were: Notter et al. (2010); Majeau-Bettez et al. (2011); Dunn et al. (2012), Ellingsen et al. (2014), Zackrisson et al. (2010). – The study of Dune et al. (2012) represents the establishement of the battery LCA module into GREET.*

*Dai et al. (2019) provided LCA of NMC battery pack with new data for **powder NMC111 from** China producer (2018) – greater energy demand than Majeau-Bettez et al. (2011)*

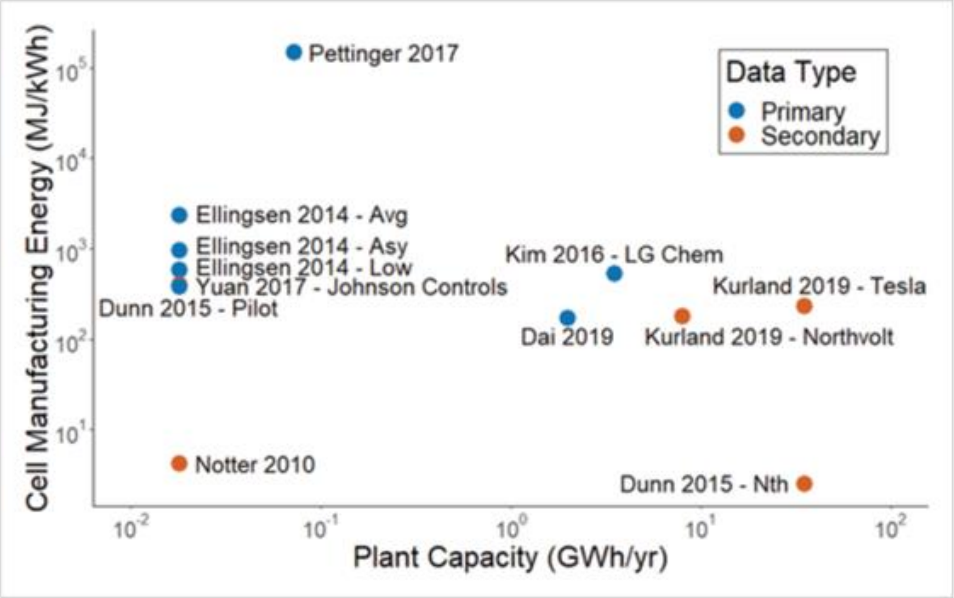
Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report - findings*

Porzio et al. 2022 *made a comprehensive review Life-Cycle Assessment Considerations for Batter and Battery Materials. They summarised the shortcomings in LCA studies (e.g. lack of informatio for other impact categories – for example the lack of site conditions for the assessing of human toxicity potential, or water use data.)*

They suggested for the improvement of the future LCAs

- *Select life-cycle inventory, midpoint, and/or endpoint metrics that are likely to yield the grea insights (and have sufficiently **high quality data)***
- *go beyond representation of industry best practices and **develop datasets that capture outlie or "superemitters,"** particularly in mining and material processing for better transparency a accuracy*
- *define two or three facilities scales, on the order of 0.1, 1, and 10 GWh per year of battery capacity output and generate results across these different scales.*
- *Specifically, scenarios that capture critical raw material availability, the geographic distribution of near- and long-term sources, and any expected shifts in extraction/processing methods would reduce reliance on sub-standard data sources and enable easier cross-comparisons between different battery studies.*
- *The same is true for the battery use-phase; - **develop detailed scenarios for battery cycling, operating temperatures, and SOC, nor can such a scenario easily be translated to expected shifts in capacity fade, efficiency, and lifetime based on verified data***

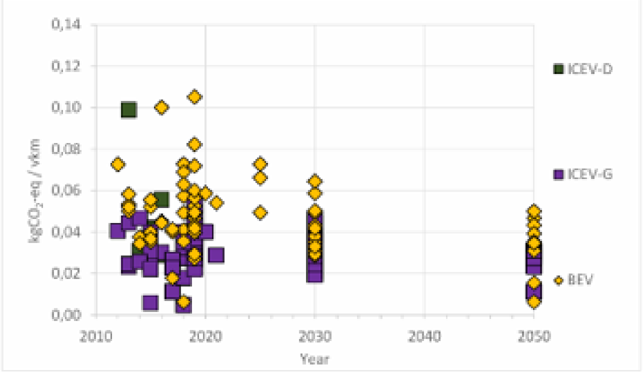
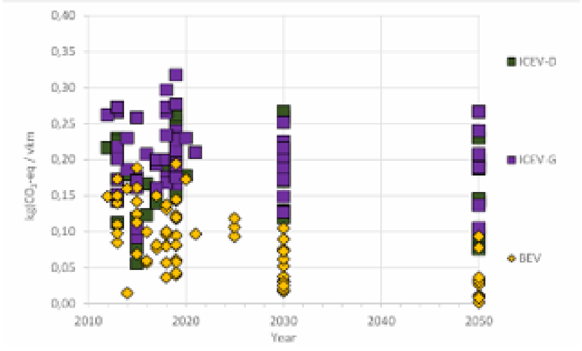
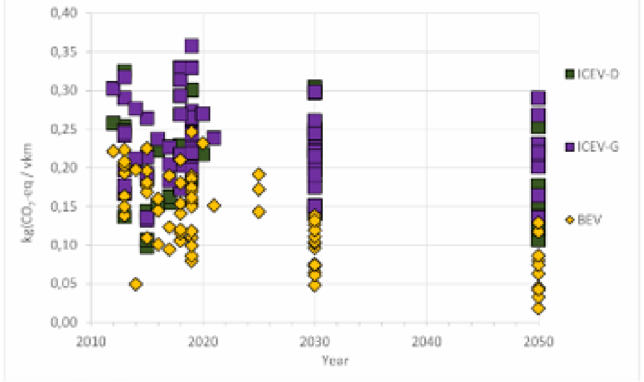


Porzio et al. 2022

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report - findings*

Hill at al. 2023 elaborated a comprehensive review of LCA analyses and base on that they conclude, that is apparent from particular studies that production of BEVs has the grater GHG emissions during the production phase then ICEVs and that the use phase is affected by electricity grid mix in different location:

Vehicle production (raw materials)	Vehicle use	Total
		

- *CO2 eq emissions per km from vehicle production vary within a narrower range compared to emissions from vehicle use*
- *BEV production emissions are 46% higher than those for ICEVs, and will be reduced to 30% difference (current ICEV versus future BEV) due to assumed improvement in battery energy density*
- *BEV production emissions vary according to different battery chemistries*
- *CO2 eq emissions per km from vehicle use vary with vehicle class and size, although this proportionality is less strong for BEVs than it is for ICEVs*
- *the more the grid mixes are decarbonised (or are being quickly decarbonised) the more the net advantage of switching from ICEVs to BEVs is higher*

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report - findings*

Limitation of studies analysed by Hill et al. 2023:

- ***new battery chemistries*** *such as all-solid-state lithium batteries (ASSB) or even sodium-ion batteries (NIB)* ***are not envisaged for future (****There are some new studies focusen on new chemistries Pinto and Bautista et al. 2024; Chen-Glasser et al., 2023)*
- ***the reviewed LCA literature also failed to address future projections in terms of the decarbonisation of material supply chains*** *(not only change in energy mixes but also for example green hydrogen as a reducing agent in steel making industry) and also not considering the better mixes than grid mixes in automotive industry. ((Yes, it is very demanding to change all processes for example data in Ecoivent and get new inventories for that)*
- ***electricity grid mix is modelled in static way*** *the grid mix composition will remain the same for the whole duration of the service life of the vehicle (except in the study Hill, 2020) (And we found that Rosenberg et al., 2023 focused on adressing this gap)*
- ***the end phase of life of vehicles is not consistent across studies*** *– (is missing, only in the form of waste treatement or some studies envisaged the benefits from recycling proces which reduce the overal life cycle impact.) - it is therefore not possible to draw clear overarching messages from the literature, as pertains to the vehicle end-of-life phase. (The literature focused on recycling is developing as it is described in below section)*
- *none of the reviewed studies explicitly addressed the ongoing changes and improvements in end-of-life recovery and recycling of battery elements, and the potentially large effects that these trends could have, not only on end-of-life (EoL) impacts, but also on battery manufacturing in the future.*
- ***none of the reviewed studies considered the possible reduction of life cycle impacts for BEVs due to the possible re-purposing of EoL batteries for a second-life use*** *(e.g. in grid storage applications). (There are some as ti is shown in below sectrion))*

They mentioned that some of the studies are focusing also on other impact categories than GWP especially material depletion or human toxicity potential but these are not aggregated but addressed basically in the report.

They did not focus on the fuel cell vehicles.

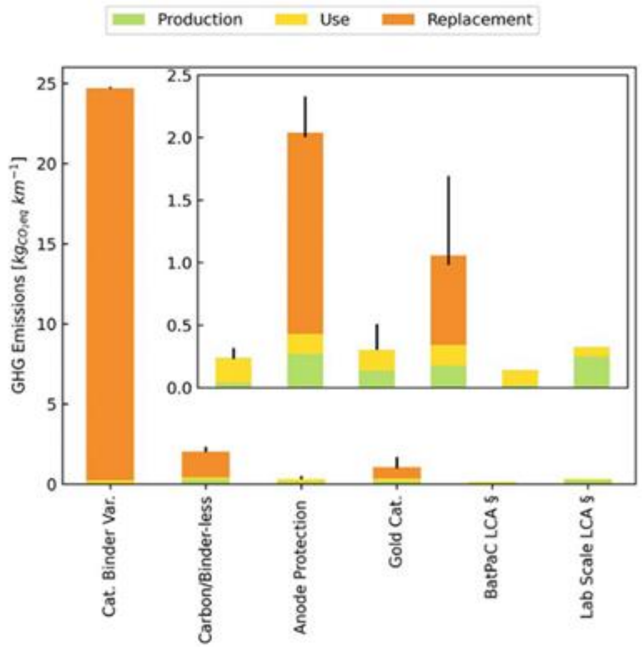
Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report – findings* - ***LCA focused on new chemistries of batteries***

- *Li-O2 batteries - Zackrisson et al. 2016 , WANG et al., 2020; Chen-Glasser et al., 2023*
- *Mg-S - Pinto - Bautista et al. (2024)*
- *LIS - Deng et al. , 2017*
- *Solide state batteries Lastoskie and Dai (2015); Keshavarzmohammadian et al. (2018); Smith et al. (2021); Troy et al. (2016); Zhang et al. (2022)*

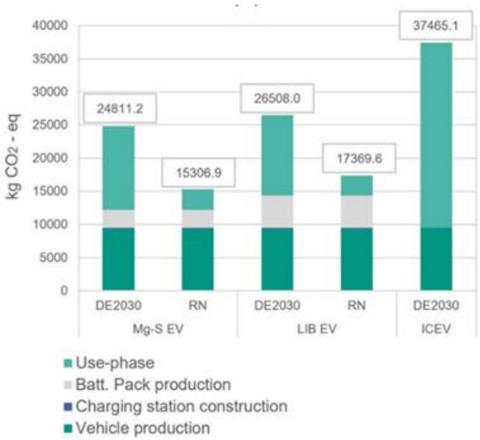
Chen-Glasser et al., 2023 made the LCA of LiO car and elaborated inventory and CO2 emissions for the production of different materials used in the LiO battery per 1 kg (different solvents, salts and additives, catalyst, binders, lithium, current collectors).

Authors	Year	Title	Chemistry	FU	Lifetime	Battery pack	Weight	Type of a car	Mix	Typ of powertrain
Melodie Chen-Glasser, Amy E. Landis, Steven C. DeCaluwe	2023	Carbon footprint of Li-Oxygen batteries and the impact of material and structure selection	$Li\text{-}O_2$ battery, focusing on various designs (without catalyst, with catalyst, carbon-less and binder-less, anode protection, gold catalyst)	1 km (The charger efficiency is **90** %, and the battery efficiency is assumed to be **80** %.) 300 km per charge 15,5 kWh/km	200000 (6 variants with different number of replacement	**46.6 kWh**	**(350 kg battery pack)**	Medium passenger	US mix	LiO BEV with open air systeme.



Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Pinto - Bautista et al. (2024) provided an initial prospective (not fully developed) evaluation of the environmental performance of a theoretical Mg–S battery for potential use in electric vehicles (EVs).



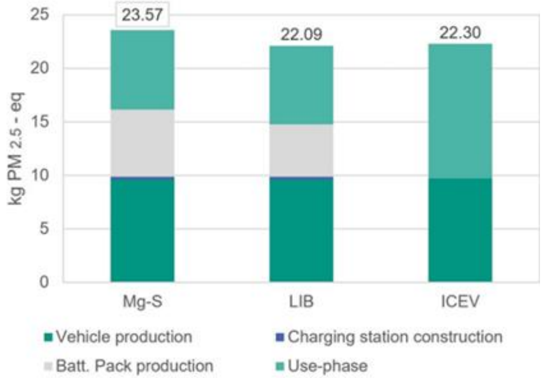
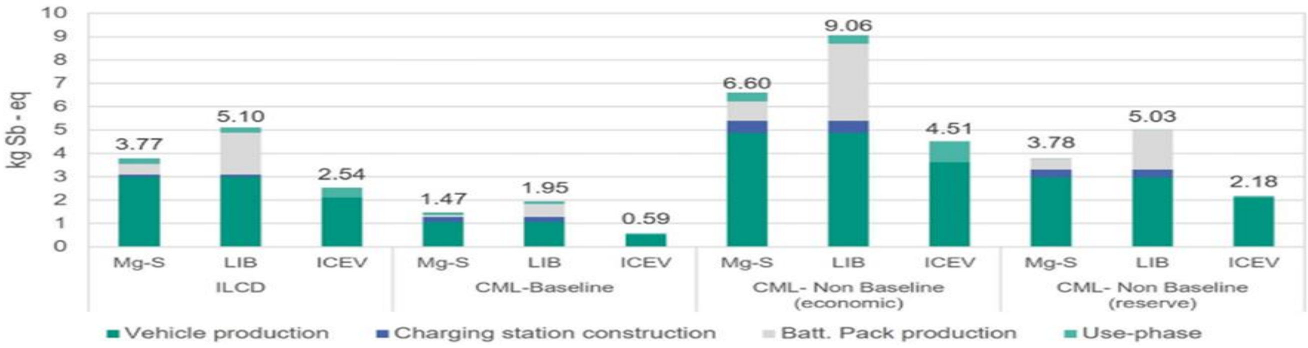
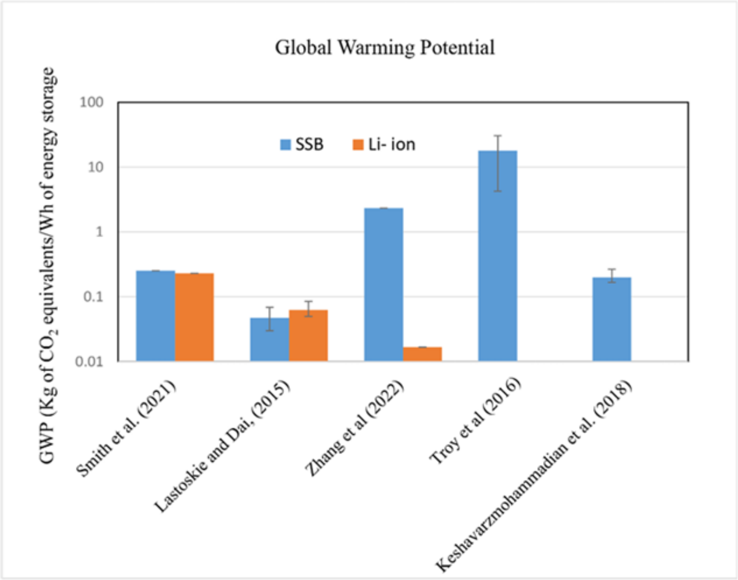


Fig. 8 Cradle-to-use impacts in particulate matter potential



*Mandale et al. (2023) analysed 5 LCA studies focused on SSBs. The studies use different functional units, system boundaries, inventory data sources, and impact assessment methods, making comparisons difficult. Key factors impacting the LCA results include the type of solid electrolyte, scale of production, and technology readiness level. **Inventory datasets provided by the studies are not sufficient to reproduce results.***

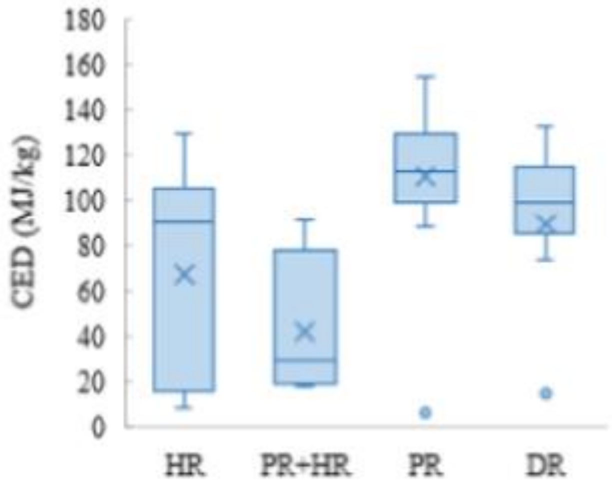


Mandale et al. (2023)

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report – findings - LCA focused on recycling of batteries*

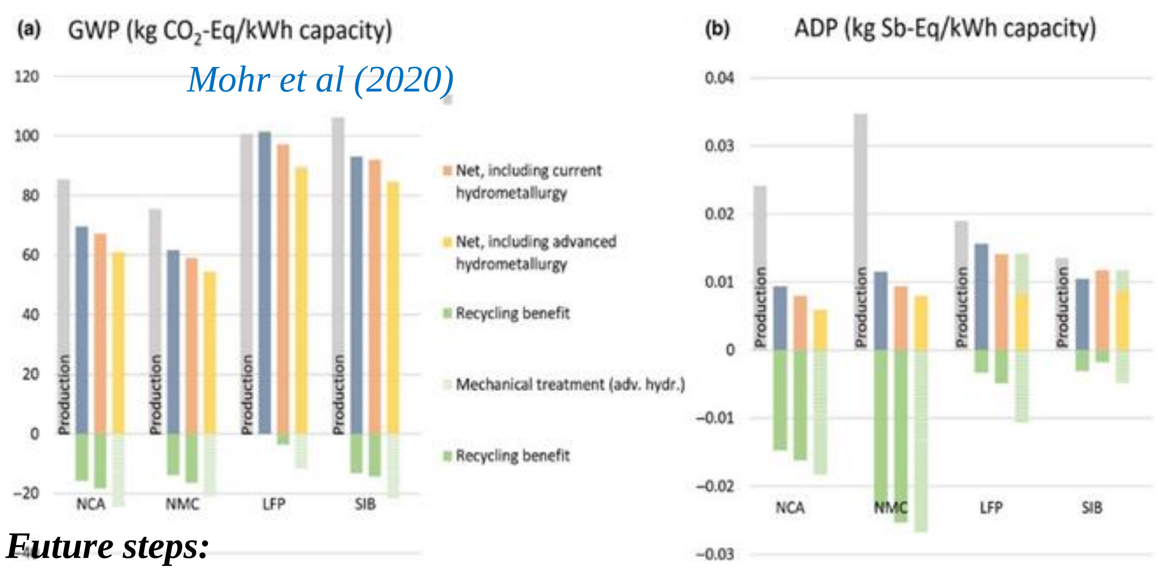
Nowadays there is an intense development of recycling processes in the recent years and new LCA studies can be found: e.g. Ciez and Whitacre (2019), Mohr et al (2020), Xiong et al. (2020); Sun et al. (2020), Cusenza et al. (2019), Rajaeifar et al. (2021), Zhou et al. (2021) Kallitsis (2022), Adhikari, 2023, Rosenberg, 2023, and also review papers: Pražanová et al. 2022, Li et al. 2023

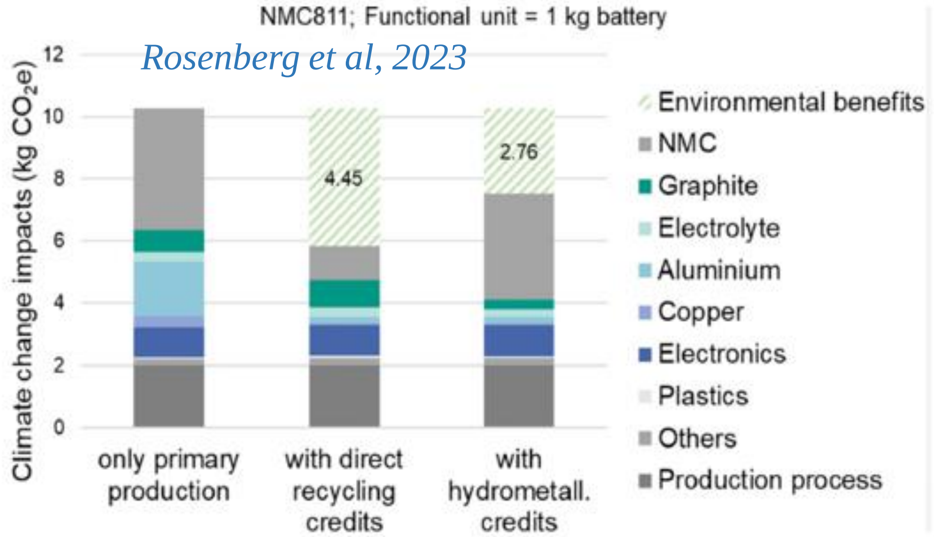


CED for different recycling processes Li et al., 2023

	Chemistries	Processes	FU	Scope	Data
Ciez and Whitacre, 2019	NMC, NCA, LFP	Pyrometallurgical, Hydrometallurgical, and Direct Recycling	Per kg and per kWh	battery cell	GREET 2016 and Ecoinvent
Sun et al. 2020	NMC 622	hydrometallurgical method	1 kWh	Battery pack	Primary data from leading LIB suppliers and recycling corporations (2017-2019) supplemented by Ecoinvent 3.0, ANL GREET (2018)
Mohr et al. 2020	NCA, NMC, LFP, SIB	Pyrometaallurgical Hydrometallurgical Advanced hydrometallurgical	kWh	Battery cell	Advanced hydrometallurgical process (industrial data - (Duesendelf), other recycling processes (Literature, Fisher, in Ecoinvent, hydrometallurgical (company Recupyl, py rometallurgical Batrec.)
Zhou et. al. 2021	LCO	In-situ roasting reduction (RR) hydrometallurgy pyrometallurgy	1 ton	Battery	Data from laboratory studies, literature, and the Ecoinvent v3.5 database
Kallitsis et al. 2022	NMC 333	Hydrometallurgical pyrometallurgical	1 kWh	Battery pack	Data from Ecoinvent database, literature, and industry sources, for recycling based on Mohr et al. 2020.
Jiang et al. 2022	NMC 111, LFP	Hydrometallurgical recycling, direct recycling	1 kg	Battery cell	Data from relevant enterprises in China, Ecoinvent 3.7 database, for direct recycling based on literature and hydrometal. Is used as a proxy.
Rosenberg et al. 2023	NMC111, NMC811	Waterjet based direct recycling hydrometallurgical processes	1 kg	Spent traction battery	Advanced hydrometallurgical process were taken from Mohr et al. 2020. and data for Waterjet based direct recycling (based on Kurz et al., 2019)

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY





Future steps:

- *improve the data inventories focused on recycling, more data from lines than labs, more impact categories in LCAs*
- *exploring new recycling processes (e.g. chemical-free recycling technologies)*
- *focuse on developing of direct recycling and understanding the limits on how much directly recycled cathode material can be mixed with virgin materials Rosenberg et al, 2023*
- *tailor recycling strategies to different geographic locations*
- *is needed to develop efficient ways to recover and reuse graphite, the potential to recover other non-metal materials, such as plastics and the electrolyte, should also be explored in more detail (Kallitsis et al (2022))*
- *the recycling processes must be tailored to maximize nickel recovery as there is a shift from NCM 111 to NCM 811*
- *addressing safety concerns related to battery recycling*
- *making batteries easier to dismantle and recycle*

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report – findings - **secondary use of batteries***

The results of LCAs focused on the secondary use vary according to different assumptions of individual studies:

The scope of the study – whether the study covers only second, second (**Bobba et al. 2018; Kamath et al. 2020**) or both (**Genikomsakis et al. in 2013, Ahmadi et al. 2017, Koroma et al. 2022, Quan et al. 2022**)).

And that is why different function units are used and different scenarios are analysed. For example **Ahmadi et al. 2017 – FU defined as** 1 kWh delivered by the battery pack over its full life (8 years in vehicle, 10 years in stationary application) and Koroma et al. 2022 modelled second life as the avoided amount of new battery and the FU was driving a European B-segment BEV equipped with a 54.6 kWh LIB for 160,000 km over a lifetime of 12 years.

The second life phase modelling – whether the electricity consumption (**Ahmadi et al. 2017; Quan et al. 2022**) in the second phase is envisaged or whether there is only the avoided new battery benefit accounted (Genikomsakis et al. in 2013; Koroma et al. 2022).

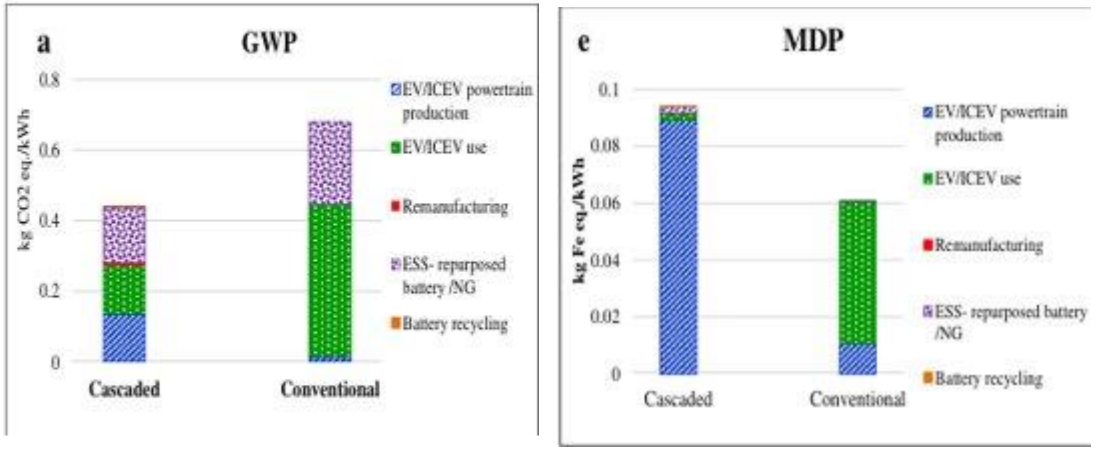
The scenarios compared: **Ahmadi et al. 2017** compared both – first and second life stage for two scenario – BEV and ESS versus ICEV and NG for electricity stabilisation. Quan et al. 2022 compared LFP and NMC battery for the first and the second use with the effect of different recycling processes but they envisaged 100 % of battery cells for the second use unlike Koroma et al. 2022 who envisaged only 50 % and made a sensitivity scenario.

Study	Battery chemistry	Functional unit	Scope	2nd life use	Refurbishment	Recycling	Data
Genikomsakis et al., 2013	LFP	Time factor as functional unit, considering a lifespan of 7 years for EV use and an additional 4 years for second-life applications in smart buildings (total: 4000 cycles) (24 kWh battery, car 40 km a day, 365 days a year in Bilbao).	Manufacturing, use phase in an electric vehicle, second use, incineration, and landfilling.	reutilization for stationary energy storage in smart buildings	No	No	LCA data pro výrobu baterie jsou ze studie Majeau-Bettez, 2011
Ahmadi et al. (2017)	LiFePO4 (Lithium Iron Phosphate)	1 kWh delivered by the battery pack over its full life (8 years in vehicle, 10 years in stationary application)	Life cycle assessment (LCA) of EV battery, reuse in energy storage systems, comparison with conventional systems	Yes, reuse in stationary energy storage systems	Yes, includes disassembly, re-manufacturing, and testing for reuse	Yes, but only qualitatively considered, no credit applied for material recovery	Secondary data from LCA databases, real-time power use data, Ontario electricity grid mix data
Bobba et al. 2018	LMO/NMC	The average yearly energy balance of the system in which the battery stores energy	manufacturing, repurposing, reuse, and recycling	Yes	Yes	Yes pyrometallurgical process	**JRC lab for battery degradation,** Secondary LCA sources
Kamath et al. 2020	LIB (Ford Focus – Kim et al., 2016)	Different according to the scenario - PV storage, firming and peak shaving	manufacturing, repurposing, second life	Yes	Yes	No	Secondary LCA sources
Quan et al. 2022	LFP/NMC	the nominal capacity of a 1 kWh battery pack	Battery manufacturing, first use, refurbishment, second use and different recycling technologies	Yes	Yes (They envisaged 100 % cells will serve for the second phase.)	Yes (hydrometallurgy, pyrometallurgy, and direct physical recycling)	Secondary LCA sources (Battery, Dai et al., 2019), Data for battery refurbishment from 2 Chinese projects
Koroma et al. 2022	NMC 111	Driving a European B-segment BEV equipped with a 54.6 kWh LIB for 160,000 km over a lifetime of 12 years (Renault Zoe)	LIB and vehicle production, vehicle use, LIB refurbishment, (avoided LIB production) recycling	Yes as avoided LIB	During the battery refurbishment, half of the components were replaced with an expected lifespan of 5 years.	Recycling as in Cusenza et al. (2019) and Chancerel and Marwede (2016)	Secondary data from LCA databases like Ecoinvent v3.6 and reports

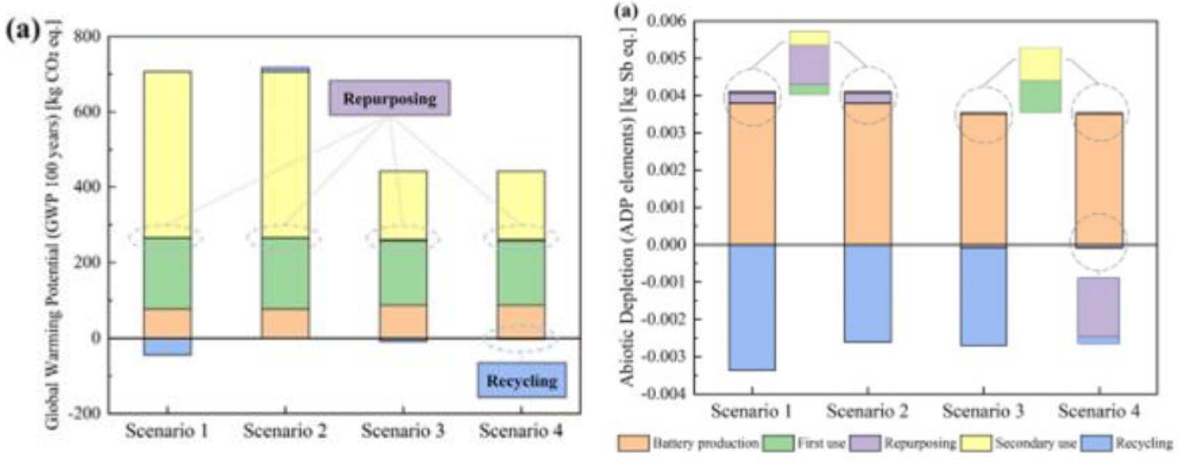
Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report – findings - **secondary use of batteries***

- Refurbishment stage had the negligeable impact in all of the analysed LCA studies.
- Ahmadi et al. 2017 showed the lower environmental impacts of the scenario envisaging BEV and ESS versus scenario envisaging ICEV and natural gas for electricity stabilisation in almost all of the impact categories except the material depletion potential, but they did not envisaged recycling phase. They concluded also that the energy **efficiency fade is a critical** factor in determining the environmental performance of second-life battery applications, especially in stationary uses like energy storage.
- Quan et al. 2022 showed the **necessity to have clean grid mix in order to have lower impact** of second life phase.
- And as it is also concluded in Dong et al. 2023 ESS using second-life batteries generally have lower carbon footprints than those using lead-acid batteries or new EVBs.
- However, when compared to baseline scenarios without energy storage, the use of second-life batteries does not necessarily lead to a lower carbon footprint as it is shown for example in Bobba et al. 2018



Ahmadi et al. 2017



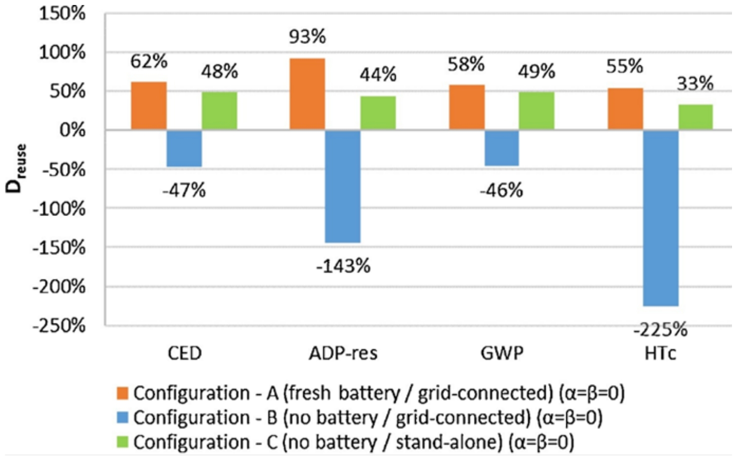
Quan et al. 2022

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

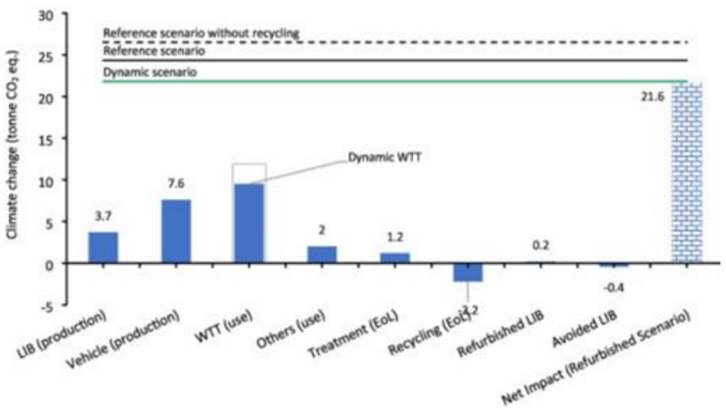
Appendices *Report – findings* - ***secondary use of batteries*** -

Future steps

- Ahmadi et al. 2017 - the need for further research on battery **degradation, safety, and the business feasibility** of second-life battery applications.
- Bobba et al. 2018 - the importance of **additional primary data** on battery degradation and repurposing for more precise assessments.
- According to Kamath et al. 2020 more research is needed on SLB quality (implementing **standardized testing protocols)** and availability, there is a necessity to **explore the relationship between repurposing and recycling** as SLBs may divert batteries away from recycling, but at the same time, their reuse helps reduce the need for new mining, **to employ internet-of things** in order to obtain relevant battery information (for streamlining the recycling and the repurposing process.
- Quan et al. 2022 recommended **improving the charge-discharge efficiency and energy density of power of batteries and increasing the proportion of clean energy**
- Koroma et al. 2022 suggested to explore improved recycling processes and longer second-life spans for refurbished batteries, especially focusing on higher recovery rates (>50%) and longer lifetimes (>5 years).
- Dong et al. 2023: **the lack of consistent LCA approaches** presents challenges when comparing various options for retired batteries. To reduce uncertainties in LCAs and provide guidance to decision-makers, it is **necessary to establish a harmonized set of LCA rules for second-life EVB applications.**



Bobba et al. 2018



Koroma et al. 2022

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report – findings LCA focused on hydrogen cars*

These findings are based on the bachelor work of Lukáš Trávníček elaborated from 09/2023 – 01/2024.

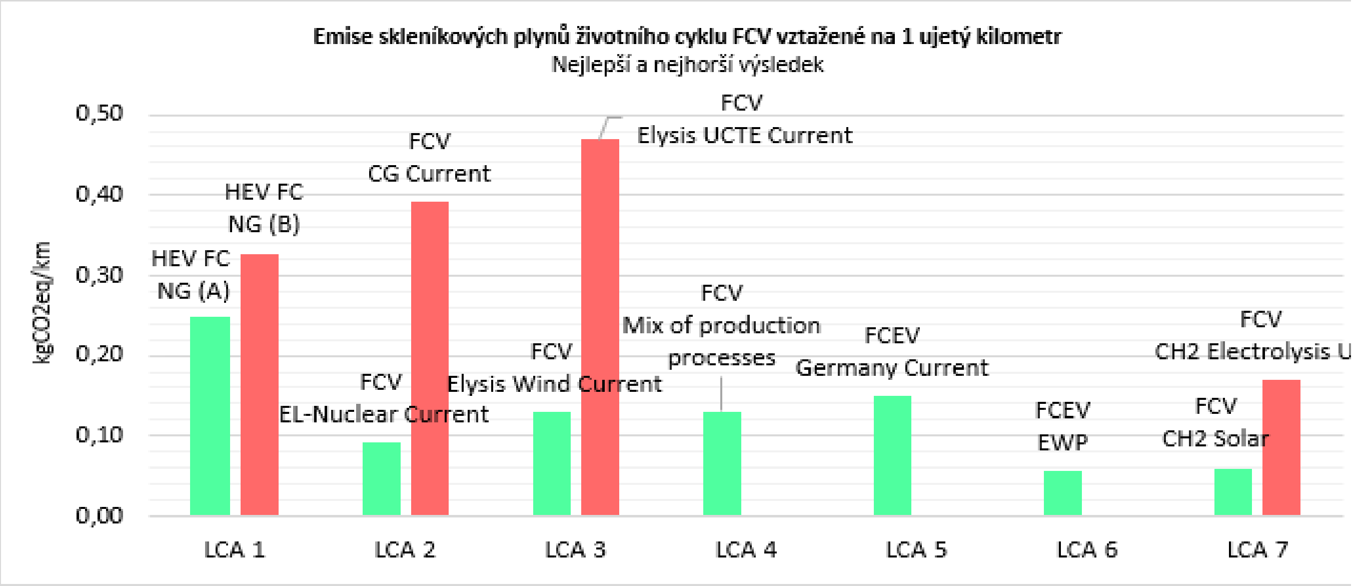
Among the selected LCA studies with summarised assumptions in the table there are studies where at least the production and use phase are considered: Baptista et al. 2011 ; Bauer et al. 2015: Miotti et al., 2015; Evangelisti et al., 2016; Benitez et al., 2020; Candelaresi et al., 2021

There are also more studies focused only on the WTW as for example: Wang et. al 2020 provide only WTW analysis of hydrogen fuel cells vehicles in China, as well as Qian et al., 2023, Lu et al., 2022 and Lee et al. 2018 for Medium- and Heavy-DutyTrucks and He et al. 2021 for Light-Duty Hydrogen Fuel Cell Vehicles in China in 2017 and 2030 or Wei et al. 2021 who analysed 5 different driving cycle of FCV and production of hydrogen by SMR, grid or naptha in Korea. These studies was not envisaged for the comparison.

Author	Year	Goal	Powertrain types	Vehicle Types	Functional unit	IC	Scope	Jízdní cyklus	Data	LCC
Baptista et al.	2011	Comparison of energy consumption and CO2 emissions of different vehicle technologies and fuels for London taxis.	ICE Diesel,PHEV-FC, HEV-FC, EV	London Taxi	1 km	CO2	Production of cars, WTW, Recycling	PCO-CENEX London Taxi Drive Cycle T.	Greet	No
Bauer et al.	2015	Comparison of the life cycle impacts of current and future (2012 and 2030) mid-size passenger cars operated in Switzerland with various powertrains and fuels.	ICEV, HEV, BEV, FCV	mid-size passenger cars	1 km	Different	WTW, production, operation, and road infrastructure maintenance	WLTP		No
Miotti et al.	2015	Analysis of life cycle impacts and costs of fuel cell systems and various types of vehicles	FCV, BEV, ICEV	Passenger vehicles a five-seat compact car (class C)	1 km	Different	WTW, production, operation, and disposal of the vehicle, including road infrastructure production and maintenance	NEDC	Ecoinvent, detailed inventory for FCS based on literature and modeling	Yes
Evangelisti et al.	2016	Comparison of life cycle impacts of different vehicle technologies, with a focus on their production.	FCV, BEV, ICEV, Diesel		1 km		Production, operation, and disposal of the vehicle			
Benitez et al	2020	Evaluation of the life cycle impacts of FCV, with special focus on the production of carbon fiber pressure vessels.	FCV		1 km		Production, operation, and disposal of the vehicle			
…i et al.		Evaluation of the life cycle impacts of different hydrogen-powered vehicles and their comparison with	FCEV, H2-ICE, HEV, H2-ICE,				WTW, production, and vehicle			

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report – findings LCA focused on hydrogen cars*



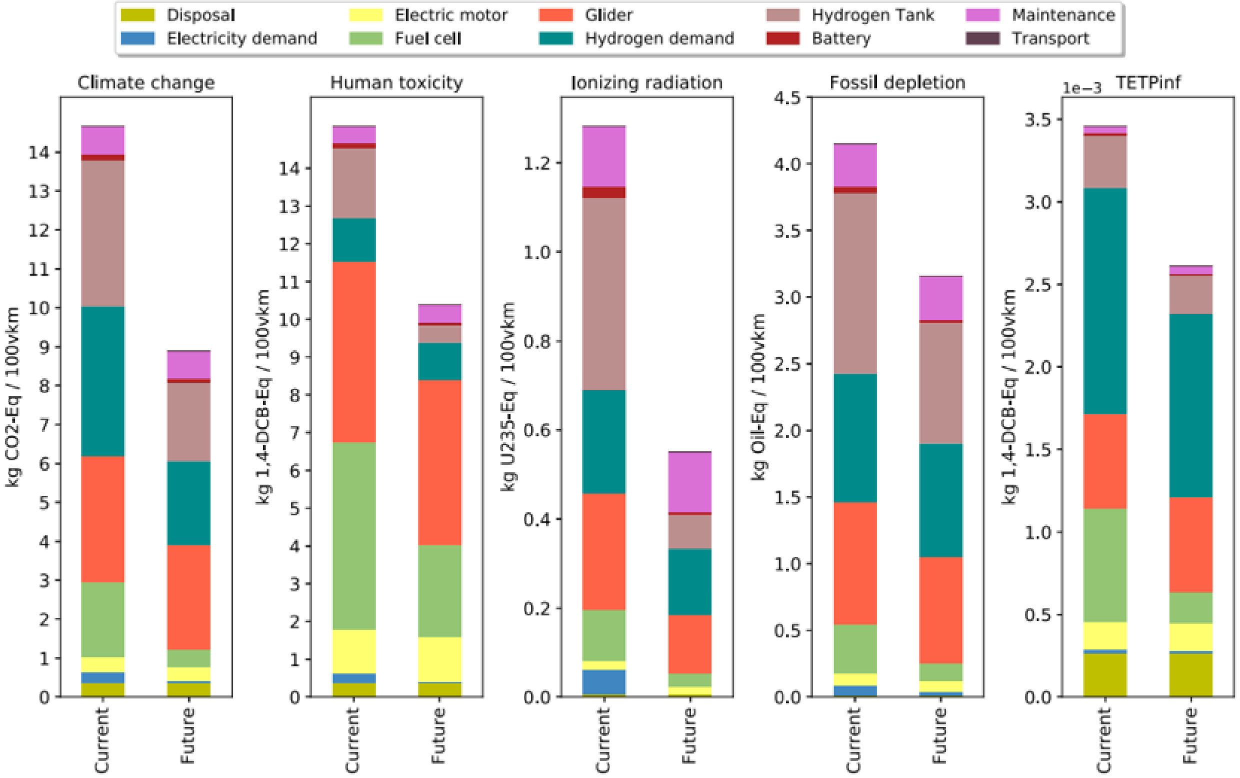
Comparison of the Best and Worst Greenhouse Gas Life Cycle Emission Values of FCVs (Trávníček, 2024)

	Author	Year of publication	Energy Consumption during Operation (MJ/km)	Lifetime (km)	Cycle	Scope	
1.	Baptista et al.	2011	2,52	563250	PCO-CENEX London Taxi	Production of cars, WTW, Recycling	HEV FC
2.	Bauer et al.	2015	1,63	240000	WLTP	WTW, production, operation, and disposal of the vehicle, including road infrastructure maintenance	FCV Current
3.	Miotti et al.	2015	1,26	150000	NEDC	WTW, production, operation, and disposal of the vehicle, including road infrastructure maintenance	FCV Current
4.	Evangelisti et al.	2016	1,02	150000		Production, operation, and disposal of the vehicle	FCV
5.	Benitez et al	2020	0,91	150000		Production, operation, and disposal of the vehicle	FCV Current
6.	Candelaresi et al.	2022	0,91	190000		WTW, production, and operation of the vehicle	FCEV
7.	Ahmadi and Khoshnevisan	2022	0,76	N.A.	NEDC	WTW, production, and operation of the vehicle	FCV

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

Appendices *Report – findings LCA focused on hydrogen cars*

- *The life cycle phase of the hydrogen vehicle with the greatest environmental impact is the* ***production*** *phase, especially the production of hydrogen storage pressure vessels and FCs (greatest impact of* ***carbon fibers)*** *is the most significant . The largest part of the fuel cell production impact comes from* ***platinum mining****.*
- *In general, the results indicate that hydrogen vehicles have the potential to reduce GWP of automotive transportation, especially* ***if renewable energy sources are used for hydrogen production****. The results of the selected analyses agree that producing hydrogen by SMR of natural gas is better in terms of GHG emissions than using electricity from an energy mix with a high proportion of fossil fuels. The greatest reduction in greenhouse gas emissions from hydrogen vehicles occurs when hydrogen is produced by electrolysis using renewable energy sources (e.g., wind, water, and solar energy) or nuclear energy.*
- *According to Ahmadi and Khoshnevisan 2022 study, an appropriate hydrogen production process for hydrogen vehicles that achieves similar emission values as electrolysis using renewable sources is the* ***thermochemical cycle using waste heat from a nuclear power plant****.*
- Desantes et al. 2020 present as ideal production technology SMR with CO_2 sequestration with NO_X-reducing catalysts at the exhaust of the SMR plant. In the short-term, H_2 production through SMR with CO_2 strategy should be extended and FCV in the market increased through cost reduction.

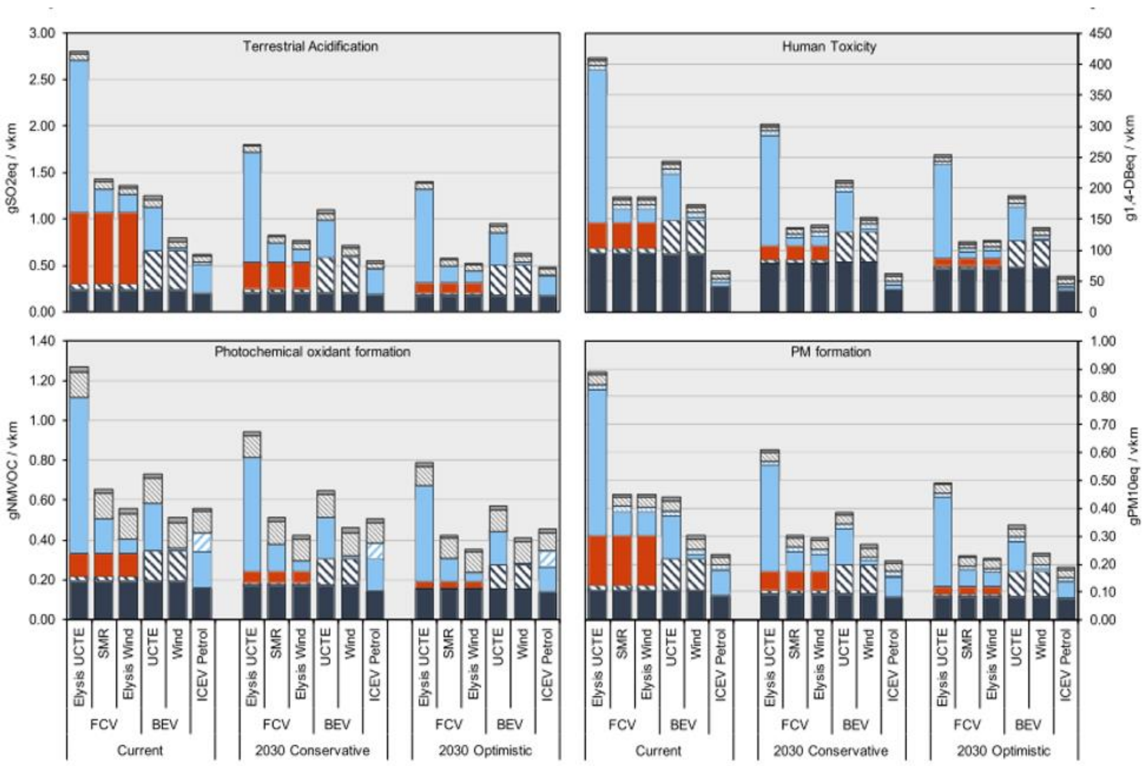


LCA results of FCEV (Benitez et al., 2020)

Appendices to 3-WP08 R&D of Knowledge Database: Design Assistance SYstem - DASY

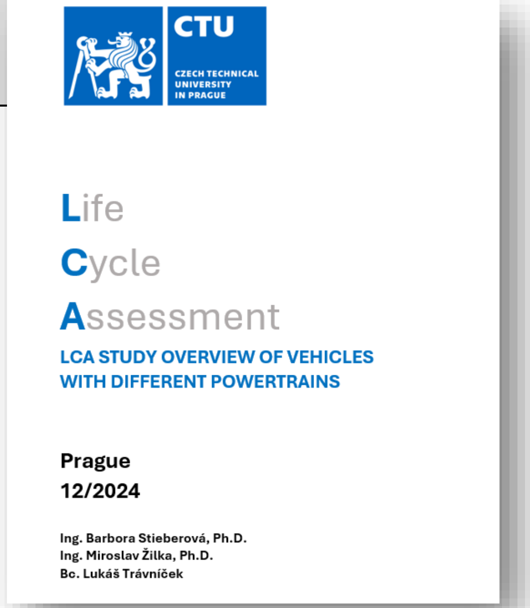
Appendices *Report – findings LCA focused on hydrogen cars*

- *Using hydrogen vehicles instead of fossil fuel-powered vehicles may increase the impact on some other impact categories. For example, the* ***life cycle impact of hydrogen vehicles with fuel cells on the HT category is always greater, and sometimes significantly higher, than that of fossil fuel-powered vehicles, regardless of hydrogen production****. Hydrogen vehicles also show similar negative environmental performance in the AP and PMF categories.*
- *A comparison of the life cycles of hydrogen and electric vehicles more often favor electric vehicles.*
- *Candelaresi et al. 2022 offers a comparison of various hydrogen-powered vehicles and suggest that using hydrogen-powered ICEV may be a better option in terms of environmental impact than using hydrogen-powered fuel cell vehicles. In combination with the results of LCA Candelaresi et al. 2023, it is recommended to use fuel mixtures of hydrogen with other fuels in road transport to achieve* ***short-term environmental goals****.* ***Hythane*** *appears to be the most suitable mixture, as it can be transported using the existing natural gas infrastructure with minor modifications.*
- *In the future, some authors expect technological development and positive changes in energy mixes. The authors anticipate a* ***reduction in the amount of platinum used in fuel cells and a reduction in the amount of carbon fiber.***
- *Lotrič et al., 2021 LCA for hydrogen technologies, critical materials, and end-of-life strategies with special attention to the recycling of platinum-group metals (PGMs) and other critical materials. (the manufacturing and end-of-life (EoL) phases)*



Environmental impact results and cost of FCS (Miotti et al., 2015)

Výtah z prací 2023 - 2025 na **4-WP04:** Analýzy životního cyklu v systémech mobility


CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Life
Cycle
Assessment

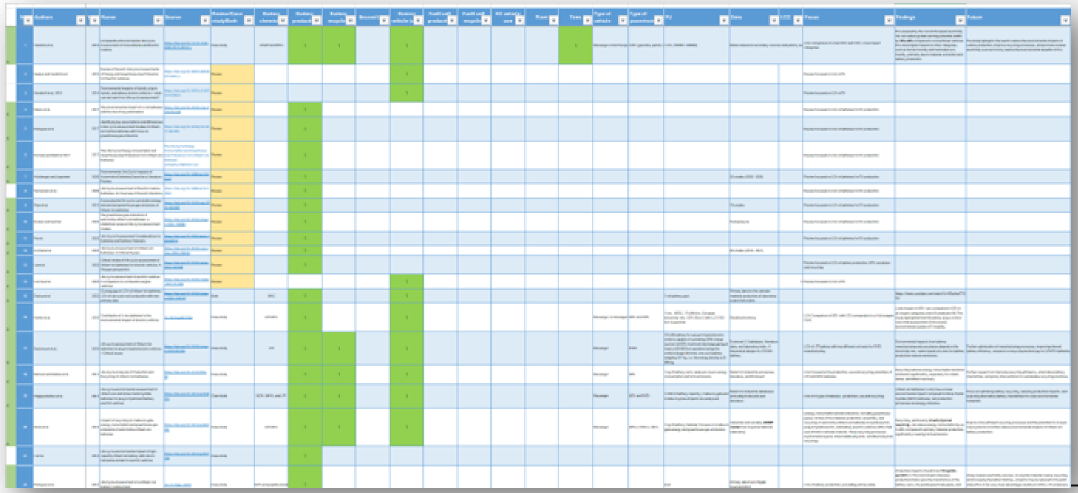
LCA STUDY OVERVIEW OF VEHICLES WITH DIFFERENT POWERTRAINS

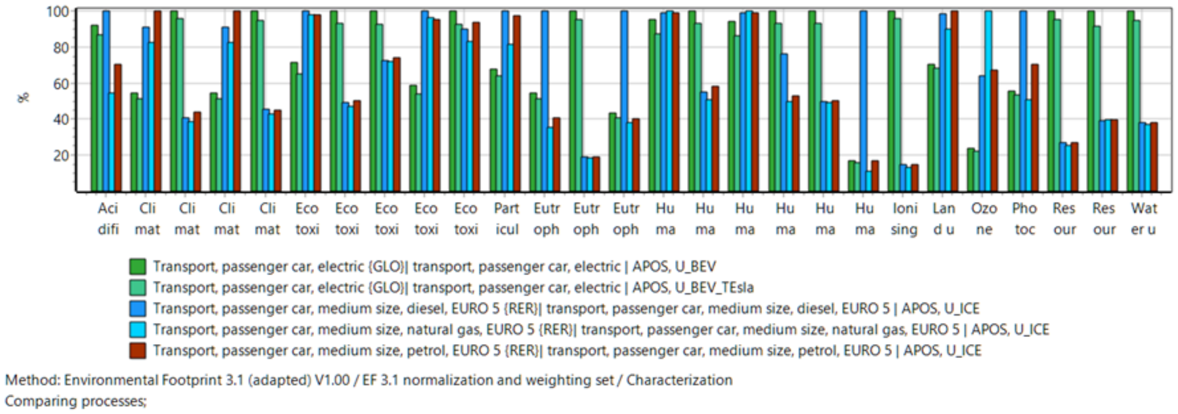
Prague
12/2024

Ing. Barbora Stieberová, Ph.D.
Ing. Miroslav Žilka, Ph.D.
Bc. Lukáš Trávníček

Ing. Miroslav Žilka, Ph.D. (ČVUT – FS) – miroslav.zilka@fs.cvut.cz

- Vytvoření databáze LCA studií zaměřených na systém mobility.
- Vytvoření reportu shrnujícího poznatky z dostupných LCA studií a směry budoucího vývoje.
- Realizace individuální LCA studie zaměřené na systém mobility v České republice.
- Identifikace a realizace vhodných případových studií LC (Life Cycle) analýz v oblasti mobility.
  - Energy Tender – Ekonomický model, potenciálně environmentální analýza
  - Urban cargo logistika – Environmentální analýza

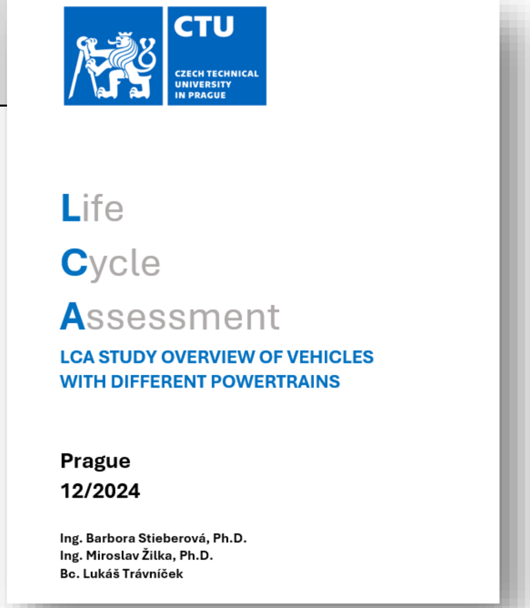


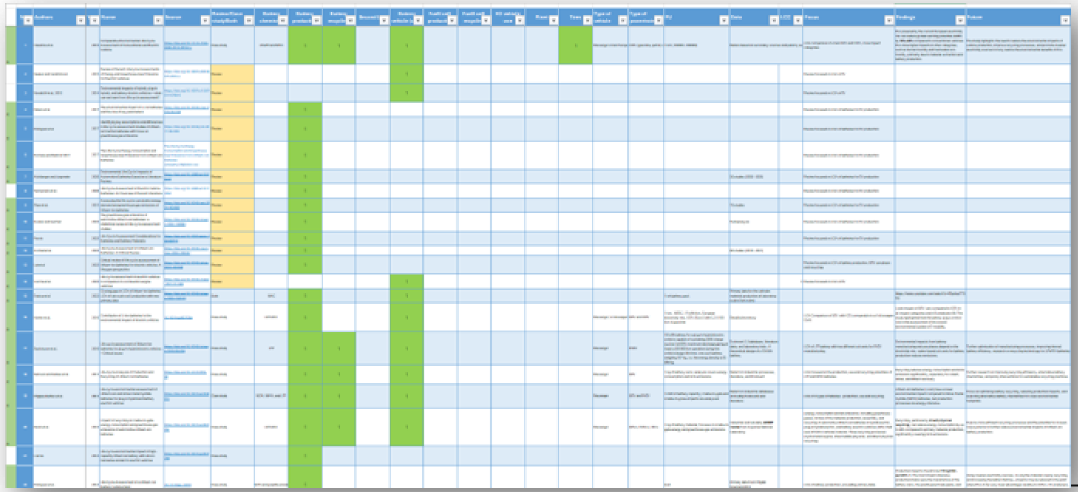


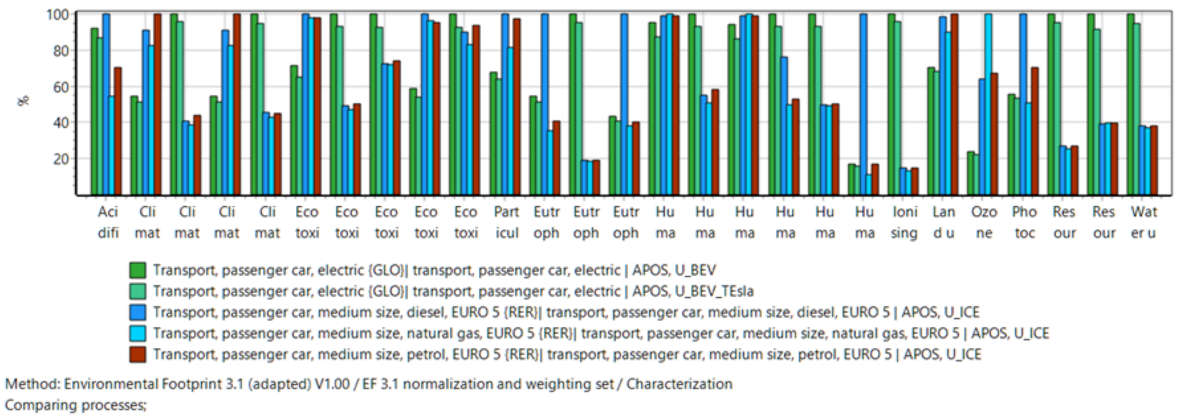
Results of **4-WP04:** Life Cycle Analysis in Mobility Systems – Achieved 2023 - 2025

Ing. Miroslav Žilka, Ph.D. (ČVUT – FS) – miroslav.zilka@fs.cvut.cz

- Creation of a database of LCA studies focused on the mobility system.
- Creation of a report summarizing the findings from available LCA studies and directions of future development.
- Implementation of an individual LCA study focused on the mobility system in the CZ.
- Identification and implementation of appropriate LC (Life Cycle) case studies in the field of mobility.
  - Energy Tender – Economic Model, Potential Environmental Analysis
  - Urban cargo logistics – Environmental analysis



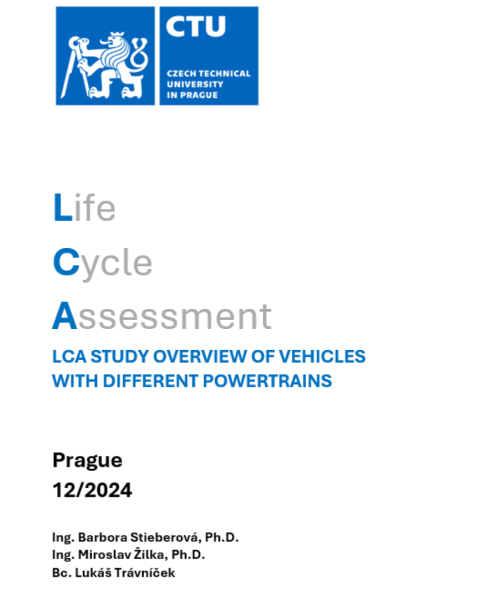




Results of **4-WP04:** Life Cycle Analysis in Mobility Systems – Achieved 2024

Ing. Miroslav Žilka, Ph.D. (ČVUT – FS) – miroslav.zilka@fs.cvut.cz

- Vytvoření strukturované databáze LCA studií v oblasti dopravy.
- Souhrn hlavních poznatků, směrů dalšího vývoje v komplexním reportu.
- Vytvoření výchozích modelů jednotlivých prvků systému mobility v programu pro podporu LCA analýz SimaPro.
- Identifikace dílčích LC studií – case studies:
  - Energy Tender (3 – WP13 – 001) – výchozí struktura ekonomického modelu, výchozí sada vstupních dat pro další jednání s partnery
  - Urban cargo logistika – navázaní prvotního kontaktu – jednání o možnosti zpracování komparativní studie ve spolupráci se společností Hral



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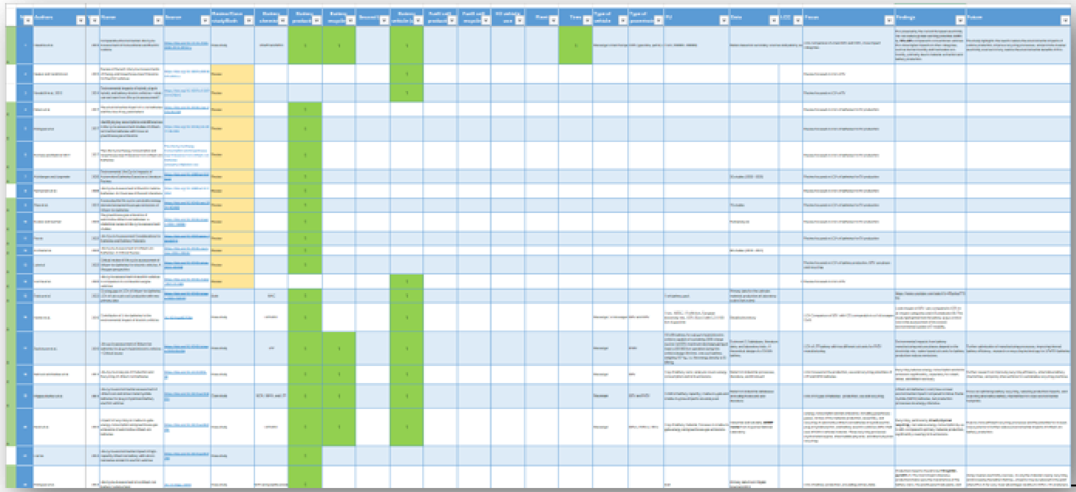
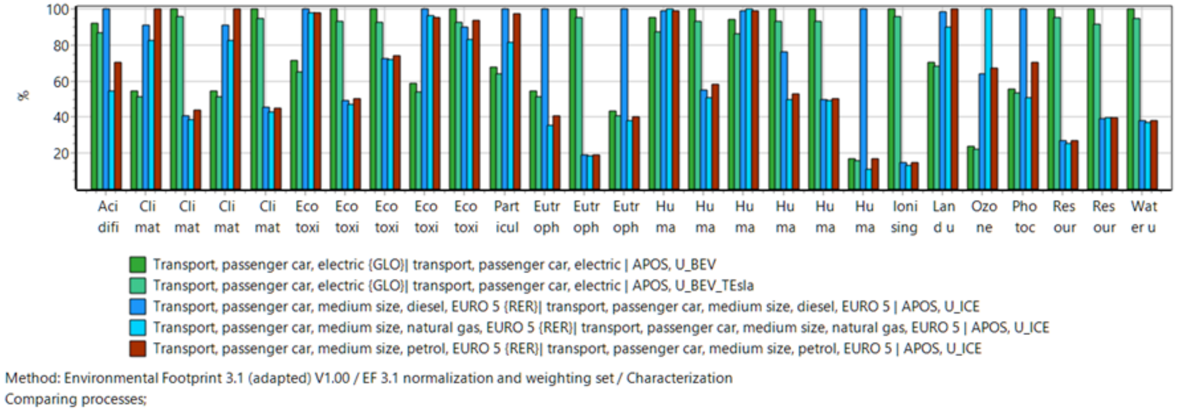
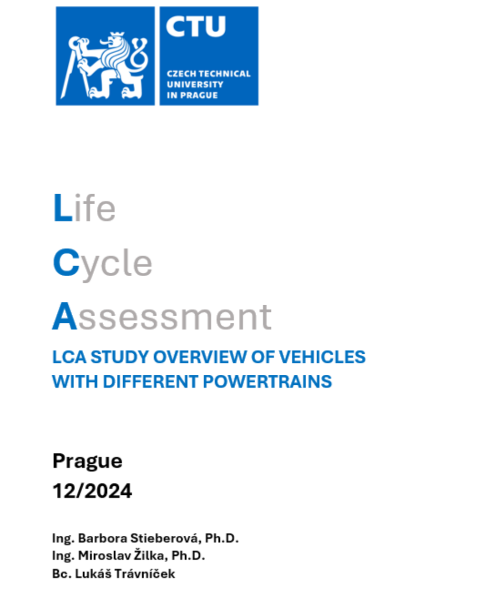




Results of **4-WP04:** Life Cycle Analysis in Mobility Systems – Achieved 2024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Ing. Miroslav Žilka, Ph.D. (ČVUT – FS) – miroslav.zilka@fs.cvut.cz

- Creation of a structured database of LCA studies in the field of transport.
- Summary of main findings and directions for further development in a report.
- Creation of initial models of individual elements of the mobility system in the SimaPro program for supporting LCA analyses.
- Identification of partial LC studies – case studies:
  - Energy Tender (3 – WP13 – 001) – initial structure of the economic model, initial set of input data for further negotiations with partners
  - Urban cargo logistics - establishing initial contact - negotiating the possibility of preparing a comparative study in cooperation with the company Hral