ESCALATE

LCA of zero-emission heavy-duty vehicles – Analysis of the ESCALATE project approach

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TranSensus LCA Final Event

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WWW.ESCALATE-EU.COM

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ESCALATE - Powering European Union Net Zero Future by Escalating Zero Emission HDVs and Logistic Intelligence

- 37 partners from 13 countries
  - 5 Truck Manufacturers
  - 3 Infrastructure Supplier
  - 4 Fleet Operators
  - 4 Tier-1 Suppliers
  - RTOs
- Budget:
  - 22,4 Million €
- Grant agreement ID: 101096598
- Part of AEVETO Cluster (https://www.escalate-eu.com/aeveto-cluster/)

Project coordination (FEV) : Dr. Servais Ouenou Gamo
Technical coordination (USR) : Prof. Dr. Ahu Ece Hartavi Karci

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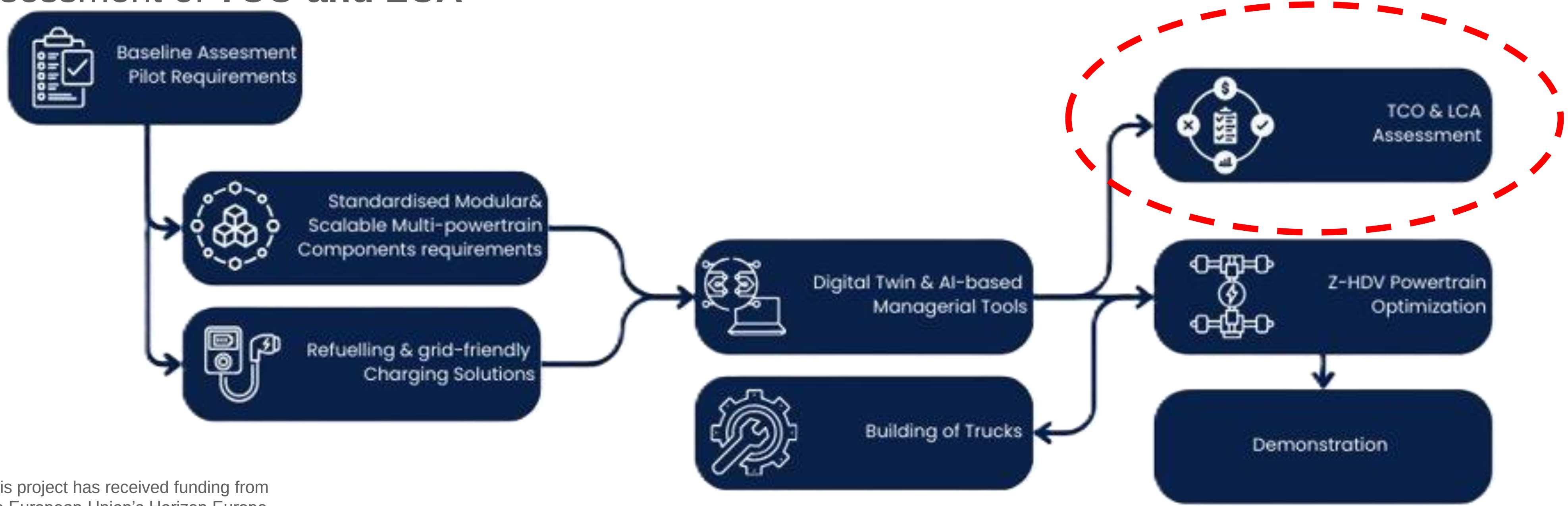
Overall objectives

- **O1.** Development and demonstration of ground-breaking and cost-effective **long-haul battery, fuel-cell and range-extender fuel-cell HD EVs**
- **O2.** Development and demonstration of **grid-friendly** (multi) energy **fast charging/refueling solutions**
- **O3.** Development of 5 modular **Digital Twins**
- **O4.** Assessment of **TCO and LCA**



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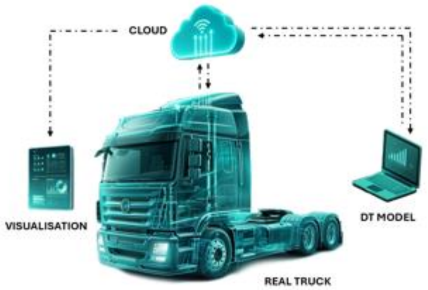
Key expected outcomes

- Modular and Standardised e-powertrain components
- Intelligent energy management
- Effective thermal management & efficient metal hydride systems for refrigeration loads
- Investigation of charging system modules' sound characteristics
- High pressure (700 bar) H2 refueling station, 1MW fast charger
- H2 powertrain & H2 storage systems
- AI-powered fleet management supporting mix-fleet
- AI-powered multi-domain toolchains for PDM (predictive maintenance)
- Cyber security and trustworthy communication solution stack



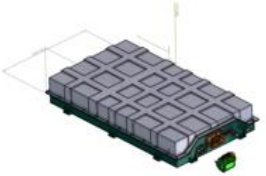

MCS Dispenser


Fuel Cell


H2 Storage


Pilot 2 Design

EMS


Battery


Cybersecurity

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ESCALATE KPIs

>10% Energy Efficiency (r-HDV)

Min. 500 km daily operation 6 Months (f-HDV, r-HDV, b-HDV)

Min. 90% load capacity

>96% EM efficiency

750+ km single refill (r-HDV, f-HDV, b-HDV)

>5% Increased Energy Efficiency (f-HDV, b-HDV)

High Speed H2 Refueling 120 g/s

Min. 86% Battery Efficiency

Min. 47% FC Efficiency

MCS up to 1MW

White papers (Roadmap to "Absolute Zero" logistics, Best-practice policies/incentives, Market needs)

Standardization of LCA for z-HDVs

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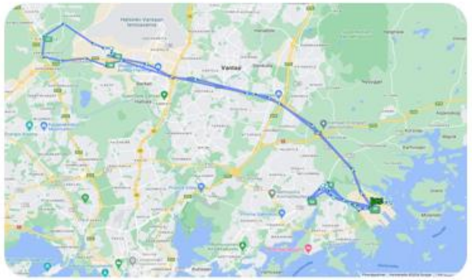
ESCALATE Vehicle Pilots

P1: SISU r-FCEV

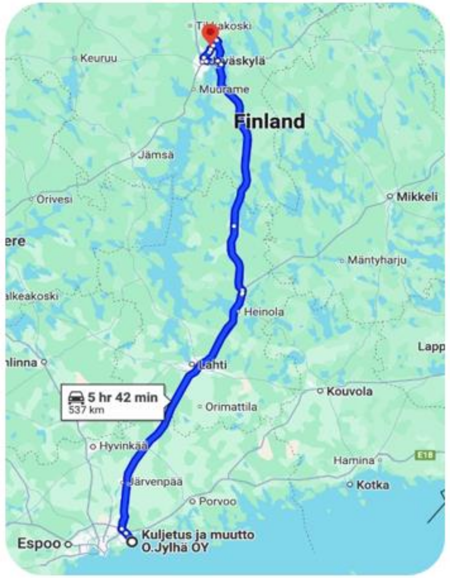
RAUANHEIMO
Part of KWH LOGISTICS

O. JYLHÄ OY

SISU



Port of Kokkola

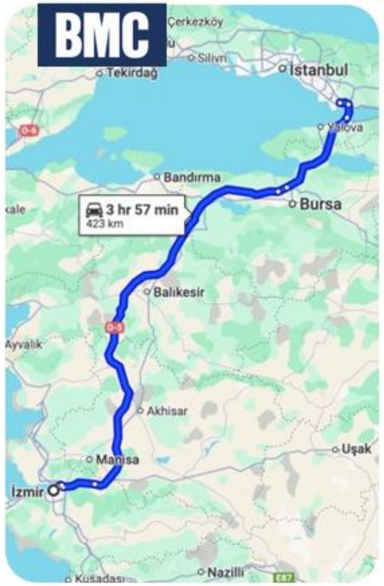


Helsinki - Jyväskylä

P2: BMC FCEV

DHL

BMC



Gebze - İzmir

Grenoble - Munich

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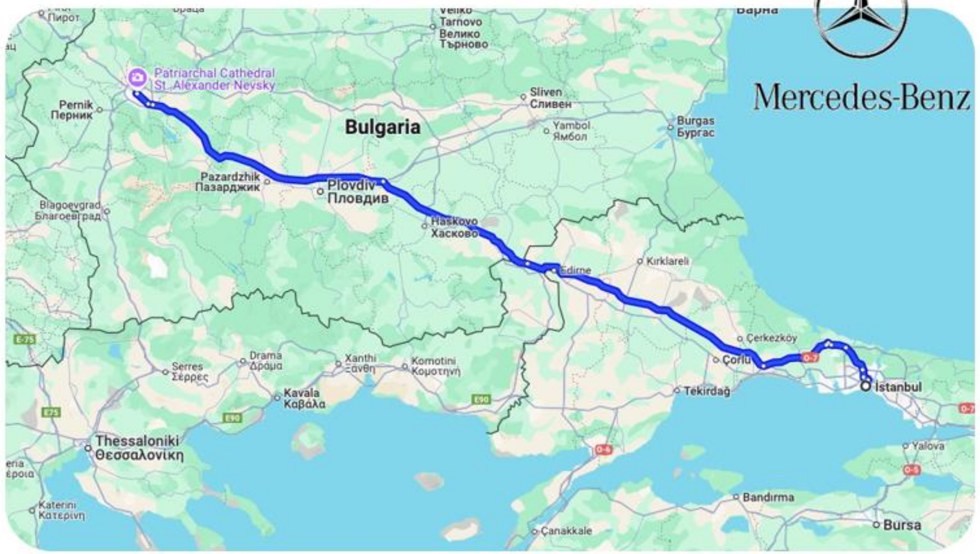
ESCALATE Vehicle Pilots

P3: MBT BEV



Mercedes-Benz

Istanbul - Sofia

P4: Electra BEV

Dundee - Cwmbran

ELECTRA Commercial Vehicles

Sttutgart - Karlsruhe

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ESCALATE Vehicle Pilots

P5: FORD BEV

Geneva - Barcelona

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ESCALATE: 3 Infrastructures Pilots

Mobile H2 Filling Station

Green fix Multi-fuel Station

Megawatt Charging System

High Speed H2 Refuelling

Noise Reduction During Charging

Hotel Functionality

1 MW Fast Charging

Grid Monitoring

Waste Heat Management

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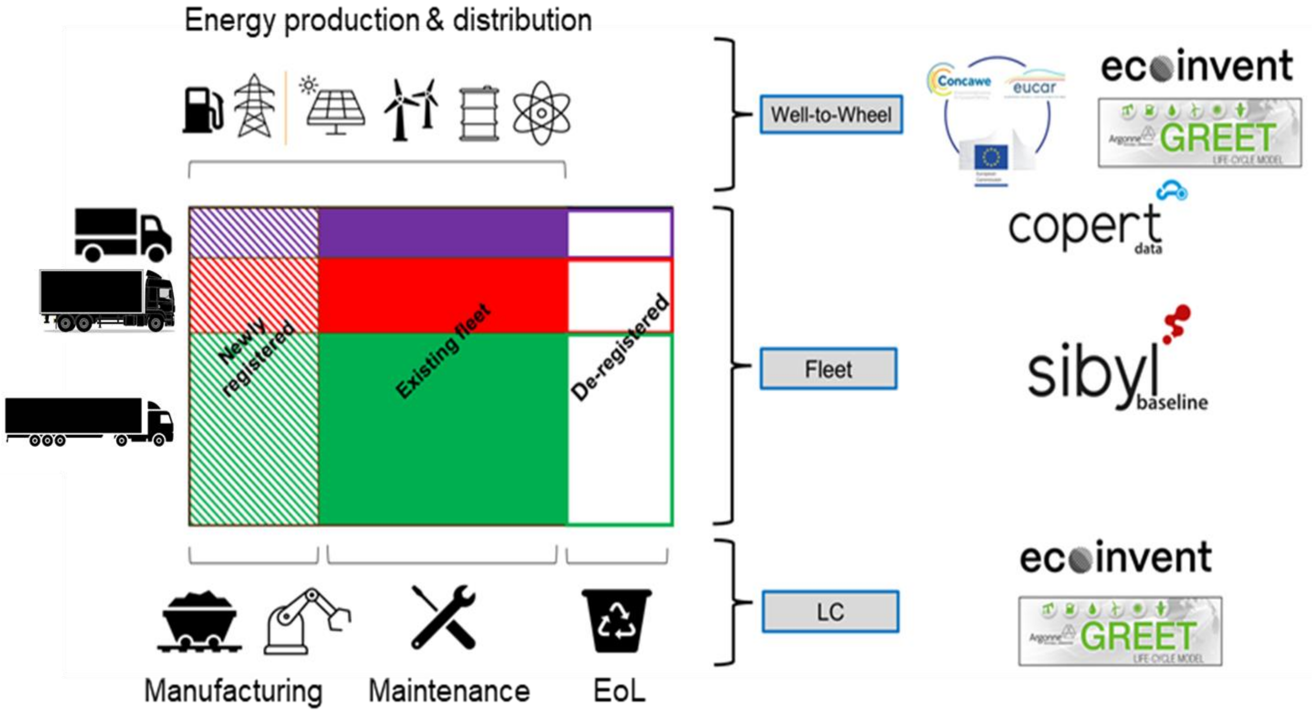
LCA, TCO and CBA-related objectives

- Develop integrated platforms for environmental and socio-economic impacts (**LCA, TCO, CBA**)
- Deliver data-driven (from ESCALATE pilots) **single-vehicle and fleet-based LCA** using pilot inputs
- Consider the **current status** of emissions resulting from the life cycle of the project pilots and **extend** this perspective using a **predictive LCA** approach to assess impacts in the target year 2050
- Propose a **standardized LCA** framework for vehicle homologation



LCA: Life Cycle Assessment
TCO: Total Cost of Ownership
CBA: Cost Benefit Analysis

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Goal and Scope Definition

Goal

Cover the entire life cycle of the pilots – Cradle to Grave

Demonstrate the impact of technical optimizations of the ESCALATE pilots

System Boundaries					Specifications			Data			
Functional unit	Vehicle production	Infrastructure and well-to-tank	Use of vehicles	End-of-life	Time	Geography	Impact Categories	Data collection	Background data	Software	Sensitivity analysis
Vehicle use case (tkm)	Focus on drivetrain technology options	Focus on energy supply	Pilot specific use cases	Estimation based on drivetrain technology	Current status (2024) scenarios until 2050 (intermediate: 2030, 2040)	Use case specific for every pilot	Evaluation of mid-point categories	Technical specifications of the pilots	ecoinvent 3.9.1 for emission factors in use phase: Copert/Sybil	OpenLCA Sundial for data inventory	Electricity mix for use phase Battery chemistry

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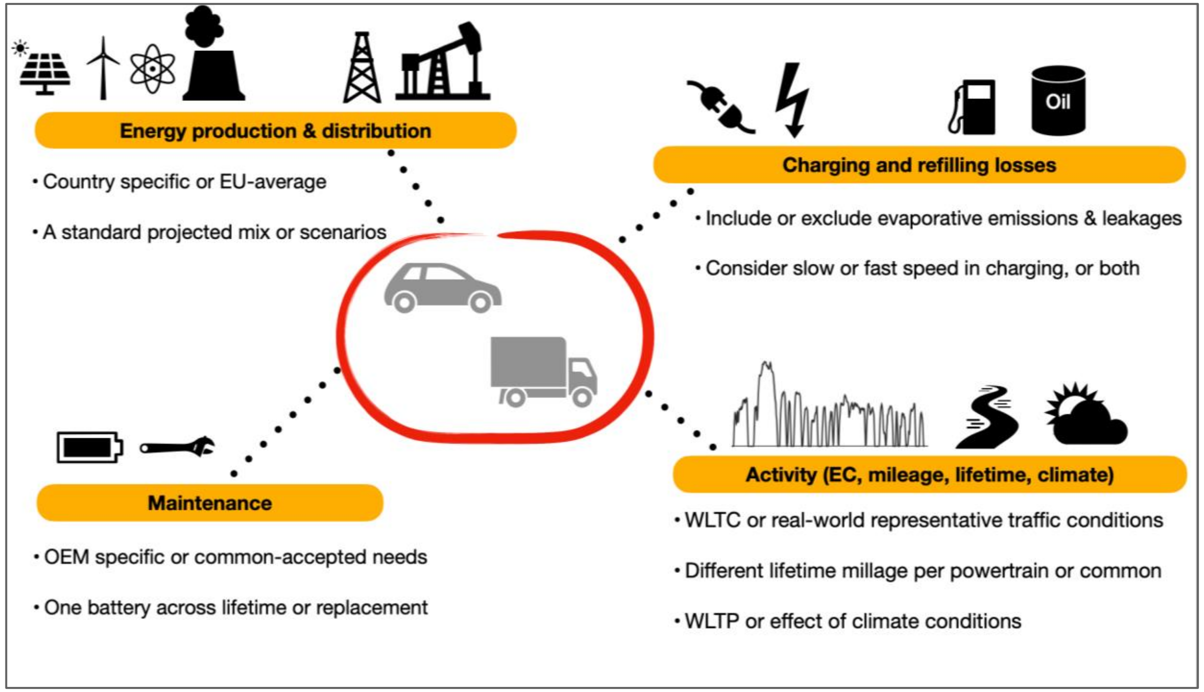
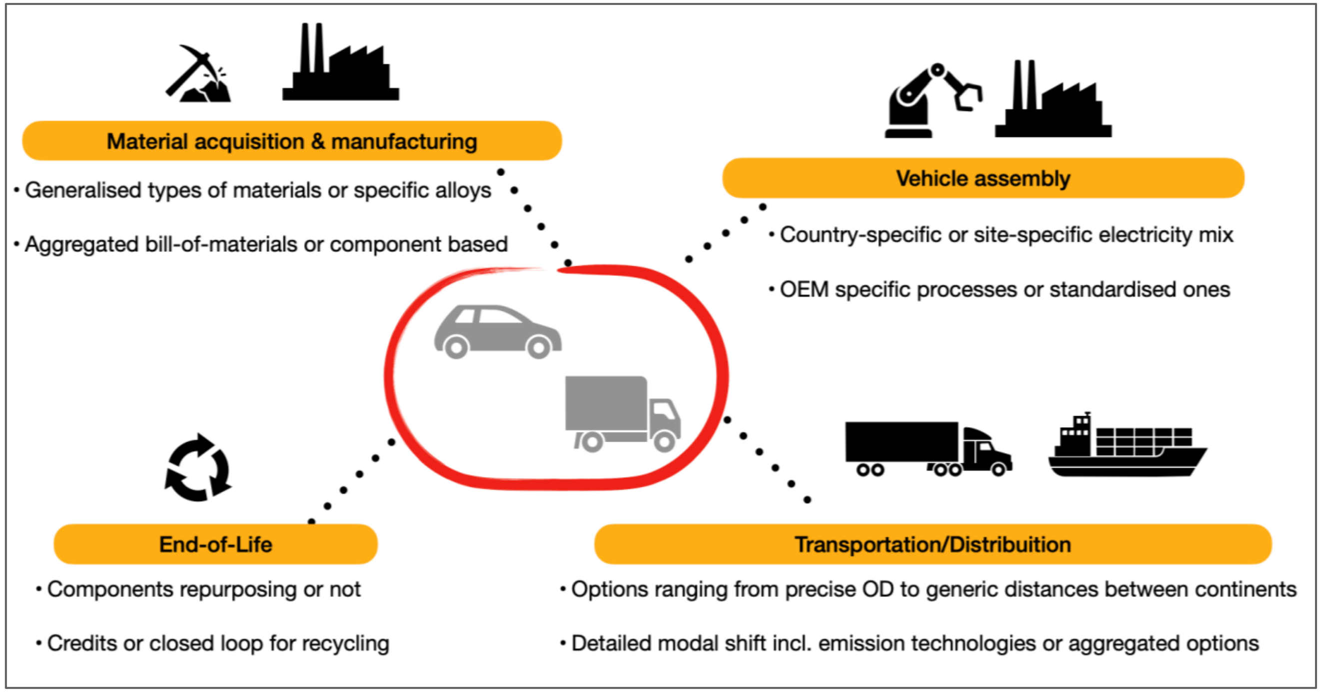
Methodological challenges per life cycle stage

Use stage



Upstream & downstream stages



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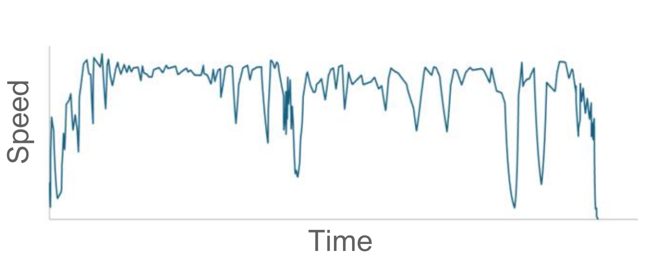
Use phase: Developing TtW factors (beyond regulatory energy consumption-VECTO)

Vehicle types

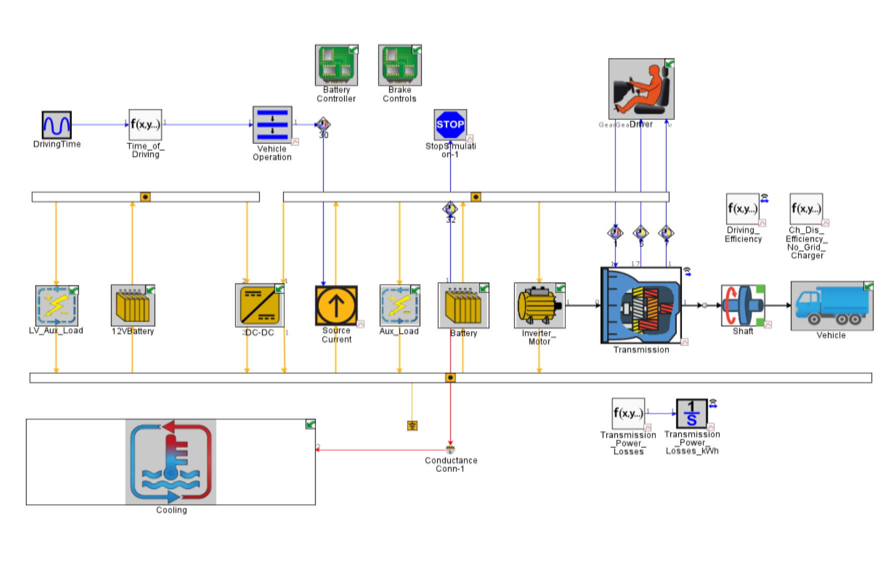
Parameters

Road grade	Variable
Loading	30t (37,7t combined)
Temperature	4ºC, 14ºC

Speed profiles from actual routes



Vehicle simulations (calibration and validation)



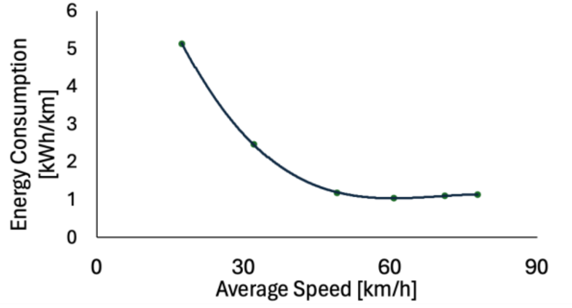
Speed profiles average speed

Istanbul - Sofia	68,8 km/h
Sub-trips split	Speeds in U,R,M

Statistical analysis

Energy consumption regression with average speed

EC macroscopic function for COPERT



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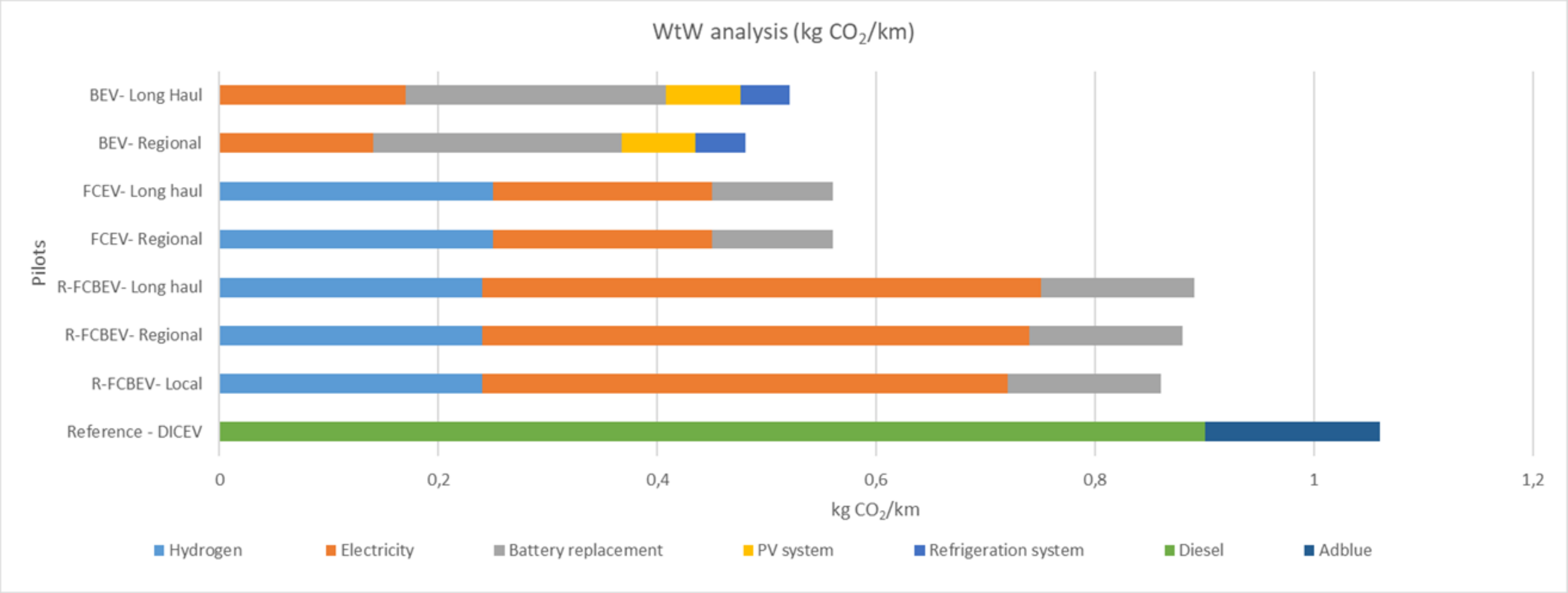
LCA results: Well-to-Wheel analysis

- The BEV and FCEVs demonstrate the lowest emissions among all drivetrains
- The range-extender fuel cell electric vehicles (R-FCBEVs) used for long haul and regional travel use cases have slightly lower overall WtW emissions compared to the reference scenario



Fuel cell range extender electric vehicle (R-FCBEV or r-HDV)
Fuel cell electric vehicle (FCEV or f-HDV)
Battery electric vehicle (BEV or b-HDV)

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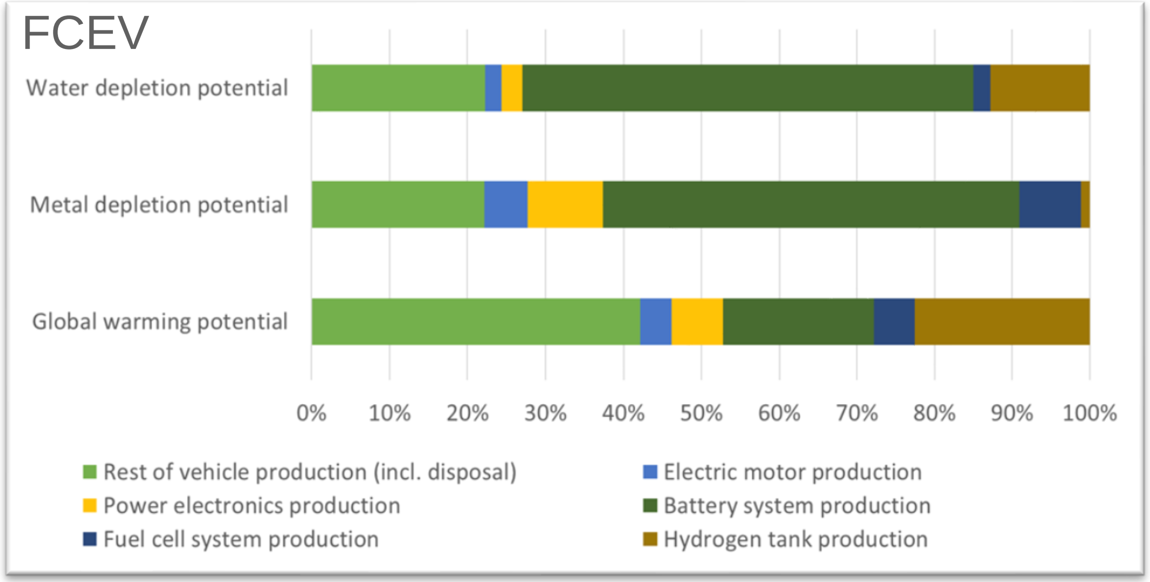
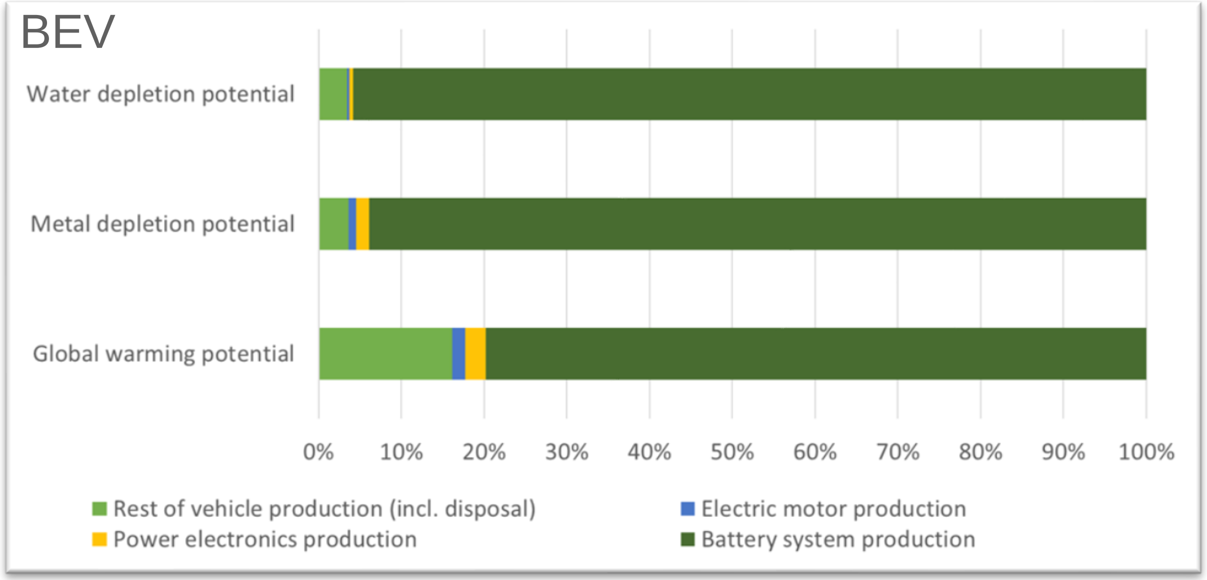
LCA results: Vehicle analysis – Production phase

Preliminary results for reference fuel cell and battery electric vehicle production

- Functional unit: production of 1 vehicle
- The individual components contribute to the impact indicators to varying degrees
- Provides the basis for modelling the pilot vehicles and use cases
- Serves as benchmark for ESCALATE pilots





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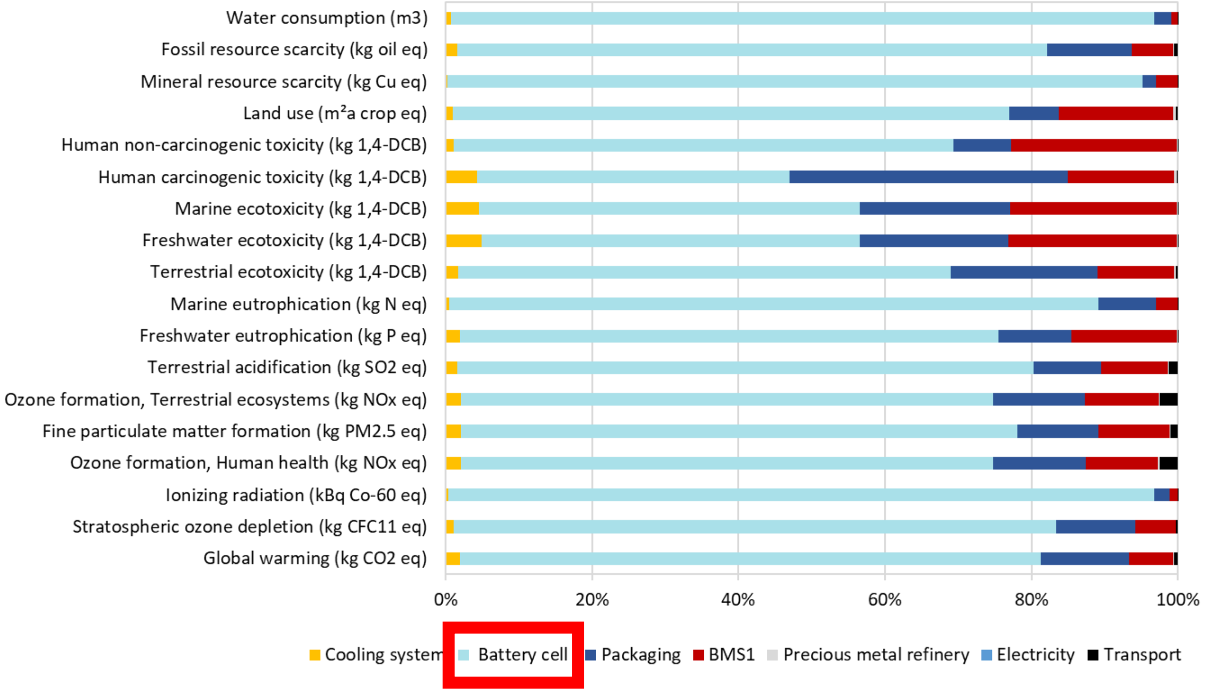
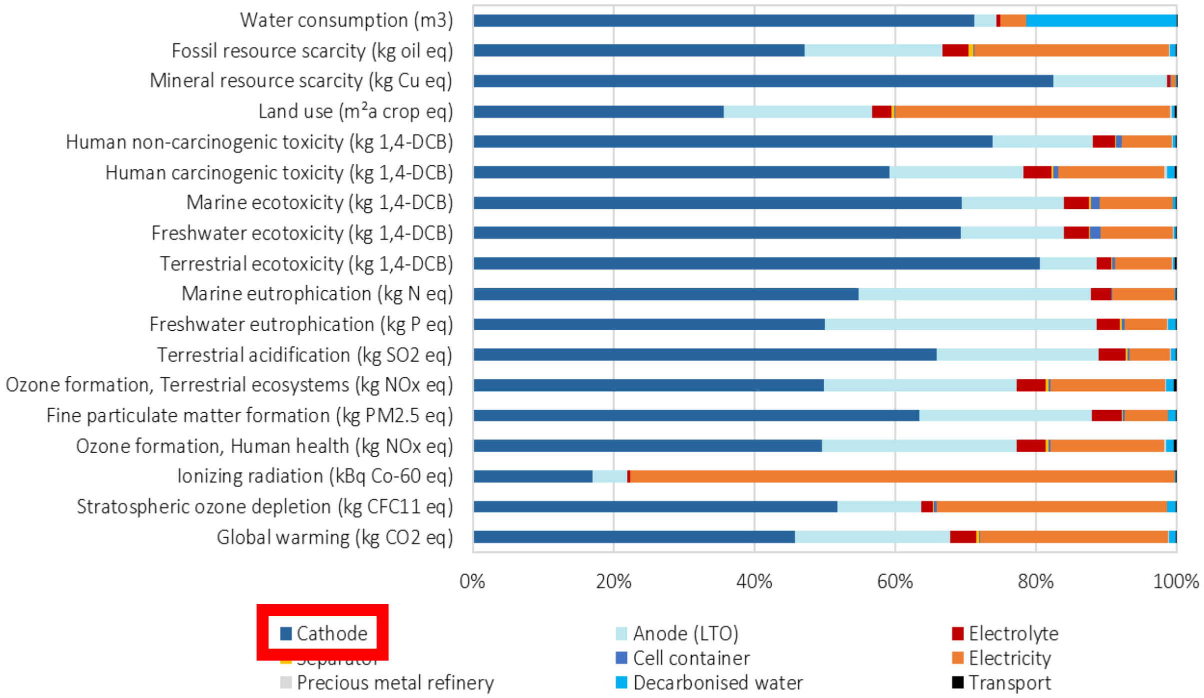
- Modelled with reference vehicle data using Recipe 2016 as LCI impact method
- LCA model realized in Umberto 11, also available in OpenLCA

LCA results: Component analysis – Battery pack/cell level analysis (example for LTO battery)

- At the battery **pack** level, the battery cell is a significant contributing component



- At the battery **cell** level, the cathode is a significant contributing component



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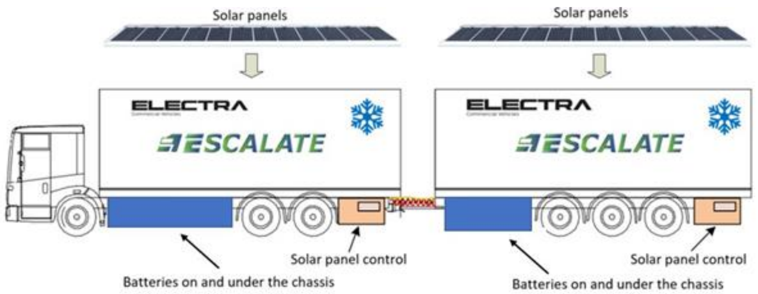
Software: SimaPro 9.6.01, Database: Ecoinvent 3.8.1 , Method: ReCiPe Midpoint (H)

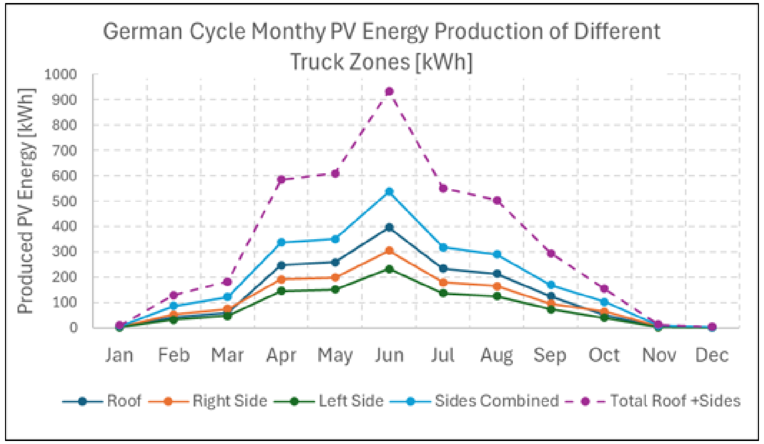
Photo-Voltaic (PV) panels (Pilot 4)

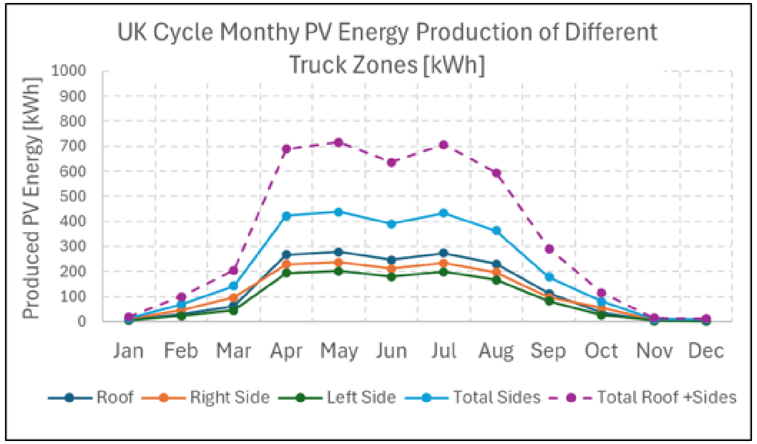


- PV (CIGS) efficiency is 16.4%
- PV placement determined the influence of driving direction and time affect PV output
- Vertical panels (under investigation) capture diffuse light more effectively, therefore, in the presented tilt scenario, the UK's diffuse-light advantage can lead to a higher annual PV output than in Germany (despite Germany generally receiving more total solar radiation)

Driving cycles for UK and Germany

Monthly PV energy production of different truck zones for Germany and the UK





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PV Effects

- Three different controller strategies were compared for the roof-only variant:

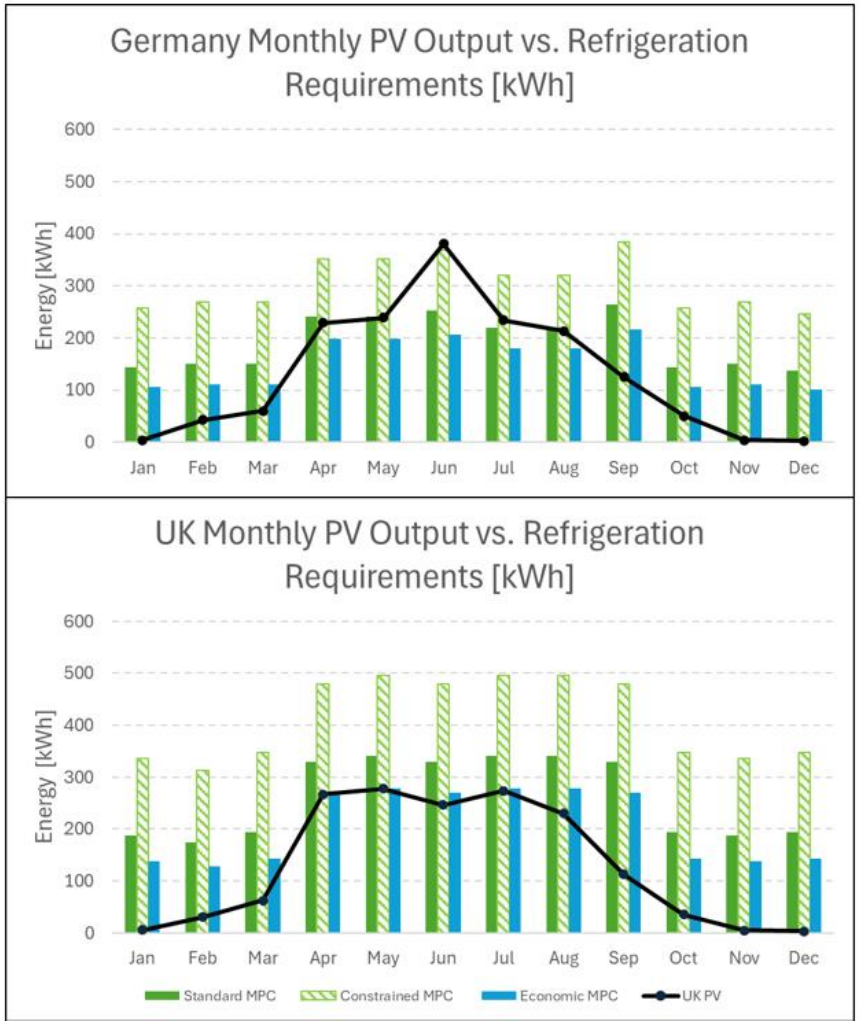
1. Standard controller: gently cools the compartment down prior to door-opening.
2. Constrained controller: for sensitive goods, aggressively cools the compartment down prior to a door-opening.
3. Economic controller: for non-sensitive goods, either turns the refrigeration unit off completely or balances reduction and increase in motor speed.

- The constrained controller achieves the shortest PV coverage period due to its aggressive cooling behavior

- The standard and economic controller perform similarly, but the economic version is more efficient, consuming about 21% less energy

	Germany	UK
Standard Controller	May till August	-
Constrained Controller	Only in June	-
Economic Controller	April till August	April till July

Monthly PV outputs compared to refrigeration requirements [kWh] for Germany and the UK



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Fleet-level LCA

In ESCALATE:

- treats the entire fleet as a unique product/system
- adds the notion of time in accounting LC emissions
- can be in-line with existing emissions monitoring practices for impact assessments / inventories
- can allocate to road-transport emissions attributed previously to other sectors

Challenges:

I. **Integration in existing models/practice**

II. **Representative vehicles & their LC CO2 definition**

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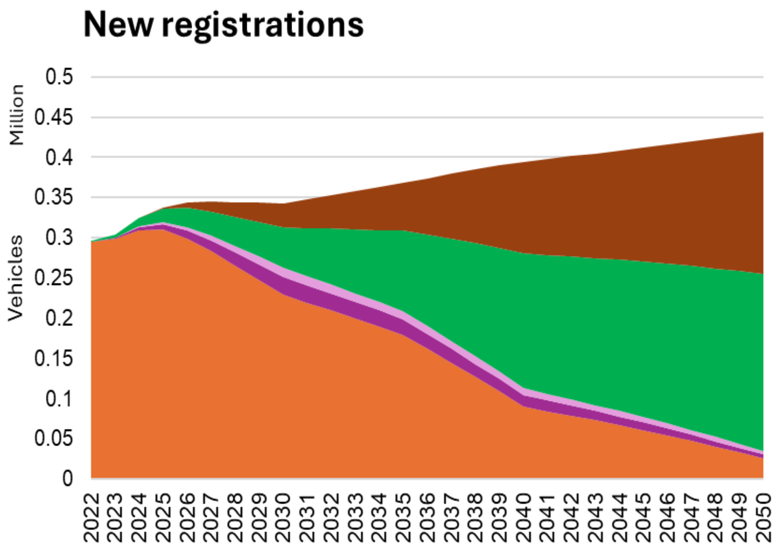
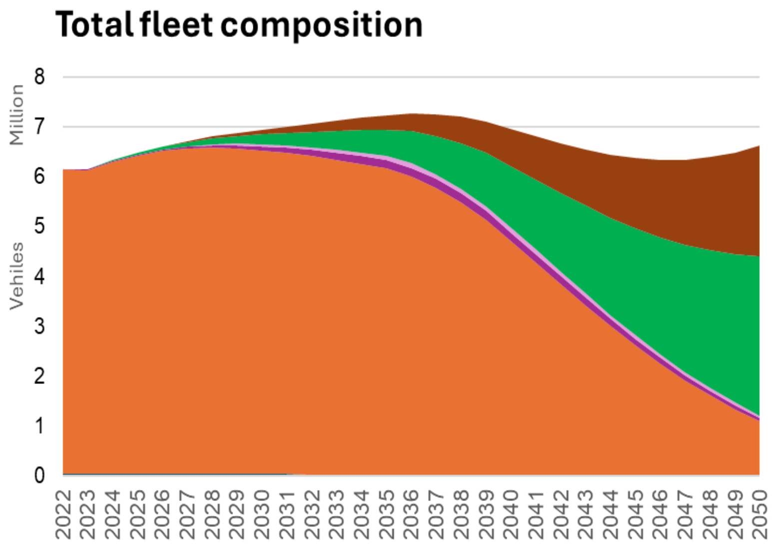
Fleet analysis

- Scenarios are developed to quantify overall emissions from road transport in Europe to depict a realistic transition of the heavy-duty market towards electrified solutions by 2050

- New sales of conventional diesel trucks are gradually reduced starting in 2035 and are largely phased out by 2050, replaced primarily by BEVs and FCEVs





New registrations and fleet composition derived from SIBYL

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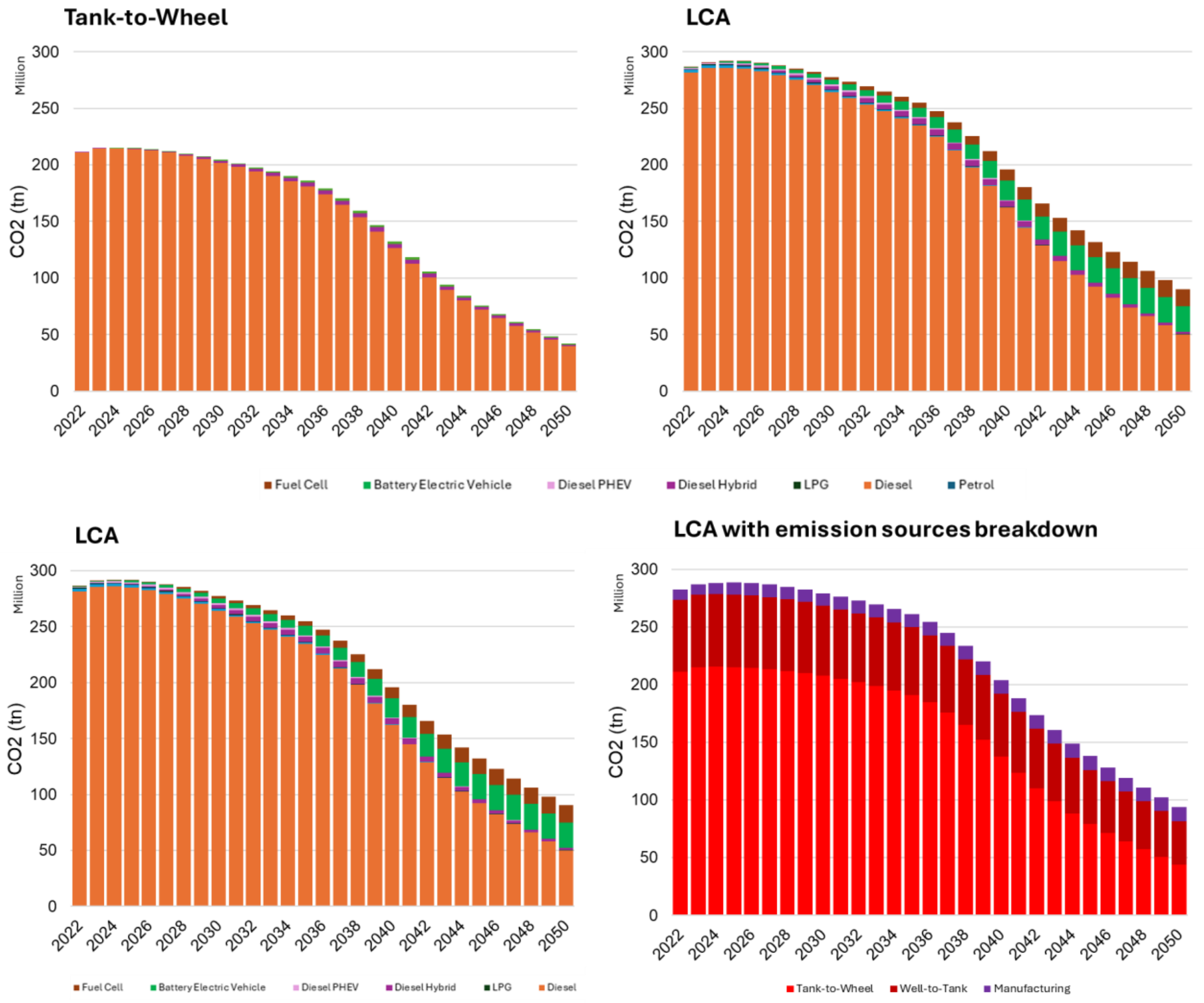
Fleet analysis

- Emissions are reduced through electrification between 2022 and 2050
- TtW emissions are reduced by 79% (2022 vs. 2050), while the cradle-to-grave approach shows a 67% reduction
- The WtT emissions of BEVs do not fully substitute TtW emissions of ICEVs, due to gradual decarbonization of the electricity mix and higher efficiency of electrified powertrains
- Manufacturing emissions from BEVs are high the early year, later improvements in battery production footprints offset the continued rise in demand

TtW and LCA CO_2 emissions for the fleet



LCA emissions with emission sources breakdown

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Total Cost of Ownership (TCO)

- Financial estimates that account for the direct and indirect costs associated with a product or system throughout its entire lifecycle
- Key Components:
  - Capital expenditure (CAPEX): Purchase, installation, or acquisition cost
  - Operational expenditure (OPEX): Energy, maintenance, repair, consumables
- Necessary inputs:
  - Vehicle operational KPIs
    - Energy use for various operational scenarios
    - Component lifetime prediction

Based on technical specifications and simulation activities

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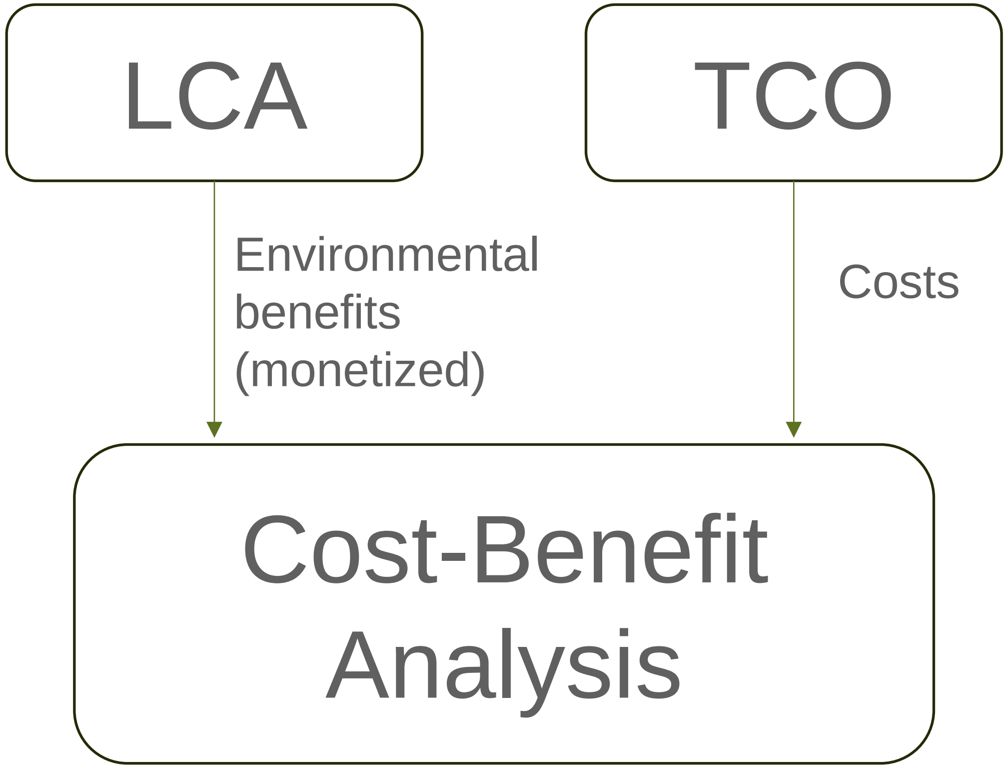
Cost-Benefit Analysis (CBA)

- For the introduced new technologies (e.g., BEVs in the HDV fleet):
  - The **monetized environmental benefit (in €)** is calculated by multiplying the emission savings (**derived from LCA**) with the external damage costs per tonne of pollutant and climate-forcer for each of the examined species
  - The **incremental costs (derived from TCO)** include hardware, R&D, infrastructure, operational costs, etc.
- CBA covers the whole life-cycle impacts of the new technologies, including production, operation and end-of-life processes



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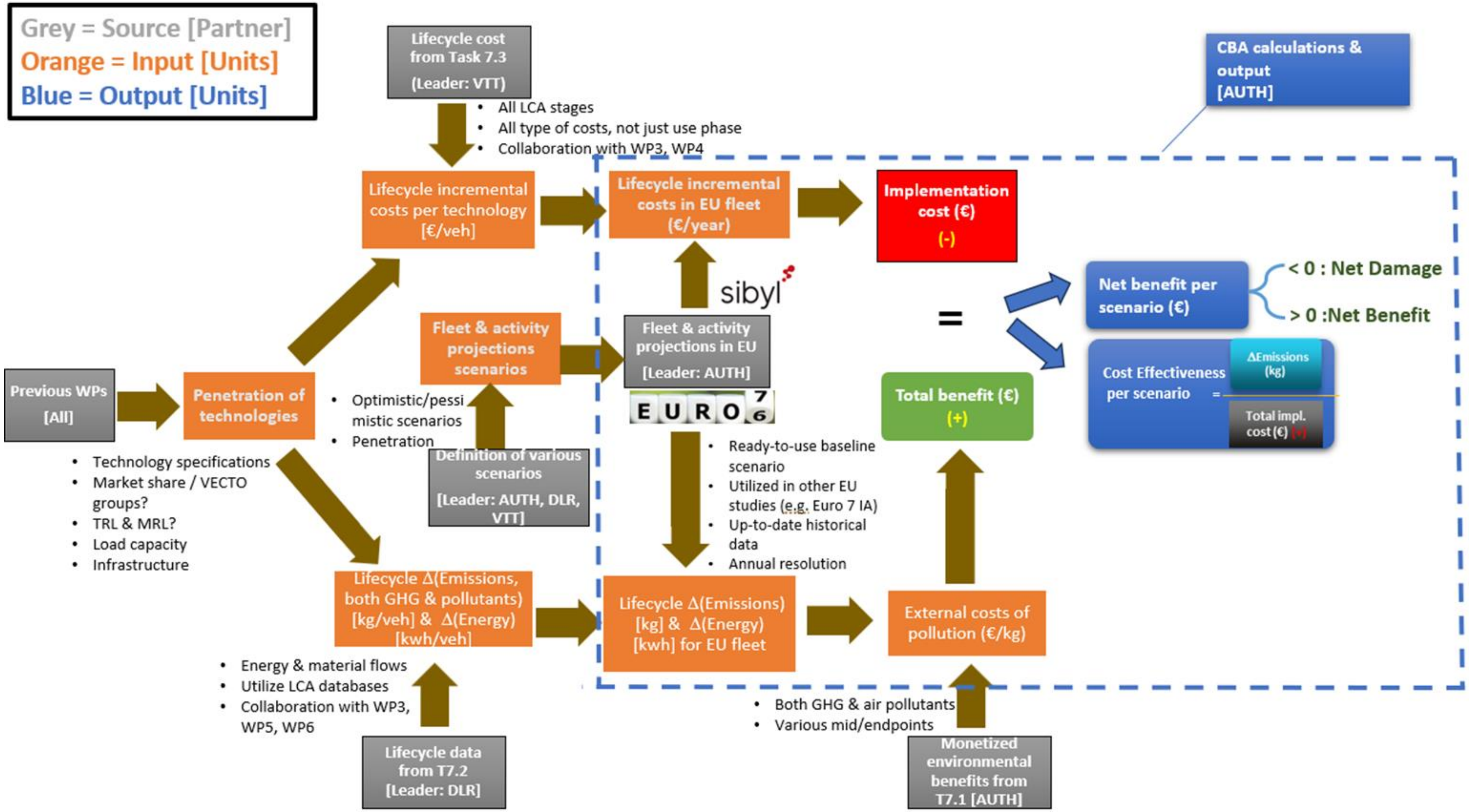
CBA in ESCALATE



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Social LCA

Objectives:

- Address the **potential social impacts** of the transition to zEVs (covering the entire life cycle of the vehicles)
- Impacts are user group specific (e.g. fair salary, child labour, living conditions, contribution to economic development, corruption)
- Necessary inputs: bill-of-materials, countries of origin, costs (supp. by literature)

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Standardized LCA framework for vehicle homologation

- Proposal for an LCA approach tailored for homologation purposes, supporting a holistic environmental evaluation of the project’s solutions
- Scope and alignment: ensure a comprehensive and well-calibrated LCA proposal, using data from pilot demonstrators and critical components
- Outputs and validation:
  - A thoroughly worked proposal, calibrated and validated against project pilot data
  - Integration of feedback from workshops and alignment with international and European initiatives for transport-specific LCA

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Conclusions

- Fleet-based & Predictive LCA: Shifted from single-vehicle models to fleet-level analysis and 2050 scenario forecasting, enabling system-wide climate impact assessment

- Integrated tools: Combined LCA, TCO, and CBA on a shared platform; linking environmental and economic performance

- Based on real-data: Developed a harmonized LCA framework using real pilot data, digital twins, and standardized tools for z-HDV assessment.

- Policy alignment: Contributes to EU-wide LCA standardization and readiness for future vehicle homologation requirements.

- Social aspects: Building a bridge between environmental and social improvements (and lifecycle cost savings) is challenging, but important

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Thank you for your attention!

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