Ricardo Energy & Environment

INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG HEIDELBERG

E4tech

Determining the environmental impacts of conventional and alternatively fuelled vehicles through Life Cycle Assessment

Nikolas Hill

Final Stakeholder Meeting,
Albert Borchette Center, Brussels, Belgium

16 January 2020

Ricardo is a Global Engineering & Environmental Consultancy with over 3000 employees: engineers, scientists and consultants in all major regions

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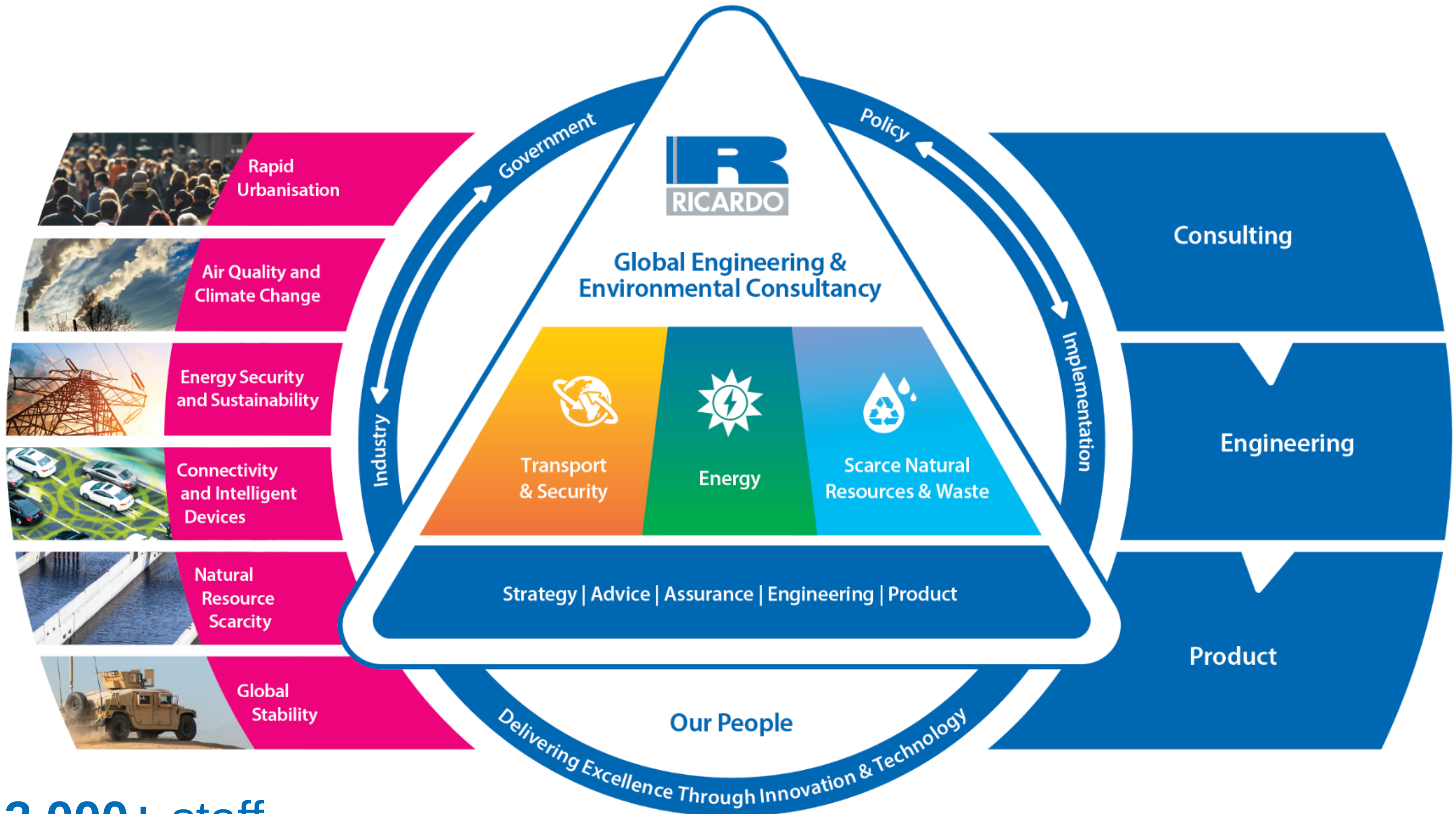
Sectors

- Automotive
- Commercial Vehicles
- Defence
- Energy & Environment
- Motorsport
- Motorcycle
- Off-Highway Vehicles
- Rail



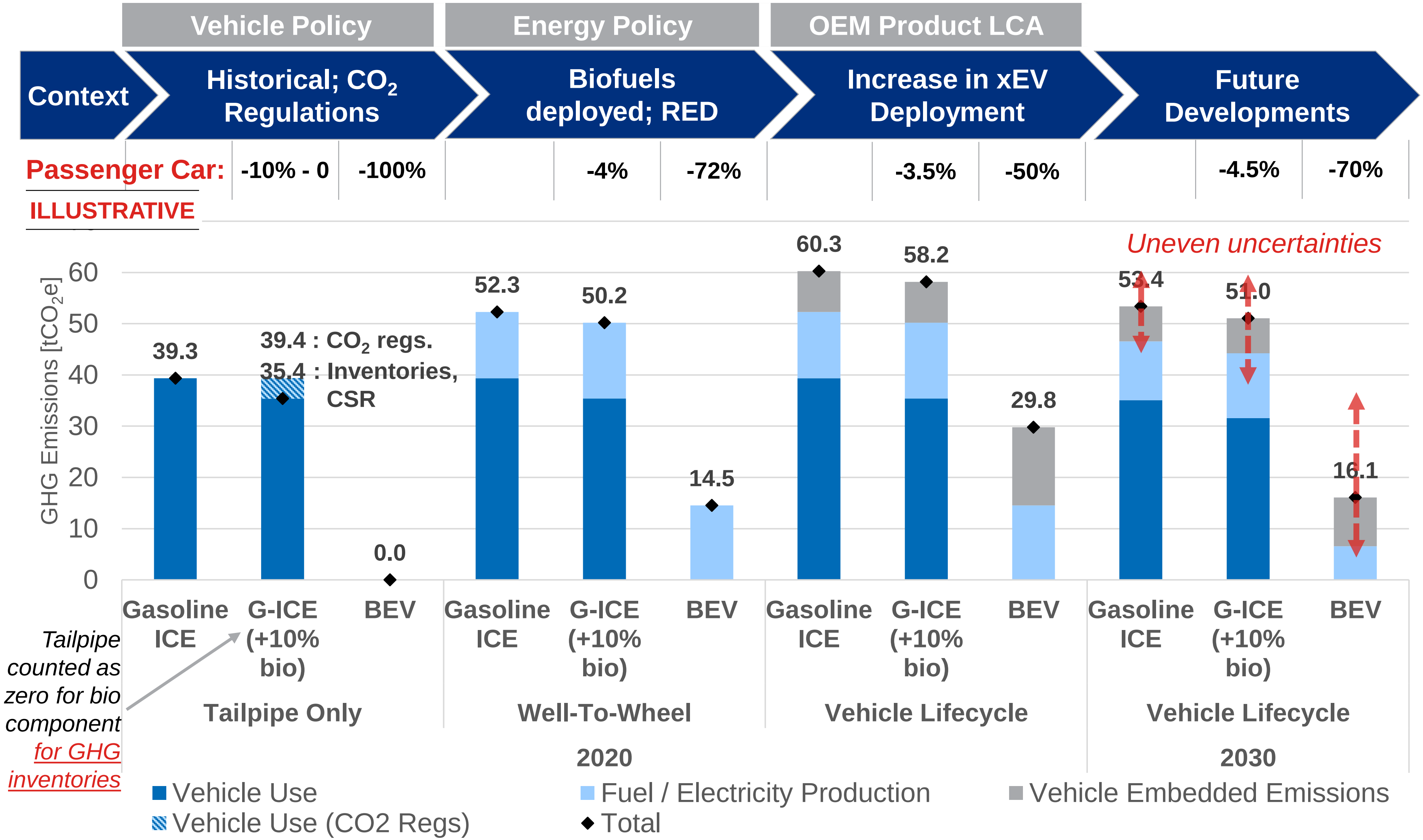
3,000+ staff
73 nationalities
48 sites in **20** countries

The objective throughout our over 100-year history has been to maximise efficiency and eliminate waste in everything we do

Agenda

	• **Introduction, background and objectives of the meeting [09:00]**
	• Overview of the developed methodology [ifeu, 09:30]
Coffee, 10:45	
	• Overall LCA results [Ricardo, 11:00] – Results and comparisons for lower medium cars – Results for other vehicle types
Lunch, 12:30	
	• Results for energy chains [ifeu / E4tech, 13:30]: – Electricity chains [ifeu] – Liquid and gaseous fuel chains [E4tech]
Coffee, 15:00	
	• Overall LCA sensitivities [Ricardo, 15:00]
	• Other assumptions and general Q&A [Ricardo, 16:15]
	• Initial conclusions & recommendations and wrap-up [Ricardo, 17:00]
Close, 17:30	

Why are we interested? Combination of changes in the regulatory environment, as well as the uptake of new fuels and powertrains



Source: Ricardo Vehicle LCA analysis (2020) for average EU lower-medium passenger car: Assumes lifetime 225,000 km, real-world fuel consumption. GHG from fuel/electricity consumption is based on the average fuel/grid electricity factor over the life of the vehicle (Baseline scenario); Calculated 147 kgCO2e/kWh battery in 2020, 85.5 kgCO2e/kWh in 2030. Includes EoL recycling credits.

The overall project aim was to develop and apply LCA methodology across a range of road vehicle types, powertrains and energy chains

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Start: June '18 *Current progress* **End: Feb '20**

Task 1 Literature review and data collection

- Desk review
- Data collection

Task 2 Methodological Development

- Methodological scoping
- Main methodological development
- Spatial considerations
- Temporal considerations

Task 4 Application of the LCA

- Framework design
- Application of methodologies
- Model QA/QC
- Review results

Task 5 General conclusions and reporting

- Analysis of outputs and development of conclusions
- Preparation of reports
- Presentation to stakeholders

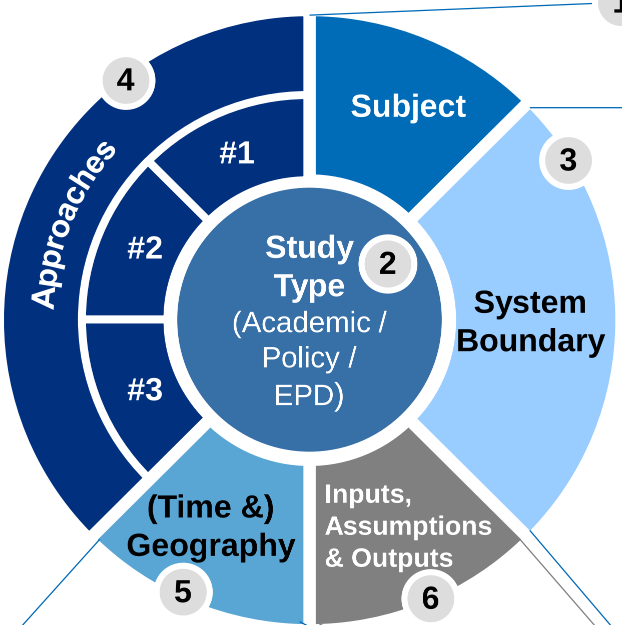
Task 3 Stakeholder consultation

- Targeted interviews and data gap-filling; Delphi survey on the methodology; Data validation
- Meetings and workshops: (1) Methodology (25/02/19), **(2) Draft findings and conclusions**
- Peer review

- The majority of work is now completed, with the methodology (developed in consultation with experts) implemented and draft results being assessed:
  - **Workshop 2 (16/01/20):** Presentation and discussion of draft findings
  - **Draft report (pending)***:* Summary of the project work including refined and finalised methodology, summary and discussion of the results from application, etc.

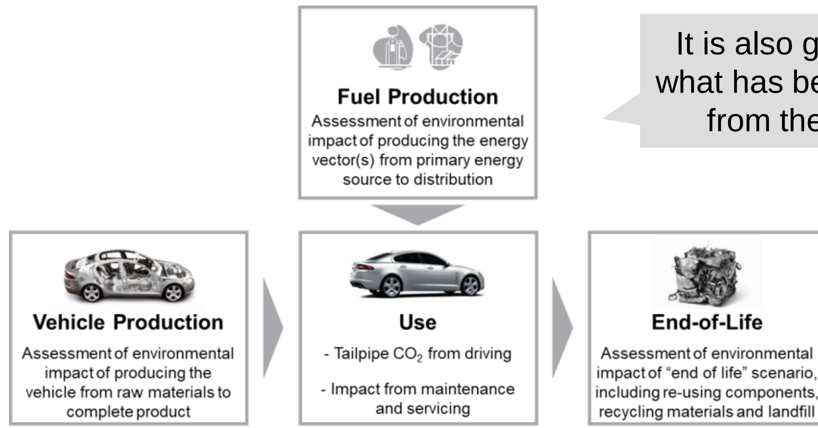
How are LCA studies used by the automotive industry and others? Studies are formulated based on a complex range of criteria, data…

Overview key LCA considerations



1 Study Subject & Functional Unit – E.g. specific vehicle, or generic example? total impacts, or impact per vkm or tkm?

System Boundary



It is also good to note what has been excluded from the analysis

(Time &) Geography	Input Data	Key Assumptions	LCI Datasets	Environmental Impact Factors
 2020 → 2030 → 2050	Primary vs. Secondary	Lifetime Mileage [km] Low Carbon Fuel use and Electricity GHG intensity [$kgCO_2e/kWh$] Battery embedded GHG factor [$kgCO_2e/kWh$ or $kg\ CO_2e/kg$]	E.g. EcoInvent *(also many choices within these…)*	E.g. Global Warming Potential (GWP) [tCO2e], Cumulative Energy Demand (CED), Human Toxicity, etc.

The vehicle LCA study will consider environmental impacts over the whole life of the vehicle

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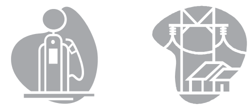
Vehicle Life Cycle

Well-to-Wheel (WTW) Analysis - Life Cycle Assessment of the fuel or electricity used to power the vehicle

Vehicle cycle "Embedded" emissions result from from vehicle production; fluid, filter and component replacement during life; and end-of-life activities. A **"cradle-to-gate"** LCA study may only consider vehicle or component production



Fuel & Electricity Production

Assessment of (WTT) environmental impact of producing the energy vector(s) from primary energy source to point of distribution (e.g. refuelling station)

Study Boundary:

Analysis of the **whole vehicle life lifecycle** including embedded emissions from vehicle production, maintenance and servicing, and end-of-life activities, and WTW (WTT+TTW) emissions from production and use of the fuel / energy in operating the vehicle, and non-fuel emissions

Vehicle Production

Assessment of **'Cradle-to-Gate'** environmental impact of producing the vehicle including extract of raw materials, processing, component manufacture, logistics, vehicle assembly and painting

Use/Operation

- Environmental impact of driving (TTW emissions)
- Impact from maintenance and servicing

End-of-Life

Adds assessment of environmental impact of "end of life" scenario (i.e. -to-Grave). Can include: **re-using** or **re-purposing** components, **recycling** materials, energy recovery, and disposal to landfill

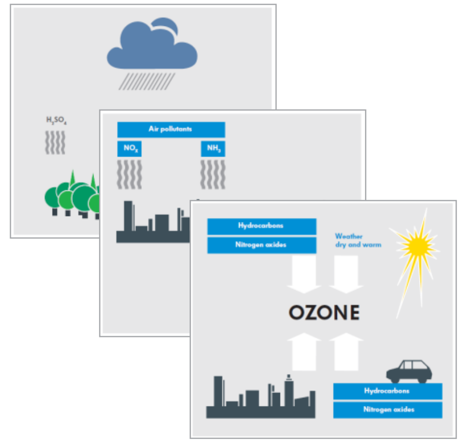
Mobility System Life Cycle … adds **Transport Infrastructure** *Not Included in this study's scope*

It isn't all about Greenhouse Gases – other impacts and factors also influence the overall comparisons of impacts…for example:

Primary Energy

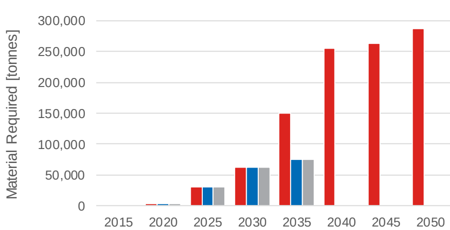
- How much / what types of source?
- What is the most efficient use of renewables?
  - BEV = 1x
  - FCEV = ~3x
  - eFuel = ~5x

Air Quality Pollutants



- Emissions impacts vary by:
  - Powertrain
  - Lifecycle stage
  - Location
- Can influence conclusions

Resources



- Availability of key materials for batteries, motors
- Biomass supply for bioenergy *and* other uses
- Water consumption

Other Impacts

- Ozone Depletion
- Ionizing Radiation
- Human- and Eco-Toxicity
- Etc.

What kind of LCA are we considering? It is important to realise that LCA is carried out for different purposes – affecting methods/data

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Academic	• **Intended audience:** wider academic and research community • **Primary interest:** the creation of knowledge • Results **may be published** in technical journals • Subject may be **real or hypothetical/generic**
Policy	• **Intended audience** is policy makers and academics • **Purpose** is to aid understanding of potential implications for policy development • **Impact** of product/service **within wider social system** • Subject may be **real or hypothetical/generic**
Environmental Reporting	• **Intended audience** is customers and general public • **Purpose** is the quantification of impacts of manufacturer's **specific products** • **Certified** to conform to LCA standards, e.g. ISO, PEF • Results usually in Environmental Product Declarations (EPDs) or Corporate Responsibility Reports

We have identified over 300 relevant documents which were screened during the literature review process

Literature Review Dashboard

347 papers & reports identified

228 are LCA studies

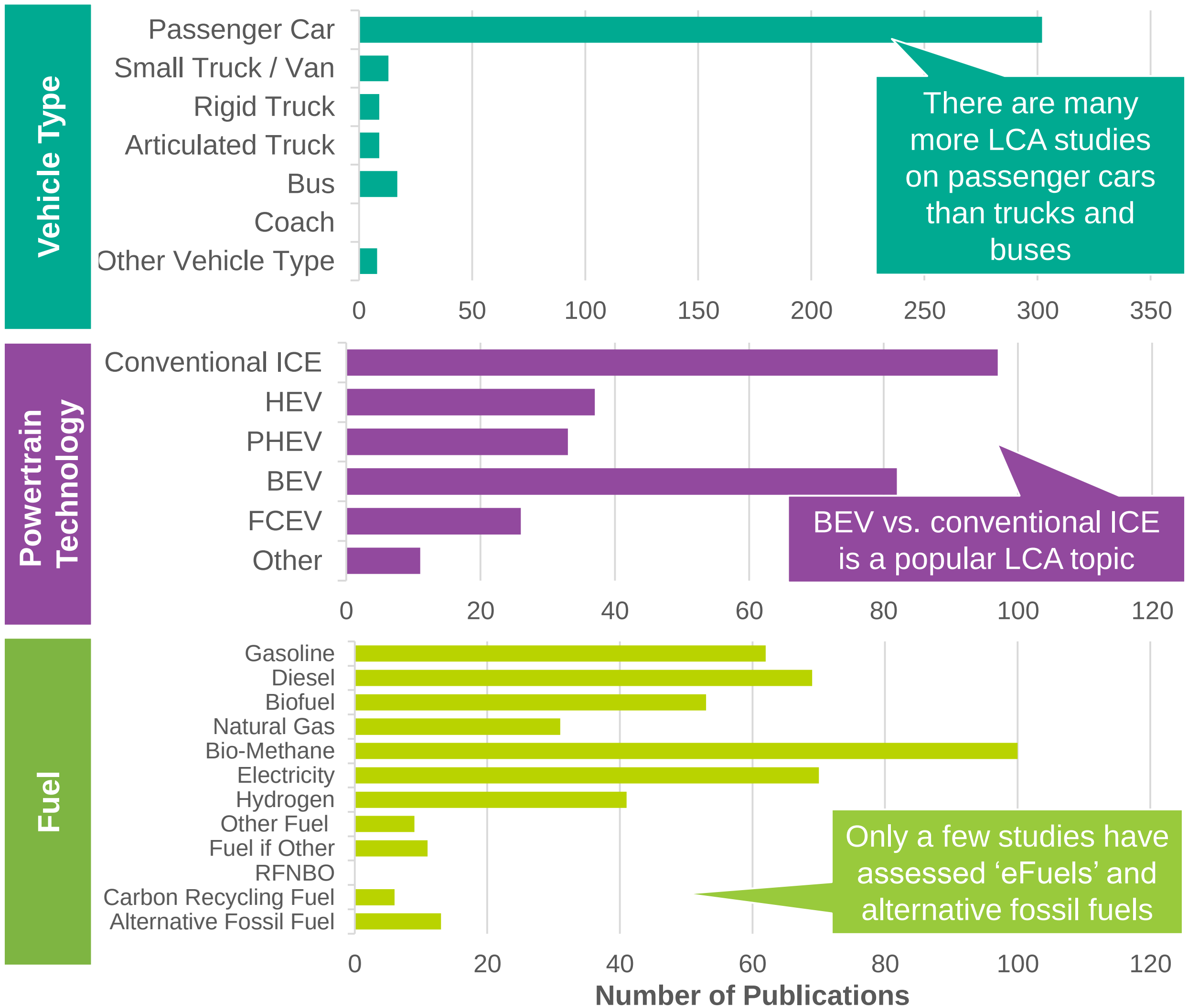
84 Have very detailed datasets

Geography

Some papers considered >1 geographical region

The LCA literature database is non-exhaustive and does not contain a complete list of all automotive LCA studies

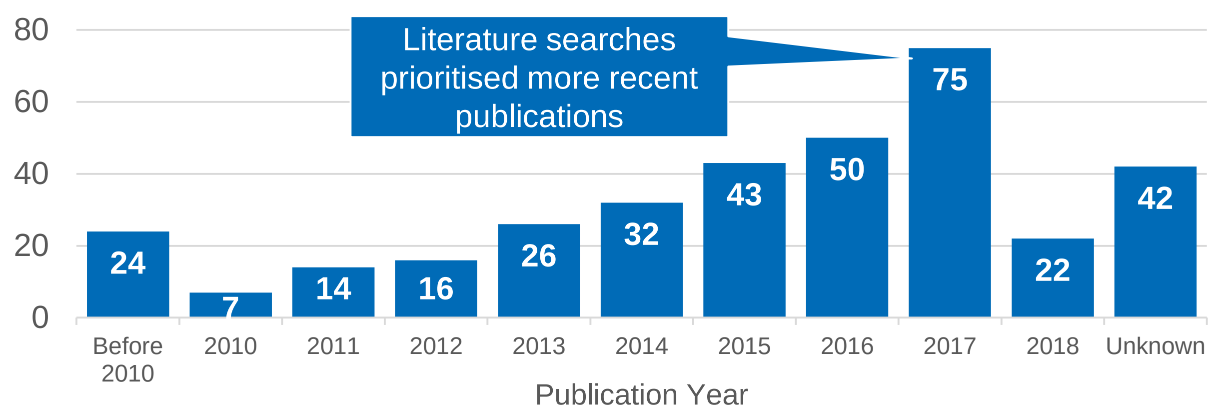
Interest by Topic Area



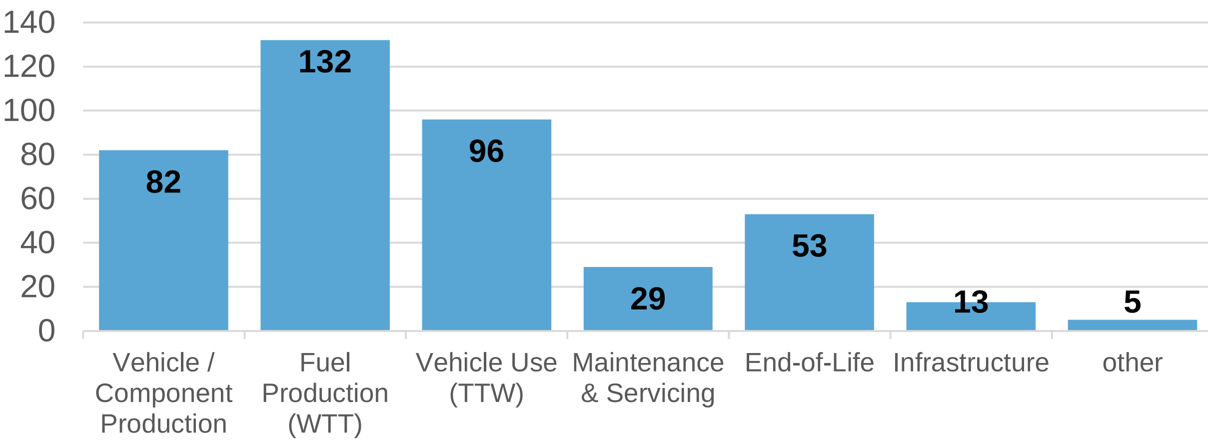
The collected literature covers all vehicle life cycle stages and relevant impacts, with a focus on more recent publications

Literature Review Dashboard

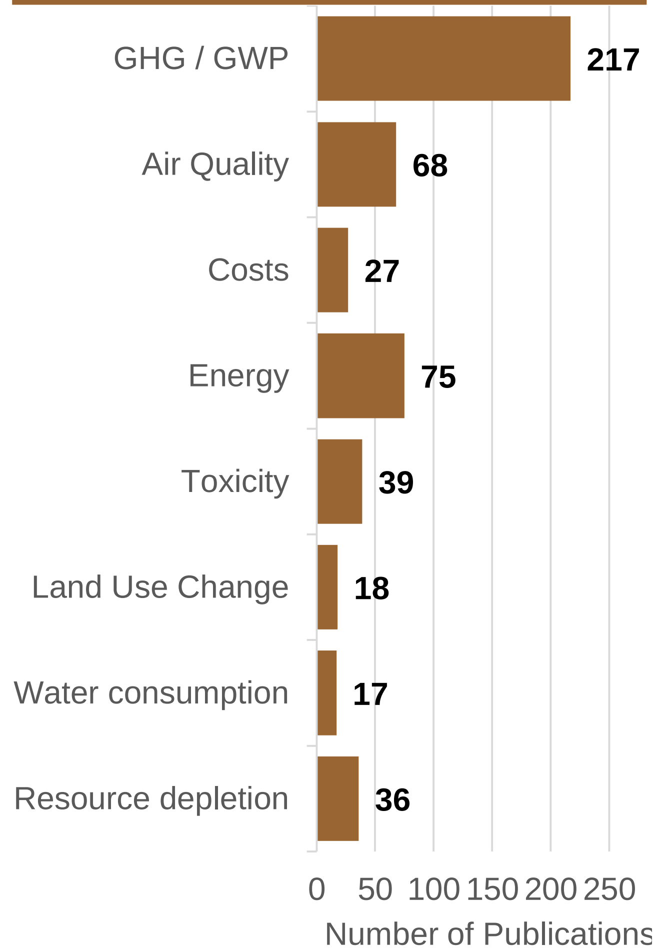
Number of studies by publication year



Interest by Life Cycle Stage



Interest by Life Cycle Impacts



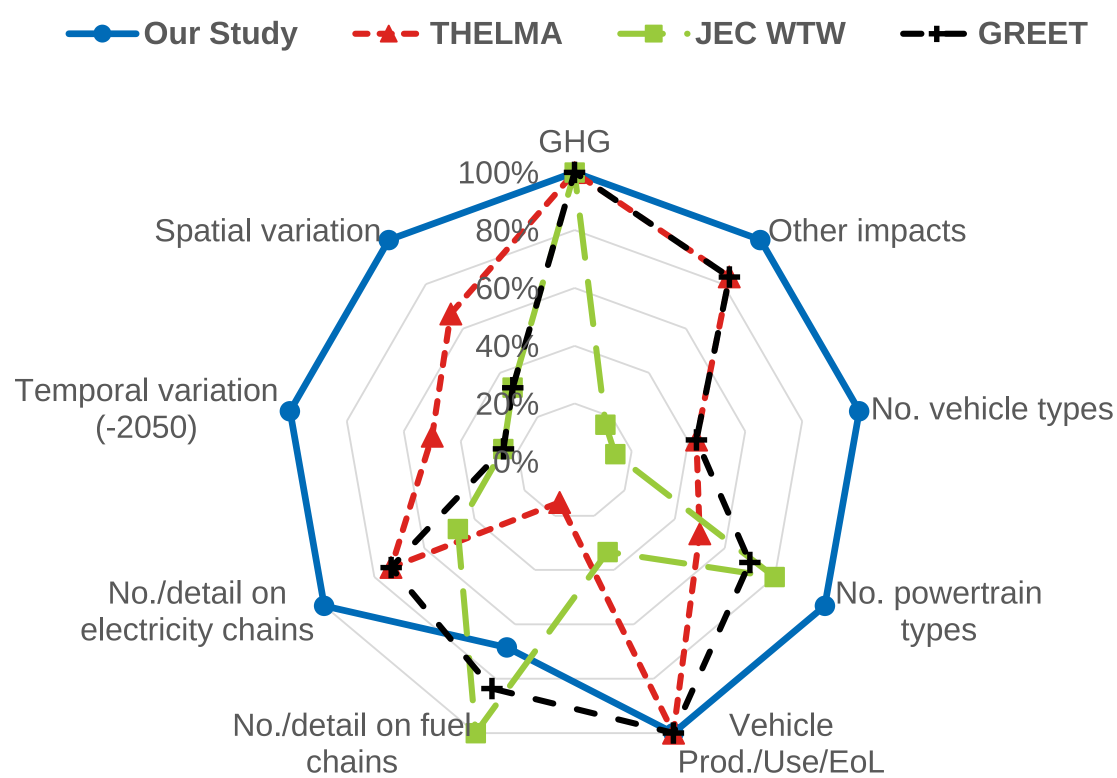
The project is covering a range of vehicle types, powertrains and energy carriers, and utilising a modular approach to define /characterise generic vehicles and to estimate changes 2020-2050

Body type:	Passenger car	Van	Rigid lorry	Articulated lorry	Urban bus	Coach
Segment/Class:	1. Lower Medium; 2. Large SUV *	N1 Class III (3.5 t GVW)	12 t GVW, Box Body	40 t GVW, Box Trailer	Full Size (12m) Single Deck	Typical Single-Deck, 24 t GVW
Gasoline ICEV	Y	Y				
Diesel ICEV	Y	Y	Y	Y	Y	Y
CNG ICEV	Y	Y	Y	Y	Y	Y
LPG ICEV	Y	Y				
LNG ICEV			Y	Y	Y	Y
Gasoline HEV	Y	Y				
Diesel HEV	Y	Y	Y	Y	Y	Y
Gasoline PHEV/REEV	Y	Y				
Diesel PHEV/REEV	Y	Y	Y	Y	Y	Y
BEV	Y	Y	Y	Y	Y	Y
FCEV	Y	Y	Y	Y	Y	Y
FC-REEV			Y	Y		Y
Diesel HEV-ERS				Y		
BEV-ERS				Y		

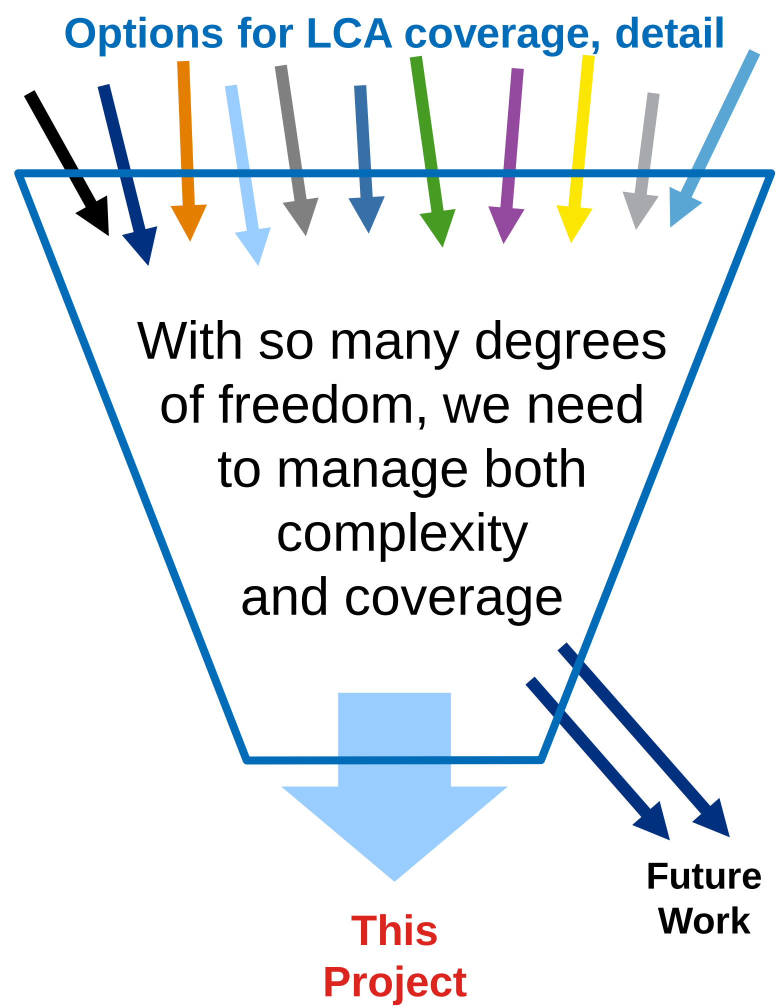
Note: * Based on EU registrations-weighted averages for: Lower Medium = defined as segment C vehicles (e.g. VW Golf) and medium SUVs (e.g. Nissan Qashqi); Large SUV = Large SUVs / Crossovers (e.g. BMW X5, Land Rover Range Rover, Volkswagen Touareg, Volvo XC90, etc.).

This study's broad scope has rarely been attempted before – we need to streamline our approach

Scope of our study vis-à-vis reference studies

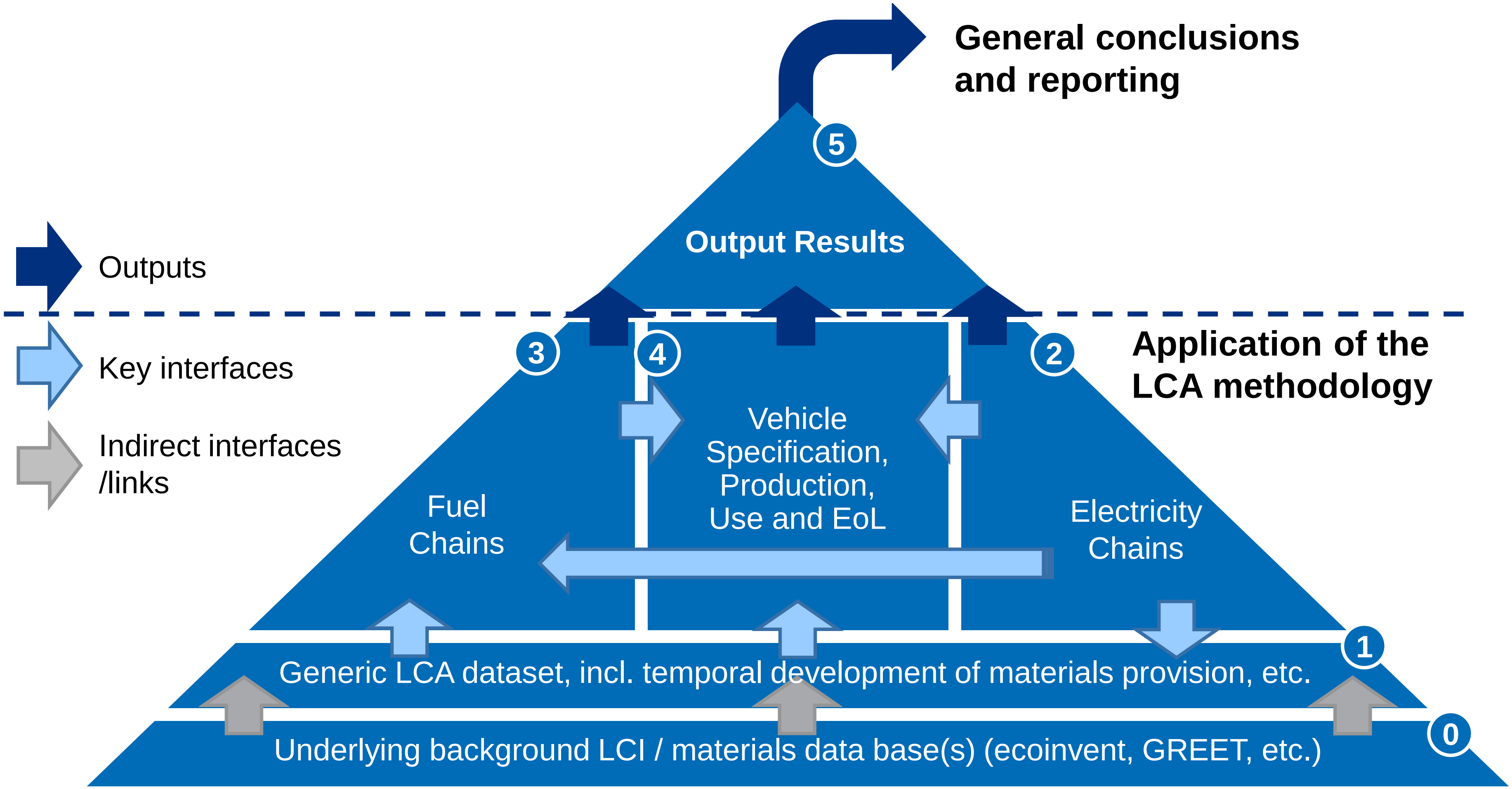


Level of coverage and detail



Source: xxx

The developed methodology was applied to generate results and conclusions for the project, and recommendations for future work



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Considerations for the meeting presentations

- The study has provided a huge set of output data: we can only provide some examples / highlights in today's meeting
  - More information will be in the final report, but even this will only sample the full data
- We will provide an overview of some key findings, subject to a number of caveats:
  - Results from LCA provide useful indications subject to definition of boundary conditions, data and process uncertainties, and pursued finality:
    - Many variables, uncertainties in key datasets
    - Alternative choices on scope, boundaries, other methodological aspects
    - → All results presented should be viewed as indicative due to uncertainty
  - Data gaps / uncertainties vary by area: results in some areas or subsets are more robust than others → further future work needed in key areas
  - Methodological choices, particularly for fuel chains, significantly impact results compared to existing LCA analyses
- The modelling calculation development is finalised; whilst results are in draft, subsequent revisions are unlikely to change them significantly
- Study outputs do <u>**NOT** represent updated methodologies nor new default values intended for regulation</u>

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E4tech Strategy | Energy | Sustainability

Determining the environmental impacts of conventional and alternatively fuelled vehicles through Life Cycle Assessment

Overview of the methodological choices

Albert Borchette Center, Brussels, Belgium – 16 January 2020

Hinrich Helms

Key criteria for methodological choices

- Compliance with goal and scope
- Practical feasibility for application
- Relevance of overall impact
- Appropriateness for the object of investigation
- Suitability for spatial and temporal differentiation
- Transparency

Methodology aims for high consistency over all stages

Methodology development

Choices are based on ...

- Extensive literature review
- Initial methodological proposal
- Two rounds of stakeholder Delphi survey
- Stakeholder workshop in Brussels on February 25th, 2019
- Finalisation of methodological proposals in an Interim report

All choices are supported by a majority of stakeholders

High level methodological considerations

1. Goal and Scope
2. Functional unit and system boundaries
3. LCA approach and multi functionality
4. End-of-Life approach for vehicles
5. Impact categories
6. Specific considerations for different lifecycle stages
   - Vehicle specification and production
   - Fuel chains and electricity generation

Goal of this study

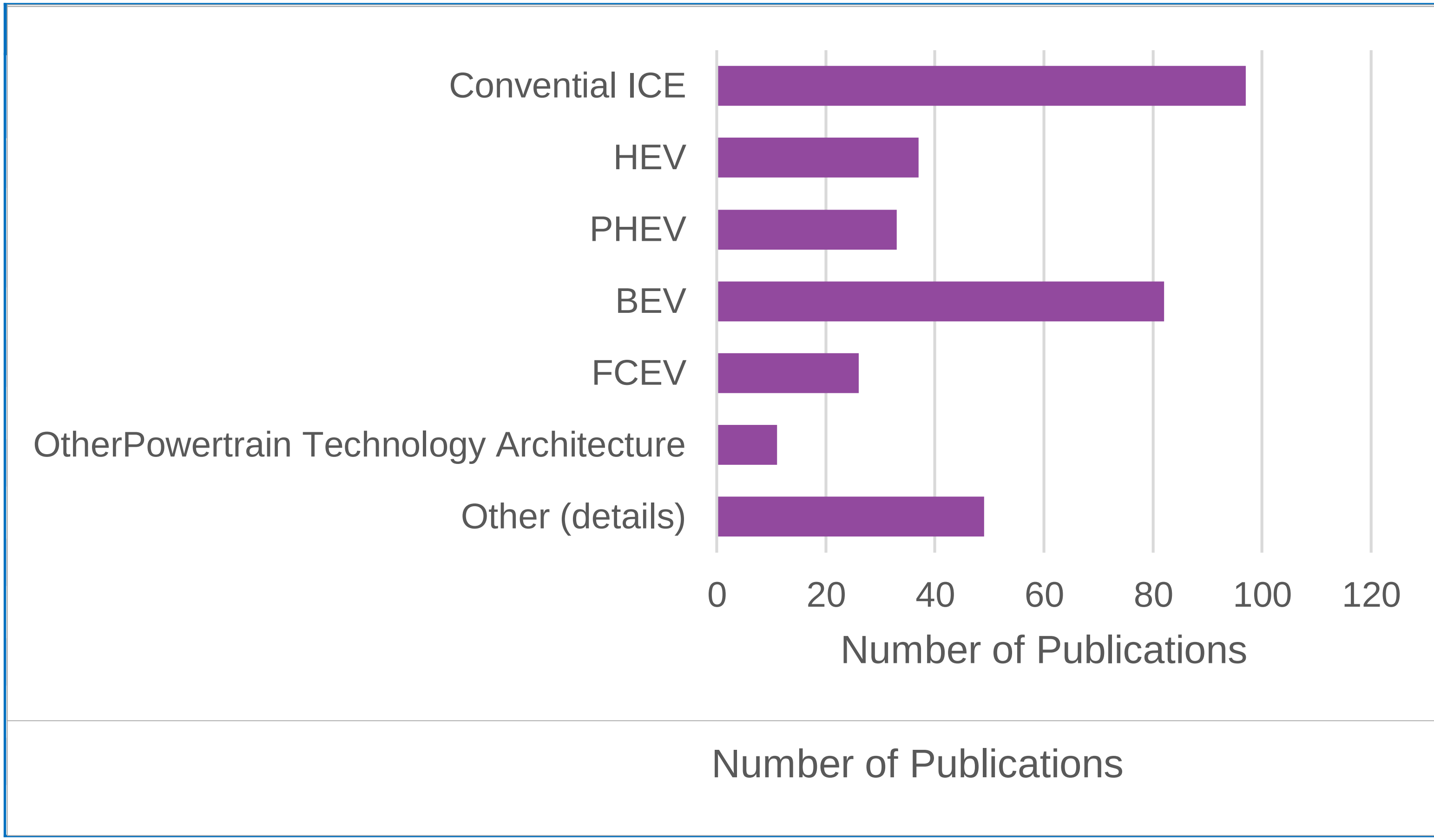
The aim of this study is

- to develop and apply a life-cycle assessment (LCA) methodology to explore different environmental impacts across a range of road vehicle types, powertrains and energy chains
- to enhance the Commission's understanding of such impacts and methodologies and
- to assess the further development for the mid- to long-term time frame (2020 to 2050).

The intended audience is foremost the European Commission and associated policymakers, but the results of the study will also be of interest to other stakeholders

Scope of this study – Vehicle product systems

50 vehicle/power train combinations have been analysed:



Coach
Typical Single-Deck, 24 t GVW
Y
Y
Y
Y
Y
Y
Y
Y

Scope of this study – Geographical / Temporal

Geographical Scope is EU28 (electricity splits for all EU countries)

Temporal scope today (2020) as well as 2030, 2040 and 2050:

- Changes in vehicle energy demand which are mainly due to an increased efficiency
- Changes in the European electricity mixes (reflecting decarbonisation)
- Changes in the fossil and renewable fuel supply
  (new fuels or new fuel production processes)
- Changes in vehicle manufacturing (different materialisation of the vehicles, different vehicle weight, improved production processes and higher recycling rates)
- Changes in the impacts from material production or recycling due to improved processes and decarbonisation of the used energy

Functional unit

The functional unit is defined by vehicle size/utility

- Technical comparison of vehicle/powertrain variants which are similar in size and utility
  - defined by the vehicle type, size class (e.g. GVW) and potentially segment (for passenger cars)
- Same average/typical use characteristics of different vehicle types and segments are considered for all powertrain options
  - In practice these may be affected by factors such as driving range, maximum speed and cost situation (including subsidies)
  - Lack of broad evidence for new powertrain concepts (esp. heavy duty vehicles) and for early adopters
  - Focus on technical potential, but acknowledgement in qualitative discussion
  - Variations of use characteristics as part of sensitivity analysis

Functional unit

Most common functional units on vehicle level

- vehicle life
- **vehicle kilometre**
- Passenger/tonne kilometre

Conversion with life-time mileage

Conversion with utility factor

Results today are presented as v-km (passenger) and t-km (goods)

For transparency reasons, interim results are also stated per:

- MJ of final energy for liquid and gaseous fuels
- kWh_{el} of electricity (including grid and transmission losses)
- Vehicle delivered to the end-user for vehicle production
- kWh_B for batteries within a vehicle
- kg of material

System boundaries

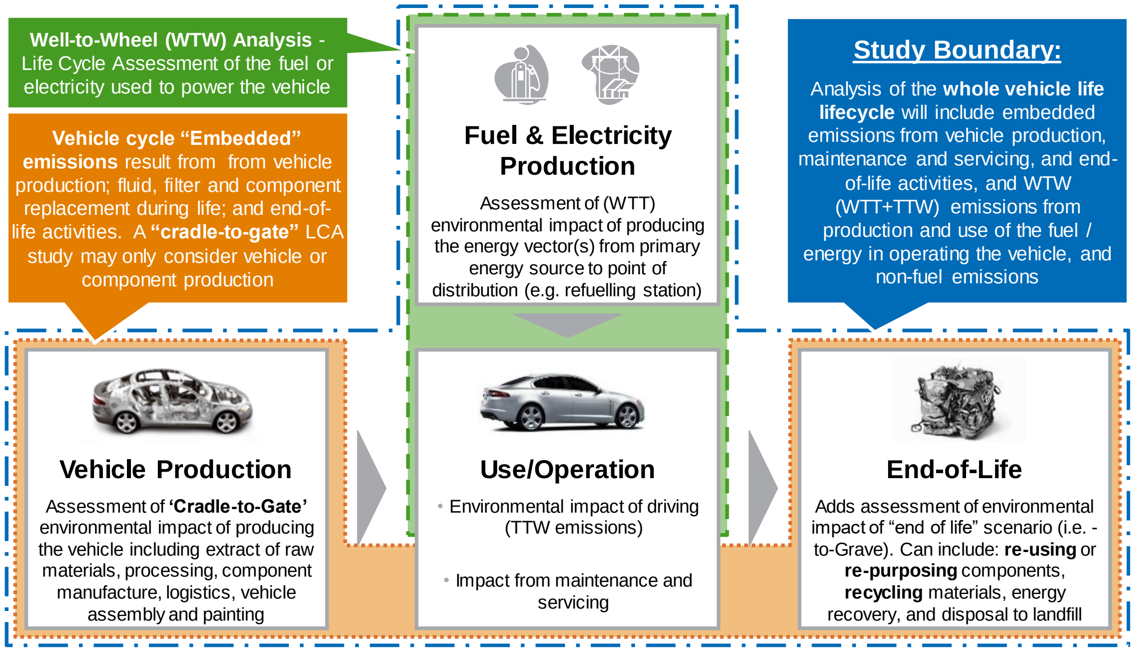
Whole life cycle of the vehicles themselves, from manufacturing over fuel and electricity production to the use phase and the end-of-life

Infrastructure for

- vehicle production,
- charging/refuelling
- and roads

excluded.

Fuel/Electricity infrastructure included



General LCA Approach

Following ILCD Handbook:

- **Situation A** used for a micro-level decision support
  - Structural changes are not likely to occur
  - Attributional model with current supply-chain recommended
- **Situation B** supporting a decision on a macro-level
  - Major and large-scale changes of the production system
- Model as situation A and then take a closer look at parts of the lifecycle identified as being affected by large-scale changes, e.g.
  - Additional electricity demand from EVs considered
  - Higher process efficiencies through economies of scale
  - Decarbonisation of materials
  - Consequential LCA and counterfactual scenarios for secondary feedstocks

Multi functionality

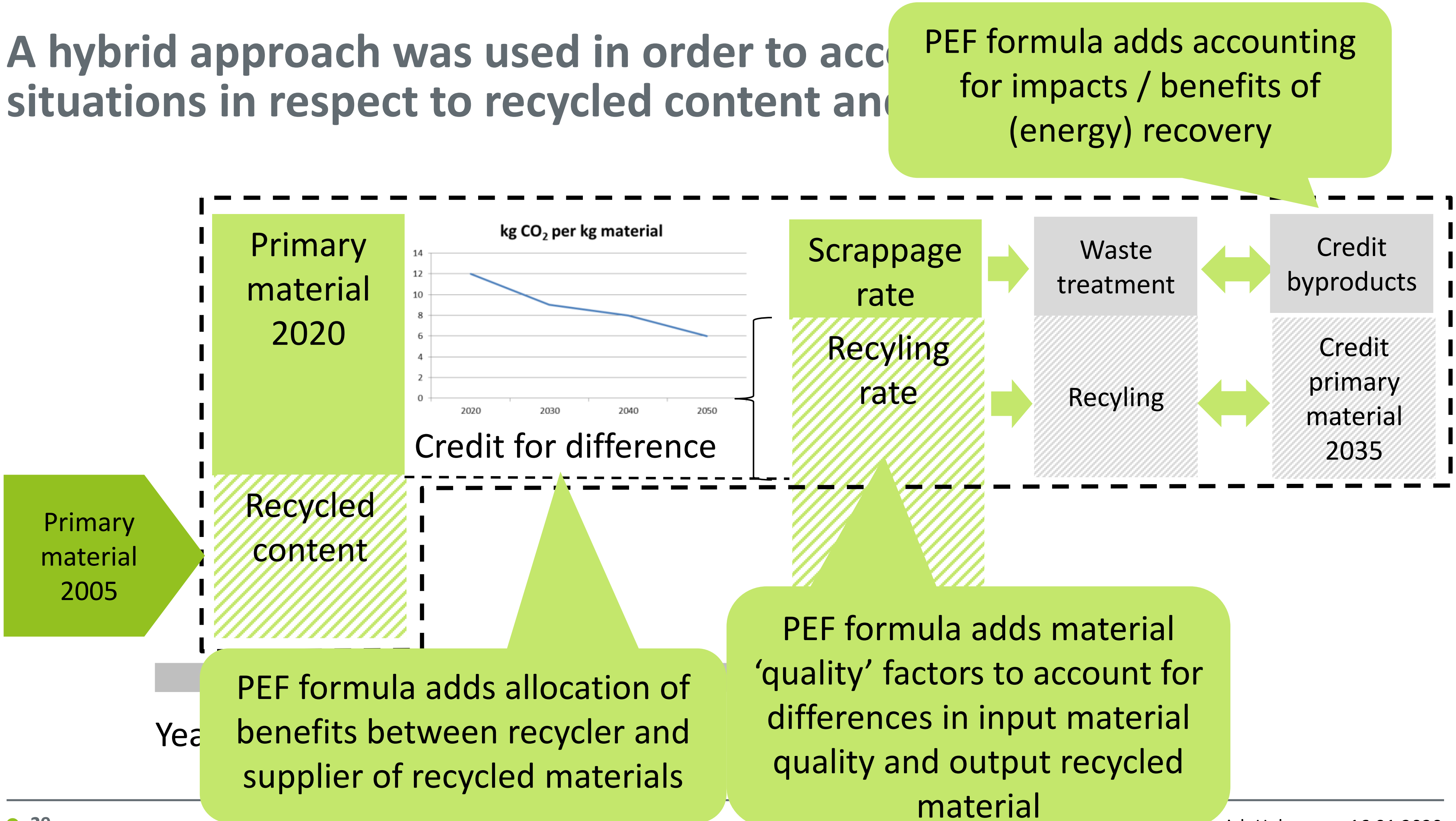
Generally following the three step hierarchy defined by the ISO standard:

- Subdivision of the product system into mono-functional single operation unit processes
- System expansion to include the function of the co-product or substitution (credit for the supplied co-product)
- Allocation according to preferably physical or other parameters of the co-products

Multi-functional processes most relevant for the electricity and fuel chains and application will be described in more detail later

End-of-life methodology for vehicles

A hybrid approach was used in order to acc… situations in respect to recycled content an…



End-of-life methodology for vehicles

- For the majority of materials with even balance between use recycled content and recycling rate this approach converges with a **cut-off approach**
  This suits the policymaker's viewpoint, since environmental burdens are mostly accounted for when they actually occur

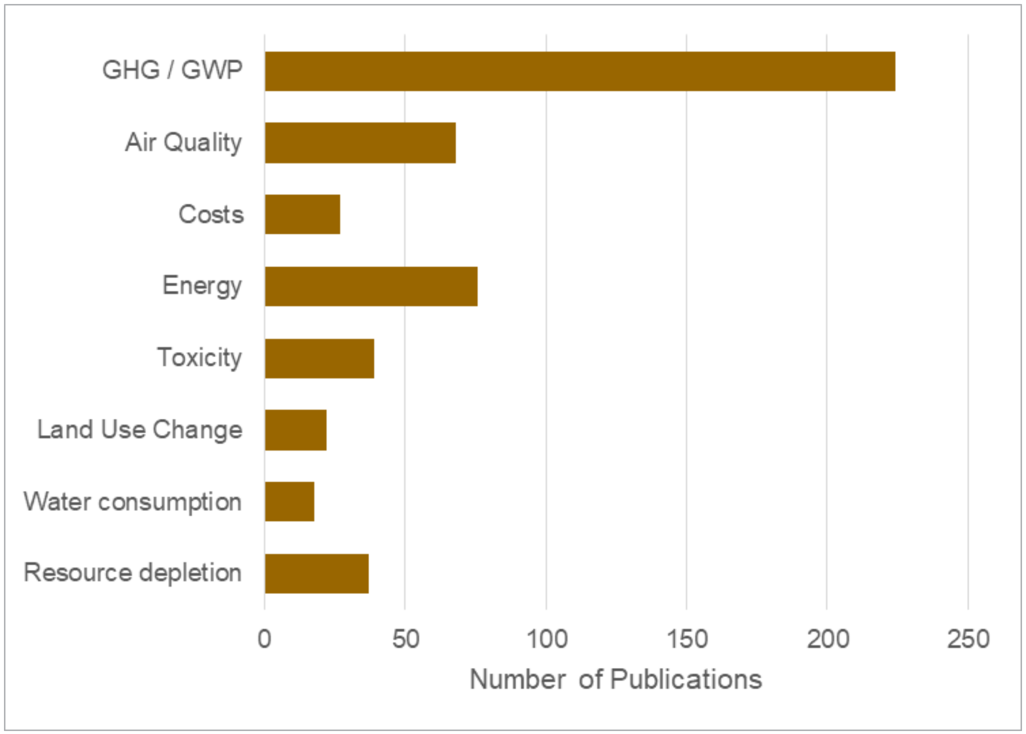
- For materials where the recycling rate (current or projected future rate) significantly exceeds the content of secondary material this approach converges with an **avoided burden approach**
  This does justice to materials for which the automotive sector is a net recycling contributor

Consistent with the circular footprint formula proposed in the battery PEFCR (Product Environmental Footprint Category Rules)

Environmental impact categories

Current LCA literature mostly uses midpoint categories and has a clear focus on climate change

Project demands a broad scope of impacts…



Environmental impact categories

Use of commonly established midpoint indicators to (a) reduce uncertainty and (b) increase compatibility with policy making

All categories from the PEF guide have been considered:

- For some categories diverging LCIA approaches were chosen because the PEF categories employed a mixture of mid- and endpoint methods
- This concerns acidification, eutrophication and particulate matter, where more established midpoint categories have been used instead

Additionally, some aggregated inventory results are given

- Main greenhouse gases (e.g. CO_2, CH_4, N_2O)
- Main air pollutants (e.g. NO_2, PM_{10})
- Energy demand

Environmental impact categories

Impact category	Abbr.	Indicator and unit
Climate change	GWP	Greenhouse gas emissions GWP100 in CO_2 eq
Energy consumption	CED	Cumulative energy demand in MJ (fossil, nuclear and renewable)
Acidification	AcidP	Acidification potential in SO_2 eq
Eutrophication	EutroP	Eutrophication potential in PO_4^{3-} eq
Photochemical ozone formation	POCP	Photochemical Ozone Creation Potential POCP in NMVOC eq
Ozone depletion	ODP	ODP in R11 eq
Ionising radiation	IRP	Ionising radiation potentials in U235 eq
Particulate matter	PMF	Particulate matter formation in PM2.5 eq
Human toxicity, cancer and non-cancer	HTP	Comparative Toxic Unit for Human Health in CTUh
Ecotoxicity, freshwater	ETP_FA	Comparative Toxic Unit for ecosystems in CTUe
Resource depletion - minerals and metals	ARD_MM	ADP ultimate reserves in Sb eq
Resource depletion – fossil energy carriers	ARD_FE	ADP fossil in MJ
Land use	LandU	Land occupation in m^2 *a
Water scarcity	WaterS	Scarcity-adjusted water use in m^3

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Specific considerations for different life-cycle stages

Specific considerations for vehicles

General approach to vehicle specification:

- Definition of EU average mass and material composition for baseline ICE representative vehicle body types normalised to current market averages
- Baseline performance assumptions for conventional powertrain types based on current models
- Variations for different powertrain types based on defined sizing /composition of key components
- Use of scaling factors to define sizing of key components for alternative powertrains

Specific considerations for vehicles

Modular approach used to define /characterise generic vehicles

Component	ICEV Liquid	ICEV Gaseous	HEV	HEV -ERS	PHEV / REEV	BEV	BEV -ERS	FCEV	FC -REEV
Glider	Y	Y	Y	Y	Y	Y	Y	Y	Y
Trailer system	Y	Y	Y	Y	Y	Y	Y	Y	Y
Engine	Y	Y	Y	Y	Y				
Transmission	Y	Y	Y	Y	Y				
Exhaust system	Y	Y	Y	Y	Y				
Aftertreatment	Y	Y	Y	Y	Y				
Fuel tank	Y	(1)	Y	Y	Y				
Gaseous fuel storage		Y							
Motor			Y	Y	Y	Y	Y	Y	Y
Battery (traction)			Y	Y	Y	Y	Y	Y	Y
On-board charger					Y	Y	Y		Y
Power electronics (2)			Y	Y	Y	Y	Y	Y	Y
xEV Transmission						Y	Y	Y	Y
Pantograph for dynamic charging system				Y			Y		
Fuel cell system								Y	Y
H2 storage								Y	Y

Note: (1) Only if dual/bi-fuel; (2) Includes: Inverter, Boost converter, Power control unit, Wiring harness, Regenerative braking system, HVAC heat-pump

Specific considerations for vehicles

General approach to vehicle production

- **Background**: Use of generic database ecoinvent for material production with additional estimate of future changes in material production impacts (decarbonisation as global average, some regional production assumptions)
- **Foreground**: Differentiated material compositions, material losses, process energy and auxiliary materials for generic vehicles in a modular way
  - Accounting for future changes in material composition of vehicles (e.g. light-weighting) and energy density or different cell chemistry of batteries
  - Electricity splits for vehicle assembly based on EU production and import
  - Electricity split for cell manufacturing regionalised and projected

Specific considerations for vehicles

Derivation of operational behaviour:

- Development of real-world profiles for EU average use and estimation of energy consumption by road type based on speed-energy consumption curves
- Simple dynamic adjustments based on change in vehicle mass (e.g. varying battery mass or vehicle loads)
- Tailpipe emissions of CO_2, SO_2 based directly on carbon and sulphur content
- Other emissions (including non-tailpipe) based on existing inventory methods (mainly COPERT) for Euro 6d / VI standards
- Age-dependent activity (annual km) profile based on the most recent evidence and modelling, calibrated to total lifetime activity/years

Specific considerations for fuel chains

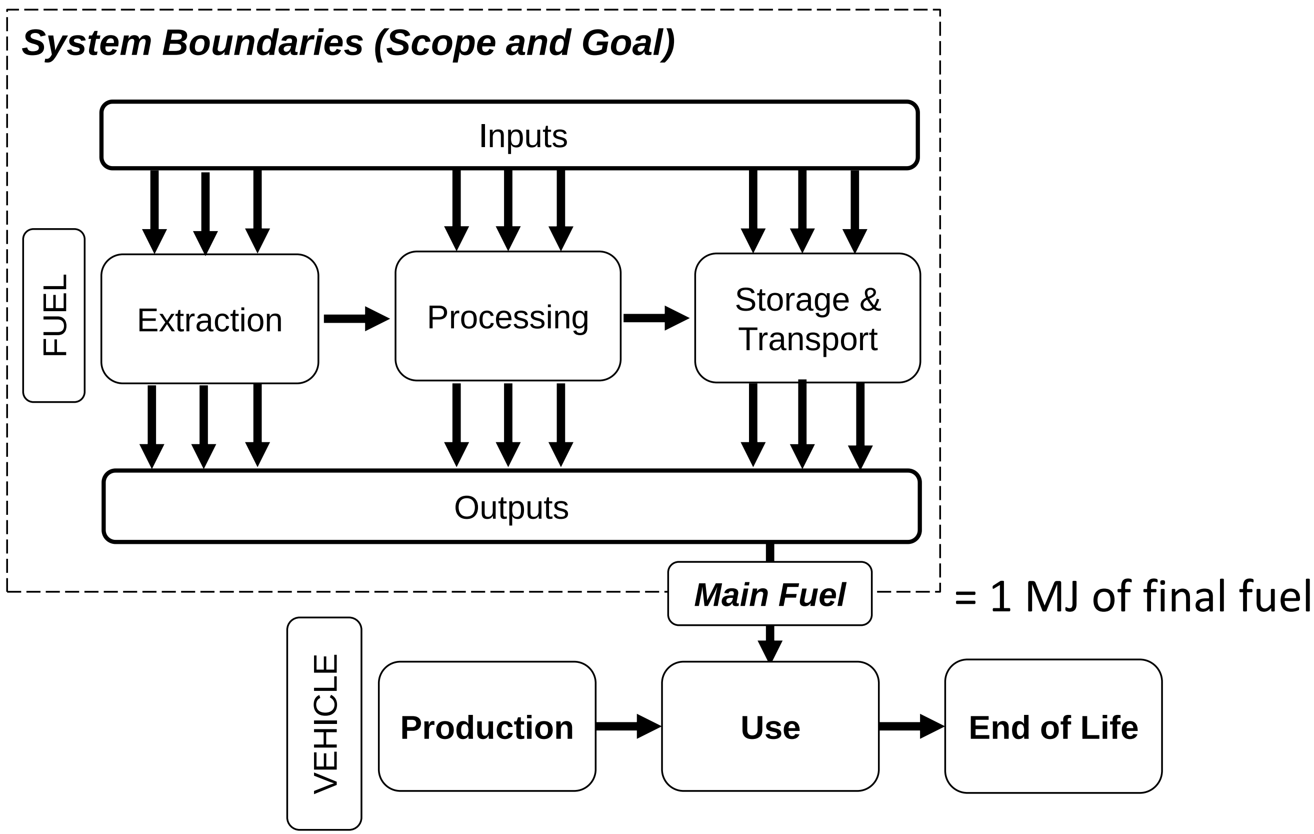
Intermediate functional unit defined as 1 MJ of final fuel

Other elements included in the scope of LCA for fuels are:

- Impacts from capital goods were included in all fuel chains
- Processing input energy (e.g. grid electricity, natural gas, biomass, heat) required for processing fossil or biogenic feedstocks into transport fuels
- In the specific case of fossil fuels on-site venting/flaring was included
- Counterfactual scenarios were used to evaluate the impact of diverting secondary feedstocks into fuel production
- Direct and indirect land-use change emission and Soil Organic Carbon emissions were accounted for in the primary biogenic fuel chains
- Crude refining was modelled by ifeu using allocation, other co-products in fuel chains are addressed via substitution

Specific considerations for fuel chains

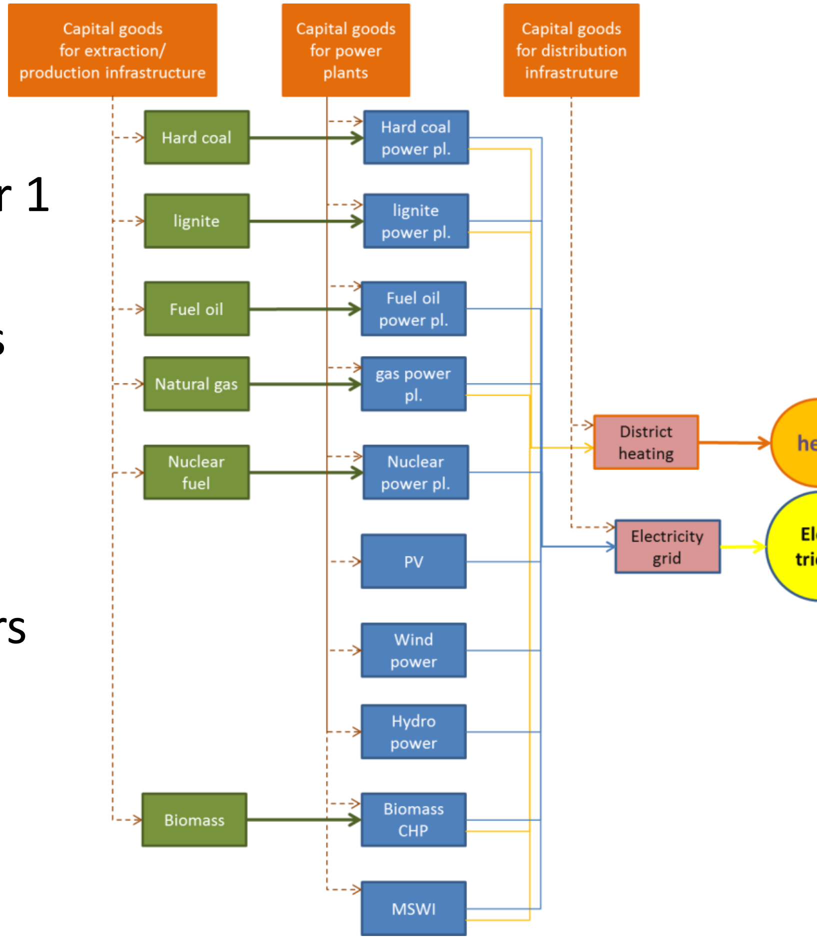
Schematic representation of overall Life Cycle Analysis (LCA) process implemented for fuel chains



Specific considerations for electricity generation

Use of the ifeu Umberto model for electricity generation

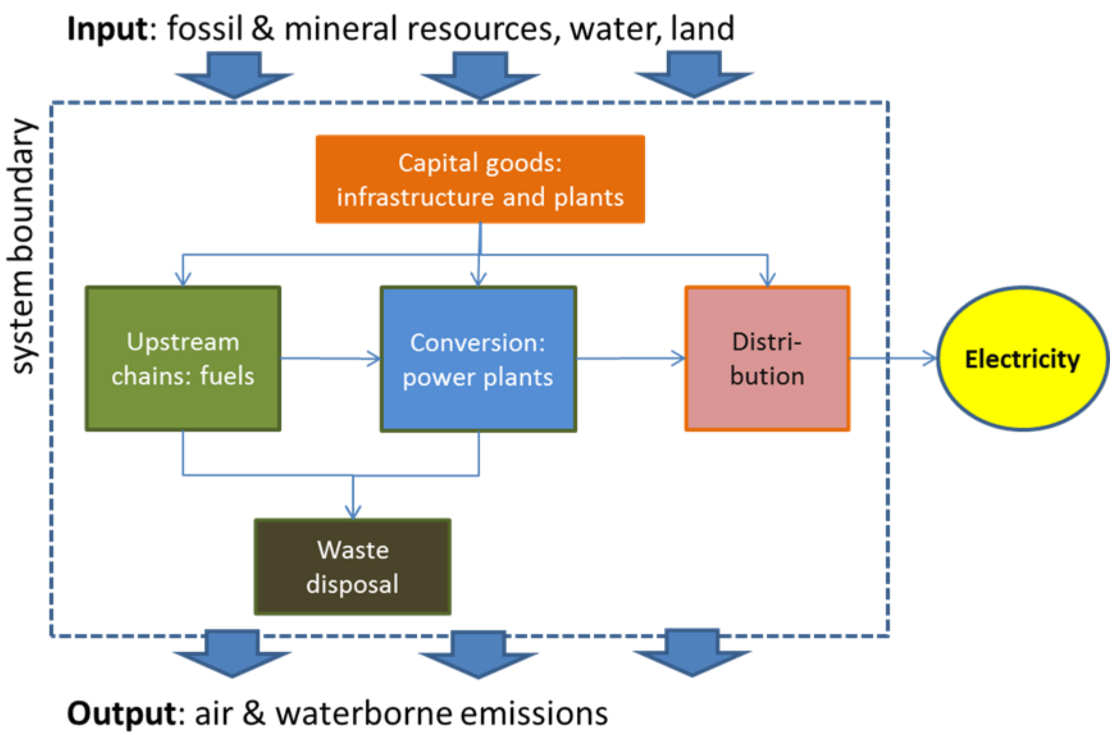
- Intermediate functional unit defined as 1 MJ (or 1 kWh) electricity delivered to the grid
- Includes basic raw material upstream processes and power plant types
- Allows for a flexible approach to different electricity splits and scenarios
- The combination of all the individual parameters leads to 3,250 single data sets
- Post processing includes transmission & distribution losses



Hinrich Helms 16.01.2020

Specific considerations for electricity generation

System boundary includes capital goods for infrastructure and plants, waste disposal and distribution losses



Summary of methodological choices

Issue	Approach used in LCA study
Goal	Enhance the European Commission's understanding of impacts of transport vehicles on a quantitative basis.
Product system(s)	Six different types of road vehicles (light and heavy duty) with twelve different powertrain options have been analysed (in total 50 combinations). Furthermore different fuel and electricity chains potentially applicable to the analysed vehicles have been included in the analysis.
Functional unit and reference flows	Technical comparisons of vehicles similar in size and utility, which are defined by the vehicle type, size class (e.g. GVW) and potentially segment (for passenger cars). Vehicle kilometre is the key reference flow for total results, additional units are possible and used for intermediate results.
System boundaries	Whole life cycle of the vehicles themselves, from manufacturing and fuel/ electricity production to the use phase (including maintenance) and the end-of-life. Additionally capital goods for energy production (electricity and fuels) are included.
LCA approaches	Overall a consistent attributional approach, considering certain consequential element where appropriate.
End-of-life modelling for vehicles	Hybrid approach in accordance with PEFCR for batteries combining aspects of cut-off and avoided burden approach.
Impact categories	Impact assessment based on commonly established midpoint indicators covering greenhouse gas emissions, acidification, eutrophication, summer smog, ozone depletion, human toxicity, eco-toxicity, resource consumption, land use, and freshwater consumption.
LCI background data	For the background system ecoinvent has been largely used as a transparent and established data base. Furthermore assumptions on decarbonisation of materials production have been made.

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Agenda

- Introduction, background and objectives of the meeting [09:00]
- Overview of the developed methodology [ifeu, 09:30]
- **Overall LCA results [Ricardo, 11:00]**
  - **Results and comparisons for lower medium cars**
  - Results for other vehicle types
- Results for energy chains [ifeu / E4tech, 13:30]:
  - Electricity chains [ifeu]
  - Liquid and gaseous fuel chains [E4tech]
- Overall LCA sensitivities [Ricardo, 15:00]
- Other assumptions and general Q&A [Ricardo, 16:15]
- Initial conclusions & recommendations and wrap-up [Ricardo, 17:00]

Introduction to Overall Results: Achievements, strengths and general findings

- A harmonised/consistent comparison of the environmental performance of a sample of vehicles has been developed for all stages of the vehicle life-cycle:
  - Good comparability of overall results
  - Novel methodological development in key areas – particularly to account for future changes in impacts key materials and energy chains, and vehicle mileage
- A key benefit of this study was to concretely try certain methodological approaches and see whether this worked/could be applied in practice and how these impact the results
- Accordance with the general principles of ISO and also other important guidelines (PEF, ILCD) were mostly established
- Stakeholder consultation / engagement predominantly favoured the chosen approaches and on many issues there was almost a consensus on the methodological choice
- Results for a broad scope of products and environmental impacts have been derived on a largely comparable and robust basis
  - Proves the general feasibility of the developed concept and approach
  - Provides a robust evidence base to help dispel common myths, highlights areas of greater variation / uncertainty, indicates potential environmental hotspots

Introduction to Overall Results: Uncertainties, caveats/limitations and data gaps

- LCA is inherently imprecise/uncertain. The broad scope of the study has also led to trade-offs with level of detail and accuracy in certain areas
- Results are for generic vehicle types, which provide a good basis for further policy decisions and can be assumed to be valid for a representative sample of such vehicles
  - ➲ Validity for specific single vehicle models is naturally limited
  - ➲ Comparisons with more novel fuels/blends needs improved data/methodologies
- Considerably less data/literature is available for certain vehicle types (mainly lorries and buses) and powertrains/fuels (especially e-fuels and alternative fossil fuels)
  - ➲ This may lead to higher uncertainties for these vehicles/energy types
- Broad scope of considered environmental impacts likely leads to differences in data robustness between these impacts due to data uncertainties and asymmetries
  - ➲ Care should be taken in result interpretation, especially for less common/established impacts (and especially for more novel fuel types)
- Some methodological areas subject to greater debate and could be further investigated:
  - the extent and application of consequential modelling, end-of-life-modelling as well as the relevance of charging/refuelling infrastructure

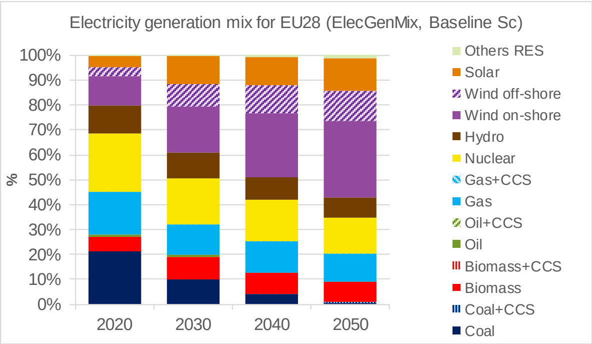
Introduction to Overall Results: Overall assessment of the application and results

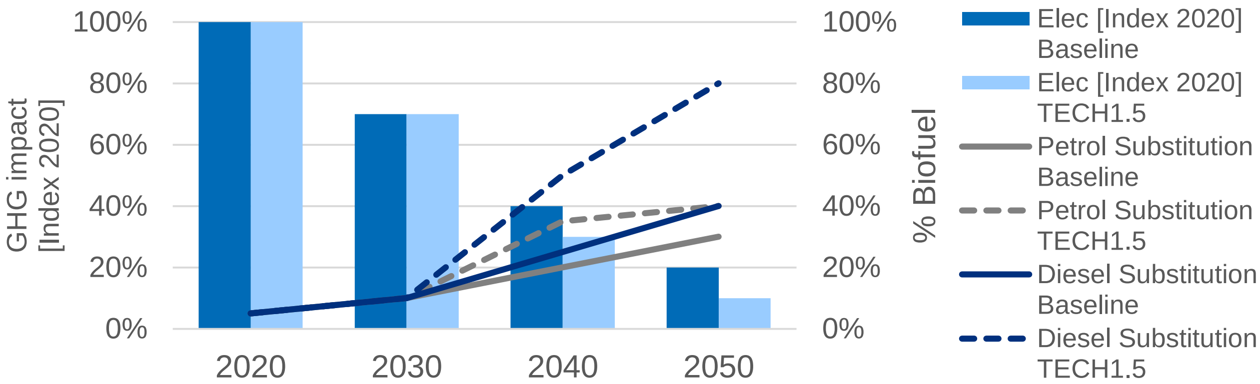
- Again: results of LCA inherently have uncertainties, so view the presented results using this lens
- Overall, results are based on a robust analysis, with key sensitivities appropriately explored
- Results for certain fuel chains are more uncertain/require further consideration/qualification, due to e.g. methodological differences to previous WTW analyses, poor/gaps in data for new processes, counterfactual choices/assumptions, etc

Area	Methodology	Datasets	Comment
Vehicle Specification			A range of sensitivities included to explore impacts on key inputs to understand uncertainty
Vehicle / Battery Manufacturing			Underlying materials / production datasets well characterised; key sensitivities implemented
Electricity Chains			Strong data and methodologies/application; the main uncertainty is future electricity mix
Fuel Chains	/	-	Some methodological areas need further consideration, data is poor for new processes
Vehicle Operation			Key sensitivities implemented; other sensitivities could be explored in the future (e.g. on climate)
Vehicle / Battery End-of-Life			EoL processes well defined; uncertainty on future battery recycling and second life impacts

Introduction to modelled scenarios

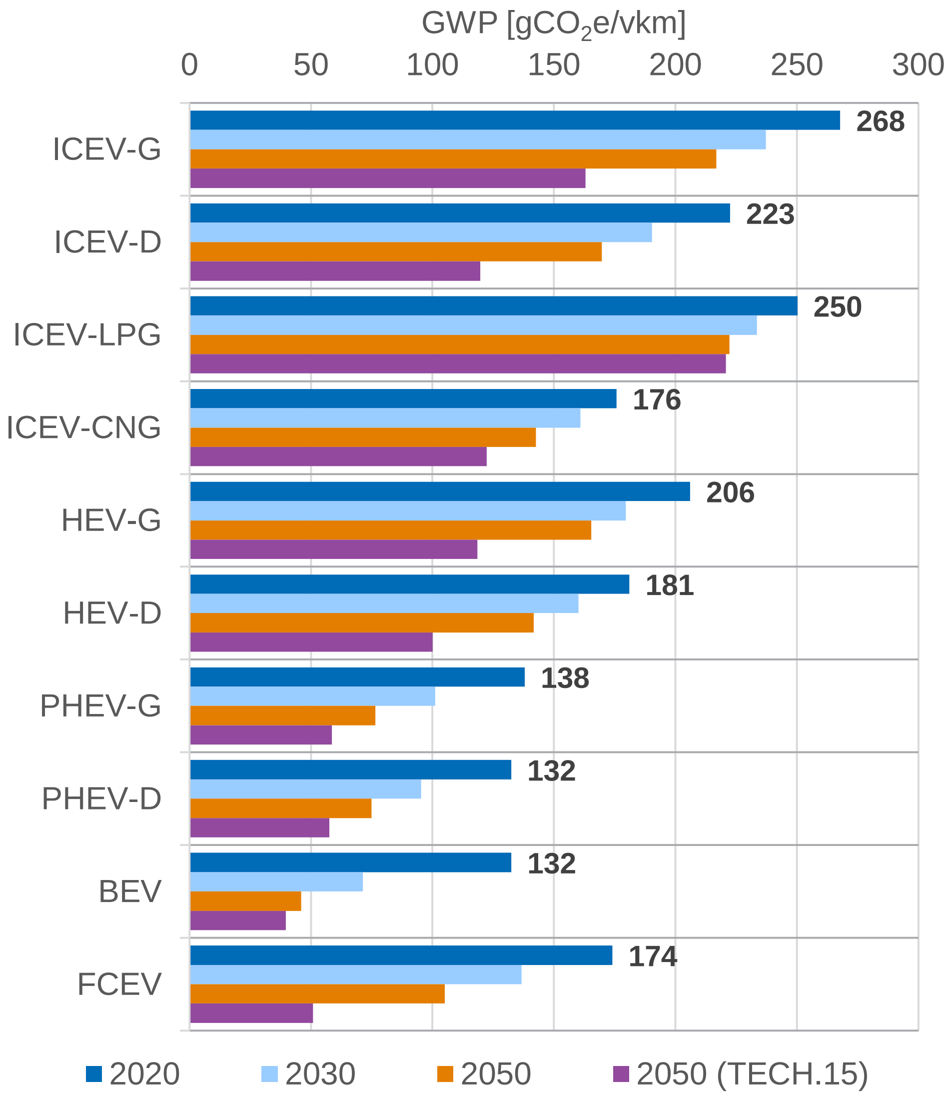
Scenario	Description	Modelling datasets used**
Baseline	Baseline scenario including all currently planned/ implemented EU and national policies	***Transport by vehicle type:*** • % improvement in real-world MJ/km 2020-2050 by vehicle/powertrain type • % share urban / non-urban driving by vehicle type (average across timeseries) ***Electricity for EU28, individual countries:*** • Electricity generation mix 2020-2050 • Generation efficiency by generation type, 2020-2050 • Transmission & distribution losses • Imports/exports ***Fuels:*** • % substitution rate of conventional fossil fuels with biofuel/low carbon fuels from 2020-2050, by fuel type
TECH1.5	Scenario consistent with the EU contribution to meeting the Paris Agreement objective of keeping global temperature increase to a max. of 1.5 ºC	





General GWP results for Lower Medium Cars – impact by period

Lower Medium Car – Baseline Scenario, TECH1.5 (2050 only)

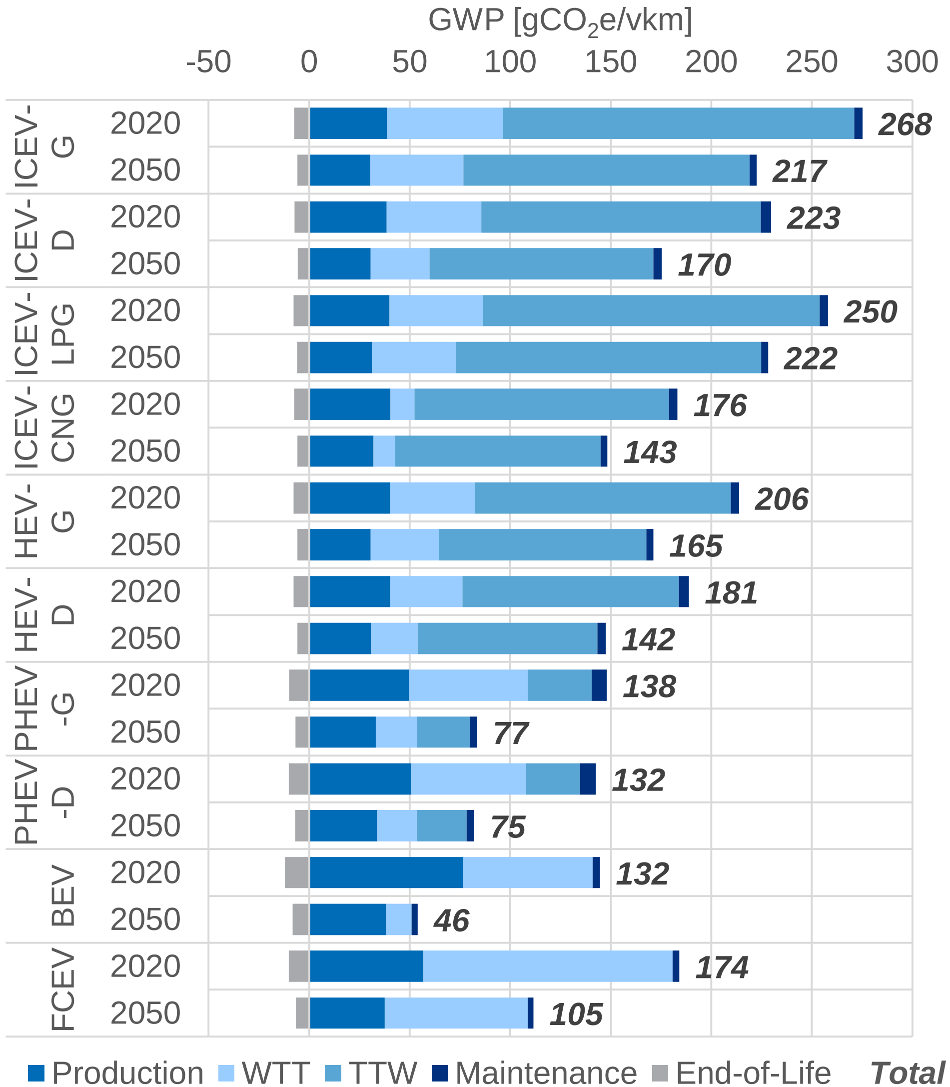


- GWP impacts significantly decrease with electrification level and over time
  - In 2020, impacts of PHEV ~ BEV for EU28 average
  - In 2020, HEV ~ FCEV (H2 SMR)
  - TECH1.5 scenario << Baseline by 2050
- Impacts of NG vehicles lower vs petrol/diesel than previous analysis: due to particularly low WTT factors (see later slides on fuel chains)
- Long-term GWP benefits of FCEV rival those of BEVs in TECH1.5 scenario (based on higher share of H2 from SMR+CCS and decarbonised electricity)

Additional information: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs.

General GWP results for Lower Medium Cars – impact by stage

Lower Medium Car – Baseline Scenario

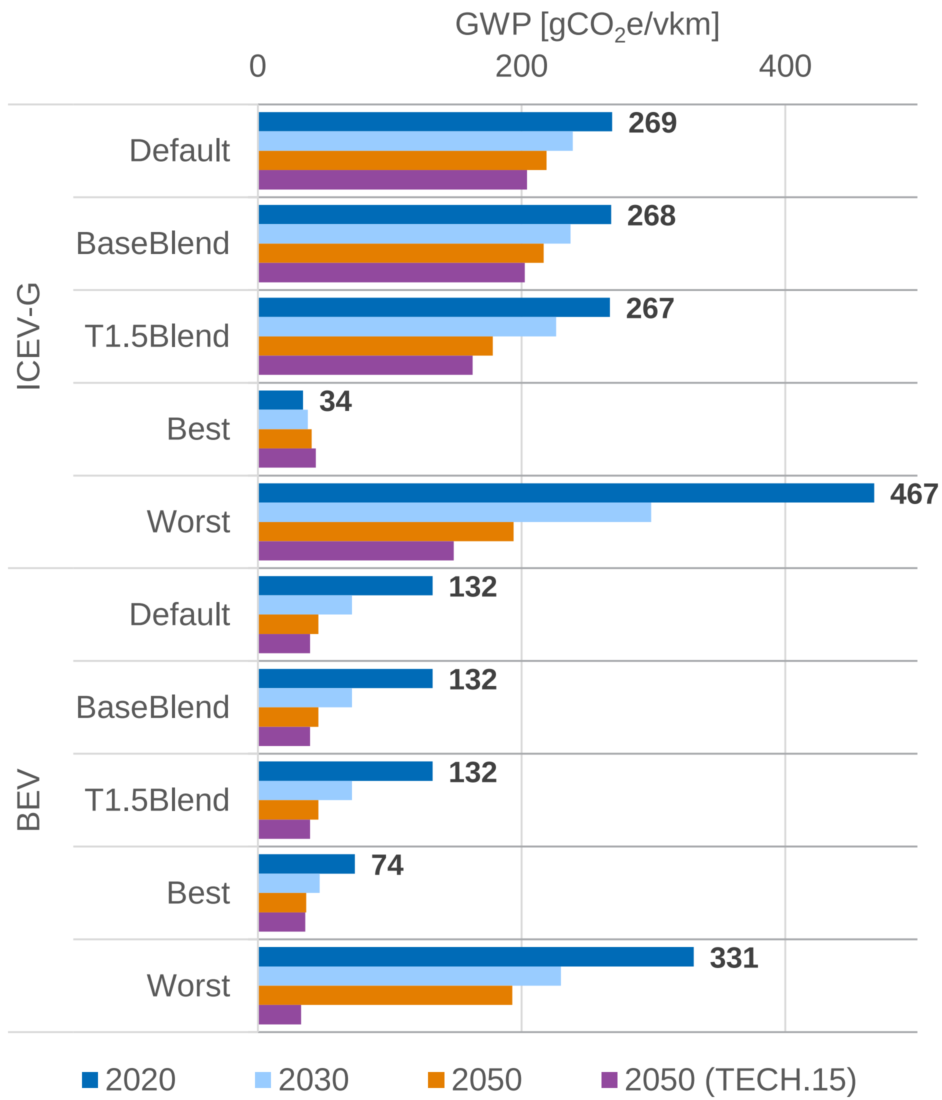


- Manufacturing impacts reduce over time for all powertrains: despite shifts in material mix (due to weight reduction)
- xEVs: Impacts of both manufacturing and operation energy substantially lower in future periods due to elec decarbonisation
  - Despite increases in range/battery size
  - Improvements less significant for FCEVs in baseline scenario
- Despite higher recycling rates, EoL credits are lower in future periods as recovered materials displace lower impact virgin materials

Additional information: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs.

General GWP results for Lower Medium Cars – impact by fuel blend, scenario

Lower Medium Car – Fuel Blend / Electricity Mix



- Default = fossil fuel comparator
- Relative impacts of different powertrain types are highly influenced by fuel and electricity chain / choice assumptions
  - The very best fuel chains rival the best for electric vehicles in terms of GWP, BUT
    - Not necessarily in other impact areas
    - Depends in some cases on the application of substitution or counterfactual methodology (for secondary feedstocks)
    - Biofuel chains may have limited biomass supply potential
    - Key materials for batteries and motors are also limited in resource/supply

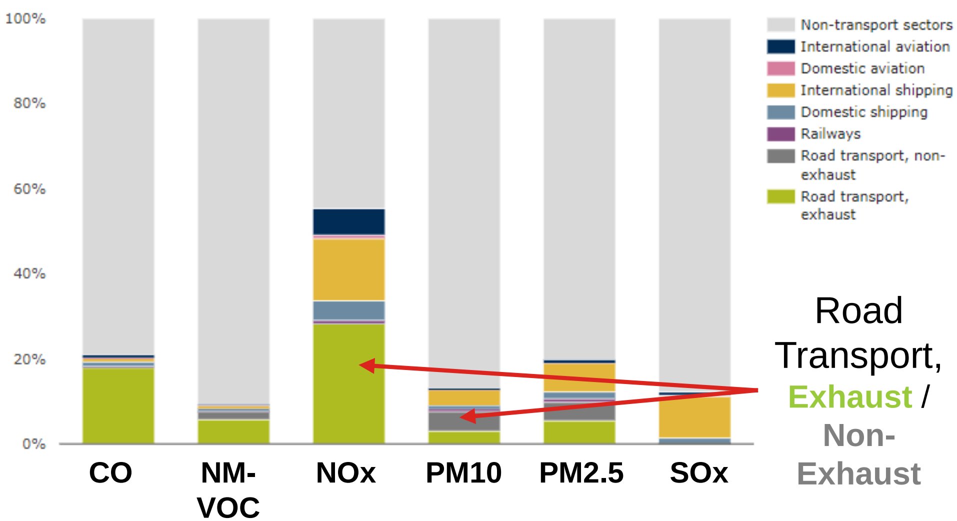
Additional information: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs.

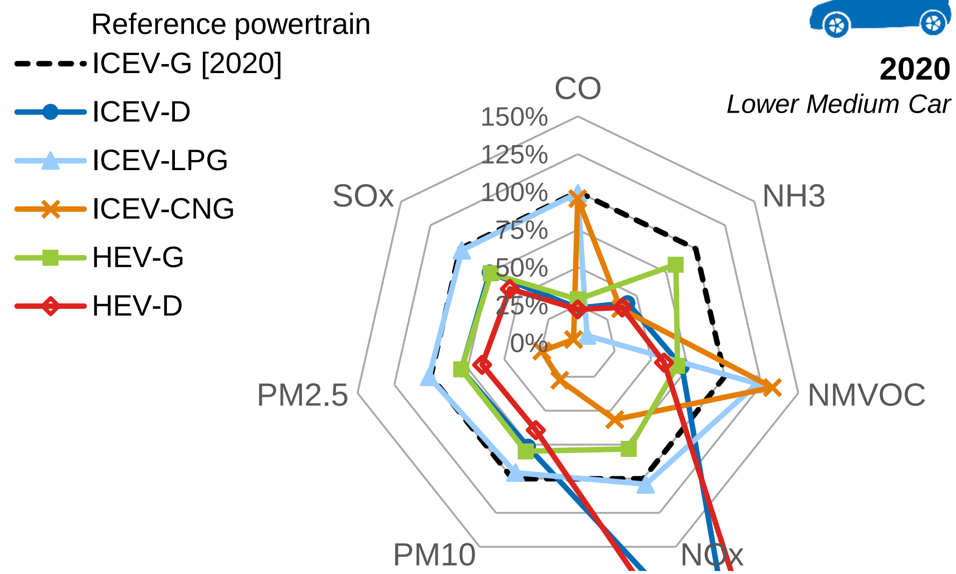
Relative impacts for Lower Medium Cars for air quality pollutant emissions (CO, NH3, NMVOC, NOx, PM10, PM2.5, SOx)

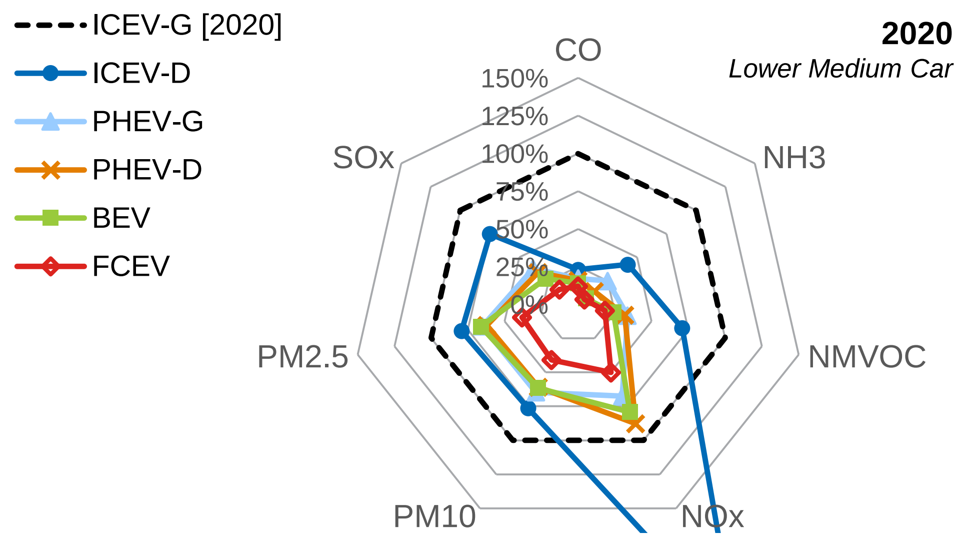
Lower Medium Car – Baseline Scenario, 2020

- Road transport is still responsible for almost 30% of European NOx emissions
  - NOx contributes to AcidP, EutroP, POCP and PMF mid-point impacts
- Electrified, electric and CNG vehicles generally all reduce lifecycle emissions of all the major AQ pollutants
  - Benefits increase in future periods

EEA (2020), transport contribution to air main pollutants in Europe





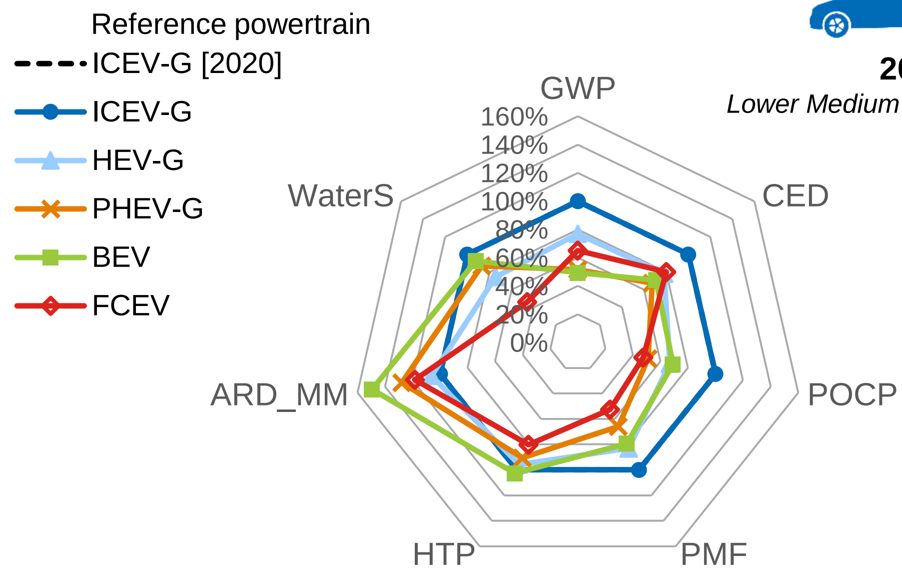


Source: AcidP = Acidifying Potential, EutroP = Eutrophication Potential, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation

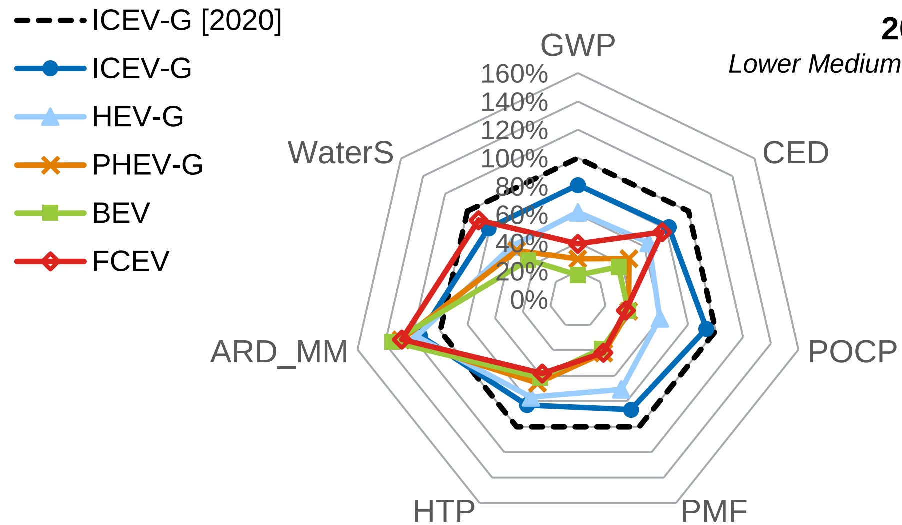
Relative impacts for Lower Medium Cars for the most significant mid-points for transport by powertrain

Lower Medium Car – Baseline Scenario

- Impacts are indexed to ICE-Gasoline 2020 reference powertrain performance
  - Impacts for ICEV-D are significantly higher for both POCP and PMF (NOx contributes to secondary PM)
- Hotspots for xEVs in ARD_MM mainly due to electronics and copper in batteries (*not* Cobalt / Lithium = v.small masses)
- Hotspots for xEVs in HTP mostly due to copper from the battery anode current collector
  - Copper in wiring and motor contribute to a much smaller extent (<20%)
- WaterS impacts increase for FCEV 2020-2050 due to higher share of H2 production by electrolysis in later periods



2020
Lower Medium Car



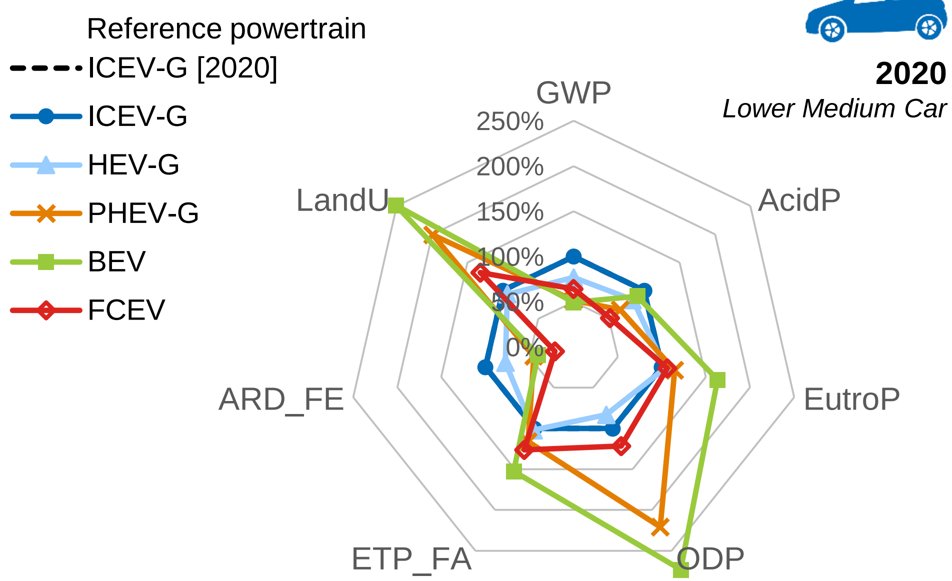
2050
Lower Medium Car

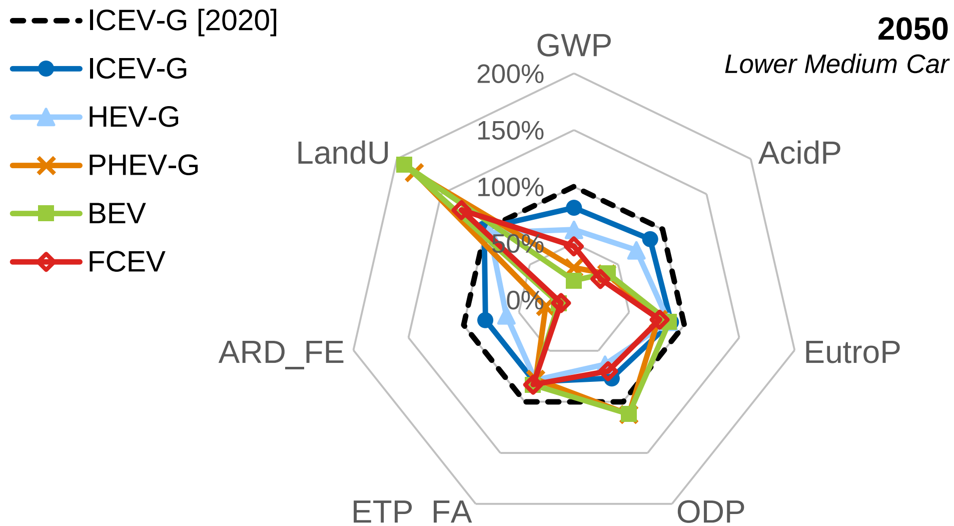
Source: GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity

Relative impacts for Lower Medium Cars for the less significant mid-points by powertrain

Lower Medium Car – Baseline Scenario

- Other impact mid-points appear variable; only some are significant for transport:
  - Impacts for ICEV-D are significantly higher for both AcidP and EutroP (NOx also contributes to both mid-points)
  - *Note*: Presented vs 100% fossil comparator, and not blend (unusual –ve LandU results otherwise)
- Higher relative ODP mainly from biomass /coal generation, but ODP impacts are not significant overall for road transport
- Higher relative freshwater ETP due mainly to battery materials: copper in the anode, nickel sulphate cathode precursor, and electronics in the battery periphery
- Higher relative LandU impacts from electricity: biomass >> wind > solar

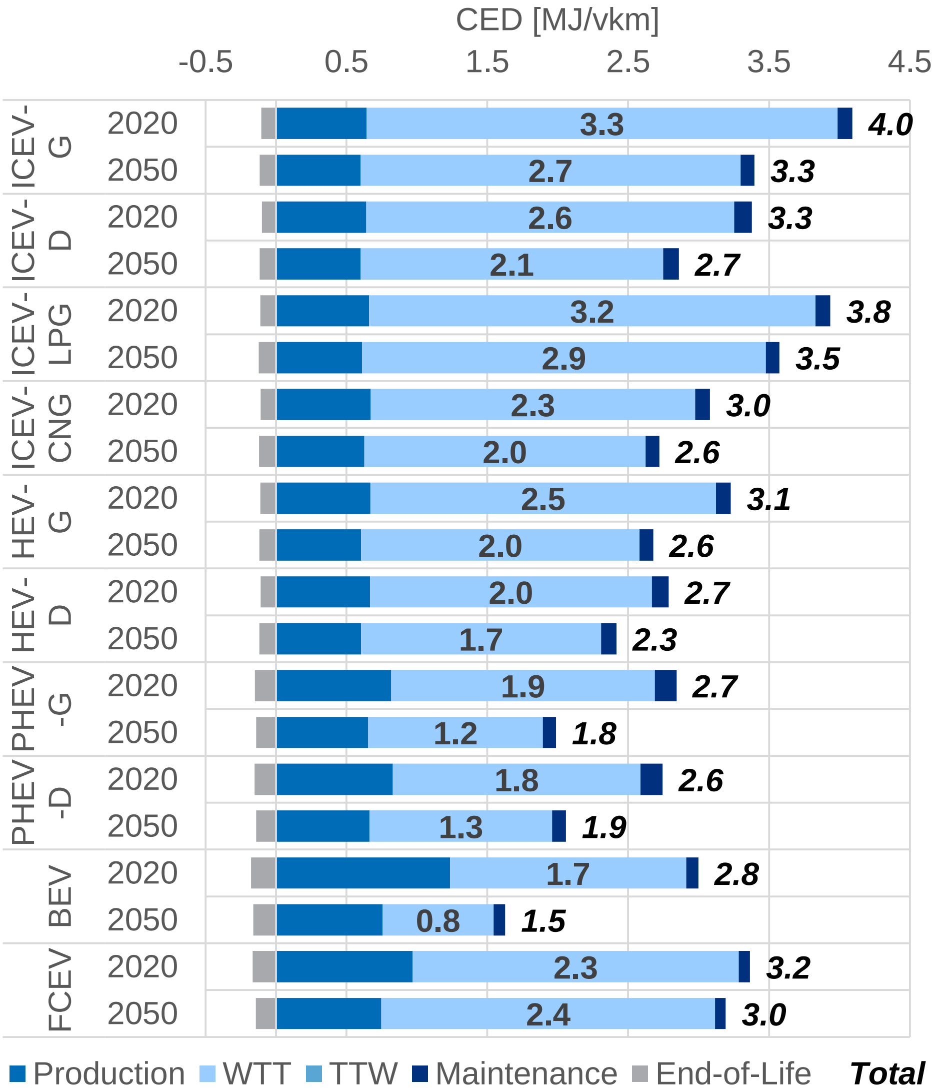




Source: GWP = Global Warming Potential, AcidP = Acidifying Potential, EutroP = Eutrophication Potential, ODP = Ozone Depletion Potential, ETP_FA = Freshwater Aquatic Eco-Toxicity Potential, ARD_FE = Abiotic Resource Depletion, fossil energy, LandU = Land Use

9 Breakdown impact by powertrain and stage – Cumulative Energy Demand, CED

Lower Medium Car – Baseline Scenario

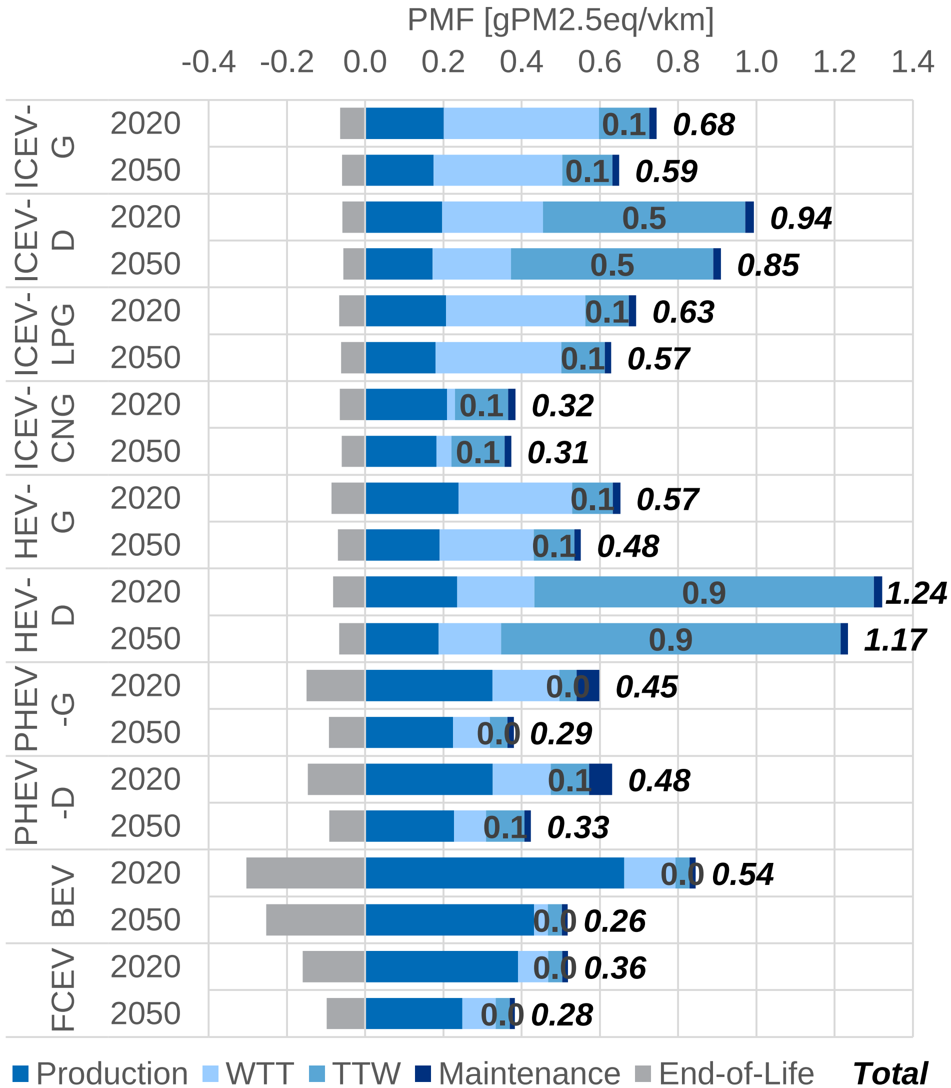


- CED significantly reduced/improved for more efficient powertrain types:
  - Results for 2030 are closer to 2050 values
- Results for most xEVs similar for 2020, but diverge in later periods
- FCEV significantly worse than BEV, PHEV after 2020
  - 50% more than BEV by 2030
  - almost double BEV by 2050
  - Due to net of fuel chain and relative vehicle efficiency

Additional information: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs.

Breakdown impact by powertrain and stage – Particulate Matter Formation, PMF

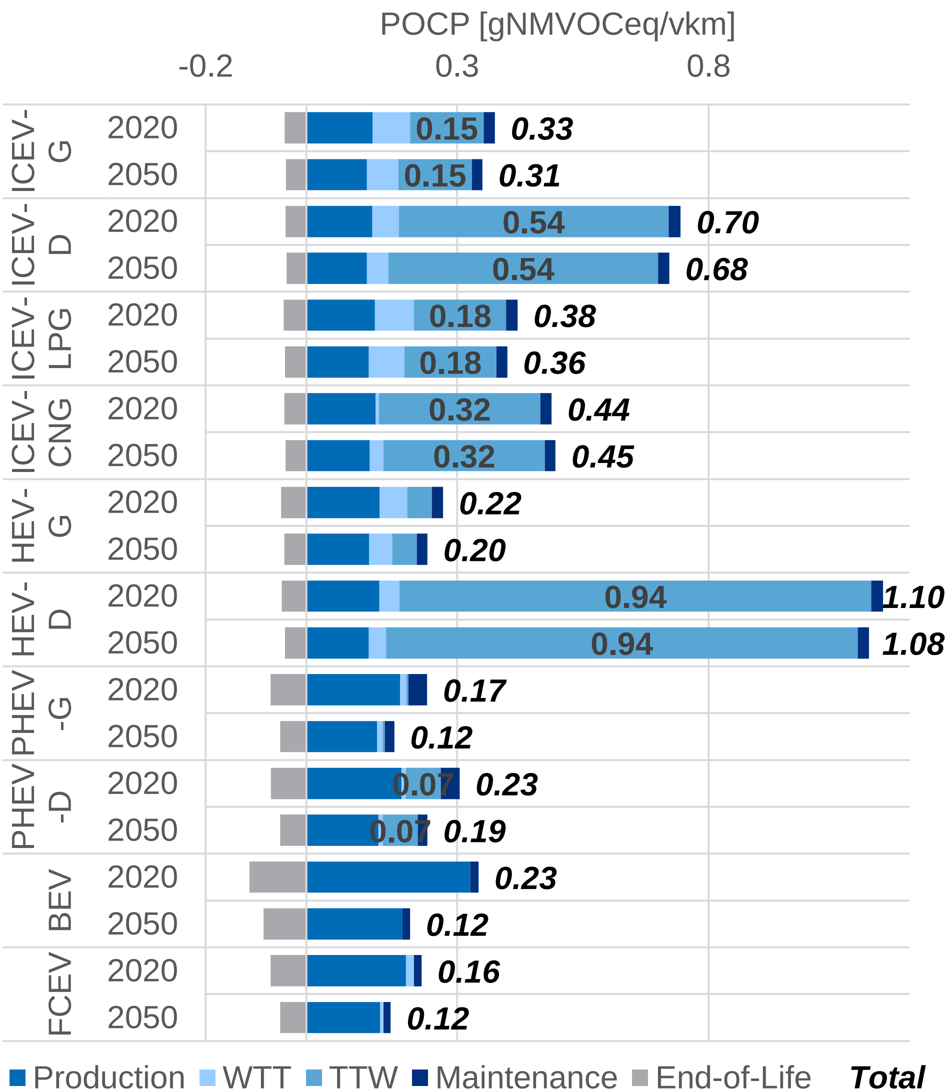
Lower Medium Car – Baseline Scenario



- Direct PM2.5 similar for all powertrains (high shares brake, tyre and road-wear)
- Significant contribution of NOx to secondary PMF for diesel
  - Higher impacts from HEV-D are based on COPERT real-world emissions factors
- Lowest lifecycle impacts in 2020 from ICEV-CNG, similar to xEVs in 2050
- For electricity, conventional fossil generation types have the highest impacts
- Higher impacts due to the manufacturing of batteries for xEVs

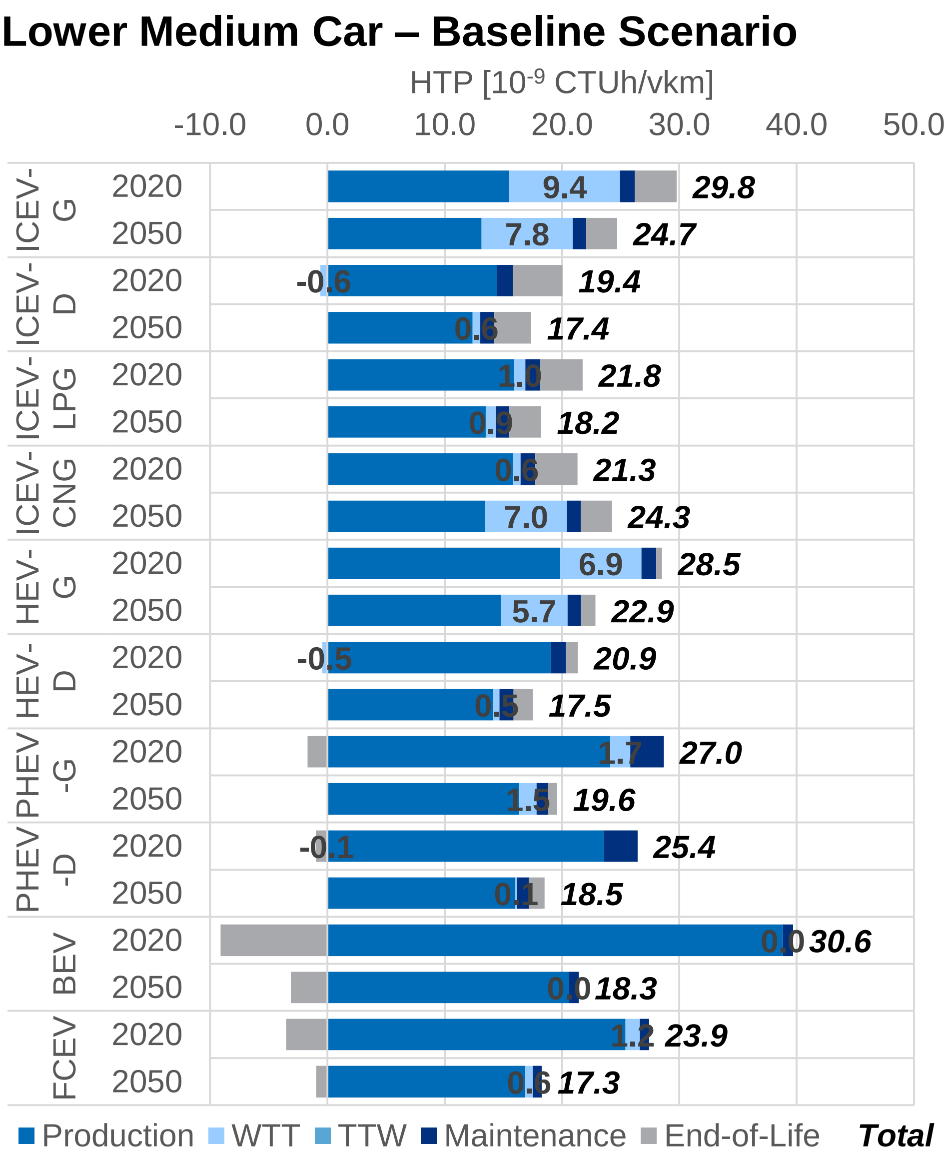
Breakdown impact by powertrain and stage – Photochemical Ozone Creation Potential, POCP

Lower Medium Car – Baseline Scenario



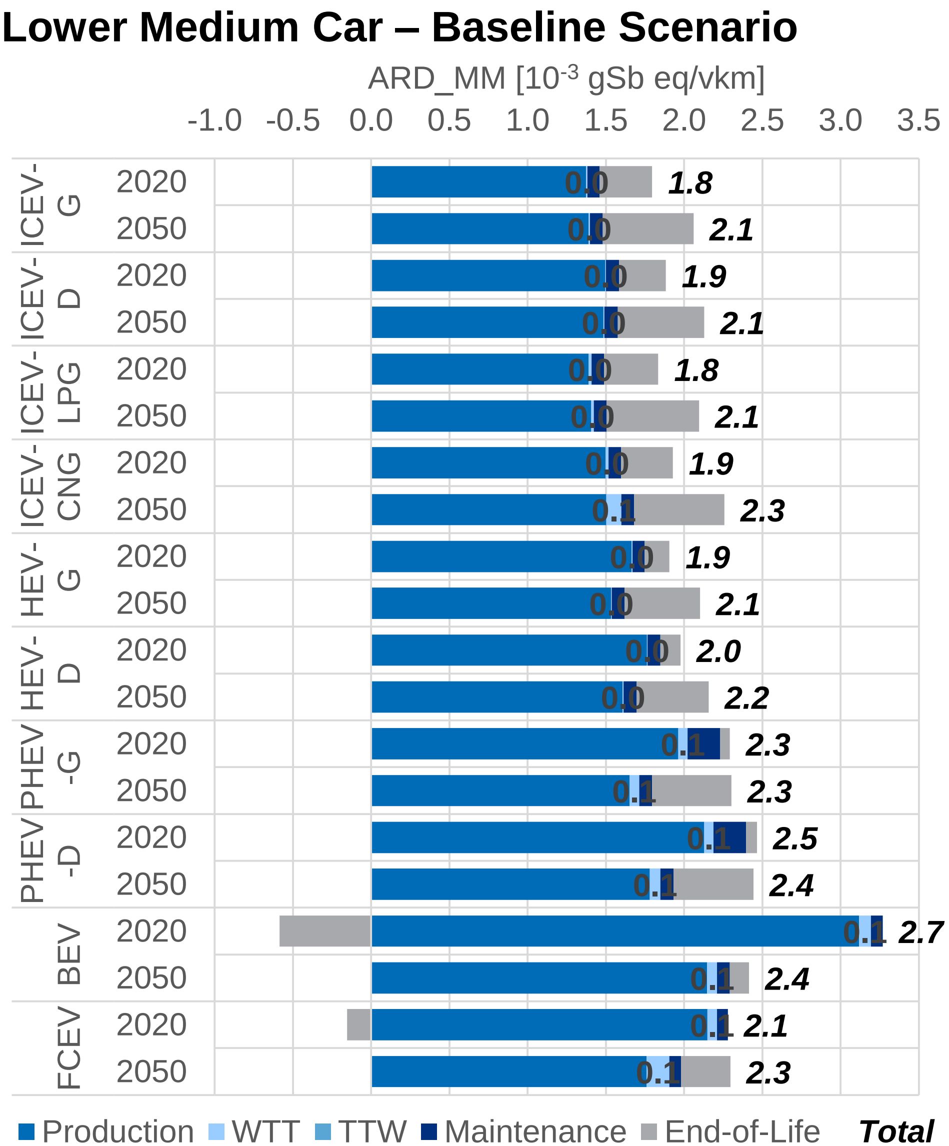
- Similarly to PMF, significant contribution of NOx to POCP for diesel
  - Higher impacts from HEV-D are based on COPERT real-world emissions factors
- Impacts for LPG and CNG vehicles similar or higher than gasoline, but lower than diesel
- For electricity, conventional fossil generation types have the highest impacts
- Higher impacts due to the manufacturing of batteries for xEVs

Breakdown impact by powertrain and stage – Human Toxicity Potential, HTP



- Majority of impacts are due to materials used in vehicle and battery manufacturing
  - Mostly due to copper from the battery anode current collector
    - Copper in wiring and motor contribute to a much smaller extent (<20%)
- Impacts are relatively low on an absolute scale

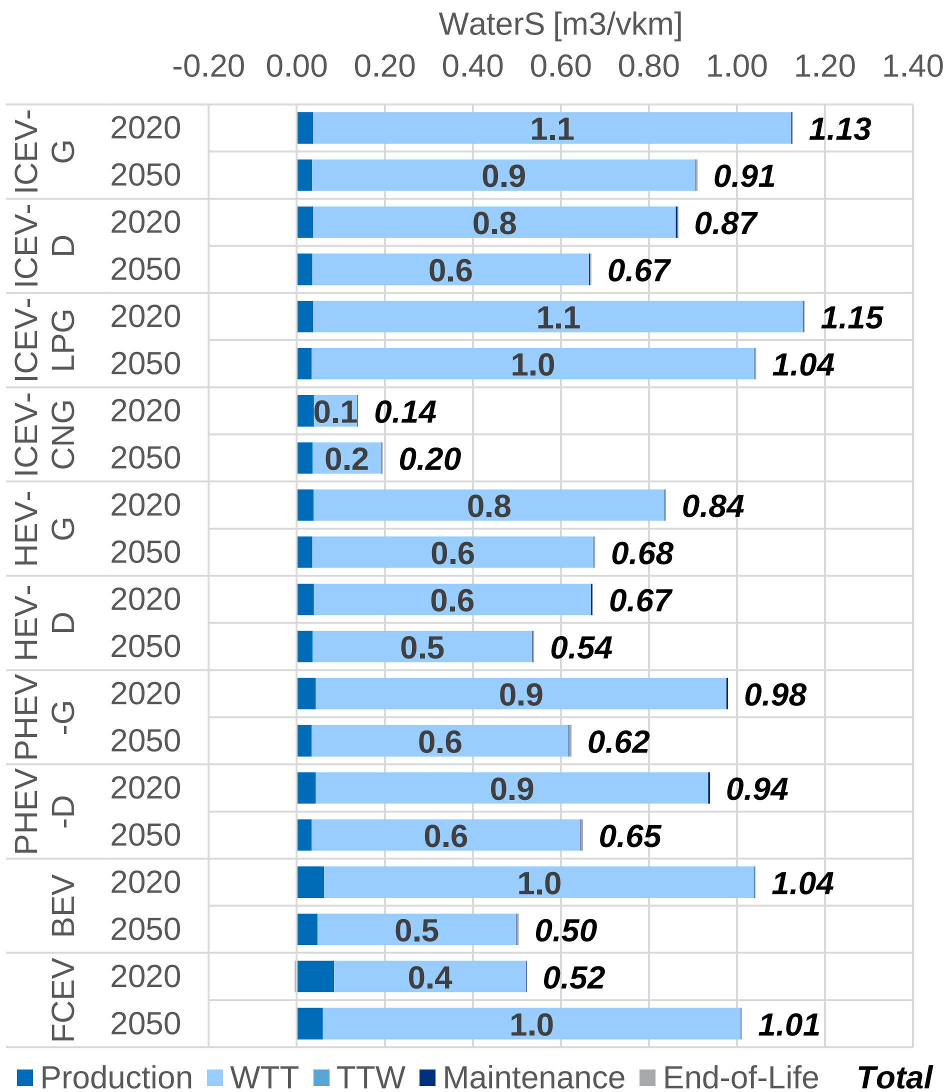
Breakdown impact by powertrain and stage – Abiotic Depletion Potential, minerals and metals, ADP_MM



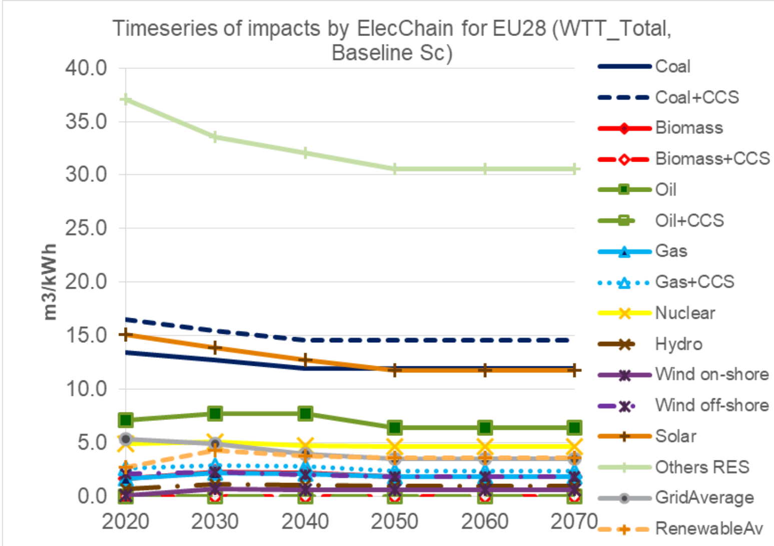
- Impacts predominantly due to manufacturing and EoL stages due to materials
- Impacts from production phase predominantly due to steel for the glider, electronics and copper in batteries
- *Positive* impacts (rather than credits) in EoL stage due to impacts of aluminium recycling (it is unclear why this should be)
- Electricity: Relatively very high for solar generation - much higher than other generation types. Also much higher for wind, nuclear vs other generation

Breakdown impact by powertrain and stage – Water Scarcity, WaterS

Lower Medium Car – Baseline Scenario



- Impact predominantly from energy production (WTT) stage
- Electricity: Highest for coal and solar generation types – similar magnitude (other generation types lower)
- H2: higher share of electrolysis in 2050
- Water consumption counter-intuitively *lower* for many biofuel chains



Agenda

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- Overview of the developed methodology [ifeu, 09:30]
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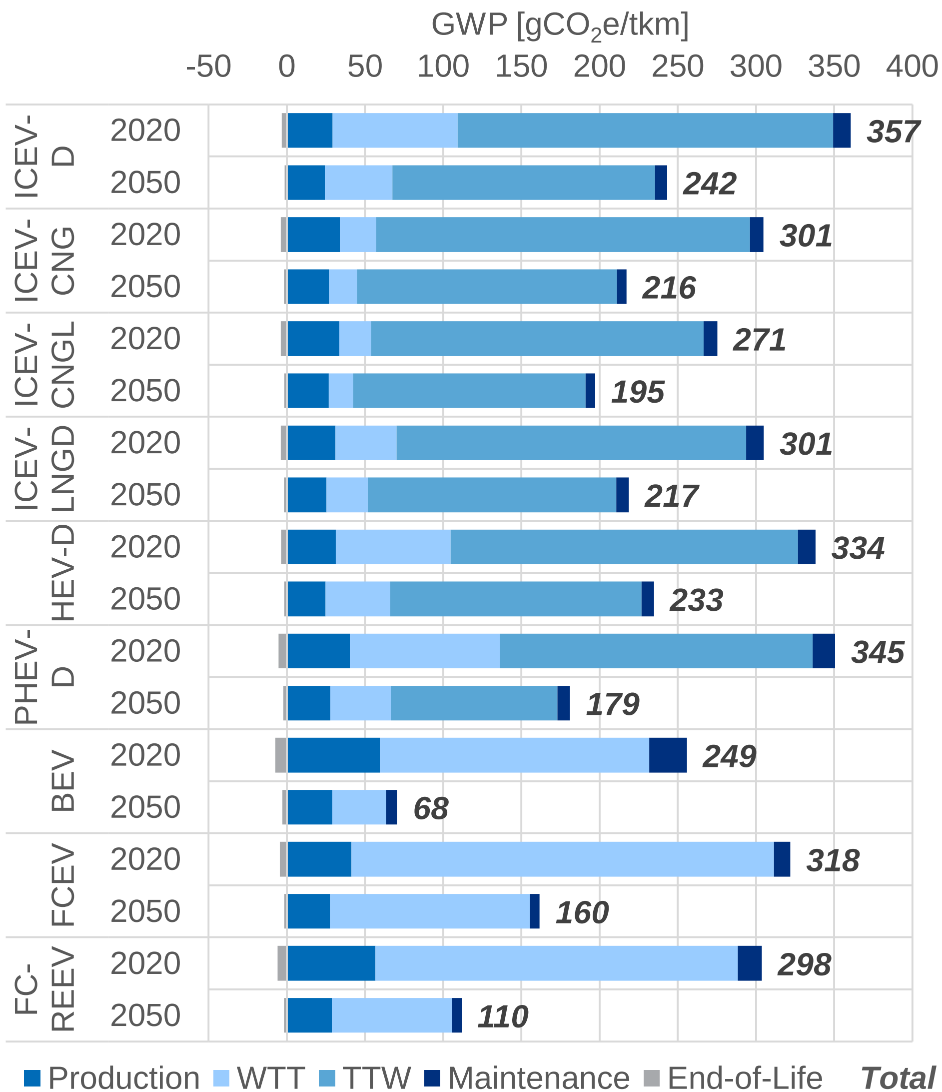
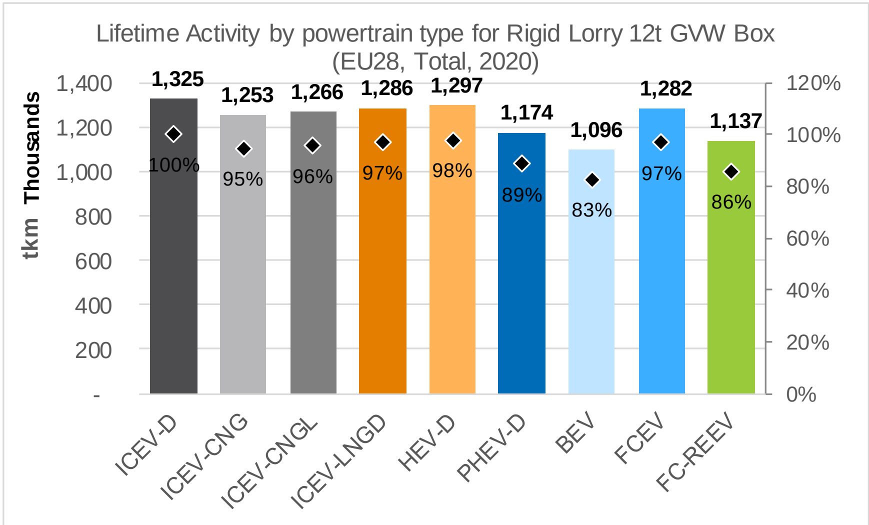
  - Results and comparisons for lower medium cars
  - **Results for other vehicle types**
- Results for energy chains [ifeu / E4tech, 13:30]:
  - Electricity chains [ifeu]
  - Liquid and gaseous fuel chains [E4tech]
- Overall LCA sensitivities [Ricardo, 15:00]
- Other assumptions and general Q&A [Ricardo, 16:15]
- Initial conclusions & recommendations and wrap-up [Ricardo, 17:00]

Overall results for Rigid Lorries: GWP and timeseries

Rigid Lorry – Baseline Scenario



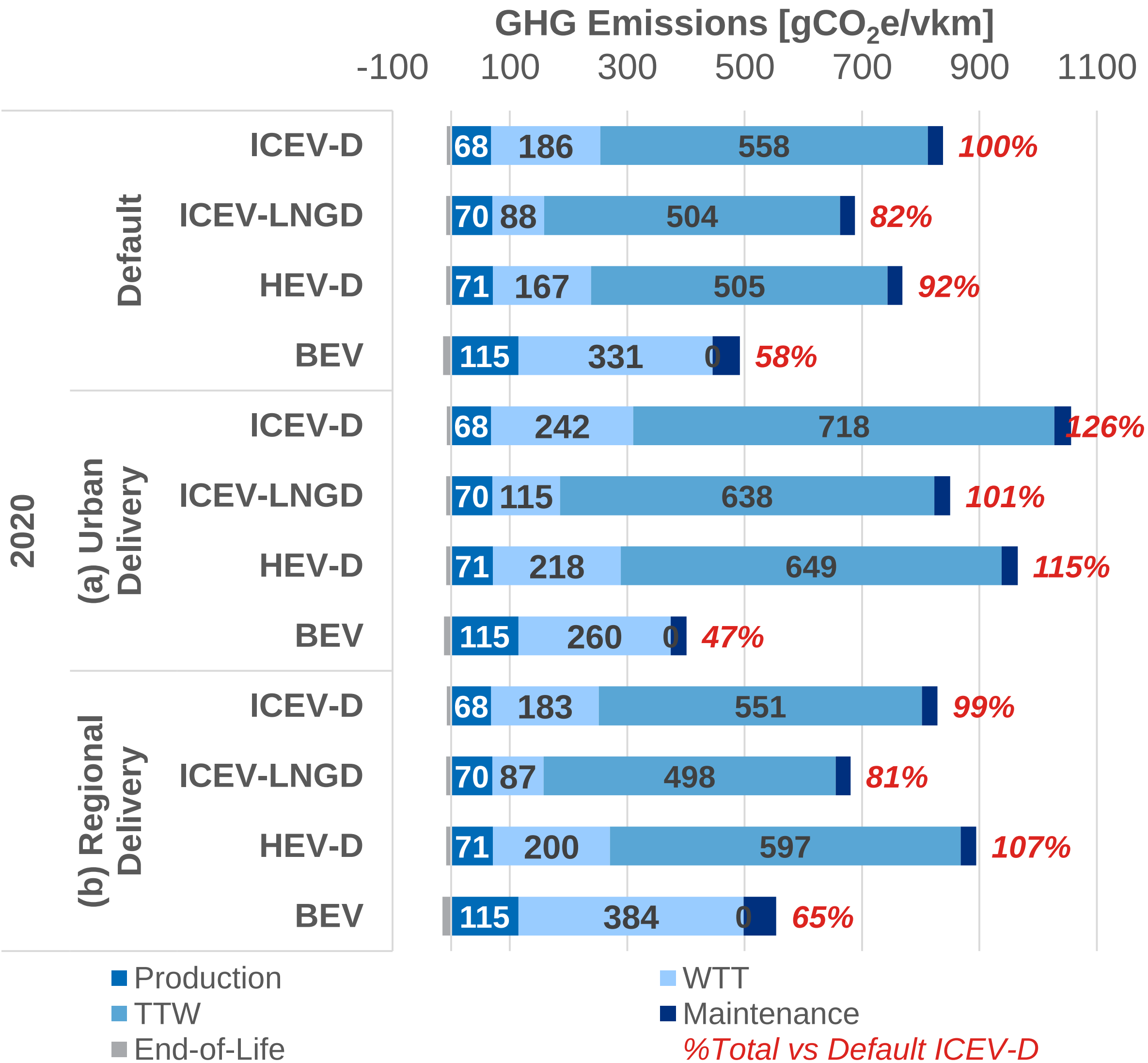
- Similar trends seen as for passenger cars, even accounting for lost load capacity, but BEV vs FCEV difference is larger vs cars
- WTT for gas low vs some WTW analyses; -LNGD highest due to methane slip assumptions (despite higher efficiency)
- Maintenance: Battery replacement required for PHEV, BEV for 2020 (only)
- Higher savings for xEV in urban use



Source: ICEV-LNGD = dual-fuel/HPDI LNG-Diesel powertrain

Overall results for Rigid Lorries: Operation on different cycle basis have significant impacts on the overall results

Rigid Lorry – Baseline Scenario



Default

- ~550,000 km lifetime (EU Av.)
- Battery cell manuf. current
- Electricity EU av. lifetime
- Av. EU ‘Real-world’ MJ/km
- EoL: Recycling credits, low 2nd life battery share

Alternative

a) Urban Delivery Cycle – road share and energy consumption

b) Regional Delivery Cycle – road share and energy consumption

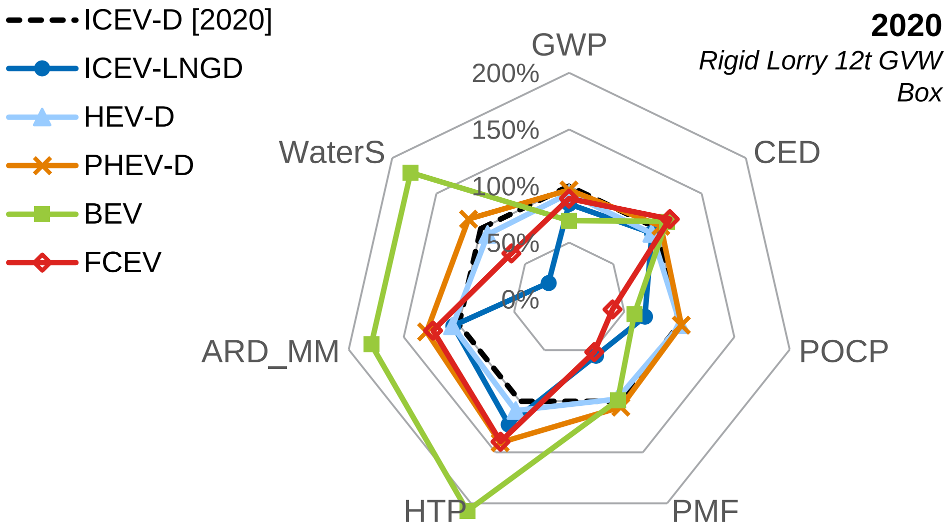
- EU vehicle statistics have higher shares of regional and motorway km versus VECTO cycles

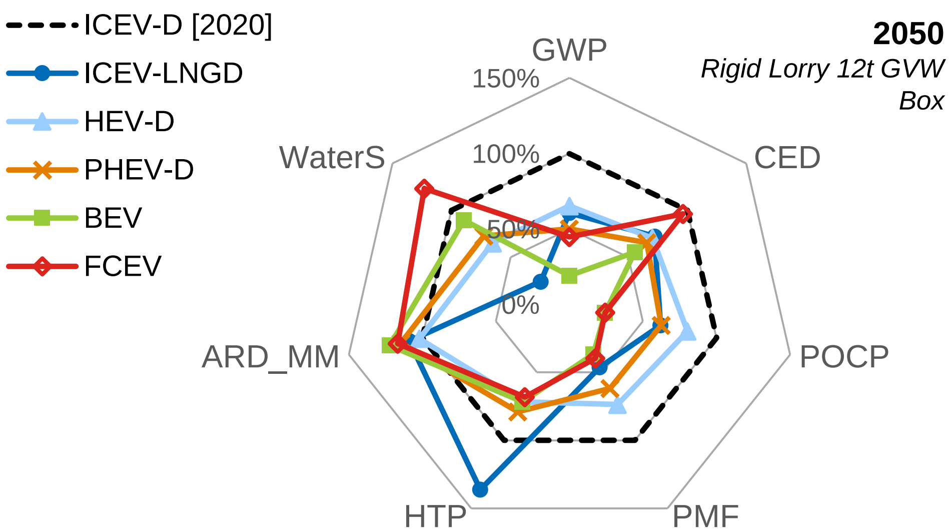
Source: Ricardo analysis (January, 2020); Draft results of EC Vehicle LCA project

Overall results for Rigid Lorries: Other impacts

Rigid Lorry – Baseline Scenario

- 2020 life-cycle impacts for xEVs (especially BEV) are higher than conventional diesel and gas powertrain vehicles across a range of categories (mainly those associated with non-tailpipe emissions)
- Similarly as for cars, higher impacts for ARD_MM and HTP for xEVs are due to vehicle (battery) materials mainly
  - Battery replacement is required for 2020 BEV and PHEV powertrain vehicles, but not in future periods
- Higher impacts for xEVs for WaterS is mainly due to electricity (coal in 2020, solar/nuclear in 2050)
- Impacts for xEVs reduce vs other non-electric/electrified powertrains after 2020

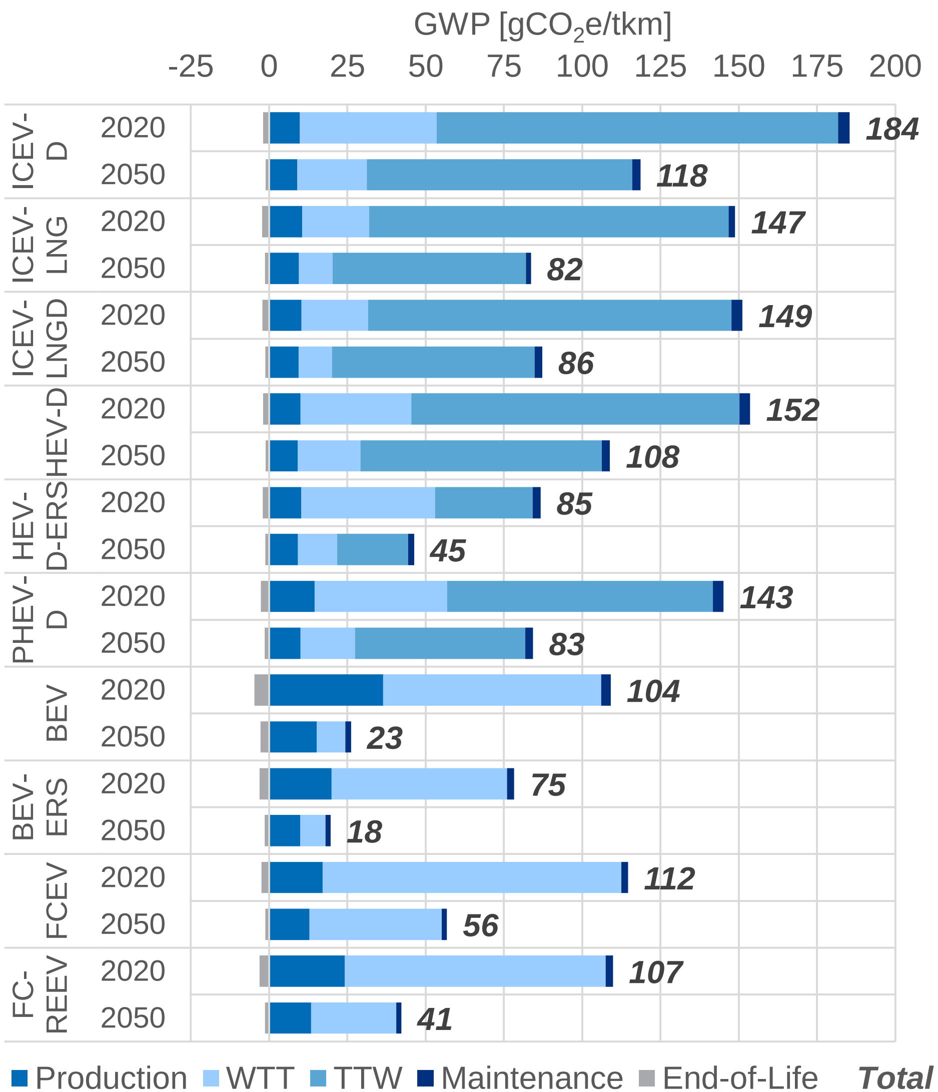




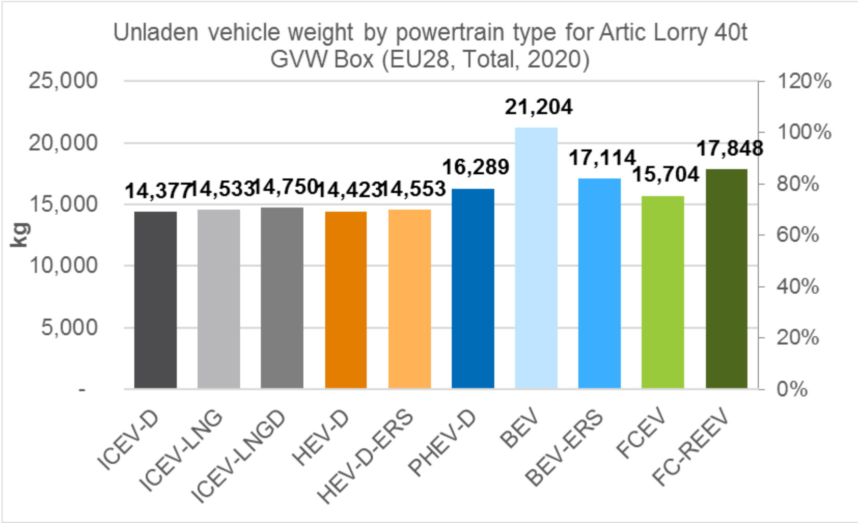
Source: LNGD = LNG HPDI engine, using ~5% diesel (estimated at only 3% energy efficiency penalty vs conventional diesel)

Overall results for Artic Lorries: GWP and timeseries

Artic Lorry – Baseline Scenario

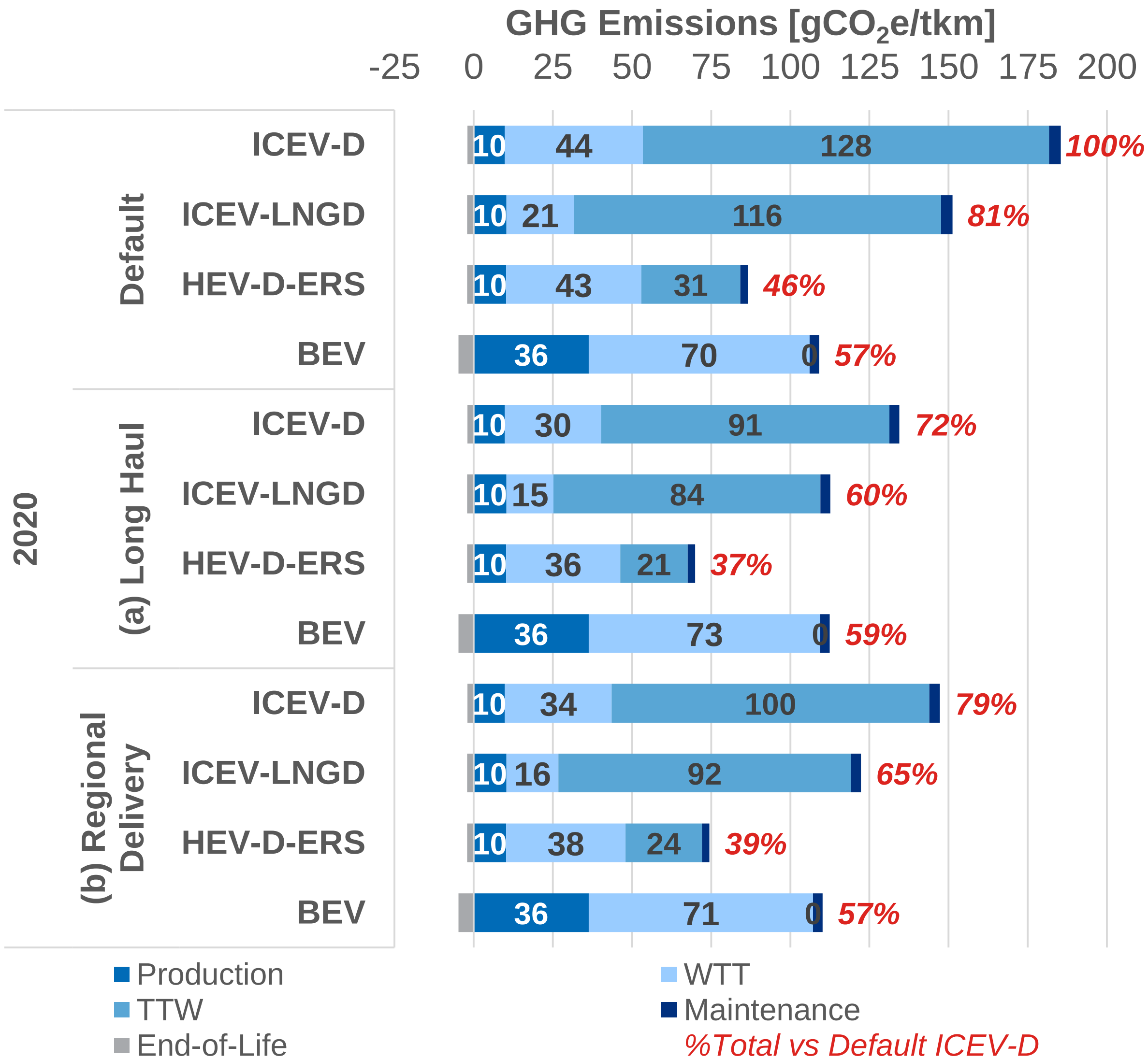


- Similar trends seen as for passenger cars, even accounting for lost load capacity
- Significant benefits of -ERS vs non-ERS powertrains (lower battery size/mass vs BEV)
- WTT for gas << previous WTW analyses, -LNGD highest due to methane slip assumptions (despite higher efficiency)
- Maintenance: Battery replacement required for PHEV, BEV for 2020 (only)



Overall results for Artic Lorries: Operation on different cycle basis have significant impacts on the overall results

Artic Lorry – Baseline Scenario



Default

- ~800,000 km lifetime (EU Av.)
- Battery cell manuf. current
- Electricity EU av. lifetime
- Av. EU 'Real-world' MJ/km
- EoL: Recycling credits, low 2nd life battery share

Alternative

a) Long Haul Cycle – road share and energy consumption

b) Regional Delivery Cycle – road share and energy consumption

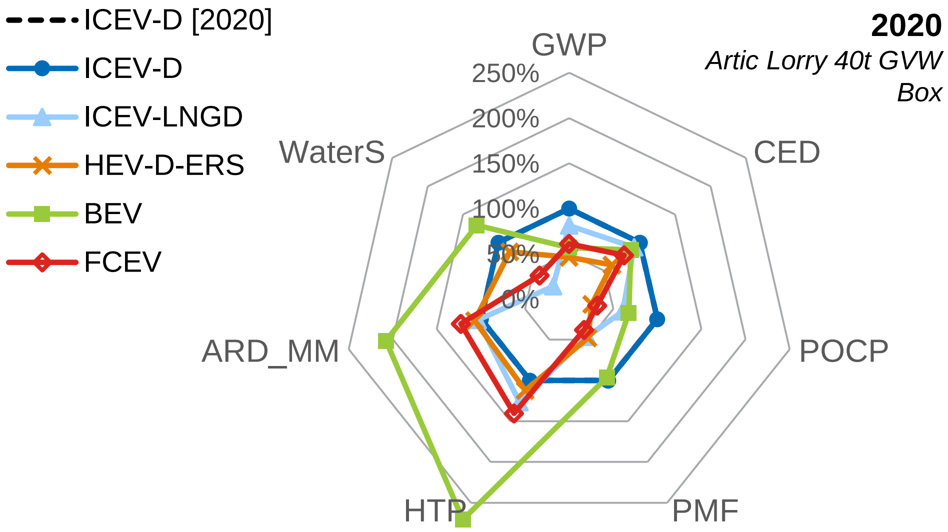
- EU vehicle statistics have higher shares of urban and regional km versus VECTO cycles

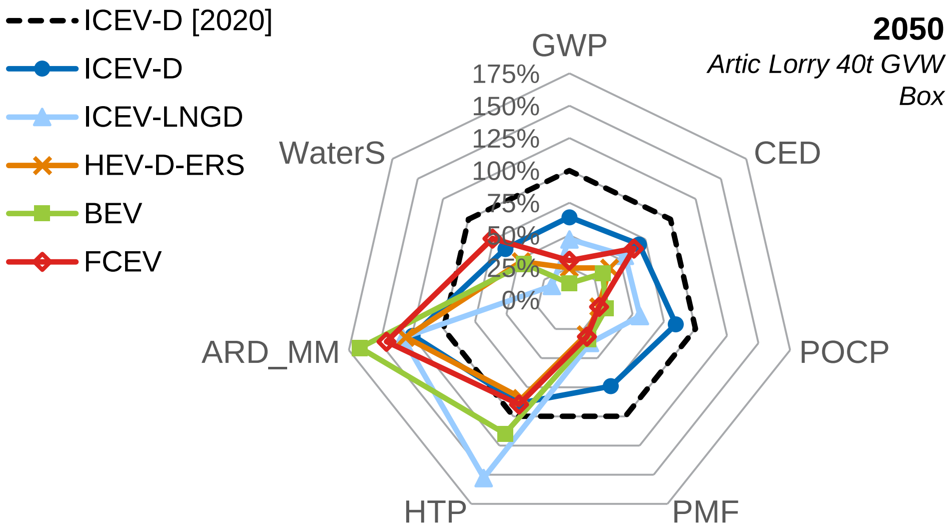
Source: Ricardo analysis (January, 2020); Draft results of EC Vehicle LCA project

Overall results for Artic Lorries: Other impacts

Artic Lorry – Baseline Scenario

- Gas powertrains (e.g. ICEV-LNGD) show significant non-GHG benefits across a number of categories vs diesel
- Higher ARD_MM, HTP impacts due to vehicle production mainly (batteries for xEVs, gas storage for LNGD, FCEV)
  - Battery replacement required for 2020 vintage BEV contributes to this
    - Not required 2030 onwards
- HEV-D-ERS show significant reduction in other impact categories, with significantly reduced negative impacts on ARD_MM and HTP in 2020
  - Relative benefits diminish after 2020
- Higher impacts for WaterS in 2020 due to electricity (as indicated for Rigid Lorries)

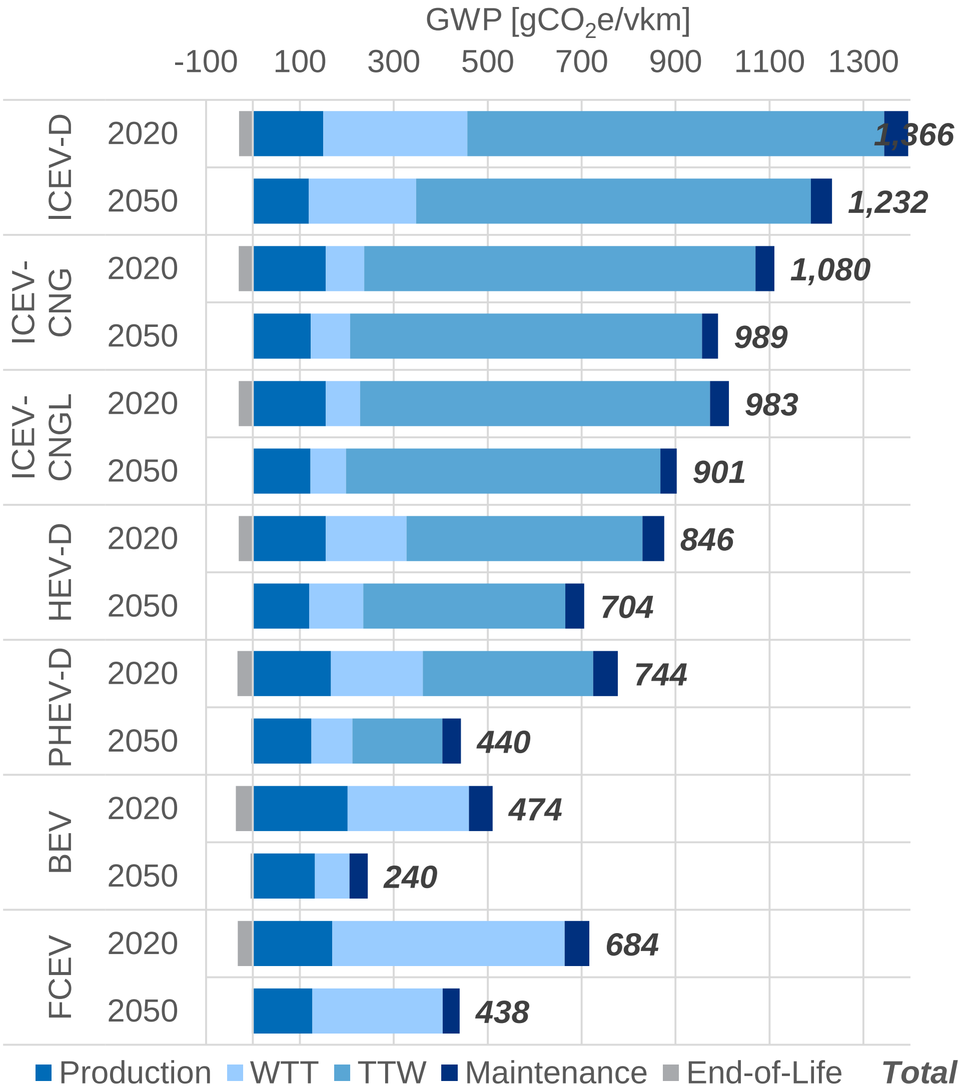




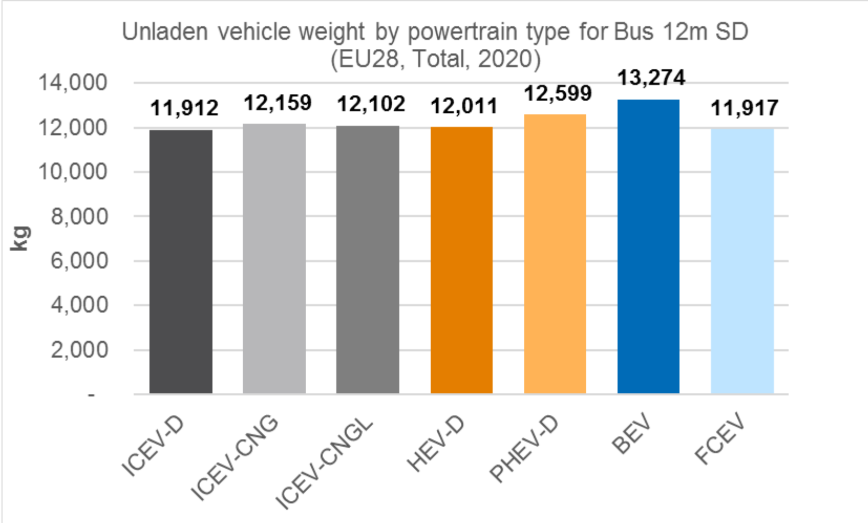
Source: LNGD = LNG HPDI engine, using ~5% diesel (estimated at only 3% energy efficiency penalty vs conventional diesel)

Overall results for 12m Urban Bus: GWP and timeseries

Urban Bus – Baseline Scenario



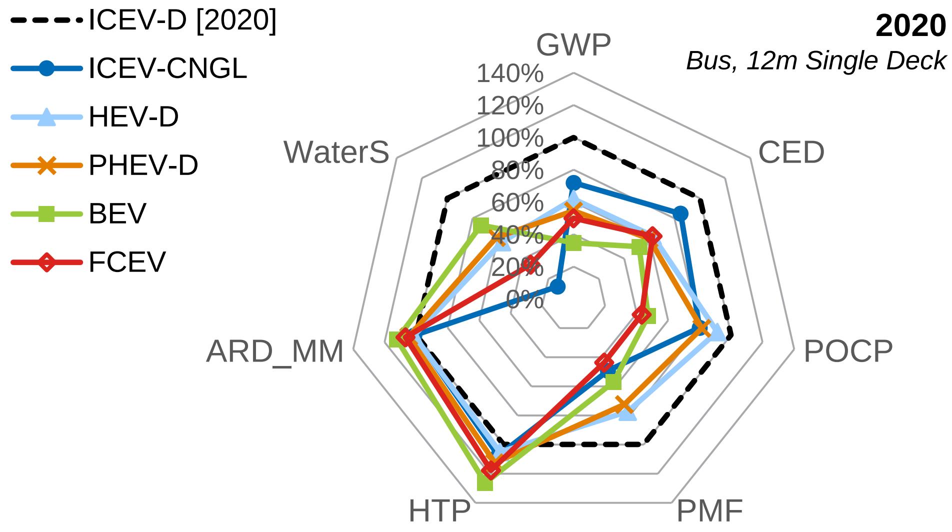
- Similar trends seen as for passenger cars
  - Urban setting enhances benefits for xEVs compared to conventional
- WTT for gas << previous WTW analyses, but hybrid savings still greater despite this
- Maintenance: Battery replacement required for PHEV, BEV for 2020 (only)

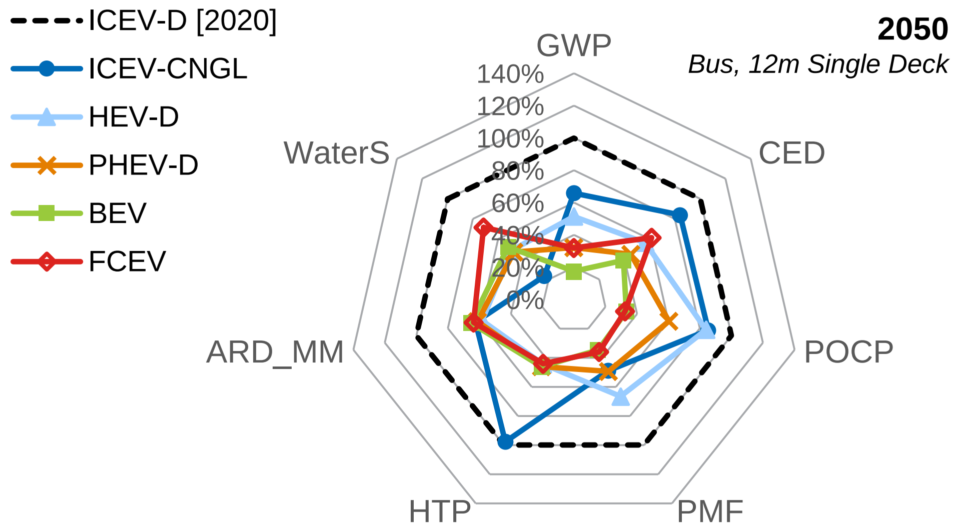


Overall results for 12m Urban Bus : Other impacts

Urban Bus – Baseline Scenario

- Gas powertrains (e.g. ICEV-CNGL) show significant non-GHG benefits across a number of categories vs diesel
- Higher impacts for ARD_MM, HTP, WaterS as previously for Rigid/Artic Lorry
  - The first two are increased due to battery replacement for 2020 vintage
  - Negative consequences relatively smaller compared to those for lorries
- xEV powertrains show significant benefits due to reduction in air quality pollutants contributing to POCP, PMF
- Benefits FCEV vs BEV
  - Greater in 2020 (H2 from SMR)
  - Similar or lower by 2050 (H2 from a mix of SMR+CCS and electrolysis)





Source: CNGL = CNG Lean-burn engine (estimated at only 3% energy efficiency penalty vs conventional diesel)

Summary of key findings from overall results

- Results prove the interesting performance profiles for EVs across all metrics assessed in the study, whilst highlighting key dependencies and hotspots to be addressed:
  - *Hotspots due to electricity*: varies by impact mid-point and generation type. Impacts from biomass generation appear to be particularly large in a number of cases
  - *Hotspots in HTP / ETP_FA / ARD_MM due to materials*: copper, electronics and certain other battery materials (but not cobalt or lithium as low % of total mass)
  - *Hotspots for CED and WaterS for FCEVs/H2*, particularly for electrolysis
- Benefits of BEV, PHEV, FCEV significantly enhanced between 2020 and 2030 due to decarbonisation of electricity/H2, battery improvements
  - No battery replacements after 2020 even for HDVs, based battery cycle life and capacity increases assumed
- The findings for natural (and bio-/synthetic-) gas fuelled vehicle show that these can provide significant benefits vs conventional alternatives across a range of impacts:
  - Some uncertainty remains over WTT components for GHG
  - CH4-slip in dual-fuel gas-diesel vehicles undermines / may eliminate efficiency benefits
- Findings for low carbon fuels are less clear, need further work: questions remain on fossil gas chains, and on novel synthetic fuels, which are further discussed later

Agenda

- Introduction, background and objectives of the meeting [09:00]
- Overview of the developed methodology [ifeu, 09:30]
- Overall LCA results [Ricardo, 11:00]
  - Results and comparisons for lower medium cars
  - Results for other vehicle types
- **Results for energy chains [ifeu / E4tech, 13:30]:**
  - **Electricity chains [ifeu]**
  - Liquid and gaseous fuel chains [E4tech]
- Overall LCA sensitivities [Ricardo, 15:00]
- Other assumptions and general Q&A [Ricardo, 16:15]
- Initial conclusions & recommendations and wrap-up [Ricardo, 17:00]

Outline for energy chains – electricity chains

Results for electricity chains

ifeu – institute for energy and environmental research Heidelberg

Outline for energy chains – electricity chains

- The ifeu electricity model
- Data background
- Definition of defined cases for data sets
- Results

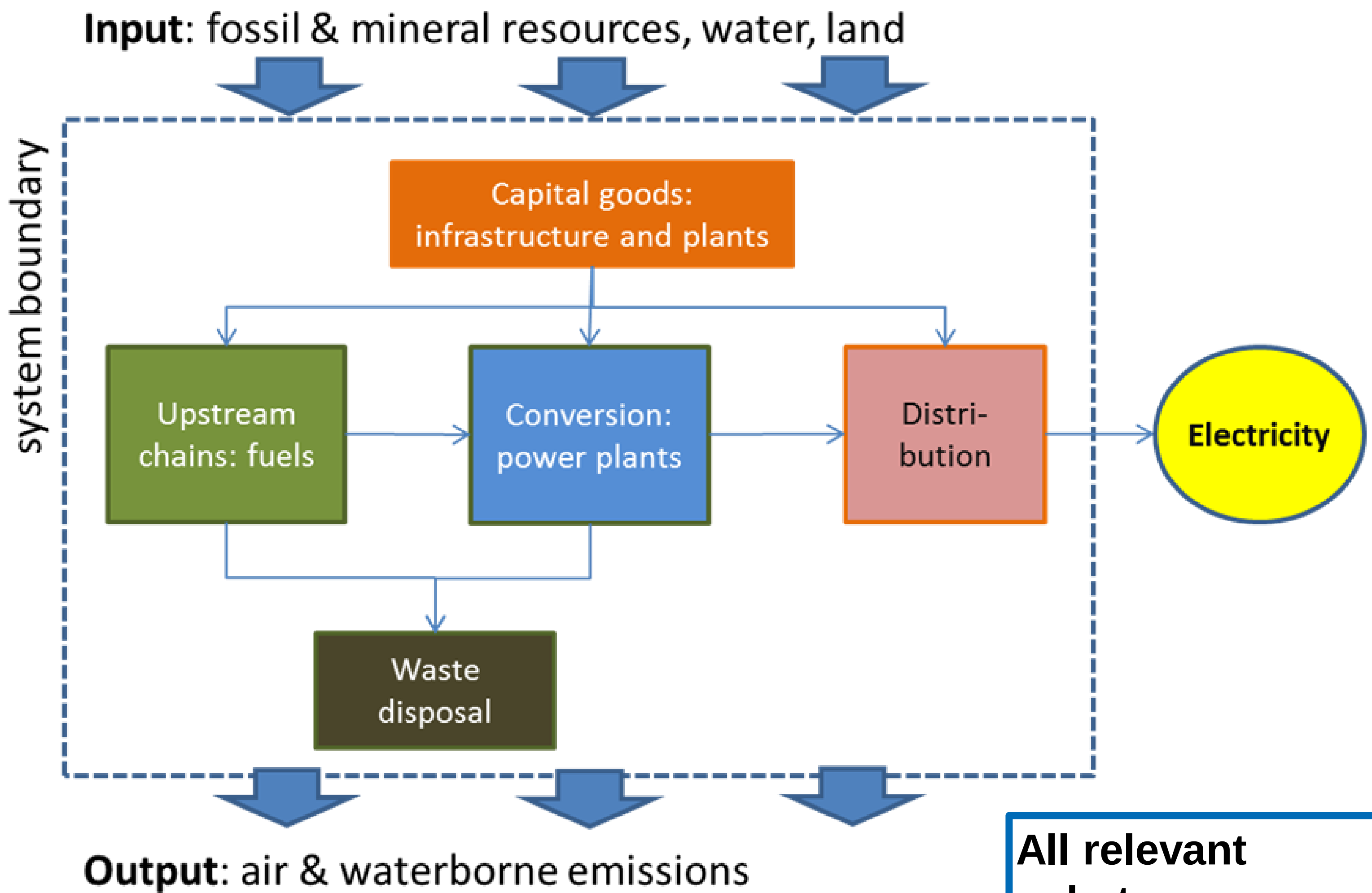
The ifeu electricity model

Reasons for using the ifeu electricity model

- The goal and scope of the LCA project requires consistent data sets
  - for defined geographical and temporal settings
  - corresponding with different scenarios (such as defined by PRIMES)
  - covering the whole range of applied impacts categories
- The ifeu electricity model can provide all required data sets and combinations of the above mentioned requirements
- Other available data sets do not cover all these settings or comprehensive LCI data for all the impacts categories

The ifeu electricity model

System boundary:



All relevant substages covered

Data background

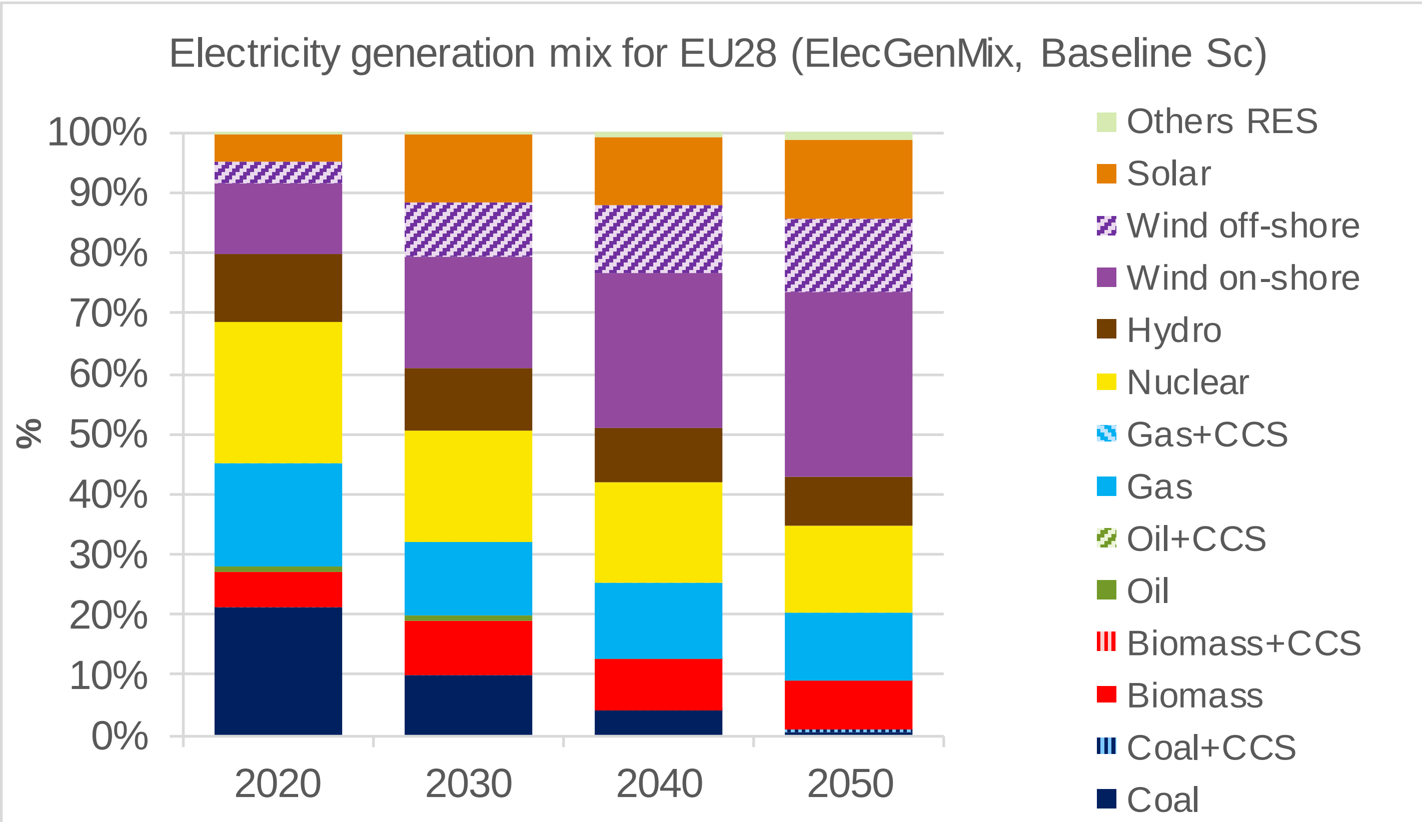
	Data type	Description	
Foreground data	Selection of the fuel mix	**EU regions:** Conversion efficiency and fuel mixes based on EC PRIMES modelling scenario outputs for different countries / EU28 as a whole.	**non-EU regions:** IEA data for fuel mix and efficiency losses based on data from Econinvent
	Generation efficiency		
	Losses		
	Temporal considerations	Starting with the current (2020) situation with robust assumptions regarding future developments and corresponding projected future mixes based on EC PRIMES for two different scenarios (baseline vs. 1.5 tech)	
	Spatial considerations	All countries under scope and additional countries that have relevant contributions to the supply chain for all relevant direct (import of electricity) and indirect flows	
Backgorund data	Fuels	Ecoinvent 3.4 in most cases.	
	Transport	TREMOD	
	Infrastructure, capital goods	ecoinvent 3.4 Including current data from producers (Wind power plant construction PV modules)	

Definition of defined cases for data sets

Fuel type	Region specific data			Timeframe	Scenario
Coal (hard coal, lignite) Coal + CCS	**EU28, all member states**			2020	2°C (baseline)
Fuel Oil Fuel Oil + CCS	AT	FI	LU	2030	1,5°C
Natural Gas Natural Gas + CCS	BE	FR	NL	2040	
Nuclear power	BG	GR	PL	2050	
Solar	CY	HR	PT		
Wind (on-shore, off-shore)	CZ	HU	RO		
Solid biofuels Solid biofuels + CCS	DE	IE	SE		
Hydro	DK	IT	SK		
Other RES	EE	LT	UK		
	ES	LV			
	Non-EU				
	CN	JP	KR		
	US	World			

Definition of defined cases for data sets

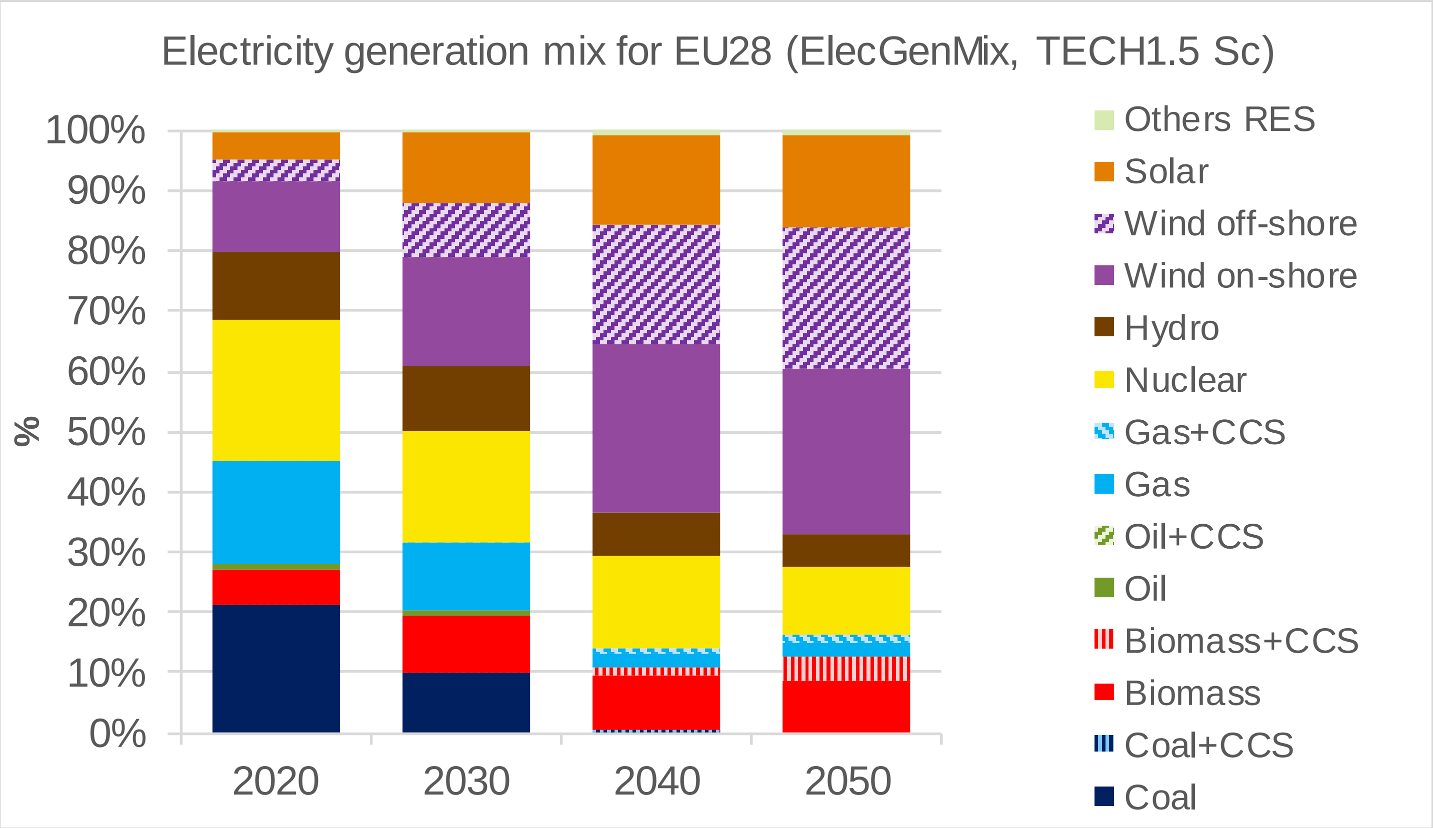
Exemplary cases: **EU28** – Timeframe: 2020 - 2050 – Scenario: Baseline



- **Transition from fossil / conventional to renewables**

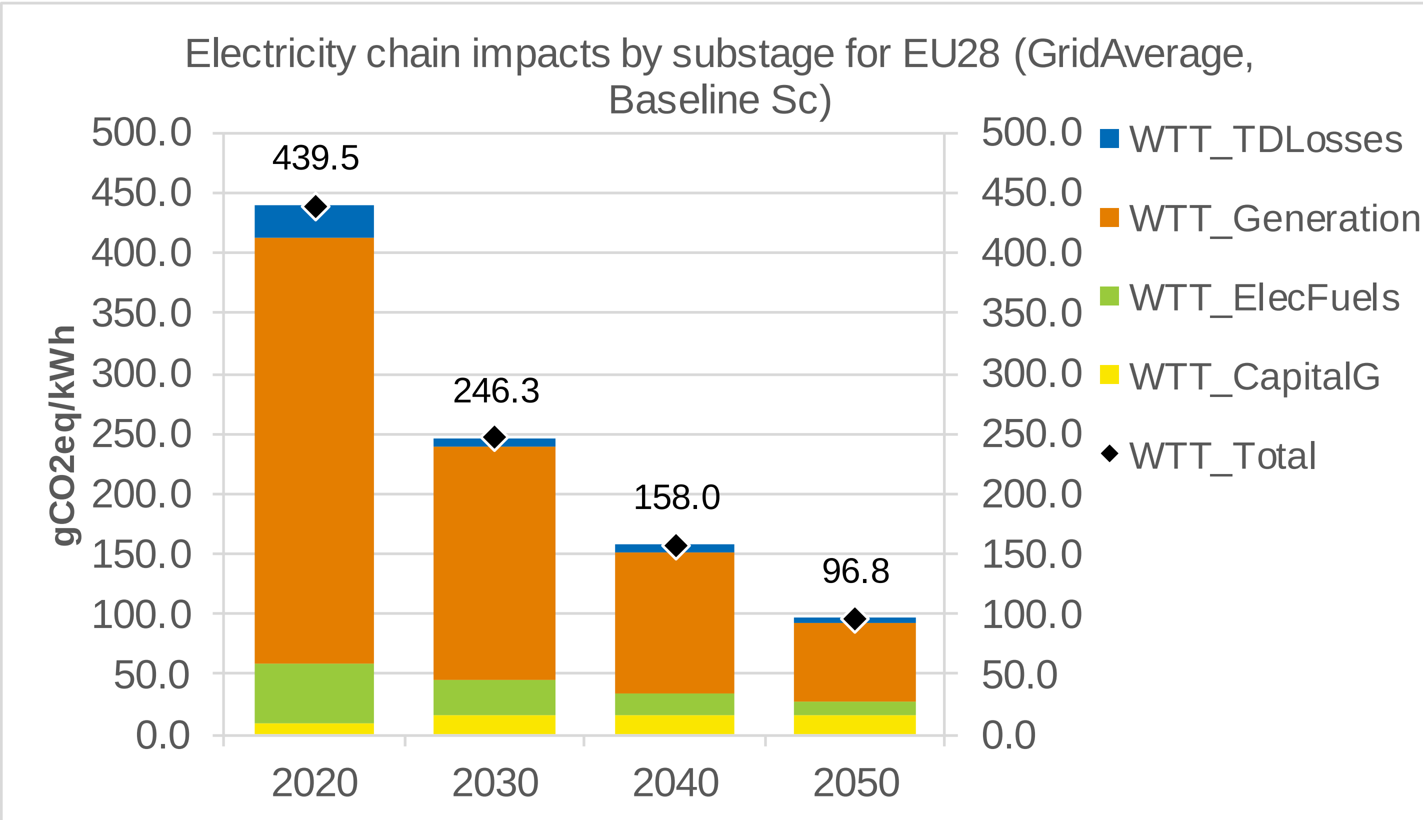
Definition of defined cases for data sets

Exemplary cases: **EU28** – Timeframe: 2020 - 2050 – Scenario: 1.5 Tech



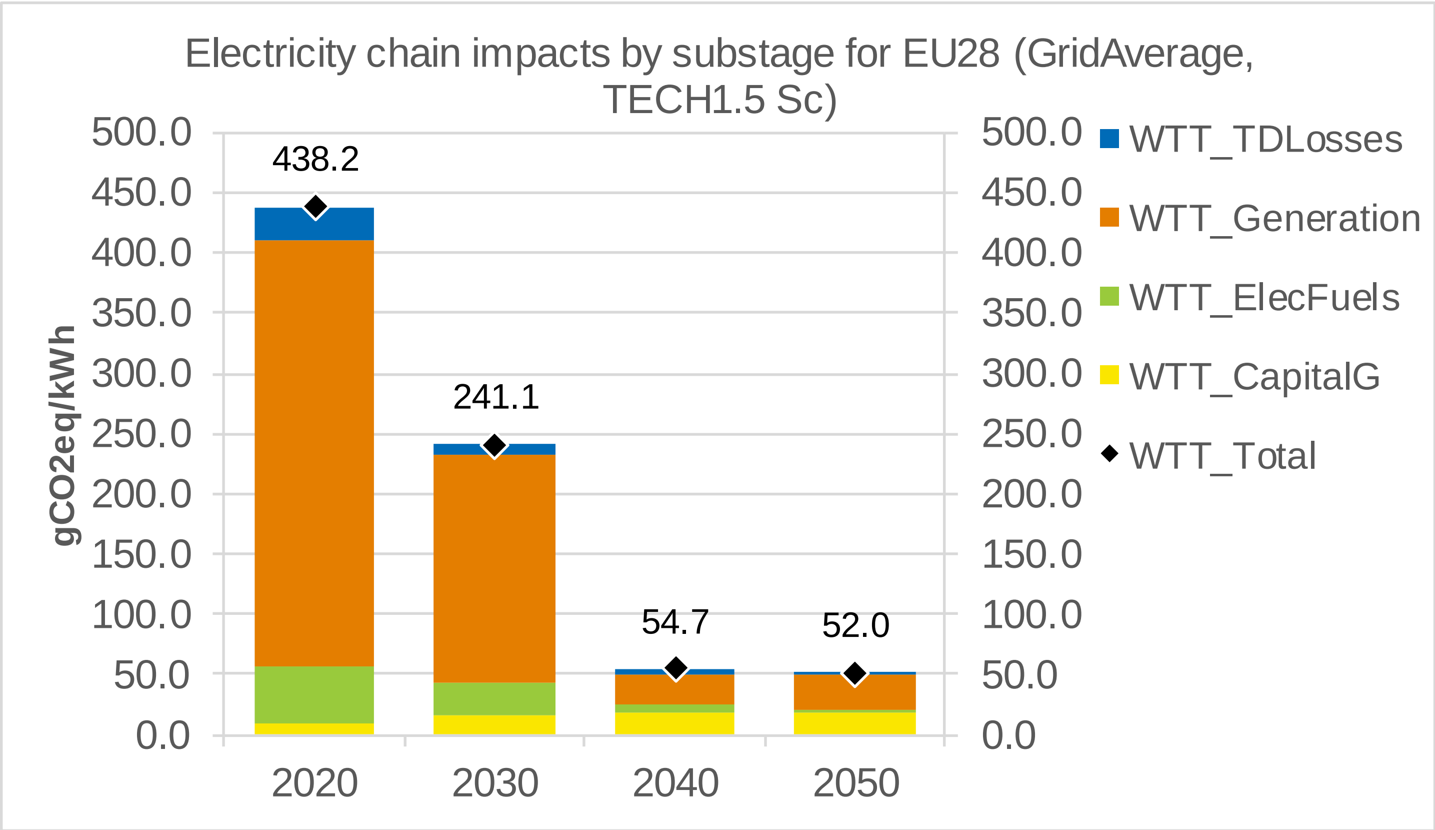
- **Transition from fossil / conventional to renewables, but faster & more progressive (e.g. Biomass + CCS)**

Results



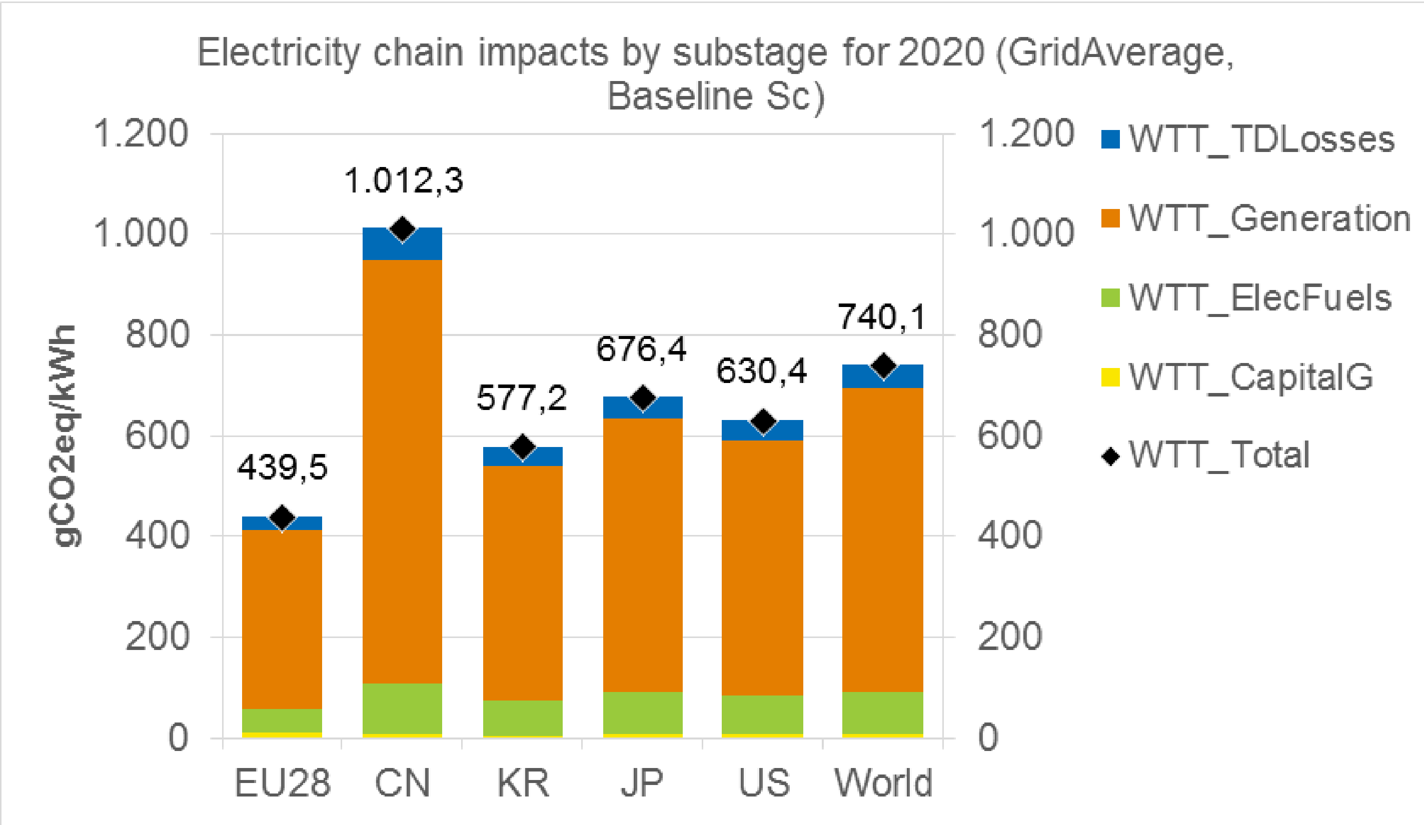
- **Significant drop in GWP following the transition to renewables**
- **Shift from generation related emissions to capital goods**

Results

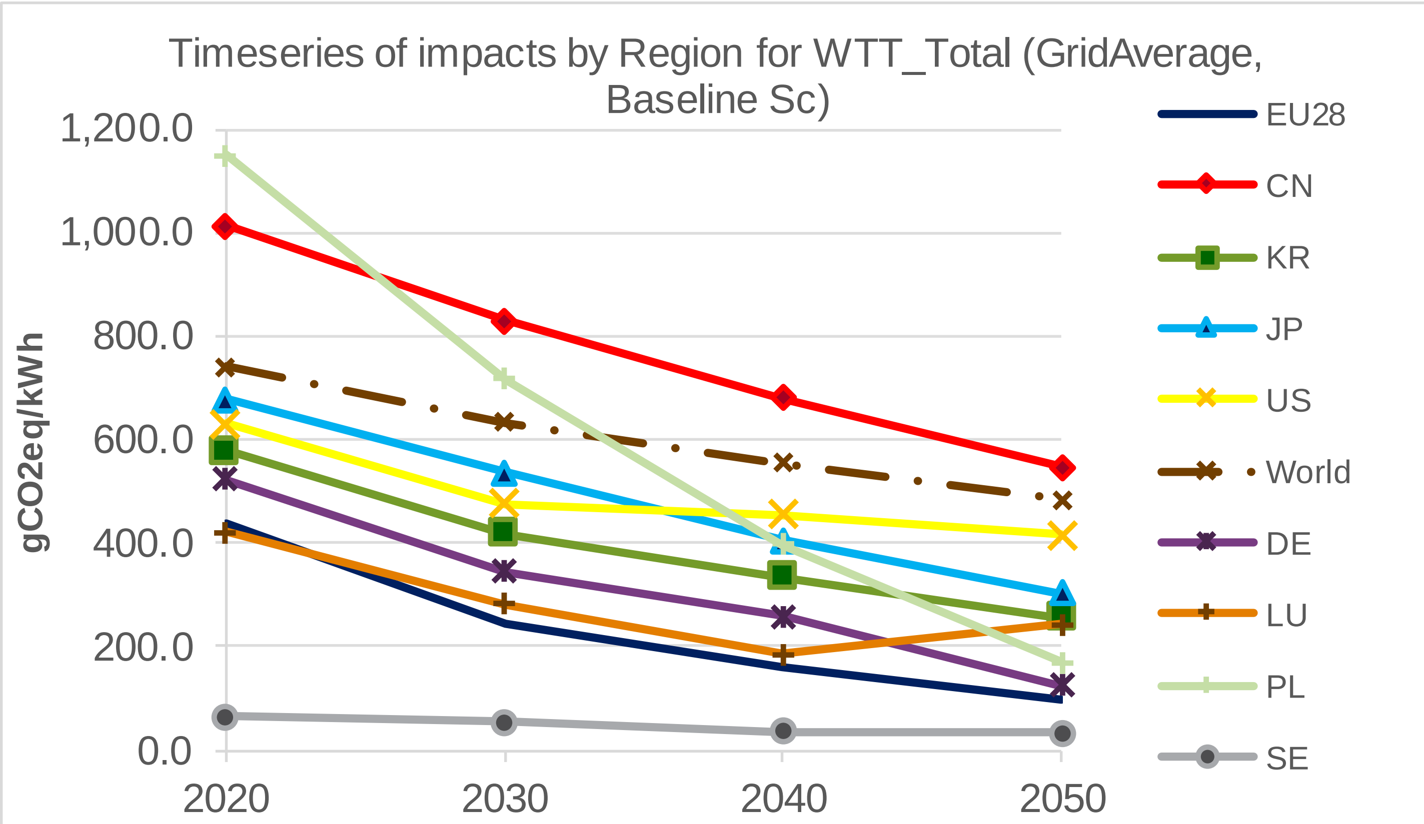


- **Marignal differences in 2020 but significant in the time period after 2030**
- **Even higher specific contribution of infrastructure provision due to larger share of renewables**

Results

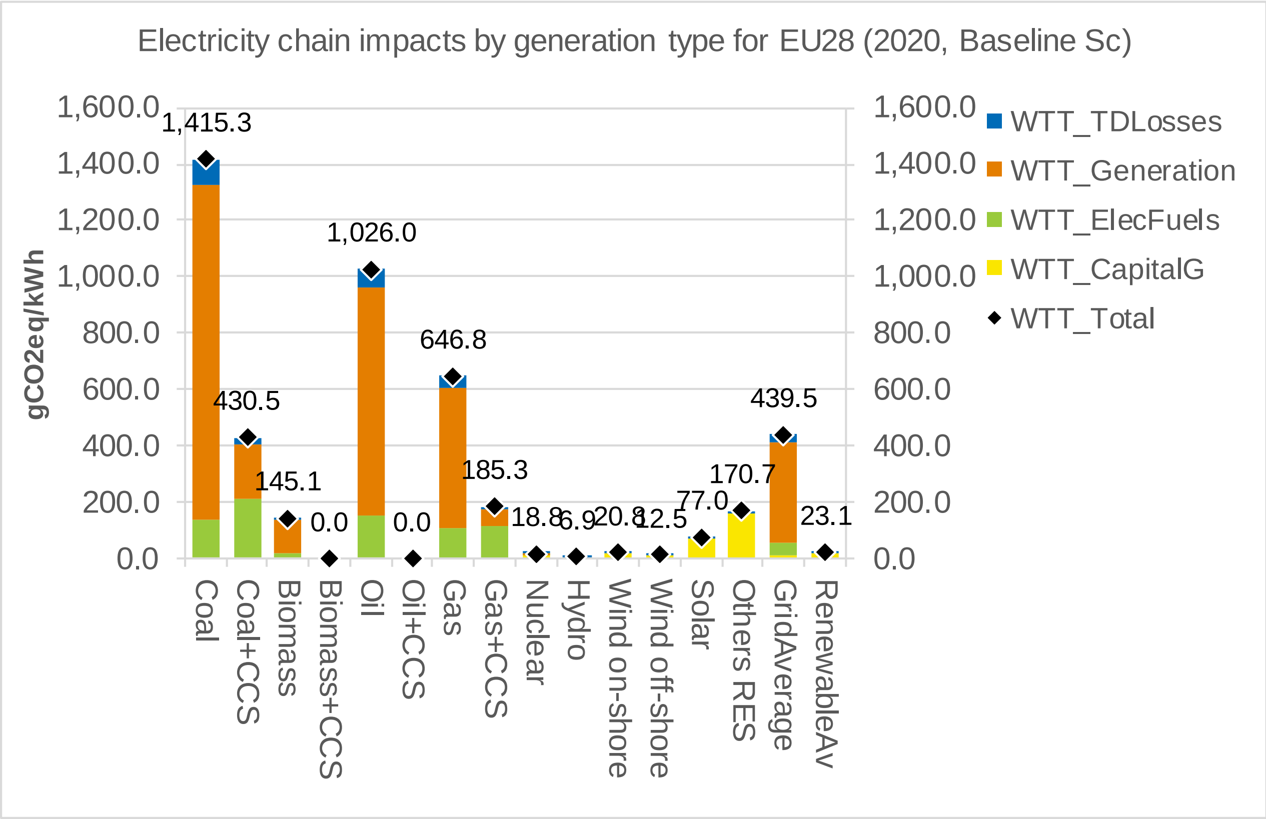

Electricity chain impacts by substage for 2020 (GridAverage, Baseline Sc)
gCO2eq/kWh
1.200
1.000
800
600
400
200
0
1.200
1.000
800
600
400
200
0
439,5
1.012,3
577,2
676,4
630,4
740,1
EU28
CN
KR
JP
US
World
WTT_TDLosses
WTT_Generation
WTT_ElecFuels
WTT_CapitalG
WTT_Total

Results



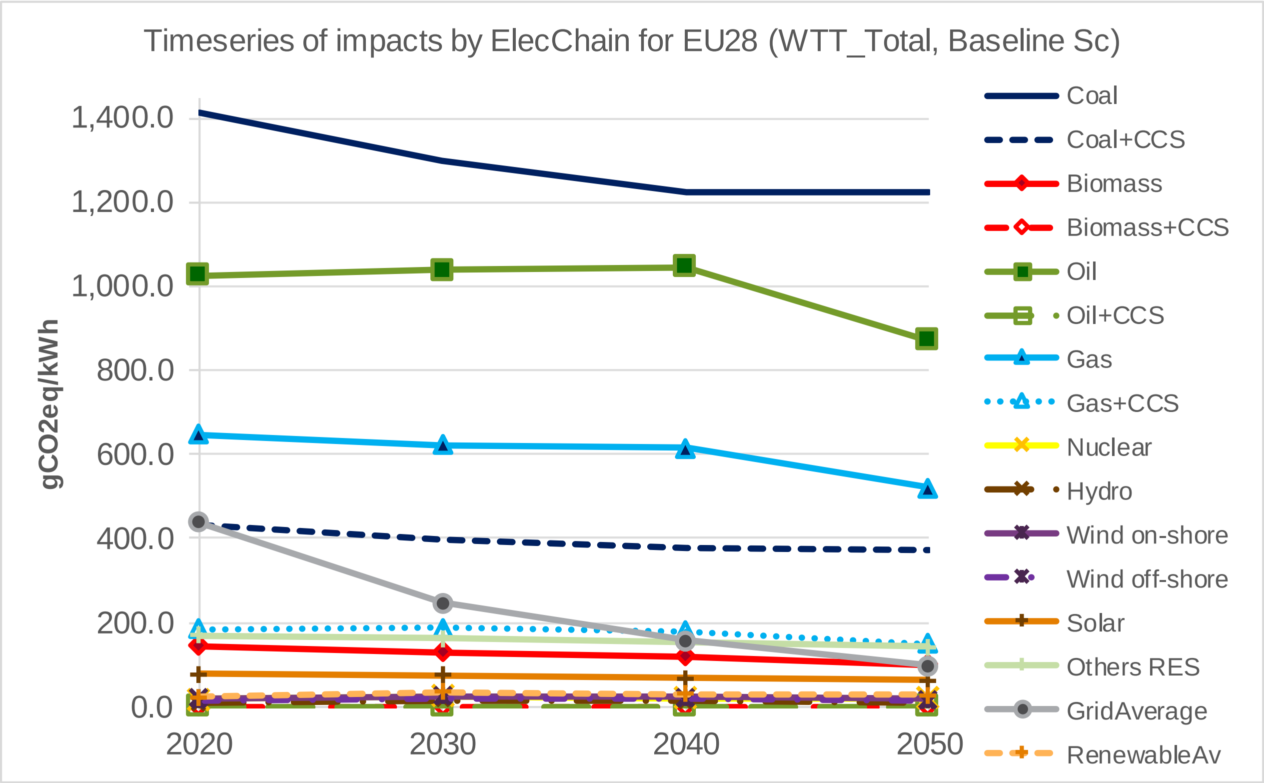
- **RoW decarbonises as well but to another degree and overall pace**
- **Differences within european power generation (differs from country to country)**

Results



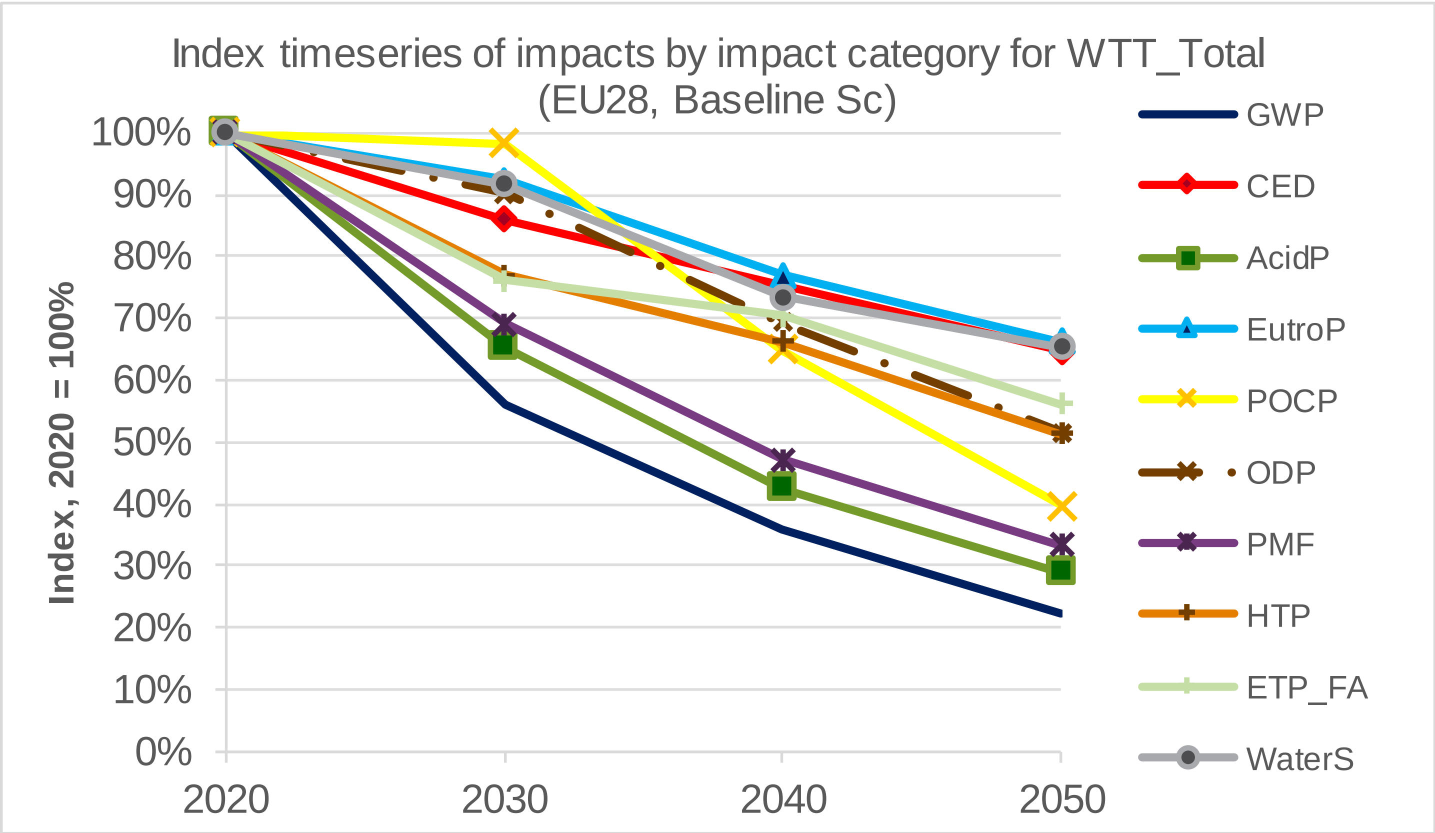
- **GWP of decisive electricity chains vary up to a factor of 200 (e.g. coal vs. wind)**

Results



- **Technologies / efficiencies moderatly develop over time**

Results



- **GWP in particular, but all other impact categories show a stark decline compared to the current situation**
- **Will impact xEV LC performance most notably, but all others as well due to influencing the manufacturing stage**

Electricity chains - summary

(a) Ifeu model for flexibility and to meet projects' goal / scope

(b) All relevant life cycle stages covered

(c) Investigated all EU countries & a number of important third party countries with influence on the product system

(d) 2020 – 2050 (& further projections)

(e) Baseline vs. 1.5 Tech scenarios

(f) Significant differences between different electricity chains (e.g. coal vs wind)

(g) Both scenarios transition towards renewables but pace / extend vary

(h) LCIA results vary accordingly but show the same trend

(i) RoW decarbonizes, too. But to a different degree / pace

Key achievements

(a) what are the key achievements, strengths and robust findings/conclusions to be drawn from our work?

I. Broad scope allows for holistic analysis of electricity generation

II. Robust data, emphasize on scenarios

III. Wide range of impact categories allows for a thorough analysis beyond GWP

(b) what are the important outstanding uncertainties, limitations/gaps and recommendations for future work?

(a) LCA only approximation of reality. The results are only as good as the underlying data and model

(b) Broad scope. Impossible to fully account for the complexity and characteristics of the power supply of each country

(c) Scenarios are always projections of the future with room for errors and or possible different developments

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Module 3: Liquid and Gaseous Fuels

Determining the environmental impacts of conventional and alternatively fuelled vehicles through Life Cycle Assessment

European Commission

16th January 2020

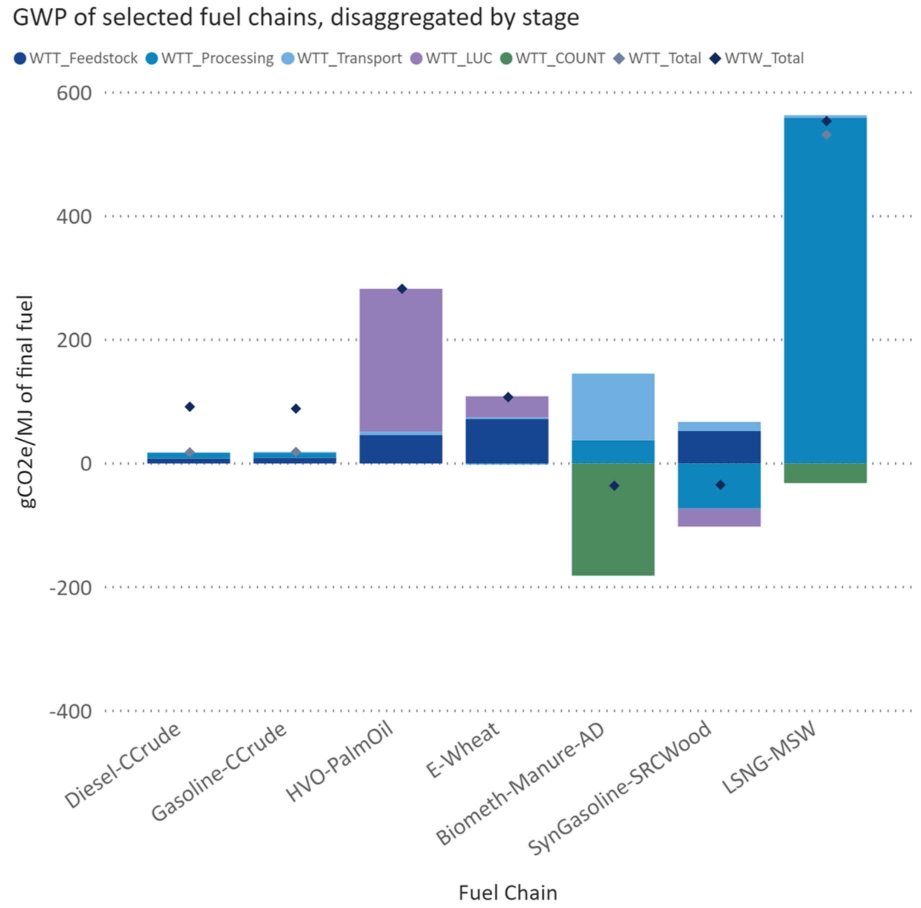
Content

1. Introduction and overview of results
2. Influence of foreground data on results
3. Multi-functionality: Impact of substitution on results
4. Use of counterfactual scenarios (secondary fossil/biogenic fuels)
5. Land-Use Change (primary biogenic fuels)
6. Impact of electricity source on LCA results for e-fuels
7. Crude refining: Modelling results (primary fossil fuels)
8. Non-GWP impacts
9. Initial conclusions and recommendations

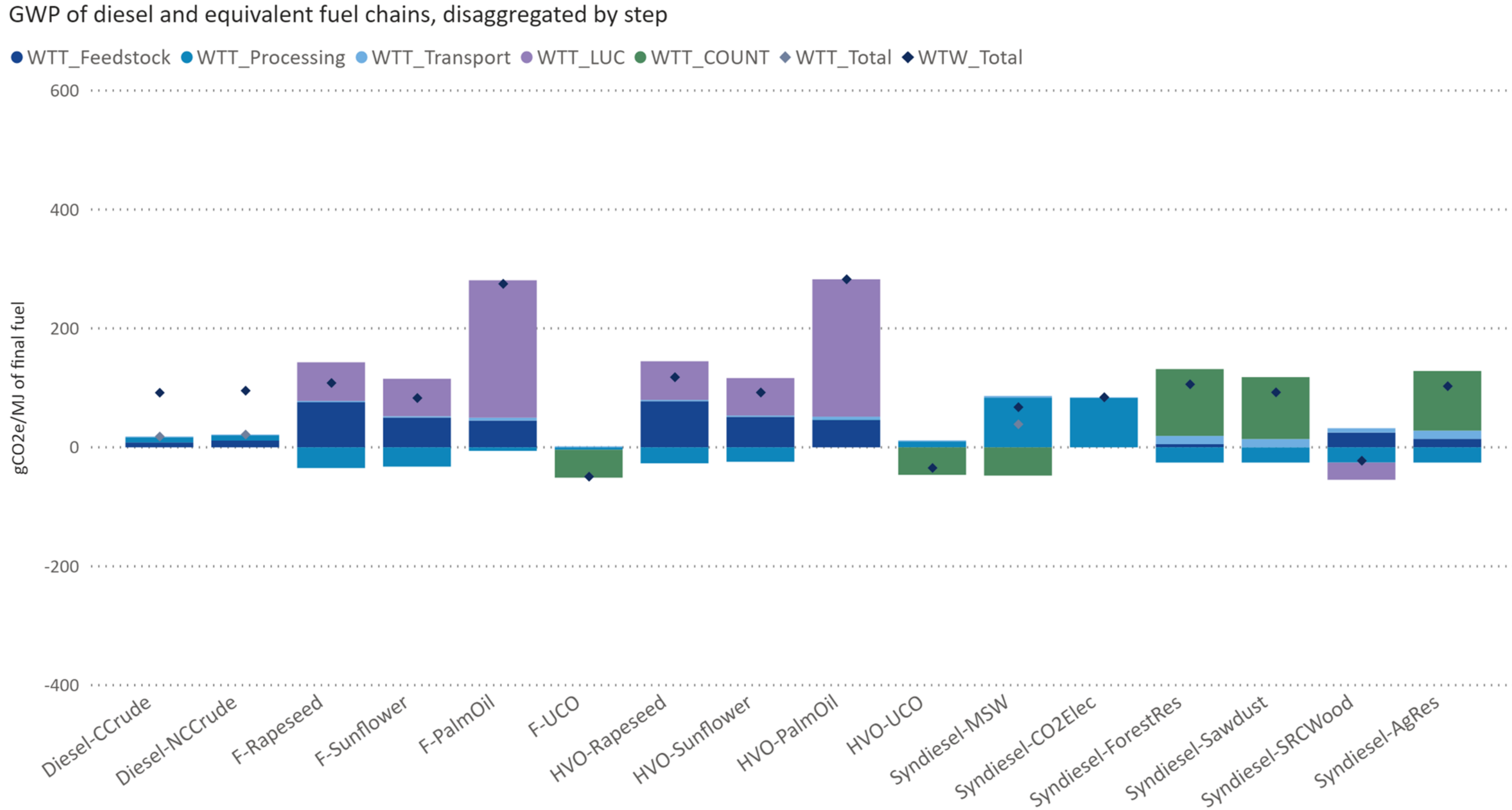
Introduction and Overview of Results

Introduction

- The scope of the fuels module was set as **Well-to-Tank** (WTT), under which 59 fuel chains have been modelled.
- In addition to the general LCA framework of the project, a number **key methodological choices** were made for fuels, which differ from other approaches (e.g. Annex V of RED II):
  - Using a **substitution method** to address multifunctionality;
  - **Counterfactual emissions** of secondary feedstocks;
  - Inclusion of both **direct and indirect LUC** for primary biomass feedstocks;
  - Inclusion of **infrastructure emissions**.
- Due to the inclusion of LUC, the results displayed focus on the GWP of the fuel chains.

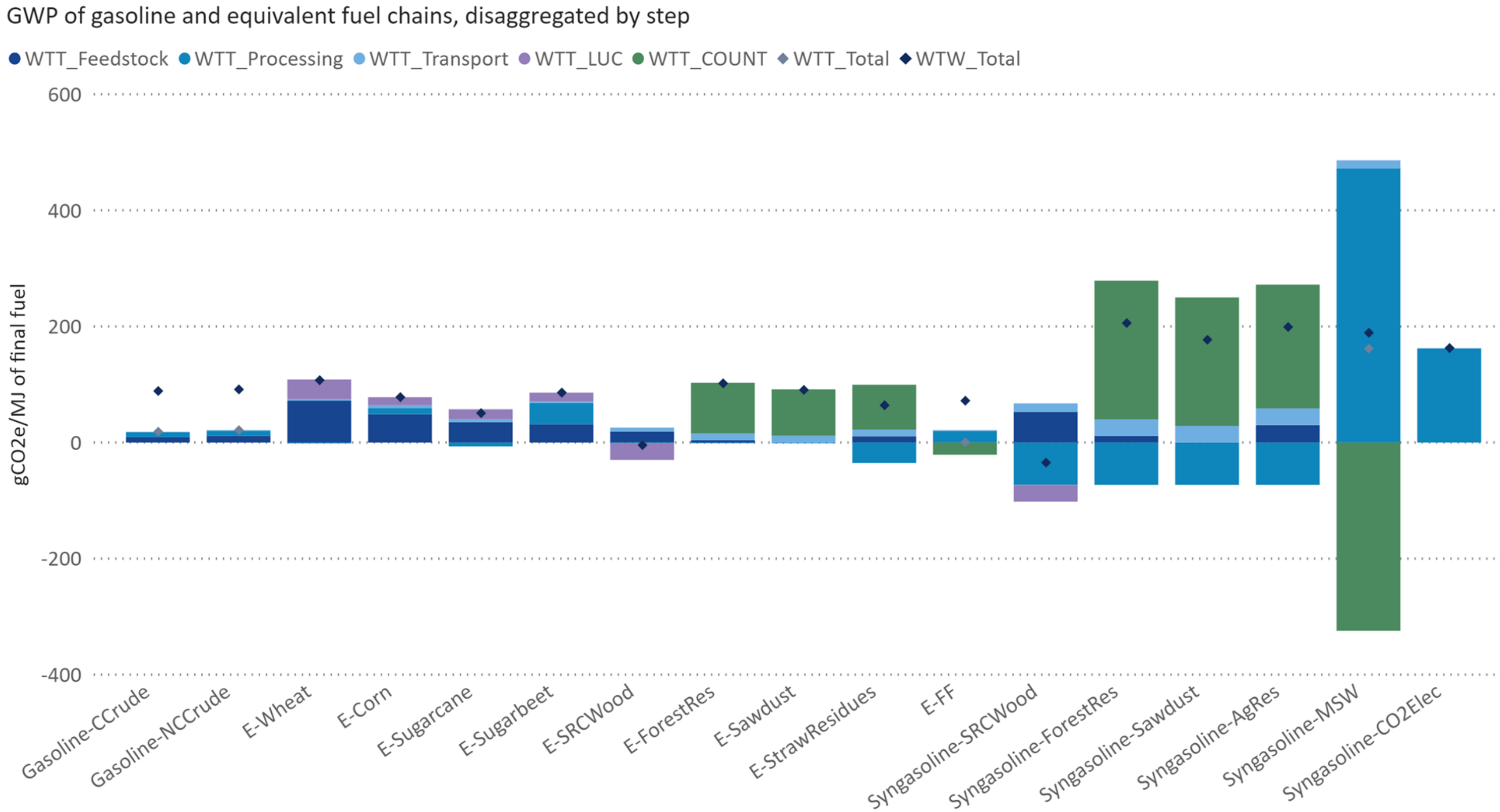


Overview of Results: GWP impacts of diesel and equivalent fuel chains



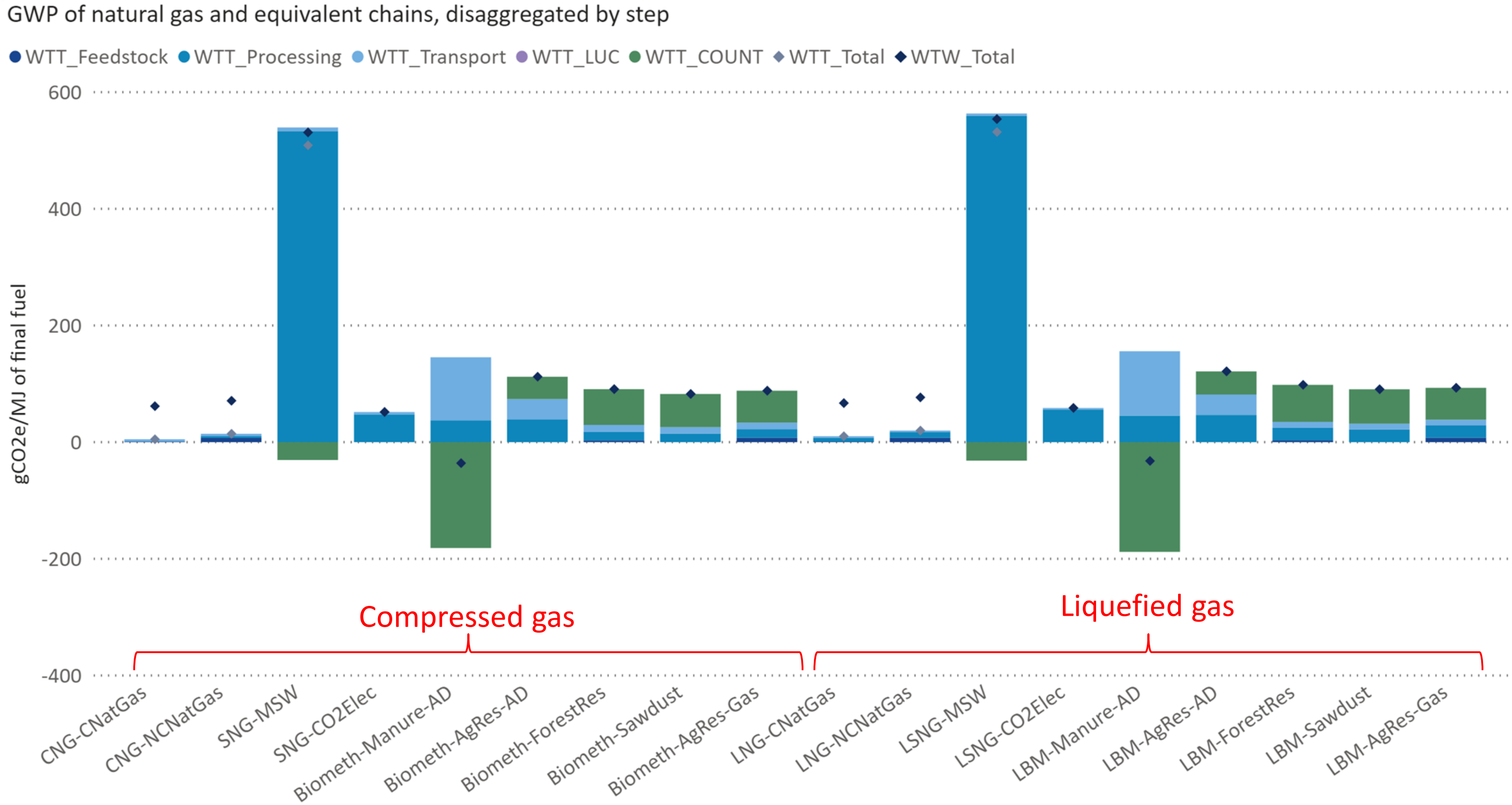
- **Combustion** represents the largest share of GWP for **crude-based diesel. GWP contribution for primary biofuels** are mostly occurring at **feedstock production** stage.
- **Land-Use Change** adds a significant contribution to feedstock production for **oilseeds.**
- **Counterfactual emissions** (negative or positive) have a significant impacts on GWP for **secondary fuels**.

Overview of Results: GWP impacts of gasoline and equivalent fuel chains



- **Similar trends** can be observed for gasoline and equivalent fuels, with the exception of LUC emissions, which are relatively smaller for starch/sugar crops than for oilseeds.

GWP impacts of natural gas and equivalent fuel chains

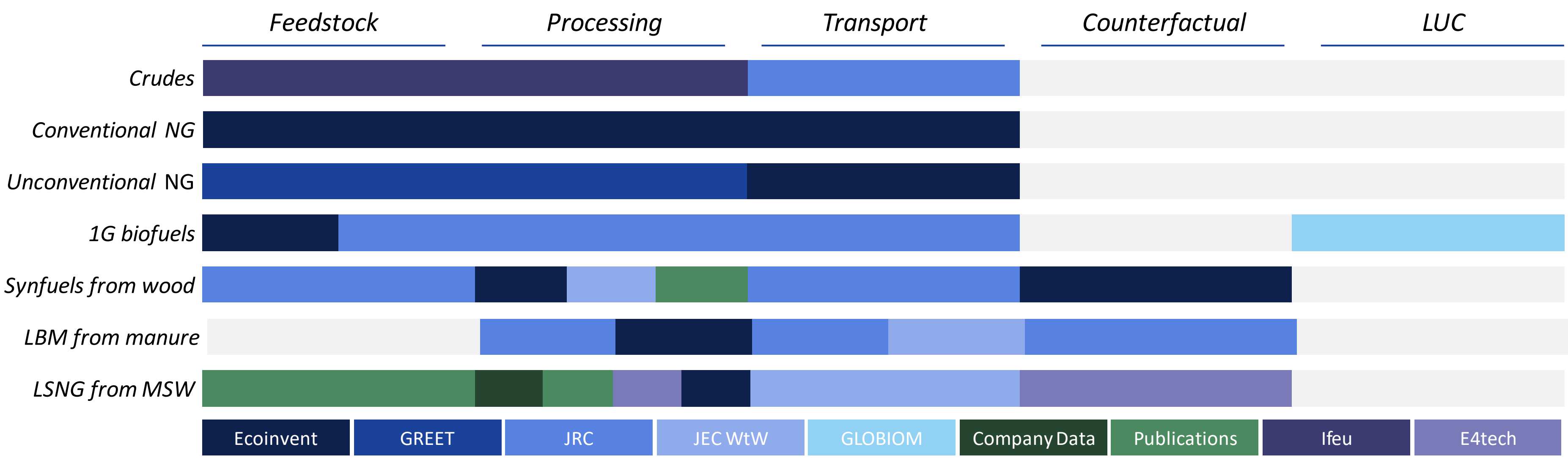


- **WTT emissions for CNG and LNG** are considerably smaller than in JEC's WTT, due to different assumptions in transport mode and distances, but remain comparable on a WTW basis.
- Abnormally high **processing emissions for SNG/LSNG-MSW** due to fossil/biogenic data mashup.
- Large avoided counterfactual emissions from manure (CH4 emissions during storage).

Influence of Foreground Data on Results

Foreground data strongly influences the results in an LCA.

Data sources used to build different fuel chains



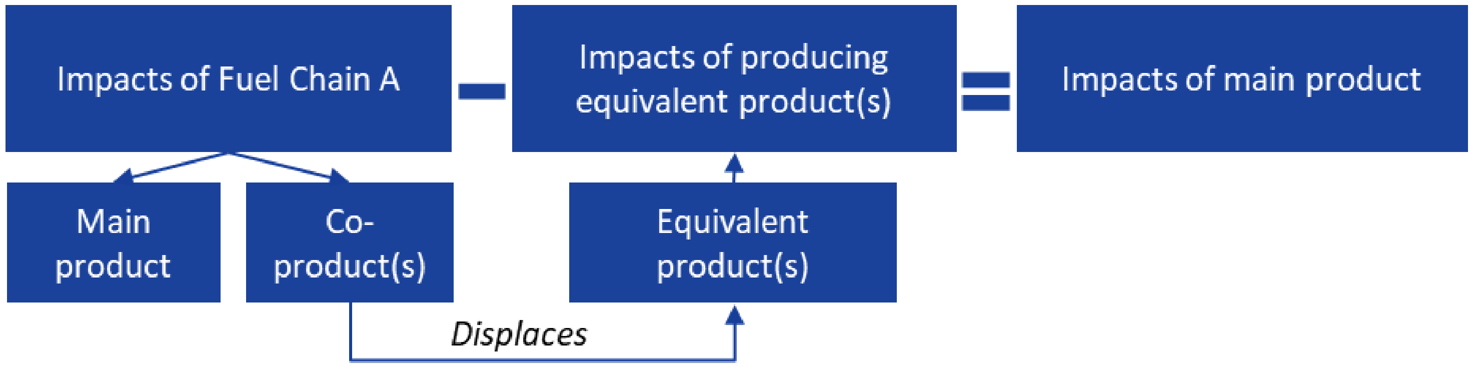
- **The focus of this study was on the development of a comprehensive WTT LCA**, testing different methodologies, not on developing a harmonised set of foreground data and primary research.
- Where possible the **best quality (JRC/JEC, Ecoinvent, GREET) foreground data was chosen** for each chain, but a comprehensive comparison between data-sets was **not** carried out.
- Foreground data strongly impacts the results in an LCA. **A wide range of sources** feed into the foreground data set, esp. for **novel or less commercially viable processes** (e.g. MSW-LSNG, wood synfuels) thus making results less robust. More data sources were required to complete the fuel chain, often paired with several assumptions, compared to more conventional fuel chains such as primary biofuels where most foreground data come from JRC.

NB: IFEU model is based on Ecoinvent dataset

Multi-functionality: Impact of Substitution on Results

Following ISO 14040, multifunctionality is addressed via a substitution method, unlike the RED methodology, which uses an energy allocation (1)

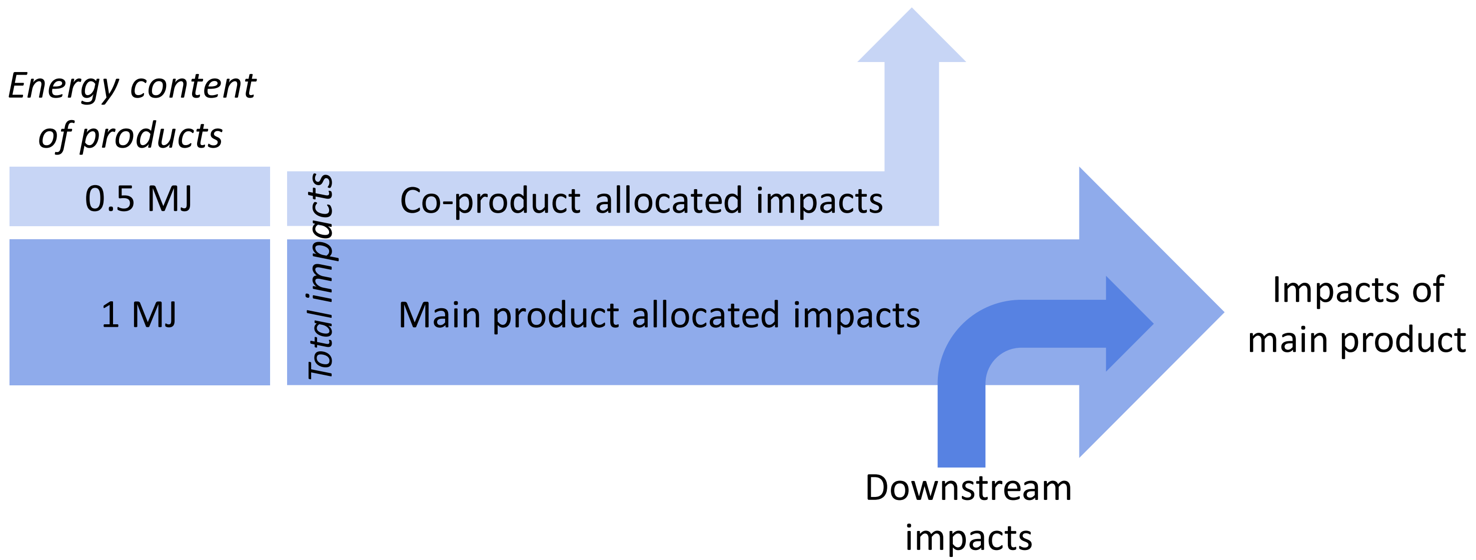
Substitution Methodology



- 32 out of 59 fuel chains were modelled as producing more than one product at various stages in their lifecycle.
- **Substitution method** was used to address the multifunctionality of these chains – in line with ISO 14040:2006 and ISO 14044:2006. ***One notable exception*****:** the impacts from extraction and refining of crude-based fuels are **allocated on an energy basis**.
- In a substitution method, **fuel co-products are assumed to replace an equivalent product** outside the scope of the assessed fuel chain (e.g. electricity, chemicals, food/feed, etc.). Such equivalent products no longer need to be produced and the **avoided impacts are credited to the assessed fuel chain**.

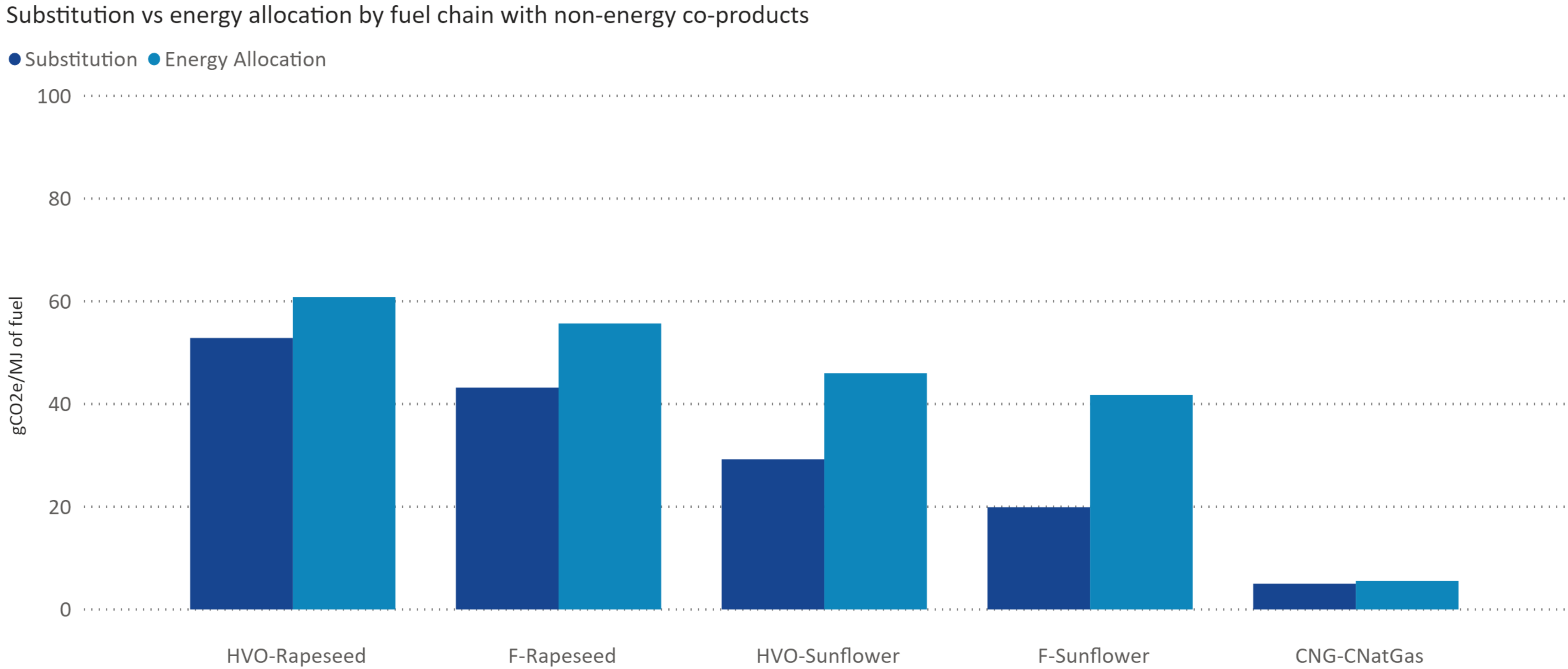
Following ISO 14040, multifunctionality is addressed via a substitution method, unlike the RED methodology, which uses an energy allocation (2)

Energy Allocation Methodology



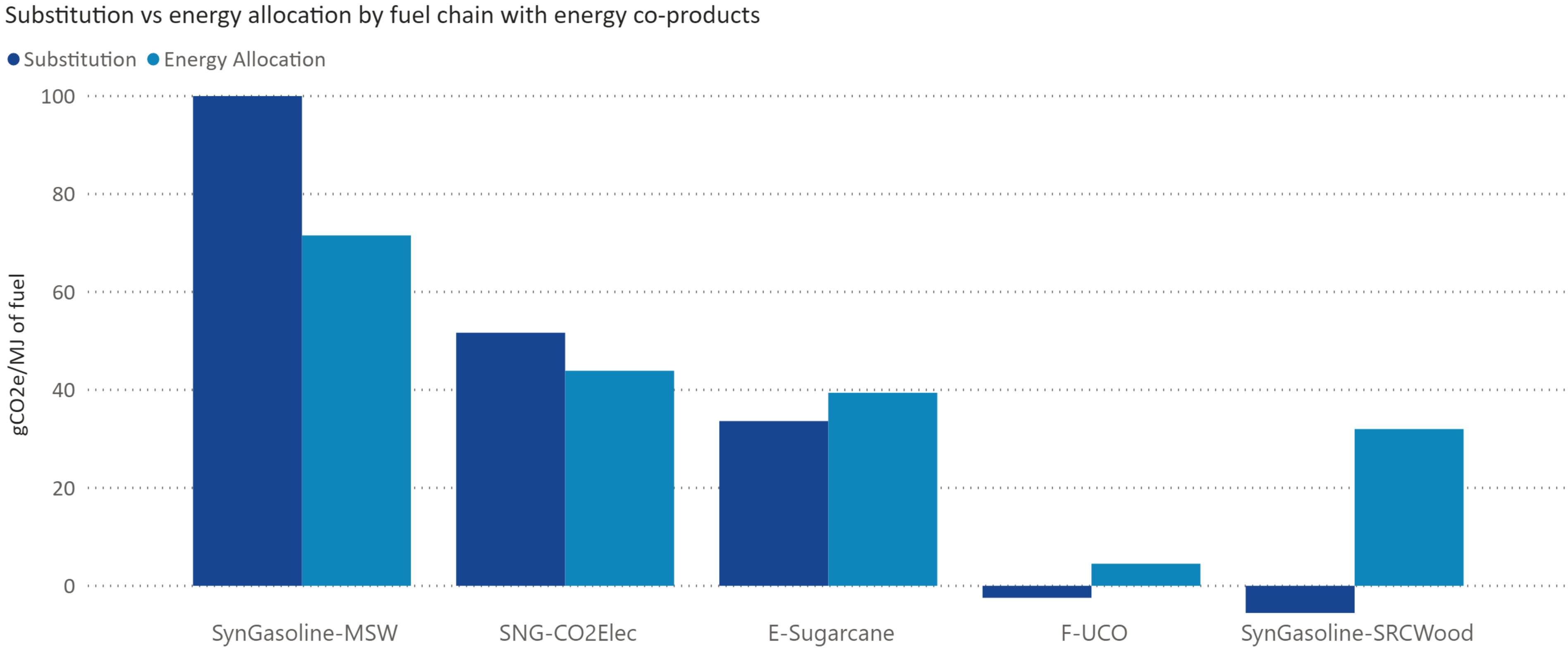
- The Renewable Energy Directive methodology uses an **energy allocation** to address multifunctionality
- **GHG emissions are assigned** between products in **proportion to their respective energy contents.**

Comparing substitution to energy allocation: Non-energy co-products



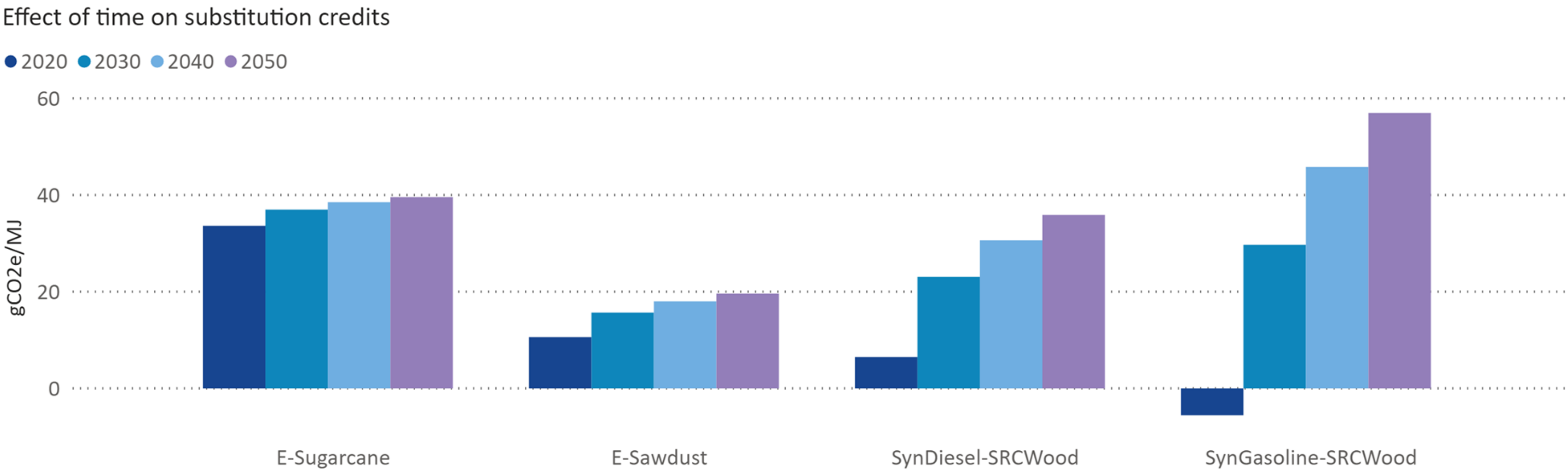
- For fuel chains producing only **non-energy co-products**, the **substitution method** generally results in **lower overall GHG impacts** for the primary fuel, compared to an energy allocation method.
- This is likely, at least partially related, to the lower energy content of these co-products and higher impact related to producing equivalent products.

Comparing substitution to allocation: Energy co-products



- Fuel chains producing **energy co-products do not produce a similar trend** - with some chains having greater impacts in a substitution method and others greater impacts in an energy allocation method.
- Some fuel chains with energy co-products have a **net negative impact under the substitution method**. This is because the displaced impacts from the substitution of equivalent products/services outweigh the gross impact of producing the fuel.

The attractiveness of fuel chains may vary over time due to substitution credits



- Unlike in an energy allocation methodology, the **substitution credit can vary over time** as the impact of producing equivalent products change.
- For example, in several chains, electricity is produced as a co-product:
  - In an **energy allocation**, emissions are allocated based on energy content – which, everything else the same, **remains unchanged** over time.
  - In **substitution methodology**, the **credit** given to the system for producing excess electricity **changes over time**, as grid mixes continue to change.
- The "attractiveness" of a fuel can vary over time and therefore conclusions based on substitution credits should be treated with caution.

Application of Counterfactual Scenarios (Secondary Feedstocks)

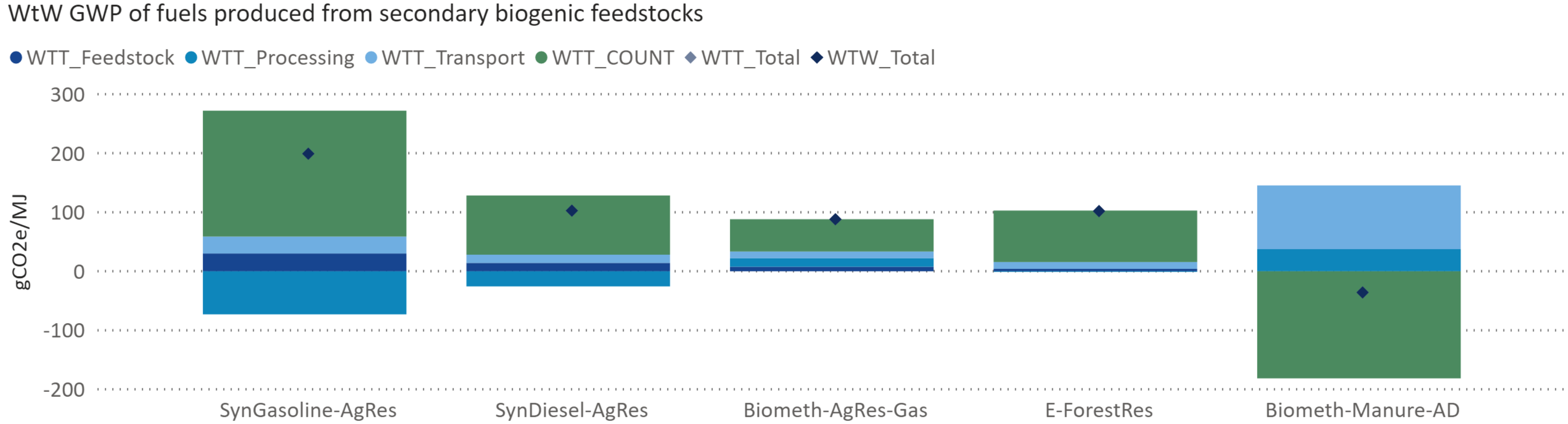
Approach to the application of counterfactual scenarios (Secondary Feedstocks)

- The environmental impacts associated with diverting **secondary feedstock** (residues) from an existing use towards fuel production (termed '**Counterfactual impacts**') is modelled as:

Environmental impact of secondary feedstock = - {environmental impact of its previous use} + {environmental impact of providing that previous use by another means}

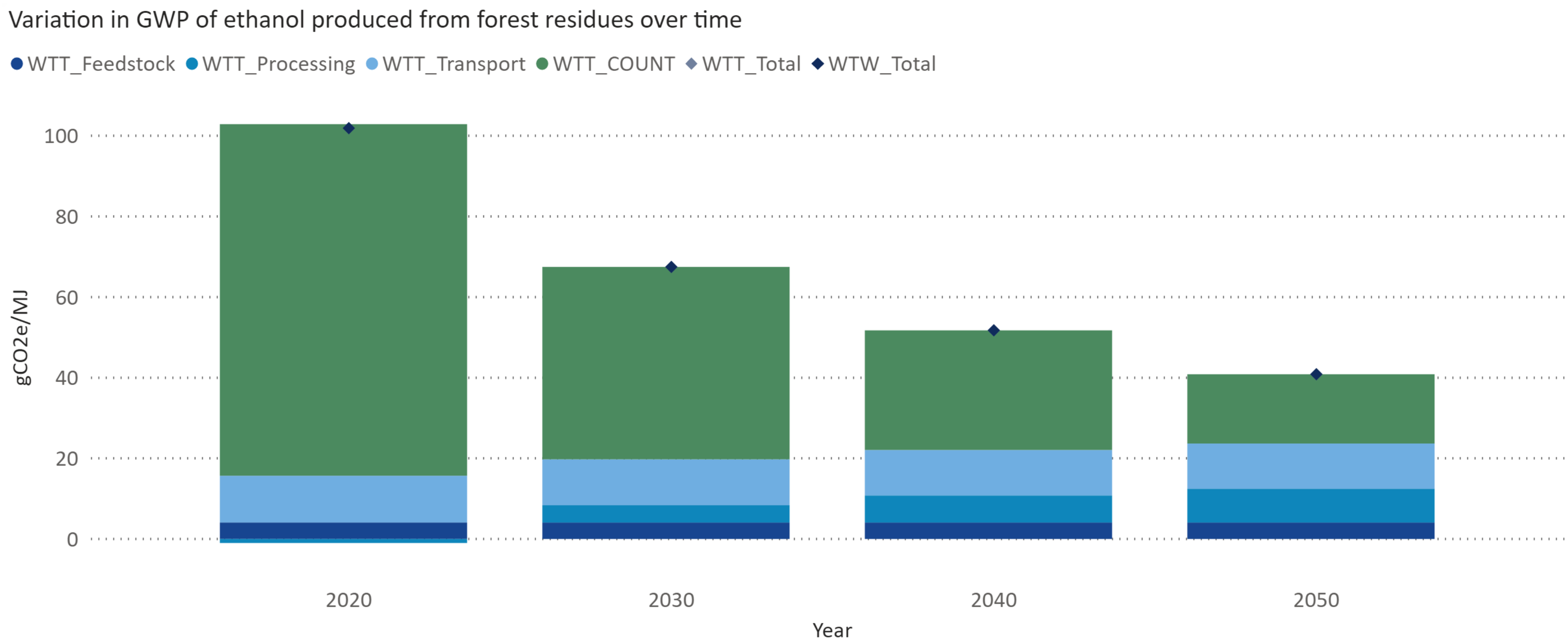
- Secondary feedstocks could be diverted towards transport fuels from **several other uses**, and may therefore be replaced by alternative equivalent products .
- In the fuel module, **only the most likely counterfactual use** of that feedstock was considered.
- The material or energy source used to replace the secondary feedstock was also selected in order to reflect the **most likely situation**. For example, in the case of secondary feedstock diverted from electricity production, it is assumed to be replaced by **grid average electricity.**

GWP impacts of fuels produced from secondary feedstocks – Results



- When previous **use of secondary bio feedstocks was power generation**, counterfactual emissions are positive, as power that was previously generated from e.g. agricultural residues is replaced by power from grid.
- Counterfactual emissions for fuels produced from **manure are negative** due to large avoided methane emissions from manure storage.
- As counterfactual GHG emissions are calculated on a per MJ feedstock basis, fuel chains which have very **low overall efficiency** have **high counterfactual emissions.** For example counterfactual emissions of syngasoline are higher than syndiesel as efficiency of syngasoline production is lower. This is partly compensated by higher production of co-products in these chains.

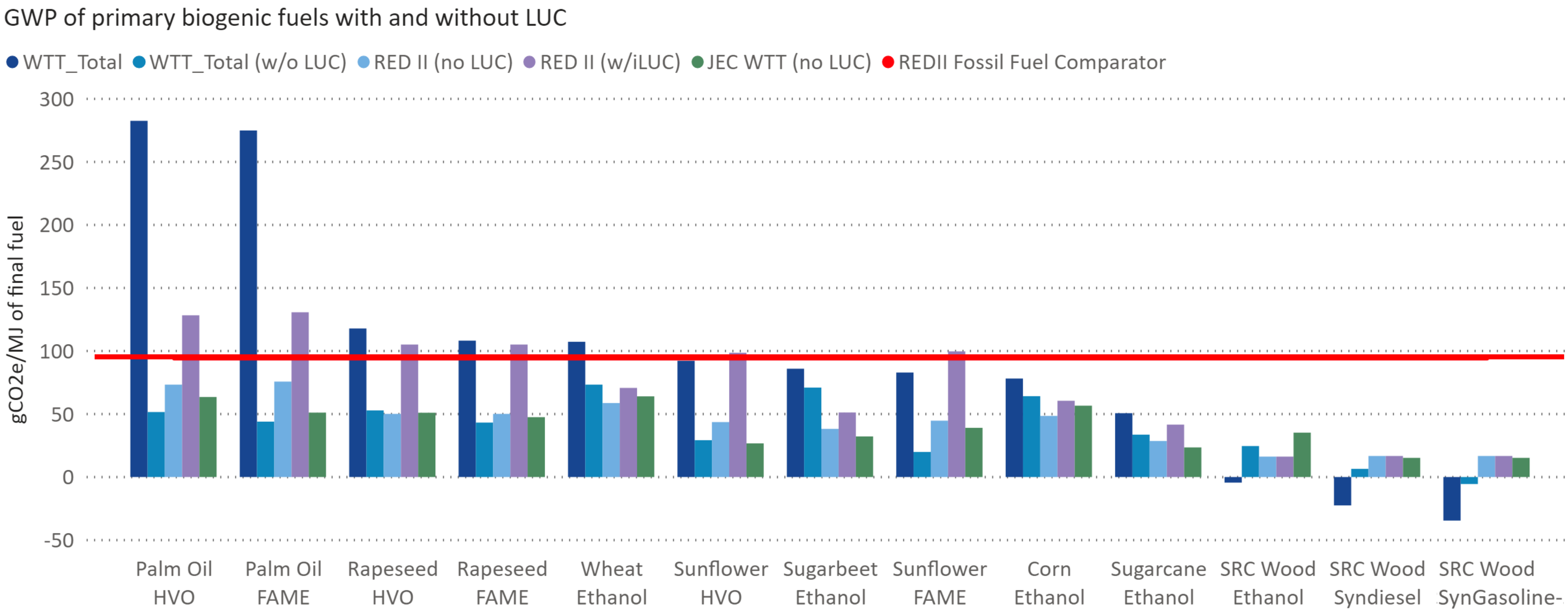
Temporal changes of GWP values for secondary feedstocks



- For fuels produced from secondary feedstocks which are diverted from **electricity production**, counterfactual **GWP emissions fall substantially over time**, as grid electricity GWP falls over time.
- Processing GWP emissions will
  - **Decrease** over time **if electricity is a major input** to the processing step
  - **Increase** over time (see above) **if electricity is a co-product** from processing. The credit given to co-product electricity gets smaller as grid electricity decarbonizes.

Land-Use Change (Primary Biogenic Fuels)

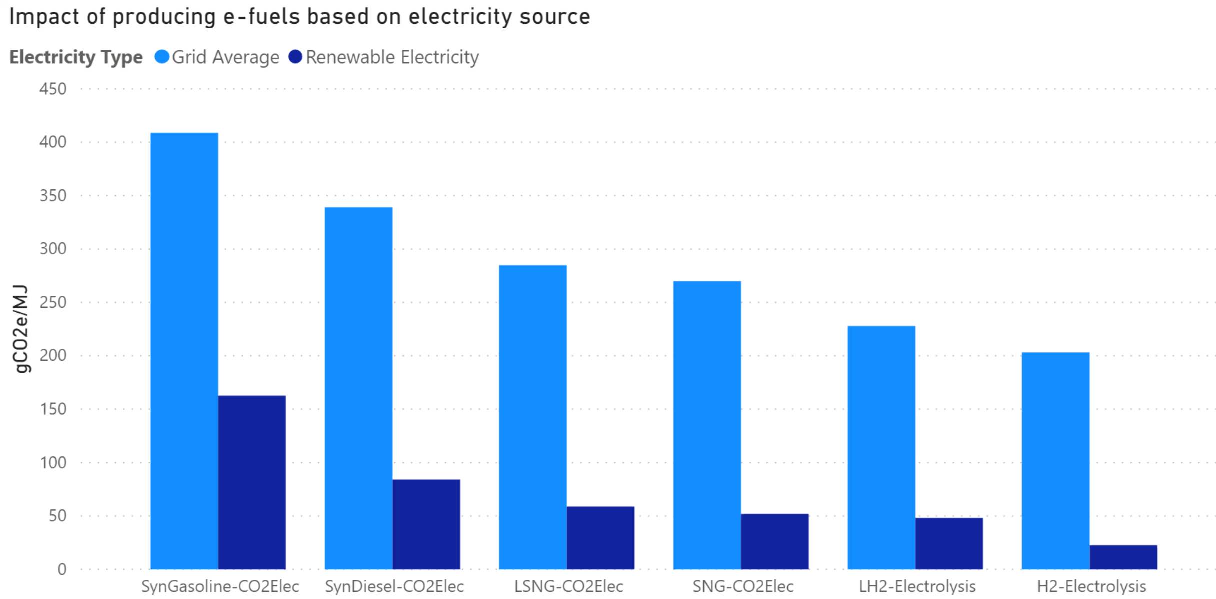
Land Use Change makes a significant impact on the GWP of some primary biogenic fuels



- **Land-use Change emissions from GLOBIOM** (Valin et al., 2015), including **Soil Organic Carbon** emissions, were added to cultivation data (Ecoinvent).
- For all crops, **adding LUC emissions increases the total GWP value**. For SRC wood, adding LUC emissions decreases the total GWP value, due to additional C storage in feedstocks.
- When removing LUC emissions, **GWP values come closer to RED II's and JEC's**, but differences remain due to co-product treatment and foreground data. Adding iLUC values from RED II also brings results close.

Impact of Electricity Sources (e-fuels)

The GWP impacts of e-fuels (WtT) are heavily dependent on the electricity source assumed for production.

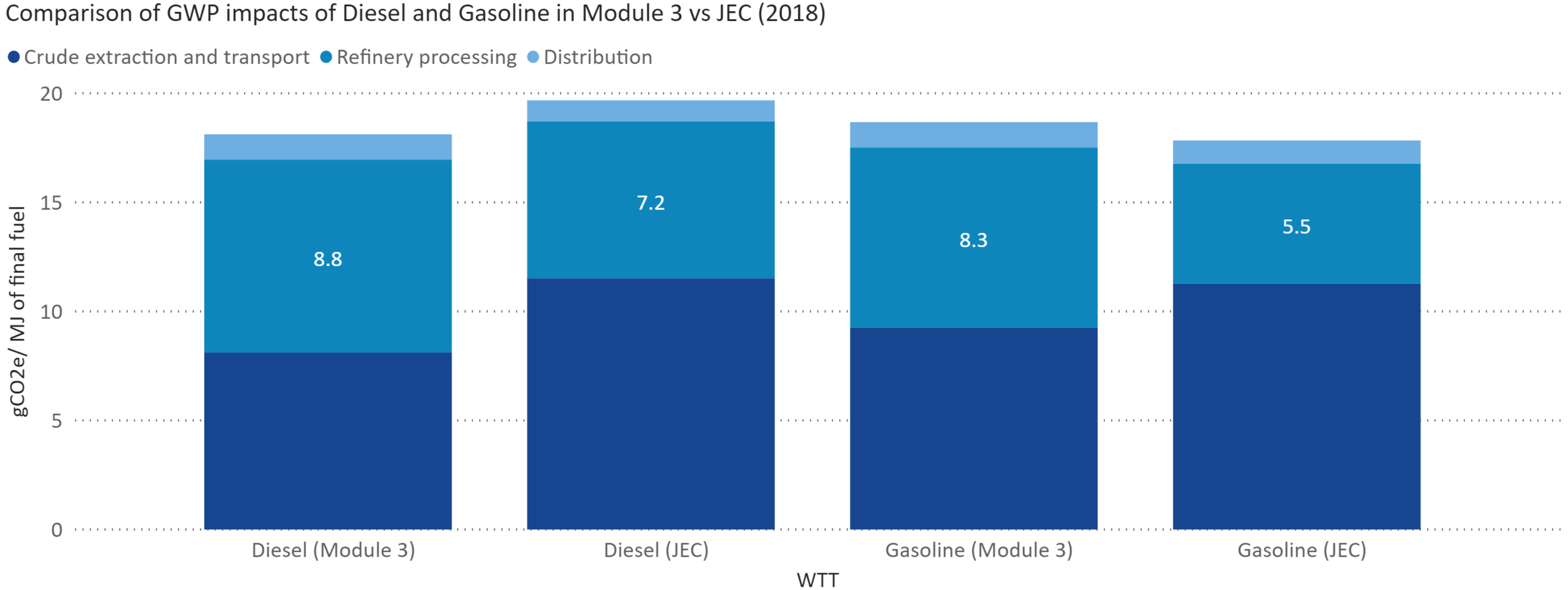


GWP (WtT) gCO_2e/MJ	Grid average	Renewable electricity
Syngasoline	408.8	162.7
Syndiesel	339.2	84.2
LSNG	284.8	58.8
SNG	269.9	51.9
LH_2	227.9	48.2
H_2	203.2	22.6

- For most chains (except e-fuels), the default electricity assumption is a **grid average mix.**
- **For e-fuels, renewable electricity is the default for production** steps except for hydrogen from electrolysis. Electricity used downstream of production is still assumed as grid average.
- E-fuels are highly dependent on the electricity source – more so than other fuels– as this is the main input.
- Even in a 100% renewable electricity, **not all e-fuels are attractive from a GHG perspective (on WtT basis)**.
  - Renewable electricity is not burden free (i.e. not 0 gCO_2e/MJ)
  - High electricity requirements in production

Crude Refining: Modelling Results

The ifeu model (primary fossil fuels) gives a similar overall WtT GWP impact compared to JEC/CONCAWE despite higher impacts for the refining step



Refinery GWP:

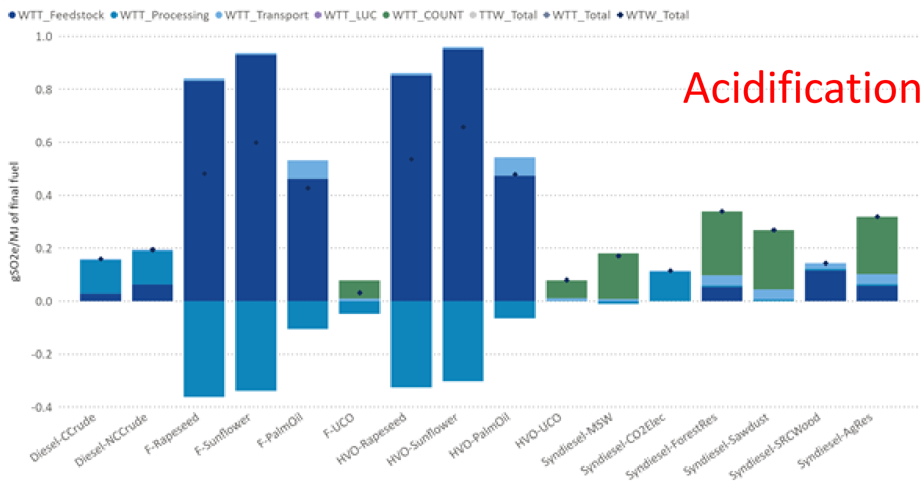
- Compared to JEC (2018)/Concawe, ifeu model gives higher GWP impacts for both Diesel and Gasoline
- *Ifeu model:* Diesel and gasoline have similar impacts due to similar energy contents, however, impact is slightly higher for diesel production (hydrogen consumption in hydrocracker).
- *JEC/Concawe:* Diesel has a significantly higher impact than gasoline.

Total WtT GWP:

- Despite differences for the refining step, overall WtT results are comparable, as JEC results give higher GWP impact for crude oil production and transport of crude, compared to ifeu.

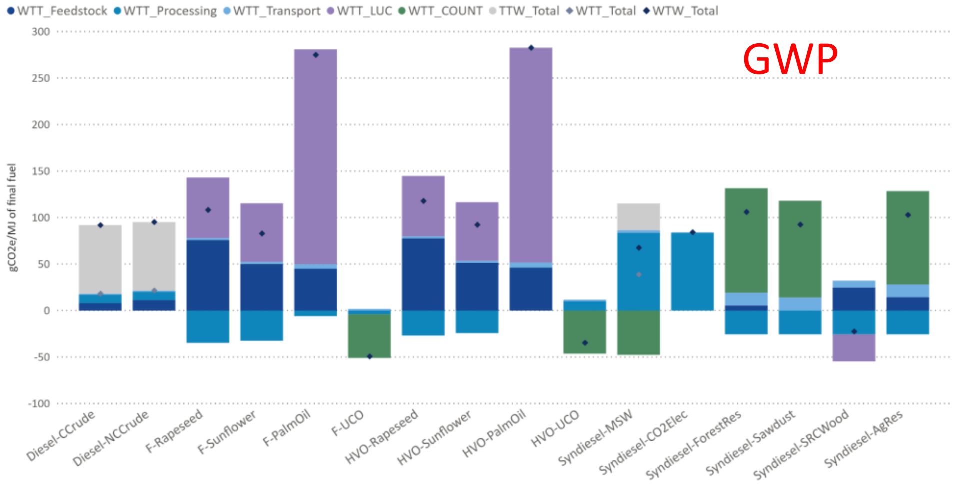
Non-GWP Impacts

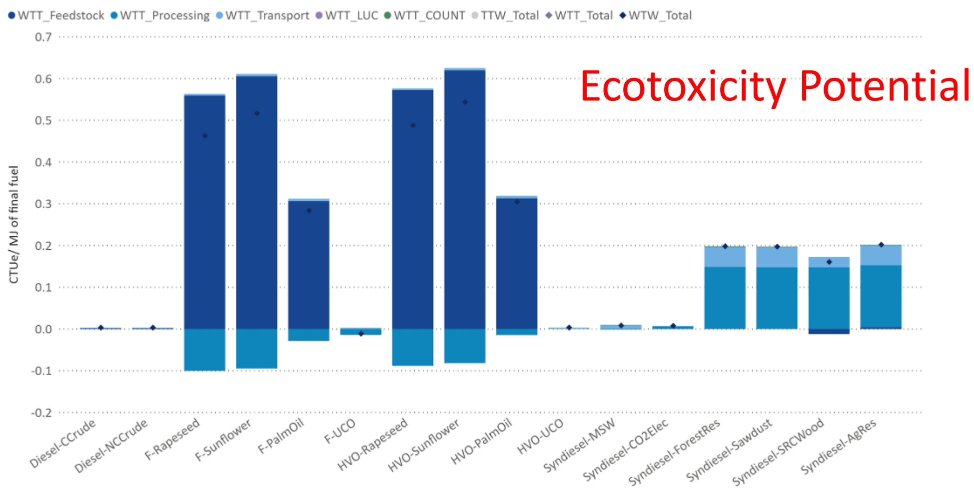
Acidification Potential of diesel and equivalent fuel chains (vs GWP)



- The acidification potential (on a WtT basis) appears to be higher for primary biogenic fuels and synfuels than secondary biogenic fuels and fossil fuels.
- As for GWP, **Feedstock cultivation** is the largest contributor to acidification potential of primary biogenic fuels, due to the use of agricultural inputs. Avoided acidification is significant due to co-products (meals), which are assumed to displace additional feed.
- **Counterfactuals** contribute significantly to the acidification potential of synthetic fuels, due to the grid electricity to be replaced.

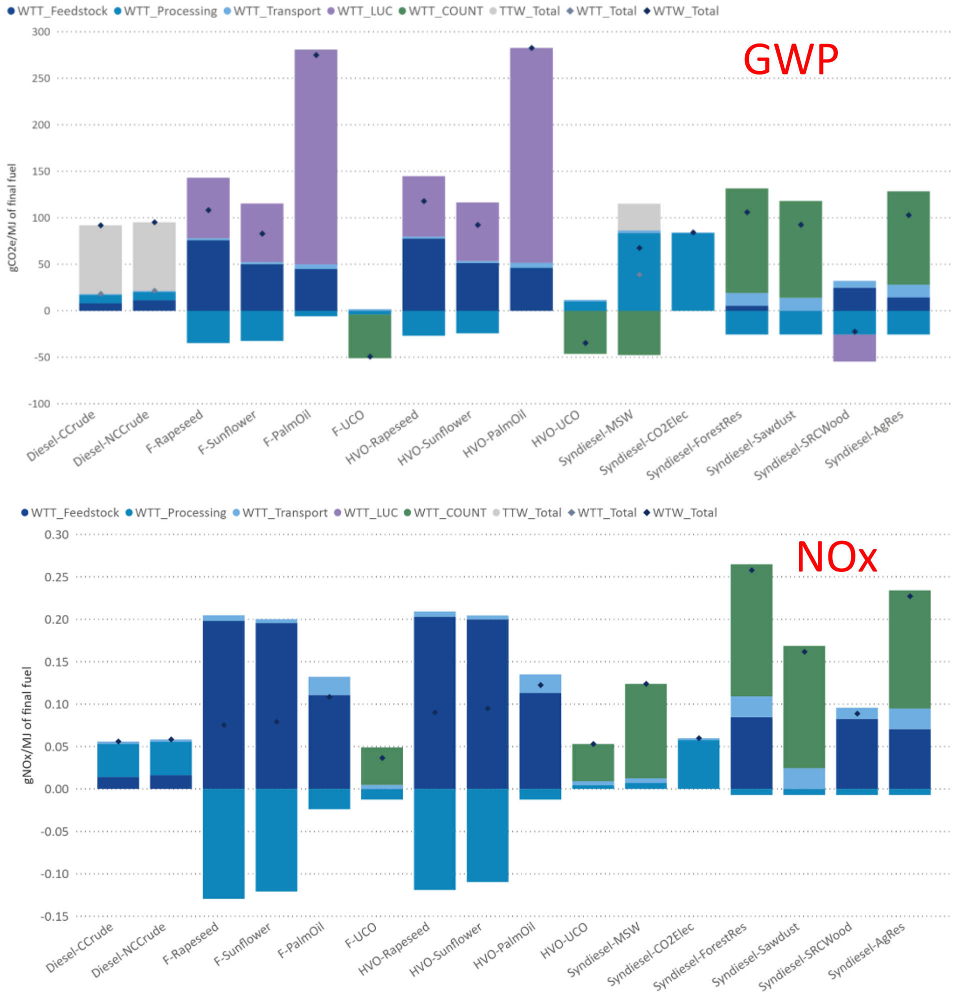
Ecotoxicity Potential of diesel and equivalent fuel chains (vs GWP)





- The **ecotoxicity potential** (on a WtT basis) appears to be **higher for primary biogenic fuels and synfuels** than secondary biogenic fuels and fossil fuels.
- **Feedstock cultivation** is the largest contributor to ecotoxicity potential of primary biogenic fuels, due to agricultural inputs. Compared to acidification, avoided ecotoxicity from producing meals is more limited.
- In the case of synfuels, the largest contribution to ecotoxicity comes from the **processing.**

NOx emissions of diesel and equivalent fuel chains (vs GWP)



- **Primary FAME/HVO and synfuels** have the largest relative NOx emissions on a WtT basis.
- **Feedstock cultivation** for primary biofuels generates relatively high NOx emissions, due to direct field emissions in agriculture, as modelled in Ecoinvent.
- NOx emissions from processing are negative for all biogenic fuels due to co-products and process efficiencies.
- For **UCO and MSW,** avoided NOx emissions (incineration) are outweighed by NOx emissions to replace grid electricity.
- **Counterfactual NOx emissions** have a significant impact for secondary biogenic feedstocks.

Initial Conclusions and Recommendations

Module 3 (Fuels): Key achievements, strengths and robustness of findings (1)

- **59 fuel chains** covered for **all LCA midpoints** + single substances covered
- Successful implementation of **substitution for multi-functionality**, thus allowing for comparison with results obtained through allocation.
- Novel approach to **secondary feedstocks**, incl. potential displacement effects (counterfactual) successfully tested. Paves the way for more research and policy work.
- **Non-GWP impacts** provide different trends than GWP for several fuels.
- Comparability with other WTW studies and RED II remains limited, however. Statistical correlation between GWP and non-GWP impacts could be further explored to understand where GWP could be used as a safe proxy for other environmental impacts.
- **IFEU refinery model** calculates a higher GHG intensity for refining operations than **JEC's** (2018), but the latter results in a higher GHG intensity for extraction operations, so GWP totals are comparable between the t.

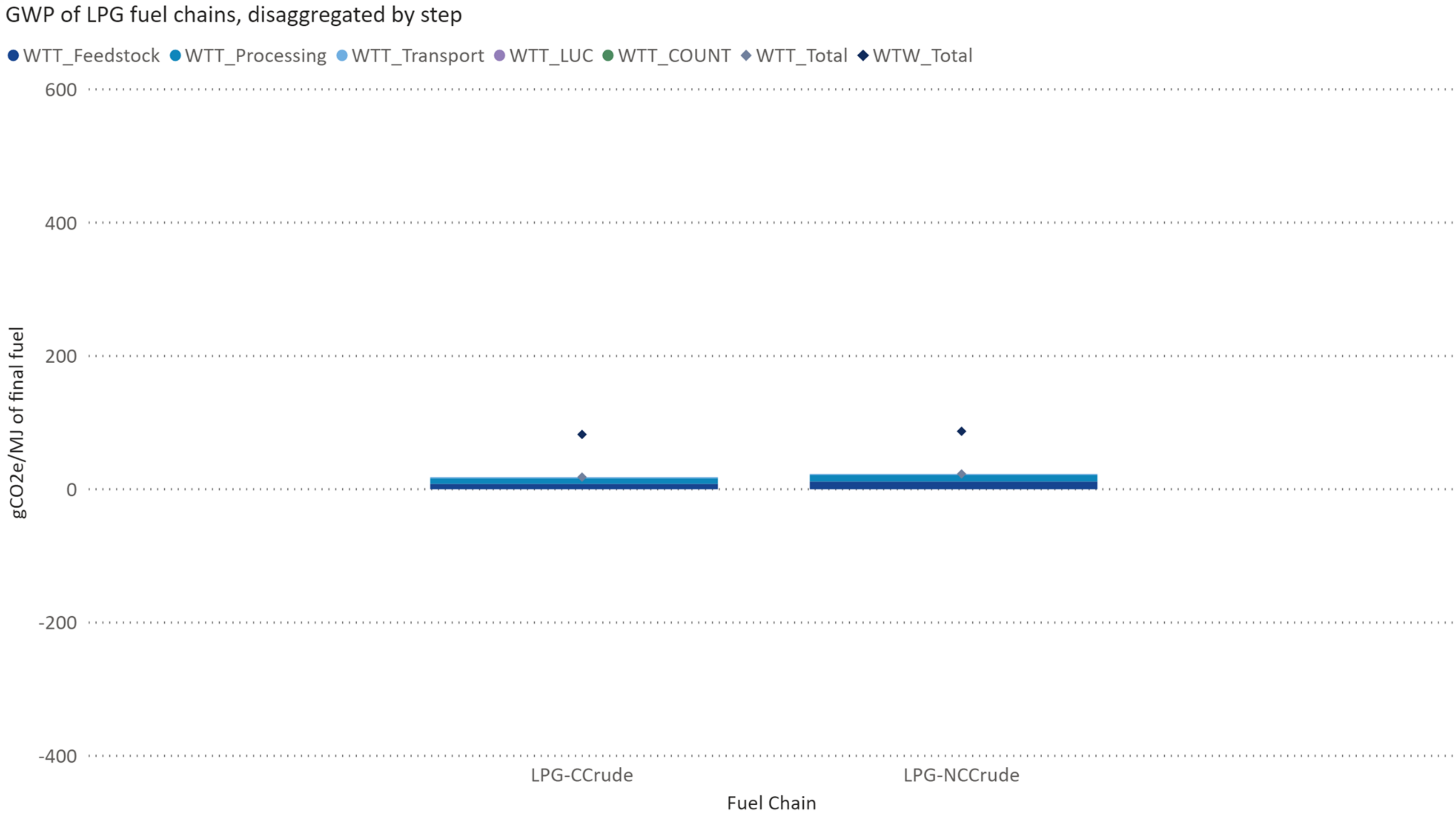
Module 3 (Fuels): Key achievements, strengths and robustness of findings (2)

- Results shall not be taken as face value. This study shows the concrete consequences of certain methodological choices on how fuels are evaluated against each others with regards to their environmental benefits. In particular:
  - Importance of the **substitution credit** chosen: Our method for selecting was simplistic, for more accuracy would require rigorous modelling – does the co-product typically feed into multiple markets? Is there a more appropriate alternative etc.
  - Importance of **counterfactual scenarios**. Diverting secondary feedstocks from existing productive uses into liquid fuel production can result in significant environmental impact if that existing use still needs to be supplied. Attributing zero impacts up until the point of collection is only valid for true wastes.
  - Using the same methodology for both secondary fossil and secondary biogenic feedstocks allows **fuel produced from mixed feedstocks** (e.g. MSW) to be treated as one consignment rather than assessing the fossil and the biogenic fraction separately.
  - Demonstrated weight of **Land-Use Change emissions** (incl. SOC) over results for primary biogenic fuels.

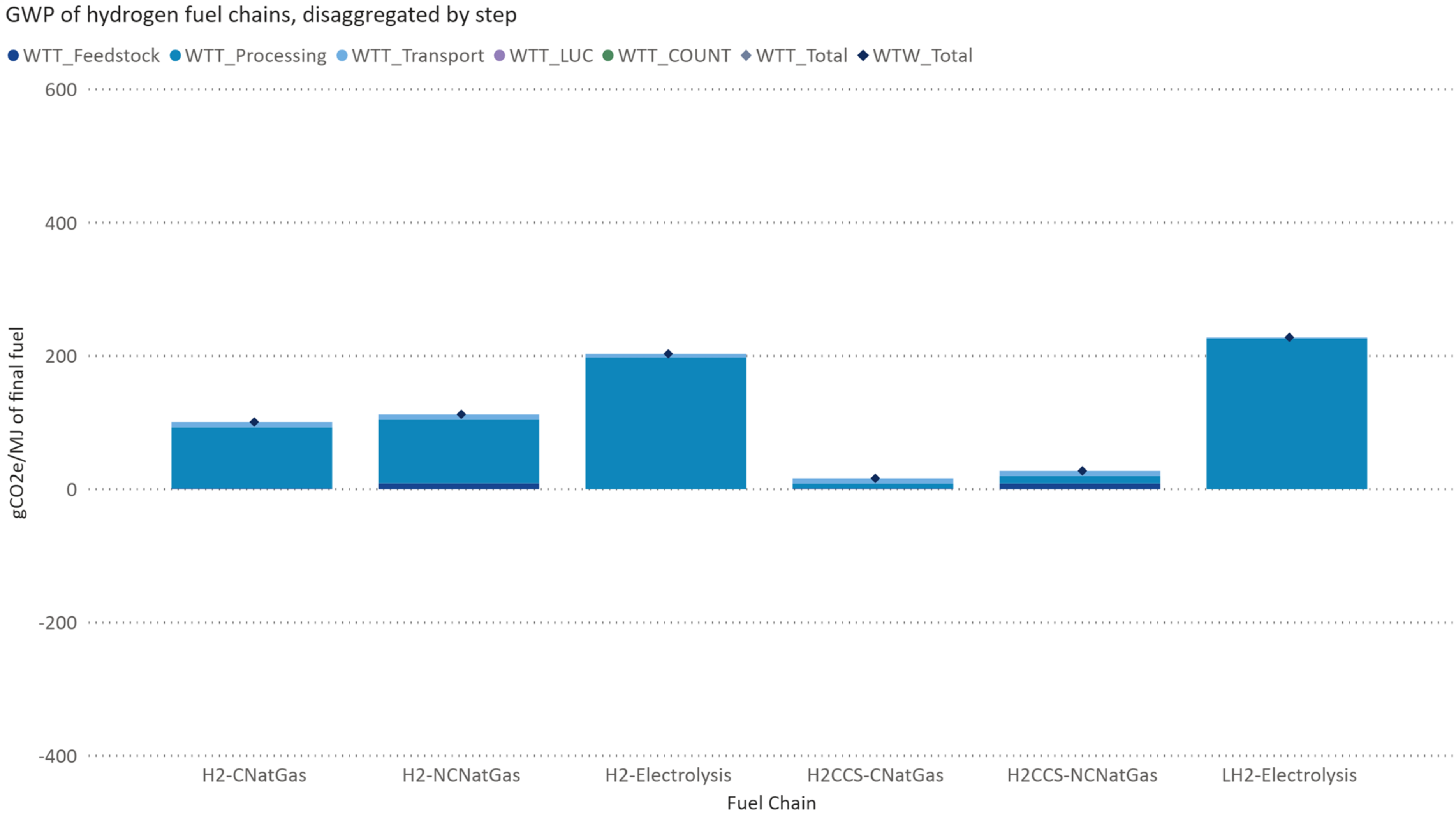
Module 3 (Fuels): Uncertainties, limitations and data gaps

- **Consistency issues** around the combination of attributional LCA (ag. Inputs, crop processing, transport etc.) and consequential LCA (LUC) elements shall be further analysed.
- **Variable accuracy and reliability of results**, primarily stemming from data sets. Some fuels well covered, some scarcely documented. Makes comparability difficult.
- A **limited number of counterfactual and substitution scenarios** were modelled. No economic modelling of counterfactual.
- **LUC values for different years could be tested in the module** on the basis of GLOBIOM results, given the dynamic nature of economic modelling. A comparison of results in the fuel module with GTAP should be conducted (not possible within current project timeline).
- A key challenge to the **evaluation of secondary feedstocks** is to account for / mitigate the risk of indirect impacts from using secondary feedstocks, given the uncertainty in assessing these – is LCA the best tool in order to do this?

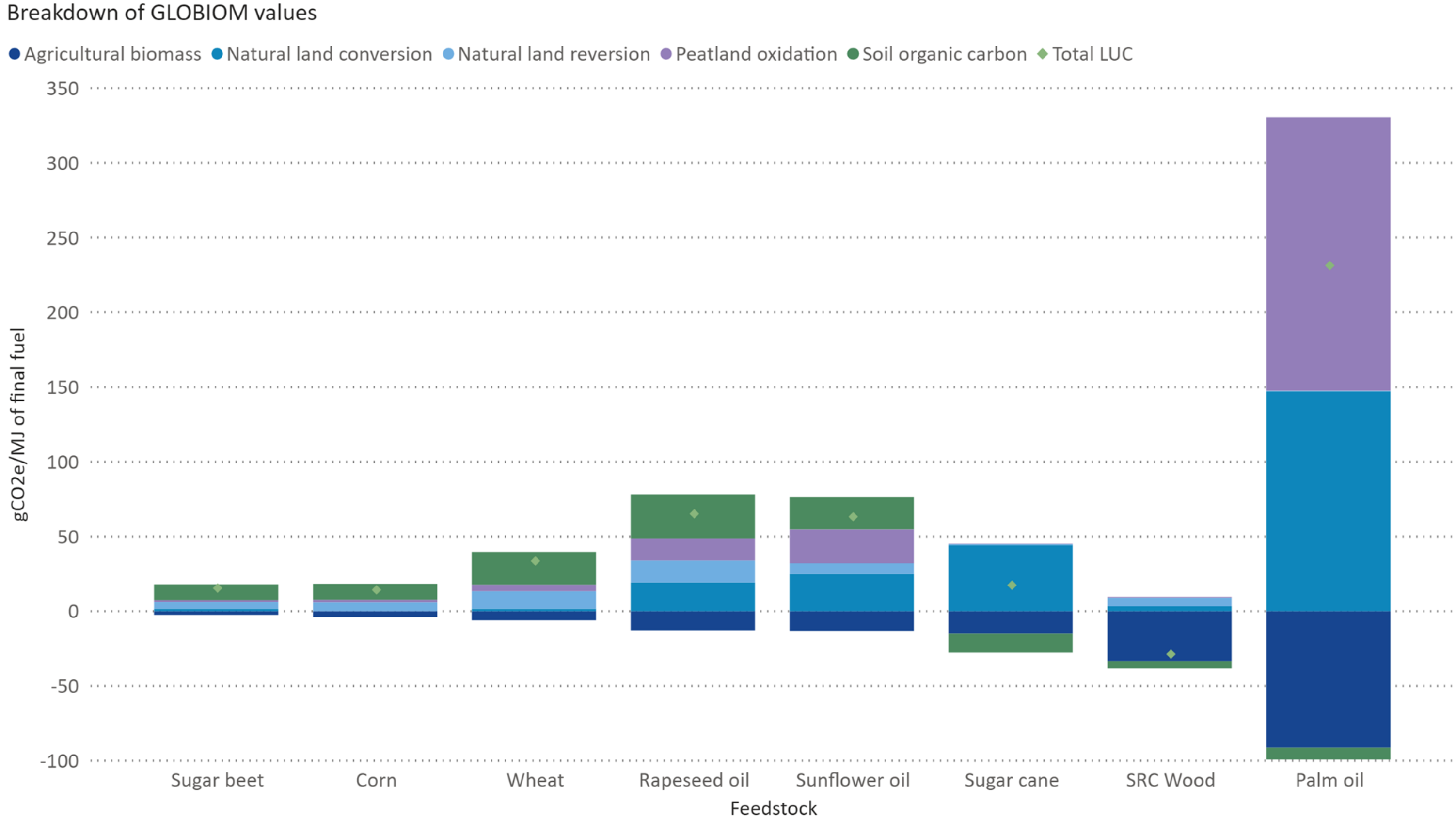
GWP impacts of LPG fuel chains



GWP impacts of hydrogen and equivalent fuel chains

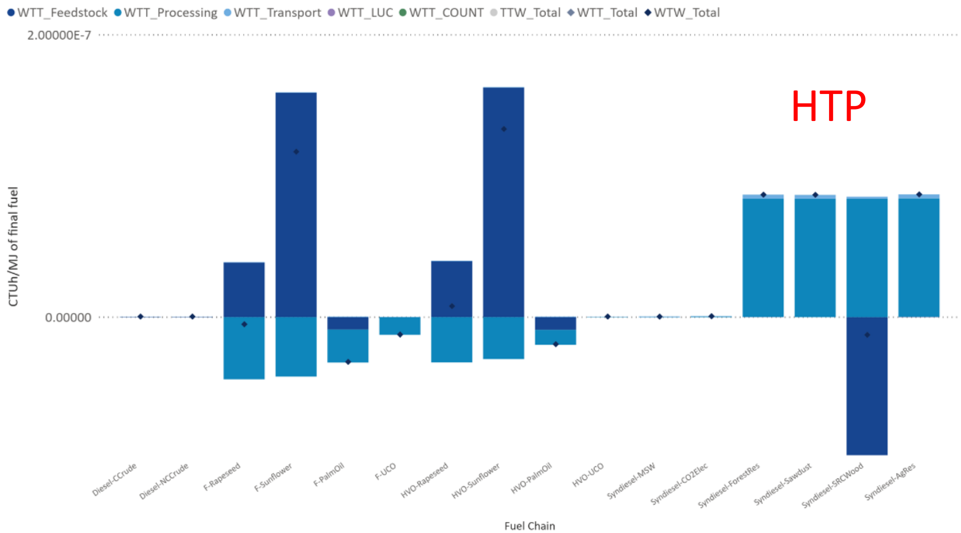


Breakdown of LUC values (GLOBIOM)

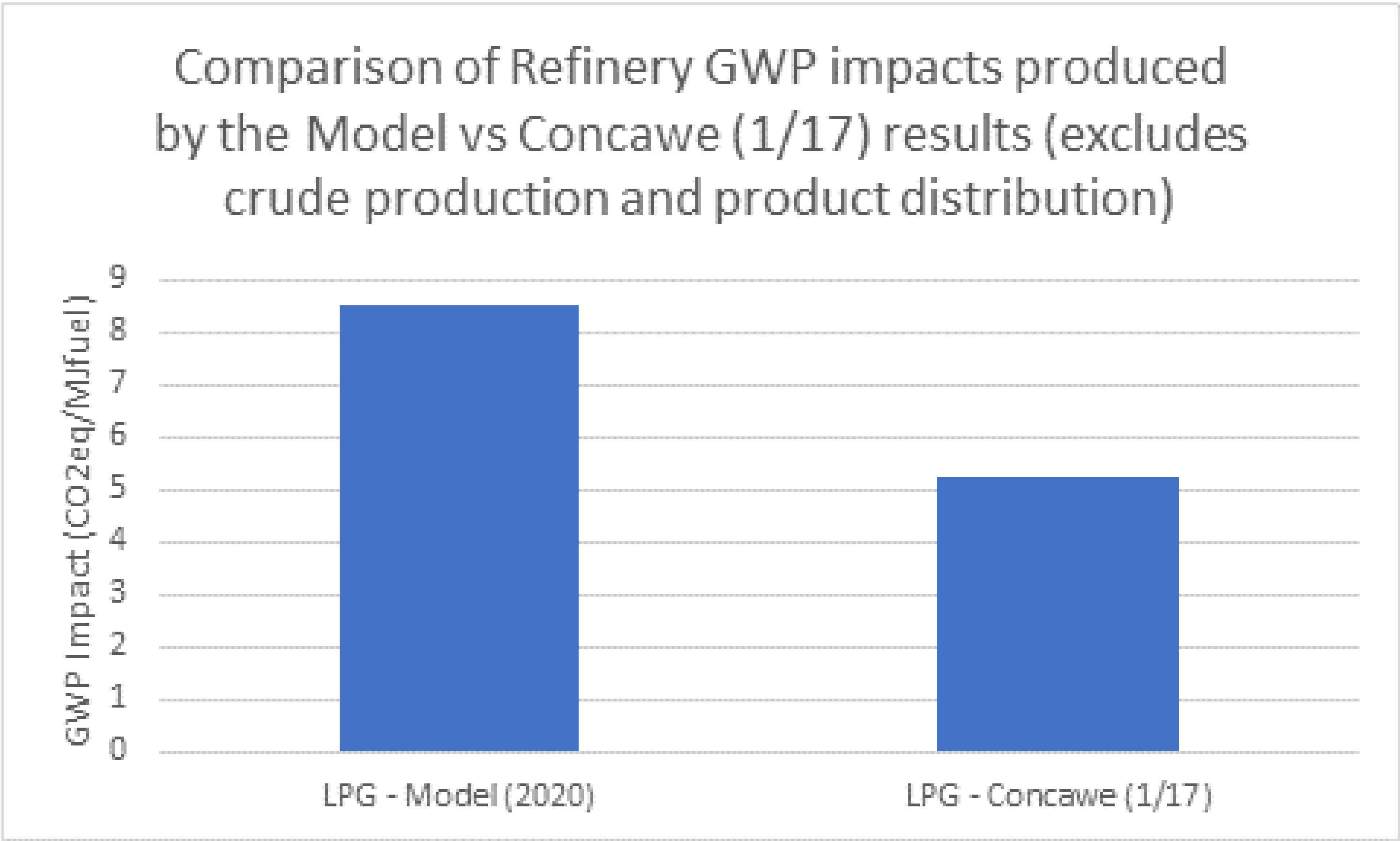


- For sugarbeet, corn and wheat, Soil Organic Carbon is the main contributor to LUC emissions.
- For oilseeds, SOC, peatland oxidation and natural land conversion dominate.
- For both PO and SRC, carbon sequestration is larger than if land was used for agriculture, which results in negative emissions (largely offset by natural land conversion and peatland oxidation in the case of PO).

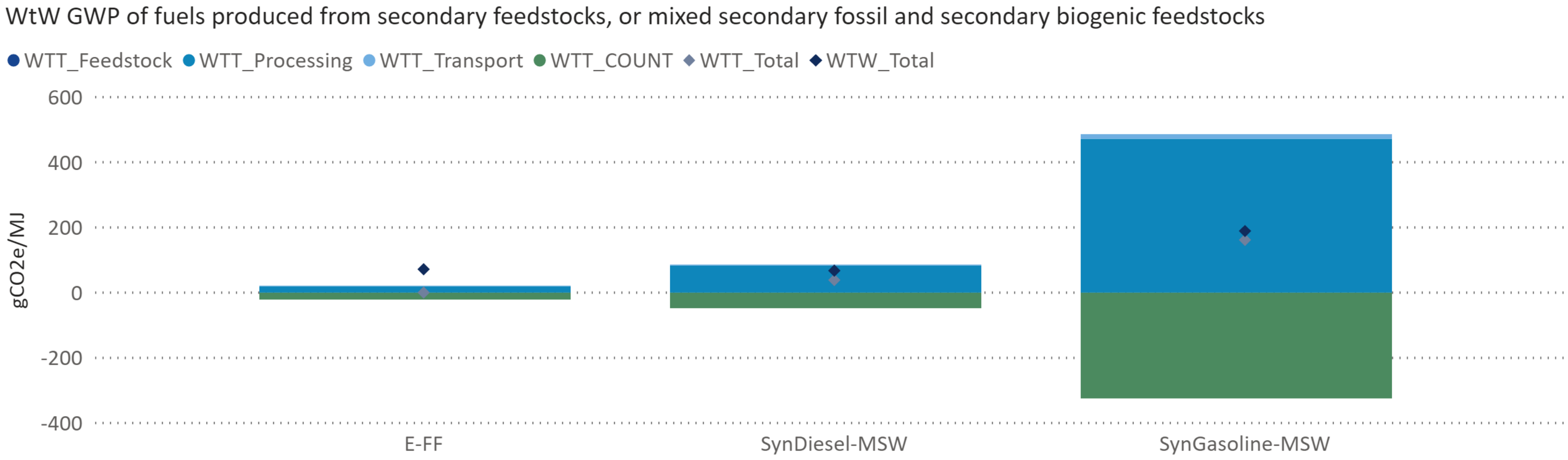
Human Toxicity Potential of diesel and equivalent fuel chains (vs GWP)



- Trends observed for HTP are somewhat comparable, but absolute numbers are extremely low.


Comparison of Refinery GWP impacts produced by the Model vs Concawe (1/17) results (excludes crude production and product distribution)
GWP Impact (CO2eq/MJfuel)
0
1
2
3
4
5
6
7
8
9
LPG - Model (2020)
LPG - Concawe (1/17)

GWP impacts of fuels produced from secondary feedstocks – Results (2)



- Same methodology is used for both secondary fossil and secondary biogenic feedstocks
- Fuels produced from mixed biogenic and fossil feedstocks (e.g. MSW) are assessed as a mixed fossil and biogenic fuel.
- For both waste industrial gases and MSW the counterfactual fate is combustion-based power.
- Large avoided GWP impacts from combustion are compensated by large release of CO_2 during processing and on combustion of the fuel.
- As noted on previous slide, fuel chains which have very low overall efficiency have high counterfactual emissions.

Agenda

INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG HEIDELBERG

- Introduction, background and objectives of the meeting [09:00]
- Overview of the developed methodology [ifeu, 09:30]
- Overall LCA results [Ricardo, 11:00]
  - Results and comparisons for lower medium cars
  - Results for other vehicle types
- Results for energy chains [ifeu / E4tech, 13:30]:
  - Electricity chains [ifeu]
  - Liquid and gaseous fuel chains [E4tech]
- **Overall LCA sensitivities [Ricardo, 15:00]**
- Other assumptions and general Q&A [Ricardo, 16:15]
- Initial conclusions & recommendations and wrap-up [Ricardo, 17:00]

Introduction and overview of sensitivities explored

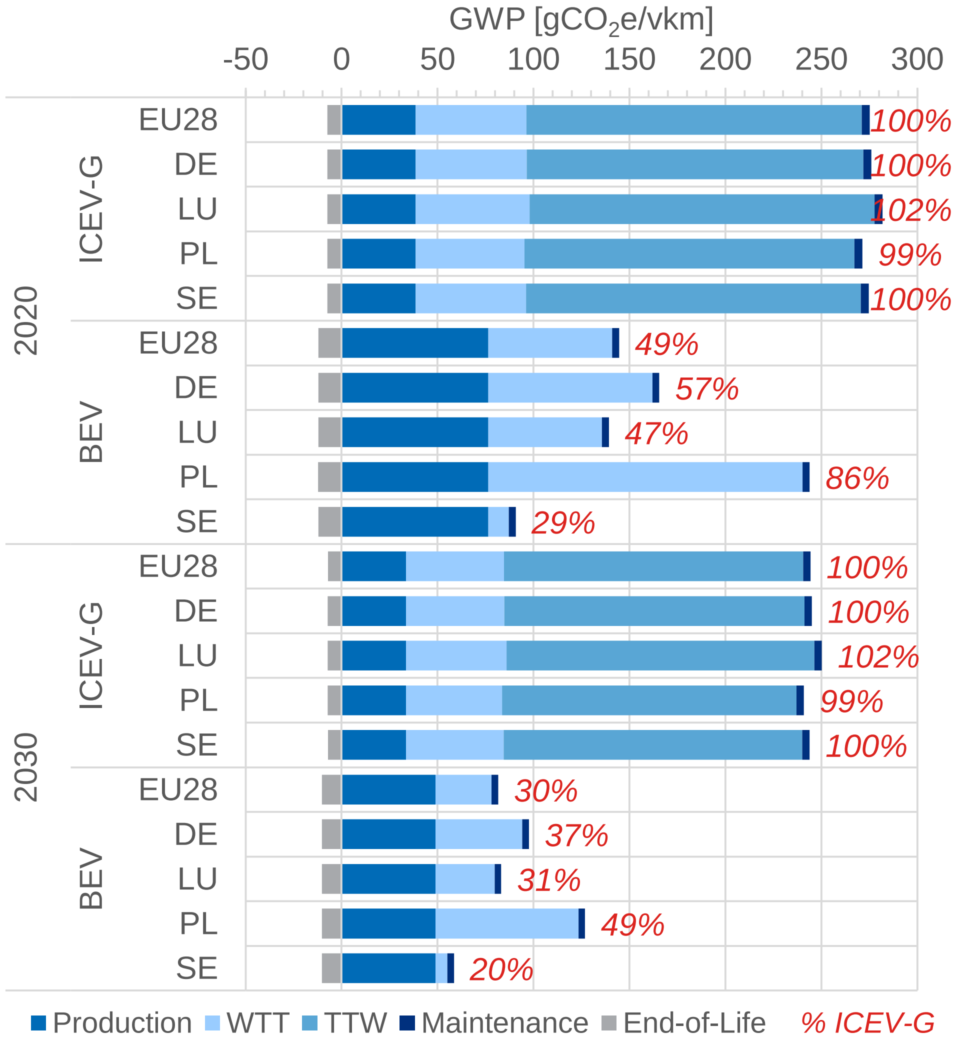
Low Impact | Medium Impact | High Impact

		Sensitivity	Description
Veh Operation	1	Regional Var	Examples of variation in impacts for different EU regions (i.e. due to different road mileage shares and electricity mix)
Veh Operation	2	Lifetime km	Low or high lifetime vehicle mileage assumptions
Veh Operation	3	PHEV fuel share	Impact of low/high shares of operation on electricity (use profile)
Veh Operation	4	Loading	Impact for 100% loading assumptions for alternative powertrains
Veh Operation	5	Future ICE AQP	Alternative scenario with significant future tailpipe AQP reduction
Veh Spec	6	Glider	Alternative trajectories for glider material composition
Veh Spec	7	Elec Range	Alternative assumptions for electric range for xEVs
Veh Spec	8	Battery EnDen	Alternative assumptions on battery technology improvement / future chemistries, impacting particularly on energy density
Veh Prod EoL	9	Battery EUSVC	Sensitivity on EU sustainable value chain for battery production and end-of-life treatment
Veh Prod EoL	10	Battery 2nd Life	Sensitivity on high share of xEV battery second life applications
Veh Prod EoL	11	Vehicle EUSVC	Sensitivity on EU sustainable value chain for vehicle production and end-of-life treatment (non-battery)

Vehicle Operational Sensitivities: Regional variation in road mileage shares and electricity mix

High Impact

Lower Medium Car – Baseline Scenario

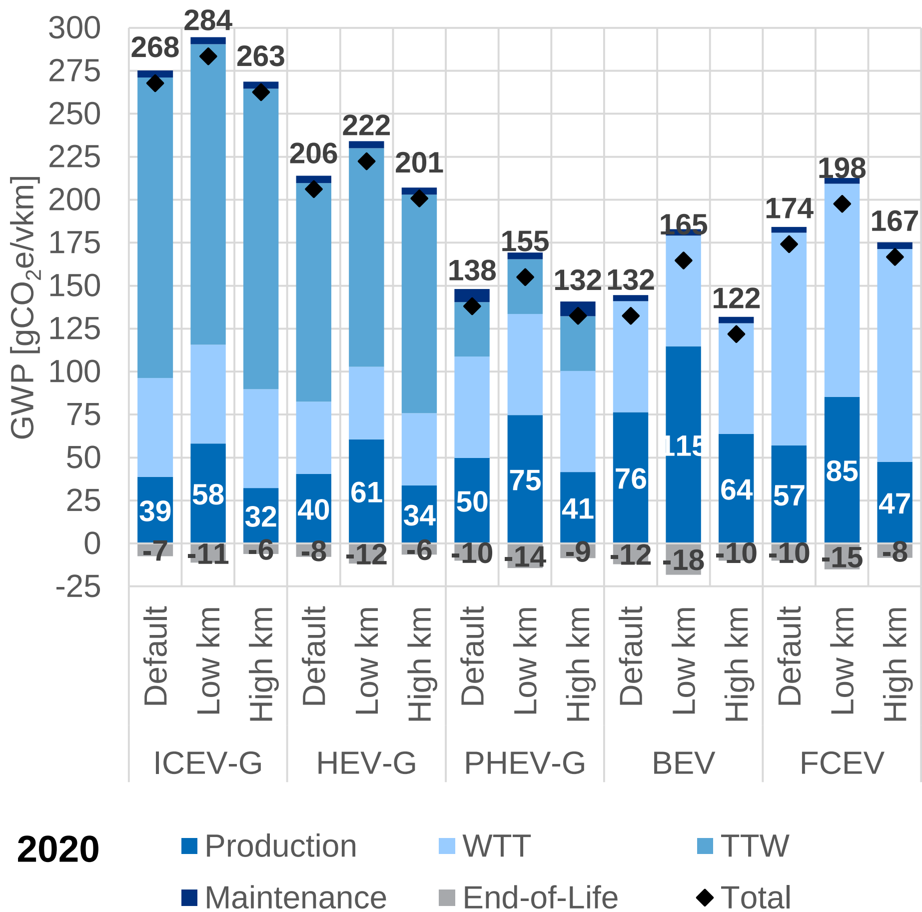


- Variations purely in road mileage shares lead to relatively small differences for cars
  - Impacts due to effects on MJ/km, and tailpipe CH_4 and N_2O emissions
  - Other regional effects (not modelled) may have greater impacts
- Impacts of regional variation in electricity mix are significant in 2020
  - Significantly reduce benefits vs alternatives for BEV.
  - Effects diminish in future periods (BEVs almost always better than all other powertrains from 2030)

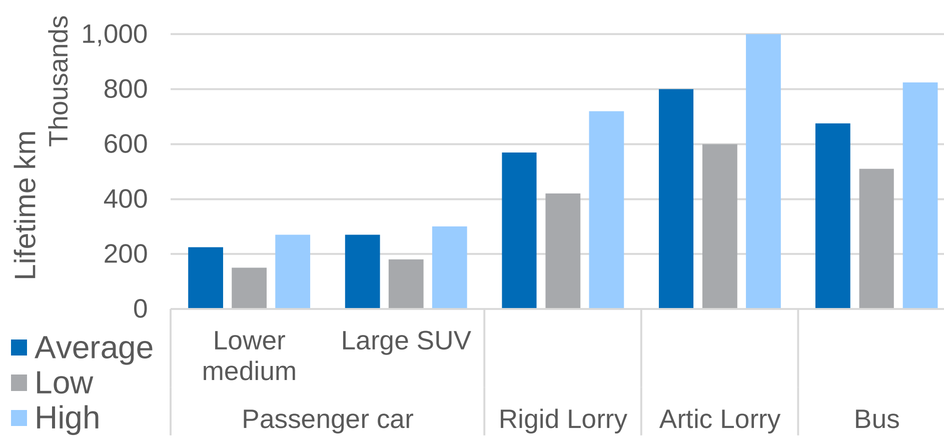
Additional information: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs.

Vehicle Operational Sensitivities: Lifetime kilometre activity

Medium Impact



- Sensitivity results in a reduction or increase in impacts <u>per vkm</u> from manufacturing and EoL
  - Effect on comparison of BEVs vs other powertrains narrows in future years (manufacturing impacts reduce)
- The size of the effect in future periods is lower due to use of lower carbon energy
- Relative effects less significant for higher-mileage vehicles (i.e. HDVs)



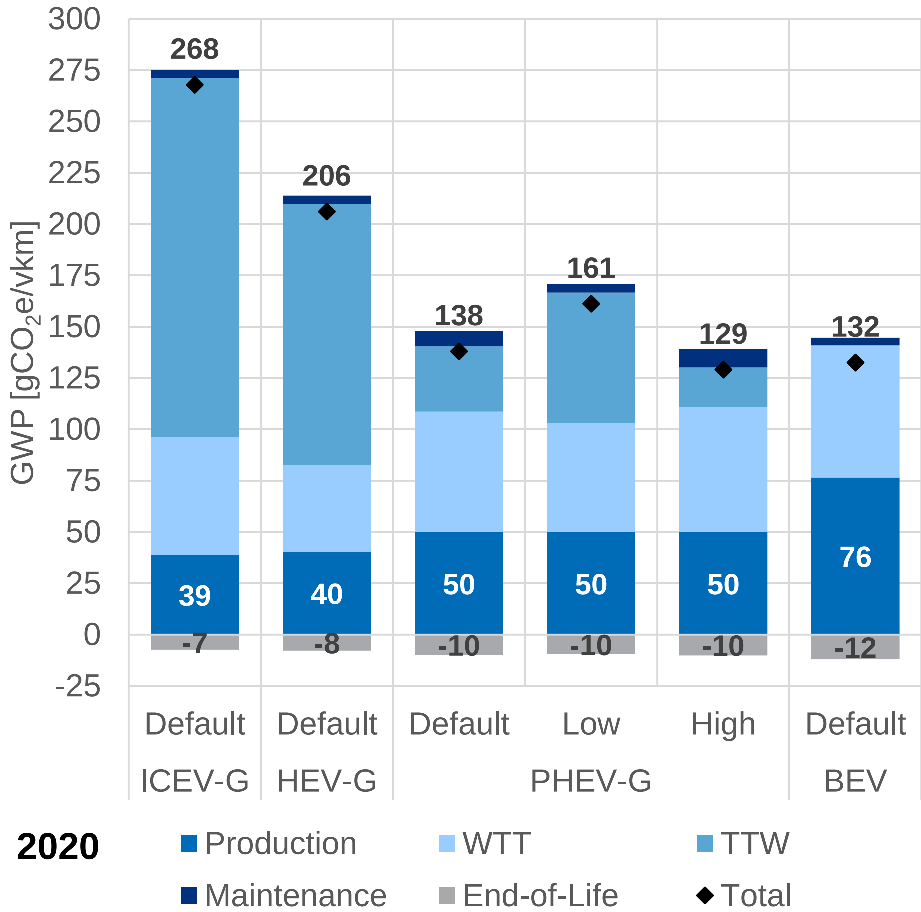
Assumptions: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs

Source: Ricardo analysis for Vehicle LCA project for DG CLIMA (2020)

Vehicle Operational Sensitivities: PHEV charging behaviour / share of electric mileage

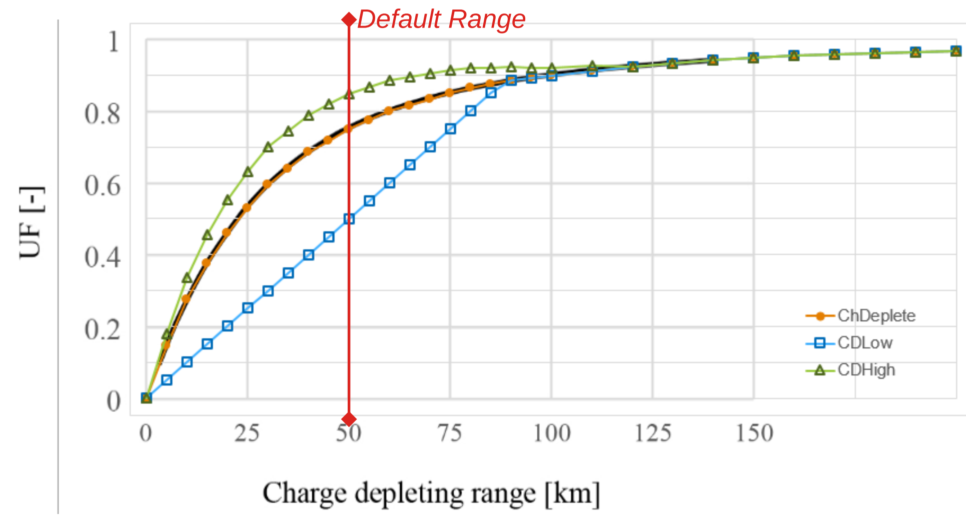
Medium Impact

Lower Medium Car – Baseline Scenario, 2020



Assumptions: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs

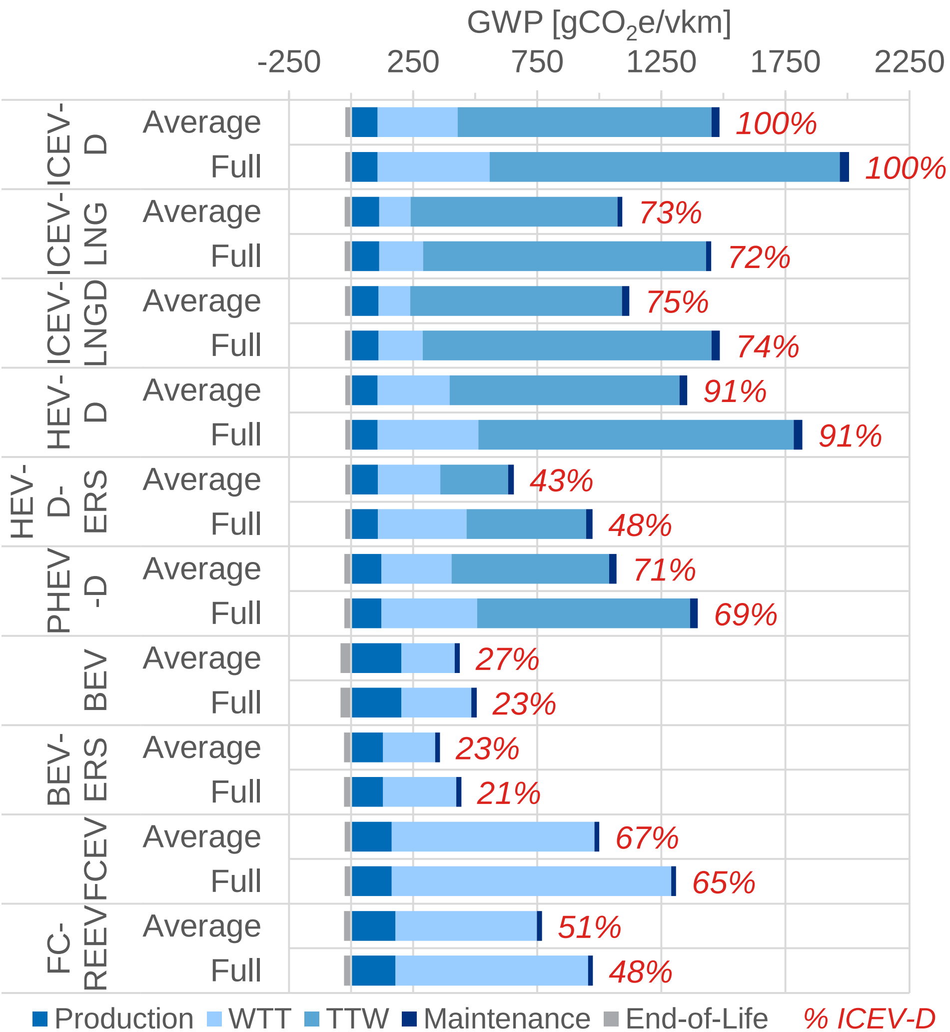
- Sensitivity explored an optimistic vs pessimistic case for PHEV electric km
  - None/100% cases similar result to HEV/BEV
- WLTP LDV utility function (UF) already assumes high %km electric, so impacts more significant in pessimistic case
- Sensitivities for HDV vehicle types show more significant effects (where a more direct relationship with range is assumed)



Vehicle Operational Sensitivities: Effects of alternative powertrain mass for high %load operation

Medium Impact

Artic Lorry – Baseline Scenario, 2020



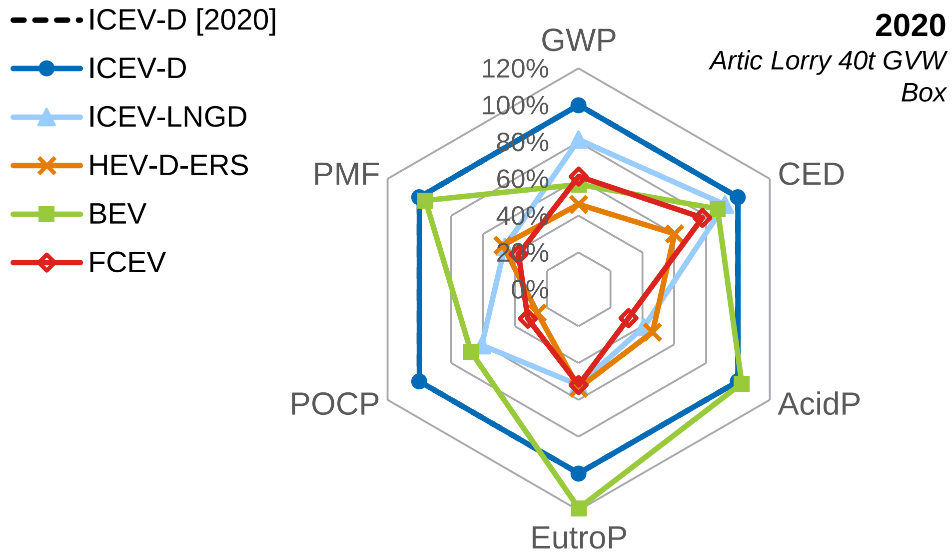
- Av. Load Factor impacts on MJ/km and will also have impacts per tonne-km (tkm)
  - vkm shown here to illustrate energy consumption impacts
- Impact on lifetime tkm for reduced load capacity for heavier powertrains uncertain
  - Depends on whether mass or volume-limited (vol. impacts may be smaller)
- High load factor actually magnifies relative benefits of xEV per vkm since WTW energy impacts are a much smaller share
- For tkm this effect is balanced out for BEV due to reduced load capacity for 2020

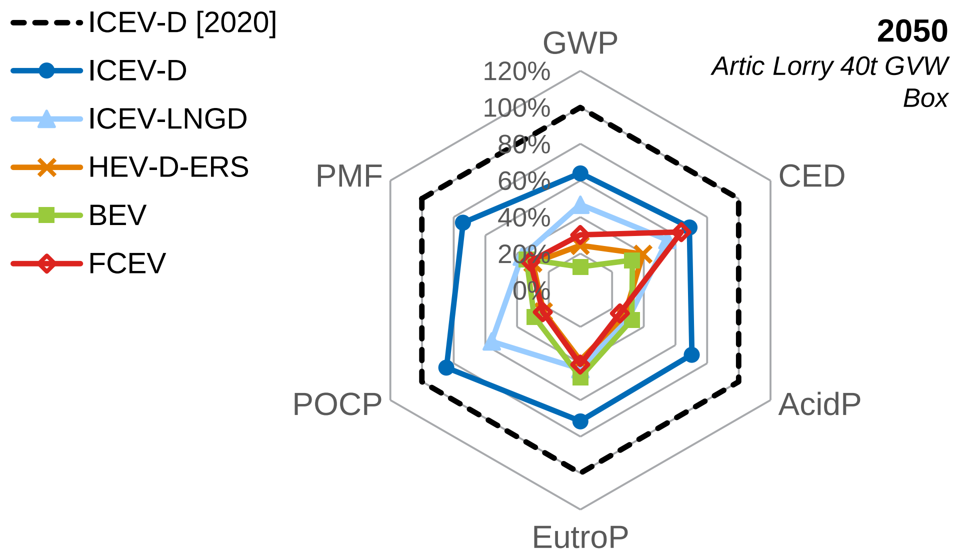
Additional information: 800,000km, 10 year lifetime. 2020 BEV battery 1370 kWh, 500km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for BEV only.

Vehicle Operational Sensitivities: Future improvements to regulated air pollutant emissions

Low Impact

- No objective information on post-Euro 6/VI
- Sensitivity explores impact of a 25% reduction in all tailpipe AQP per decade
  - NOx contributes to all AQP mid-points: AcidP, POCP, EutroP and PMF
- For HDVs, assumptions result in significant improvements, but xEVs still perform better across all categories
  - POCP, EuroP and PMF impacts for diesel cars still >> xEV powertrains
  - Impacts for gasoline cars still > xEVs
- Gas-fuelled vehicles perform similarly to xEVs by 2050 in all AQP mid-points, except for POCP
- More substantial improvements would be needed mainly to tailpipe NOx to bring vehicles mainly using ICE closer to xEVs

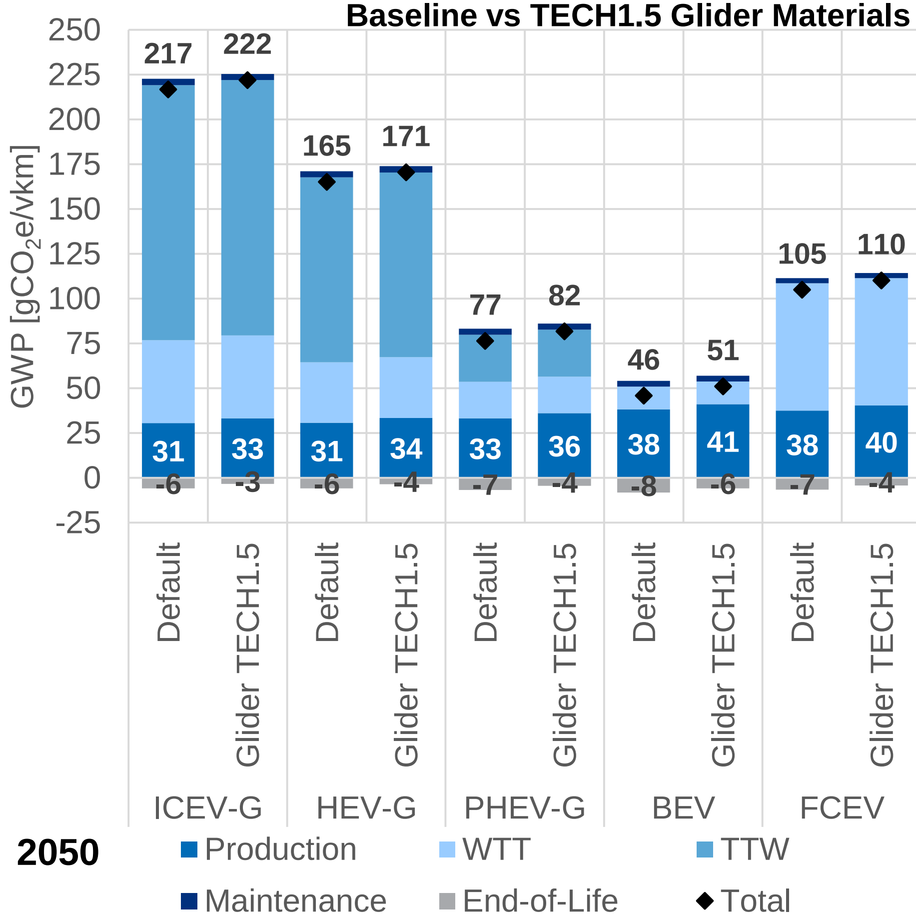




Vehicle Specification Sensitivities: Glider Material Composition

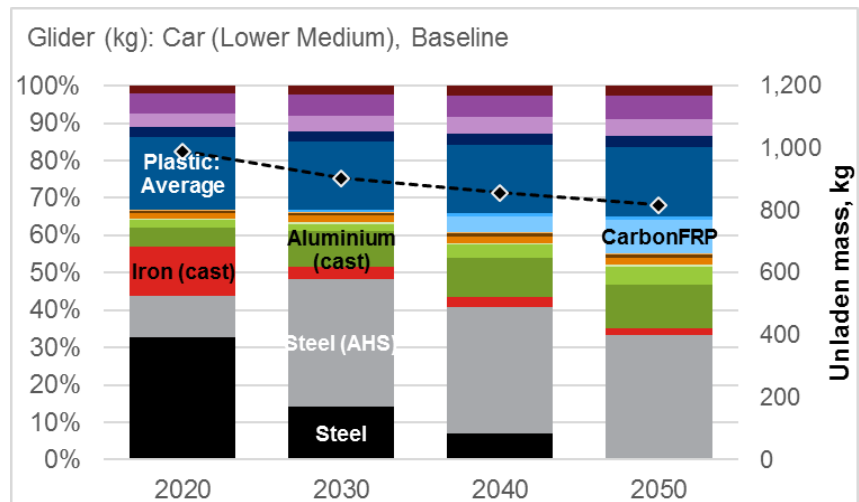
Low Impact

Lower Medium Car – Baseline Scenario, 2050



Assumptions: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs

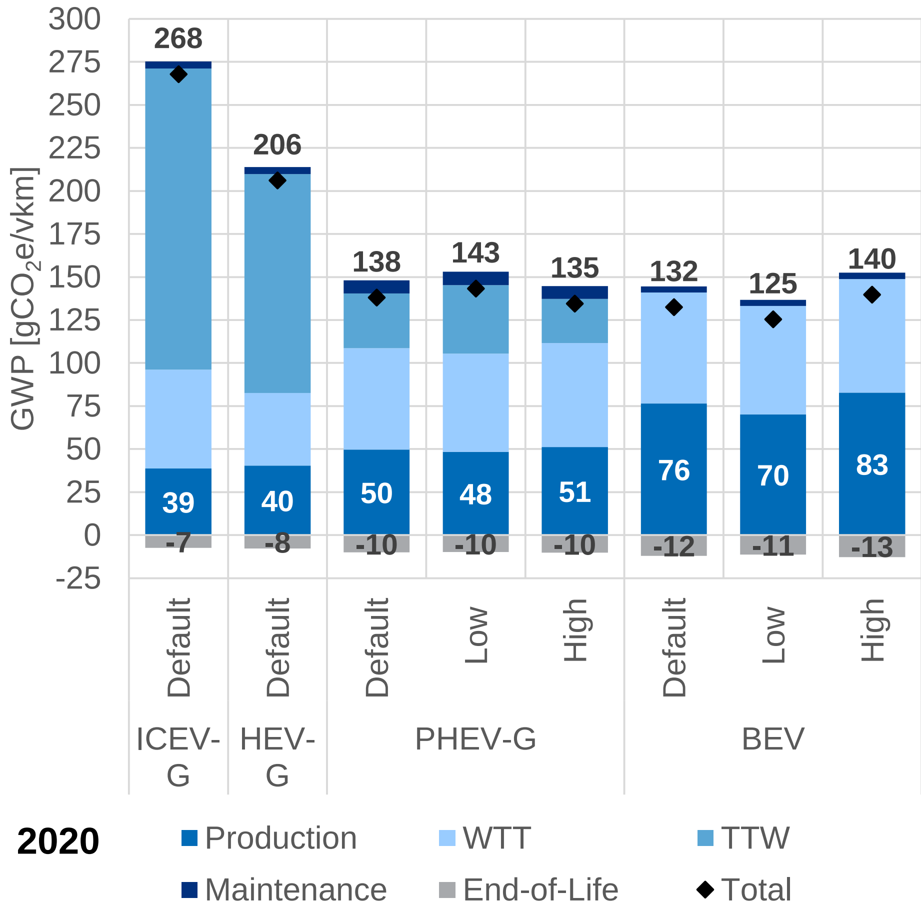
- Sensitivity illustrates material composition impacts independent of effects on MJ/km
  - Higher shares of plastic, aluminium and eventually carbon fibre reinforced plastic in periods 2030-2050 for TECH1.5 scenario
- Overall impacts (from production and EoL recycling/disposal) on GWP are relatively modest (and are balanced by mass reduction benefits on MJ/km in reality)
- Similar for different mid-points, vehicles



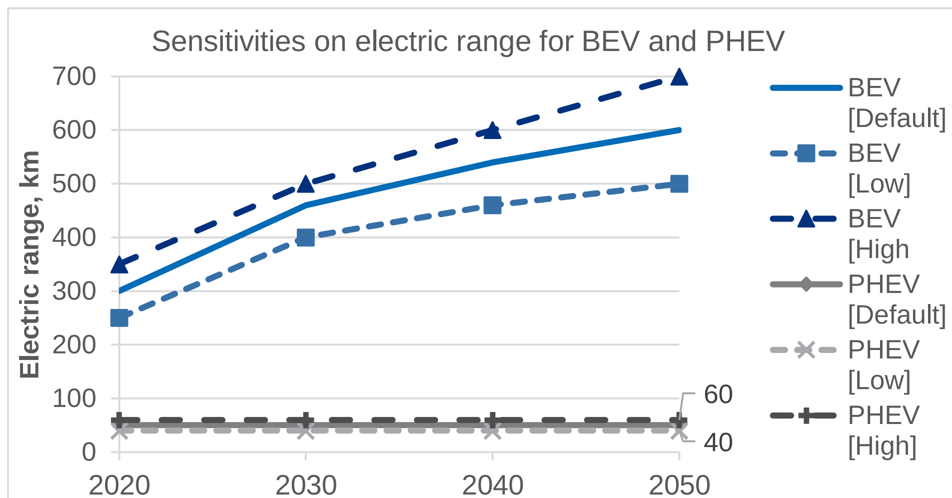
Vehicle Specification Sensitivities: xEV Electric Range

Low Impact

Lower Medium Car – Baseline Scenario, 2020



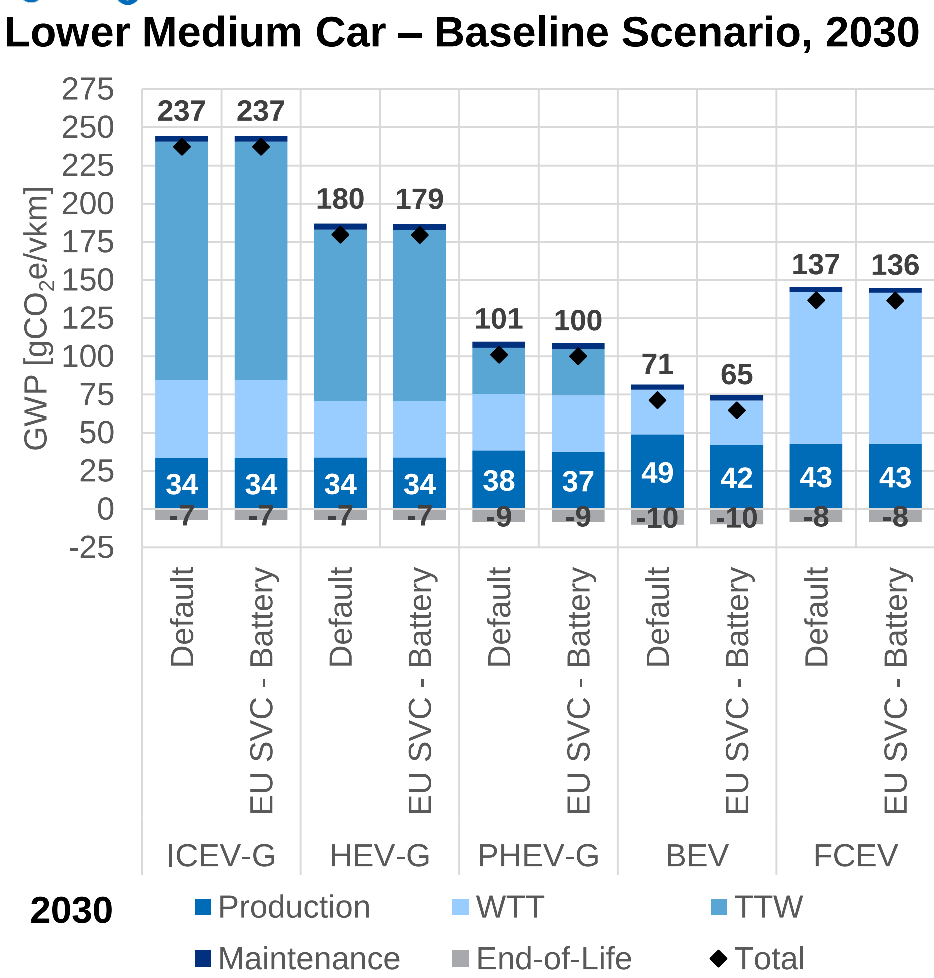
- Sensitivity results in a combination of impacts on manufacturing (battery size) and MJ/km (by change in vehicle mass)
- Longer range reduces PHEV impacts (>share of electric km) but increases for BEV (>manufacturing emissions)
  - Reducing electric range for PHEV significantly reduces net benefits
- Effects narrow in future years for BEVs



Assumptions: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs

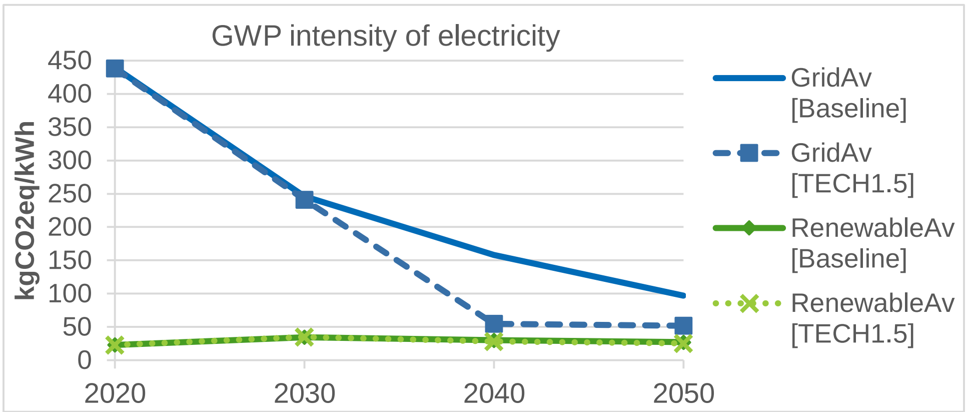
Vehicle Production and End-of-Life Sensitivities: EU Sustainable Value Chain for Battery Production and EoL

Low Impact



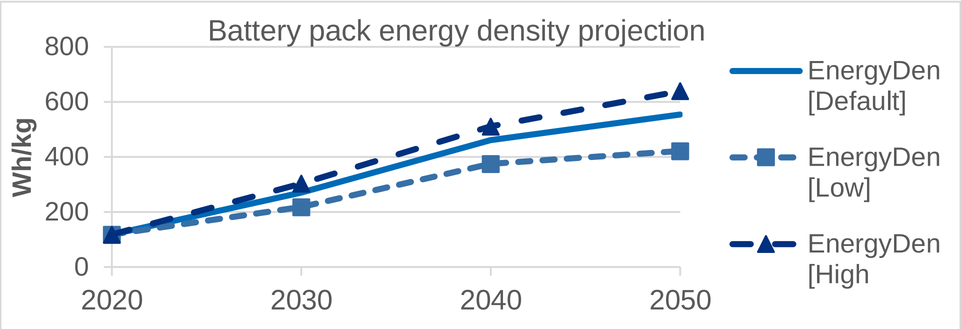
Assumptions: 225,000km, 15 year lifetime. 2030 BEV battery 64 kWh, 460km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs

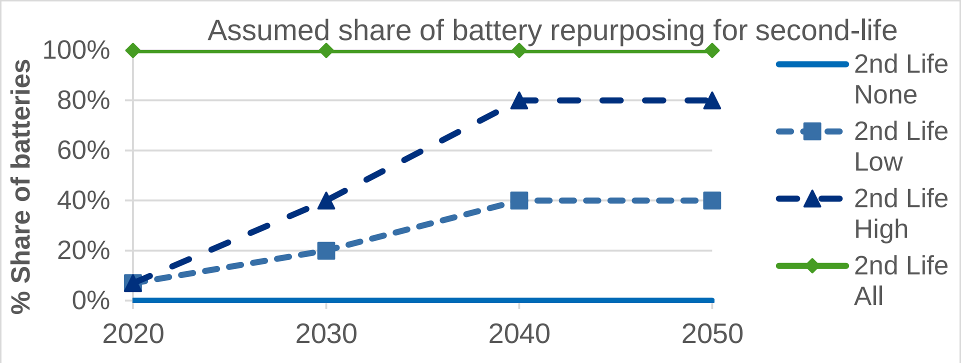
- EU SVC – Battery sensitivity assumes:
  - Renewable electricity for manufacturing and end-of-life processes
  - Higher recycling rates
  - Higher share of EU-based manufacturing
- GWP impacts are relatively low per vkm
  - More significant for ARD_MM, HTP (increase in key recovered materials)

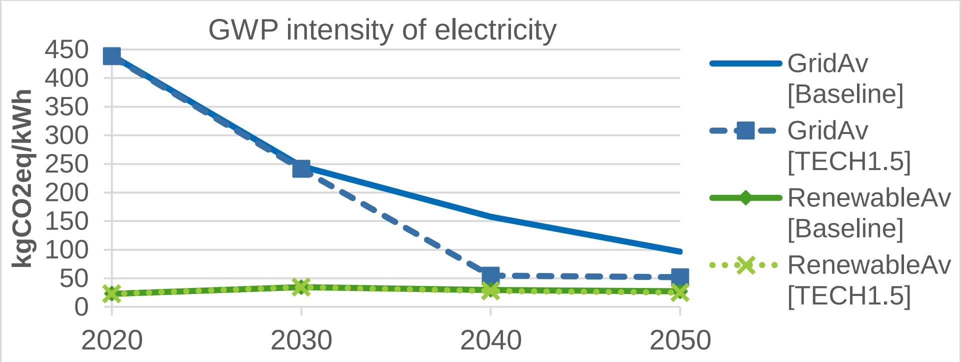


Other Sensitivities

- Effects of **future battery technology improvements** are low (1-4gCO_2e/vkm), except for certain impact categories (ARD_MM, HTP) and vehicle types (Artic Lorries - high range, impact on load capacity)
- Effects of **high share of second life applications of batteries** on GWP impacts are relatively low (1-2gCO_2e/vkm) and diminish in future periods (batteries offset/replaced are of lower impact, so credit is lower)
- Effects of **EU Sustainable Value Chain for Vehicle Production and EoL** on GWP impacts are relatively low (2-4gCO_2e/vkm) but some other impacts can increase slightly: where renewable electricity has slightly higher impacts



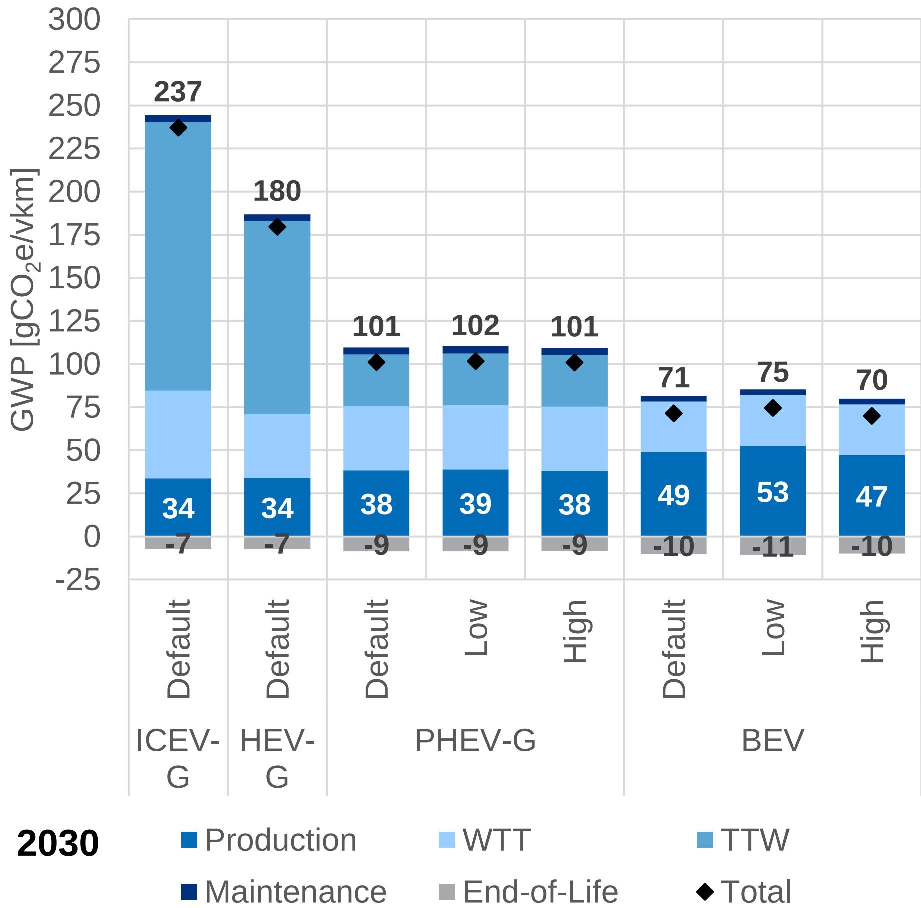




Vehicle Specification Sensitivities: Future battery technology improvements

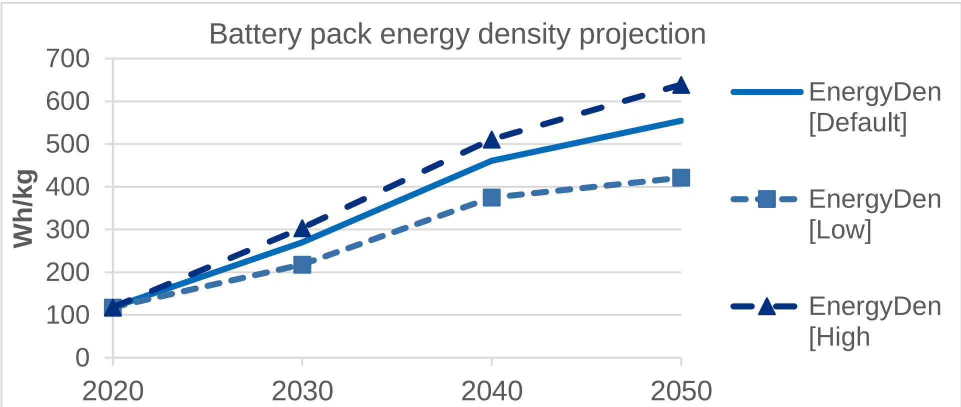
Low Impact

Lower Medium Car – Baseline Scenario, 2030



Assumptions: 225,000km, 15 year lifetime. 2030 BEV battery 64 kWh, 460km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs

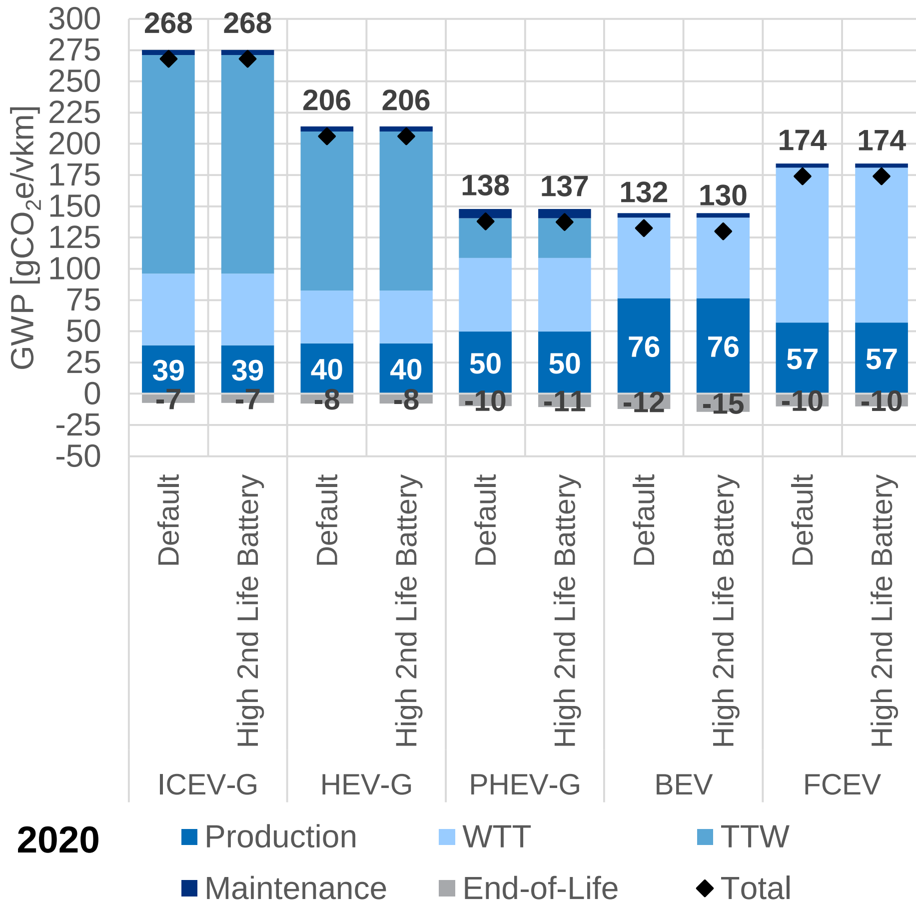
- GWP impacts are relatively low per vkm
  - more significant for ARD_MM, HTP
- Effects less pronounced in future periods (due to lower impacts per kWh battery)
- Improved energy density due to a combination of changes in chemistry, cell and pack improvements
- Similar significance for other vehicle types
  - More pronounced for Artic Lorries: high range, impact on load capacity



Vehicle Production and End-of-Life Sensitivities: High share/benefits of 2nd life applications for xEV batteries

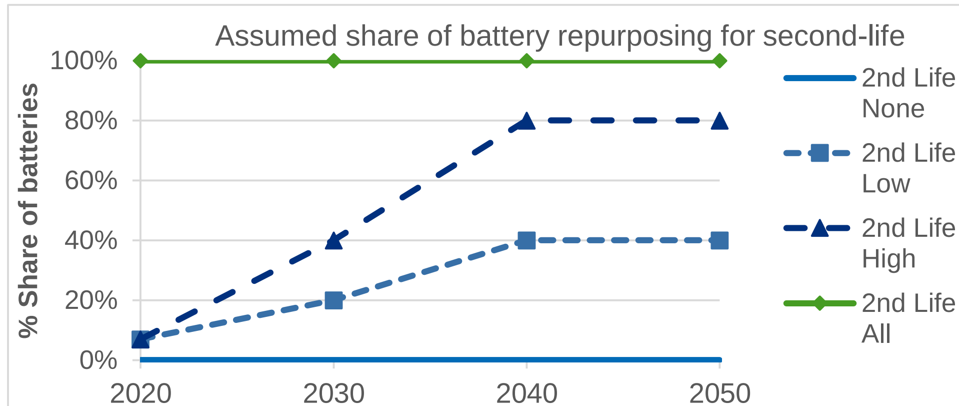
Low Impact

Lower Medium Car – Baseline scenario, 2020



Assumptions: 225,000km, 15 year lifetime. 2020 BEV battery 58 kWh, 300km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs

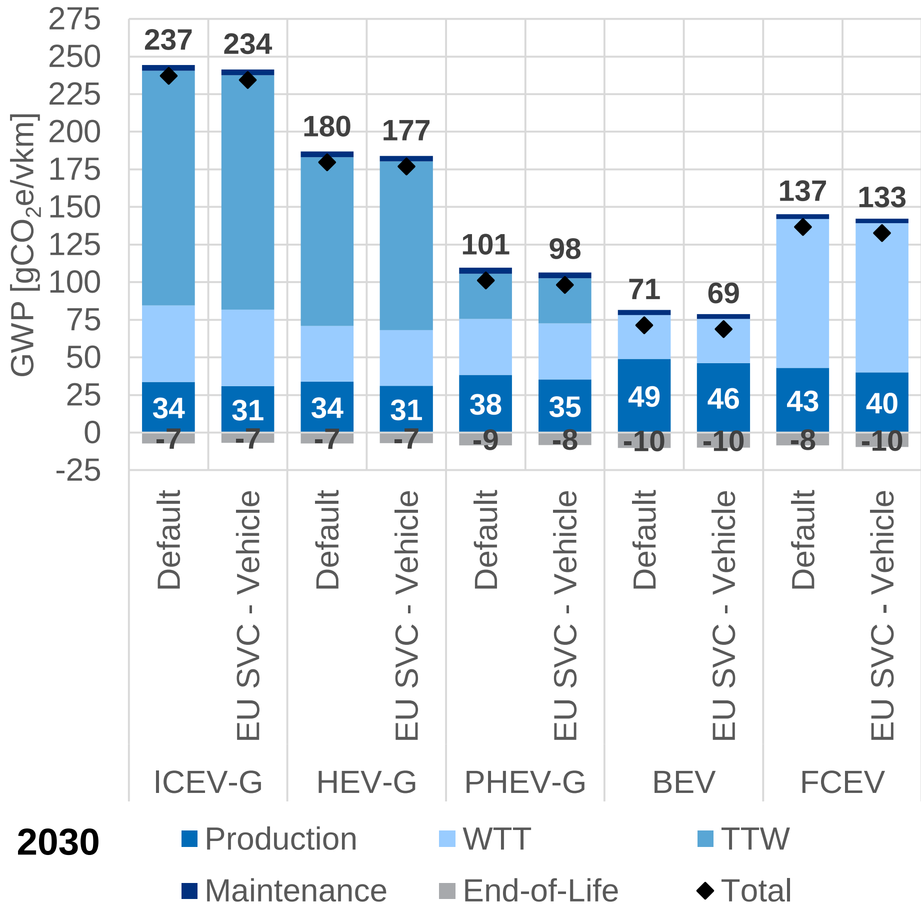
- High 2nd Life Battery sensitivity assumes high share of xEV batteries going to second life applications (default is low share)
- Effects on GWP impacts are relatively low per vkm
- Effects diminish in future periods (batteries offset/replaced are of lower impact, so credit is lower)



Vehicle Production and End-of-Life Sensitivities: EU Sustainable Value Chain for Vehicle Production and EoL

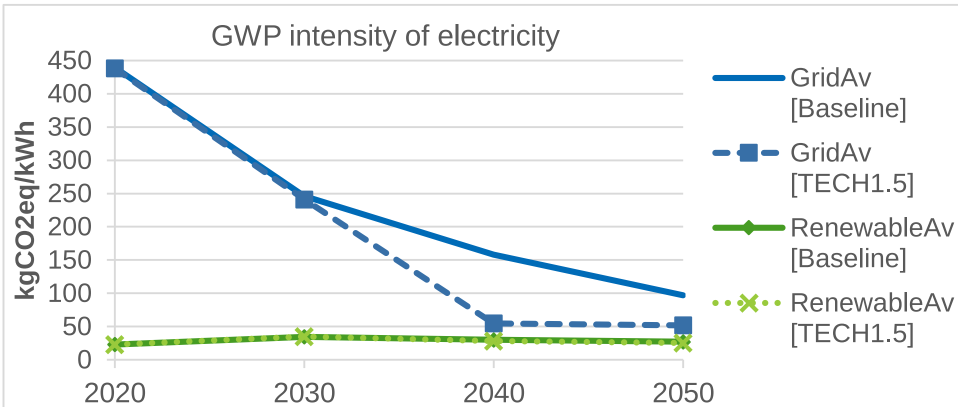
Low Impact

Lower Medium Car – Baseline Scenario, 2030



Assumptions: 225,000km, 15 year lifetime. 2030 BEV battery 64 kWh, 460km range, with av. lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement needed for xEVs

- Sensitivity assumes renewable electricity for manufacturing and end-of-life processes, higher recycling rates
- Effects on GWP impacts are relatively low per vkm
  - Some other impacts can increase slightly: where renewable electricity has slightly higher impacts
- Effects diminish in future periods to an extent, as grid electricity decarbonises



Agenda

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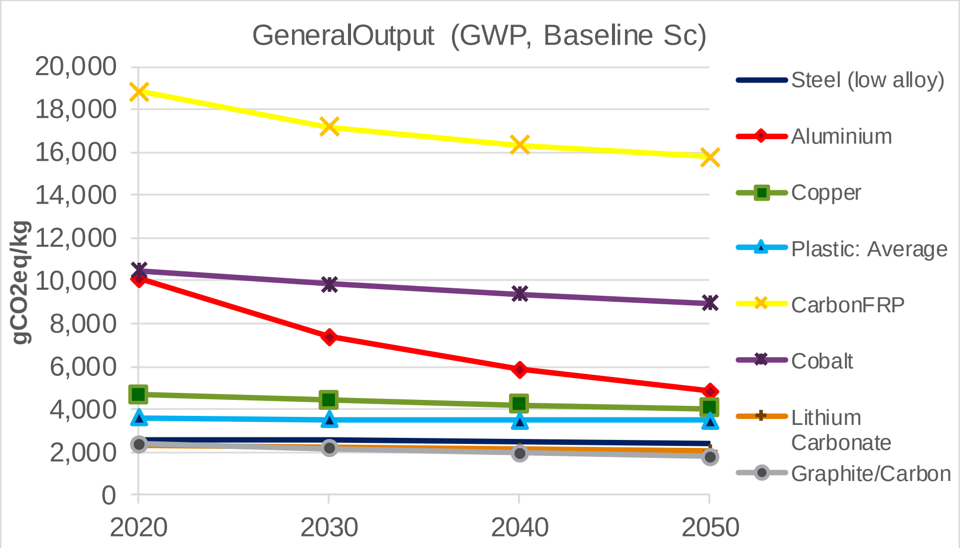
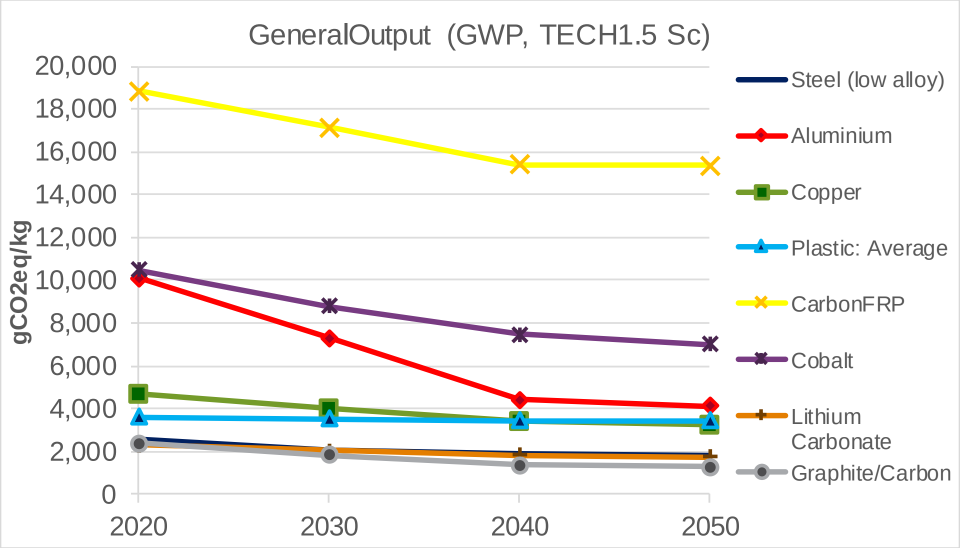
  - Electricity chains [ifeu]
  - Liquid and gaseous fuel chains [E4tech]
- Overall LCA sensitivities [Ricardo, 15:00]
- **Other assumptions and general Q&A [Ricardo, 16:15]**
- Initial conclusions & recommendations and wrap-up [Ricardo, 17:00]

Key assumptions for materials: Projecting future changes in impacts for production of key materials

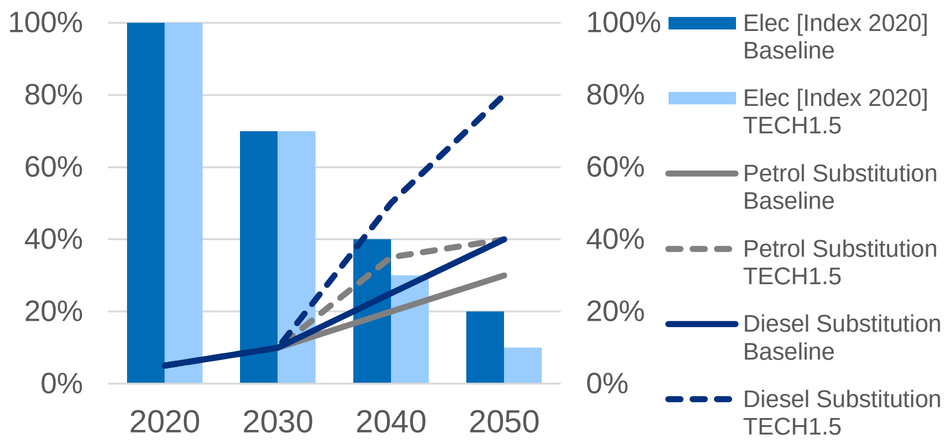
RICARDO

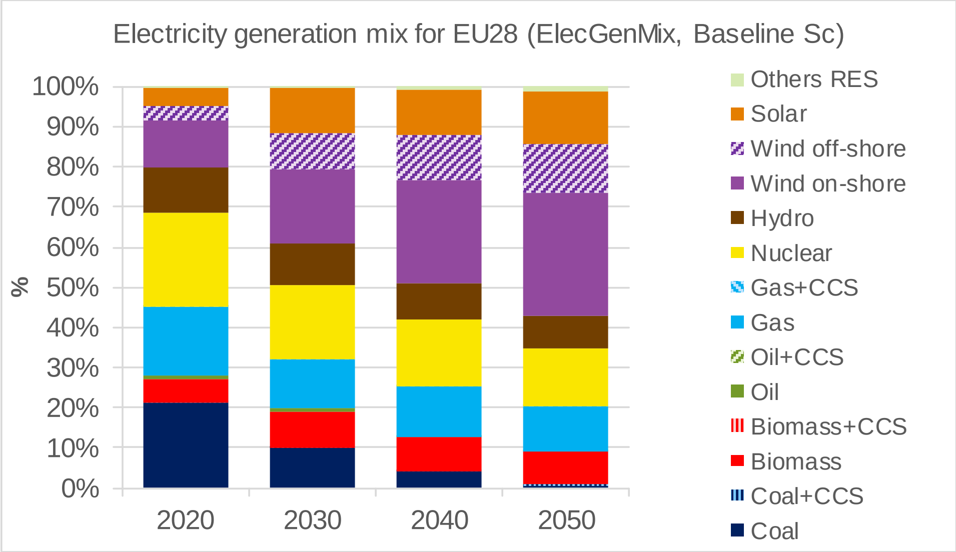
- Key material and process data was based on Ecoinvent, with a limited number of gaps filled with data from GREET (2019)
  - Data was also extracted on the process electricity consumption / impacts
- Estimates for future decarbonisation of the production/processing of materials were developed using the projected future impacts from electricity for the appropriate region (generally World or EU28 average) for the Baseline or TECH1.5 scenario
  - Similarly for EoL recycling / recycled materials
- For Steel and Aluminium production, future improvements in material production / efficiency were also estimated based on data from IEA materials analysis



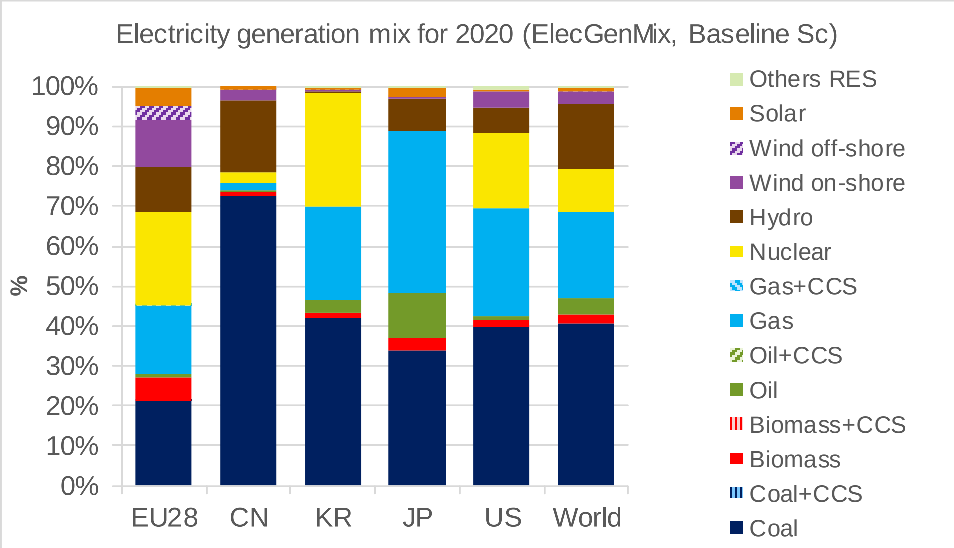


Key assumptions for fuels and electricity: Assumptions on electricity mix and fuel substitution/blends



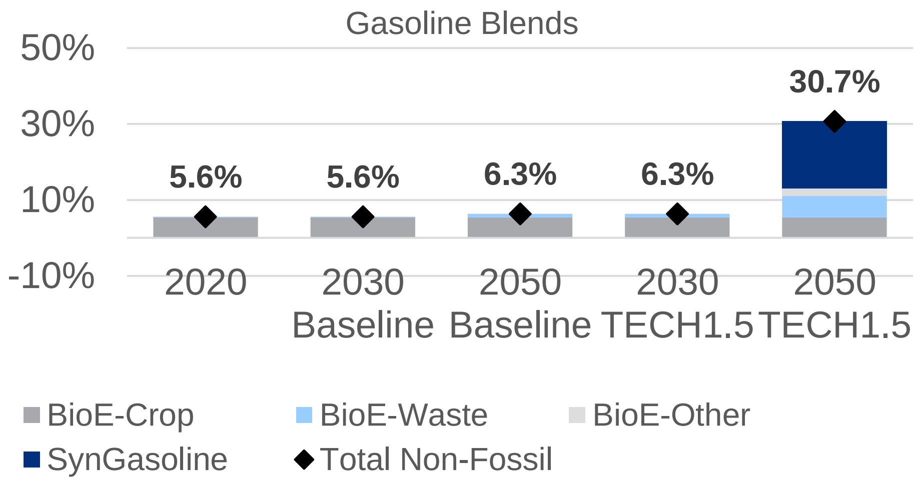


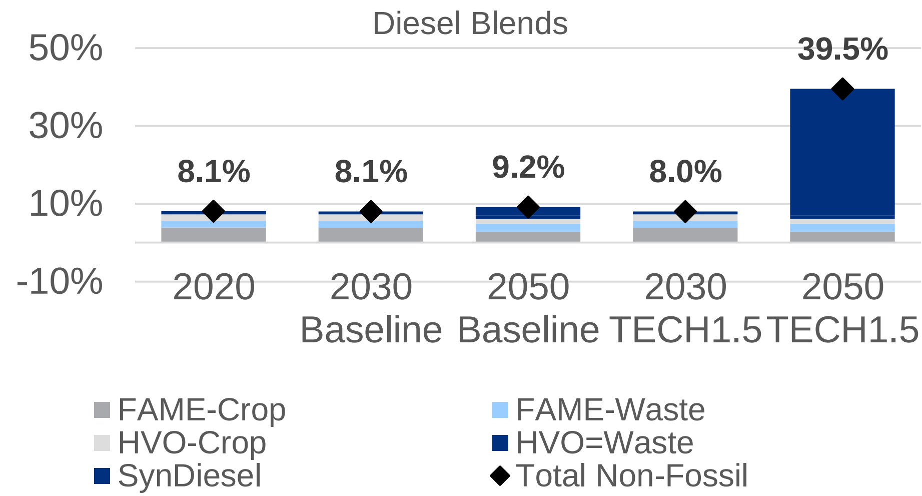
- Electricity mix defined by scenario (Baseline, TECH1.5) and region
  - Impacts calculated based on this and region-specific generation efficiency
- Fossil fuel substitution rate based on EC modelling for Baseline and TECH1.5 scenarios
  - Composition of substituted bio/synthetic fuels estimated based on current norms and expectations for future feasibility

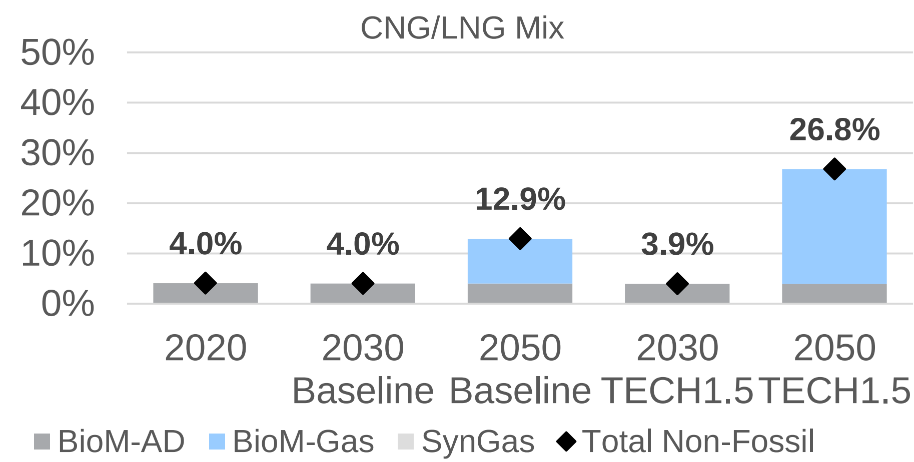


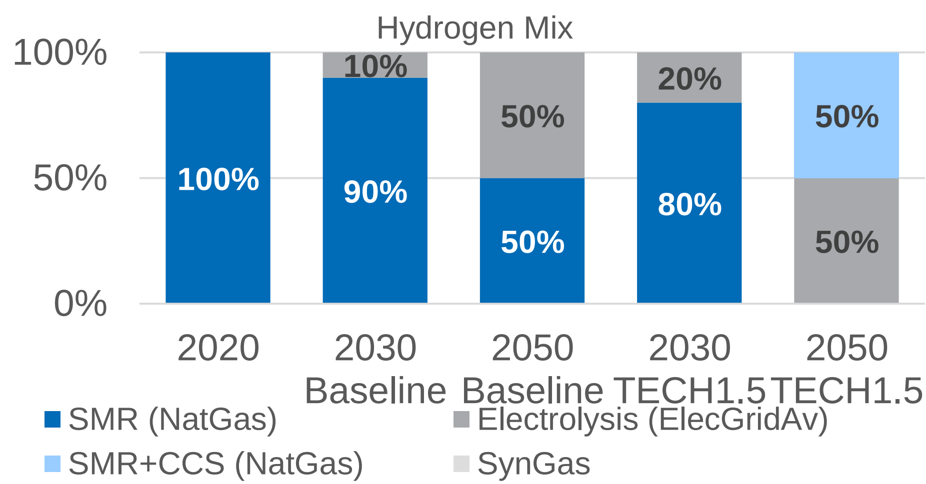
Key assumptions for fuels and electricity: Assumptions on fuel substitution/blends

Baseline Scenario Fuel Blend assumptions used in the full Vehicle LCA modelling







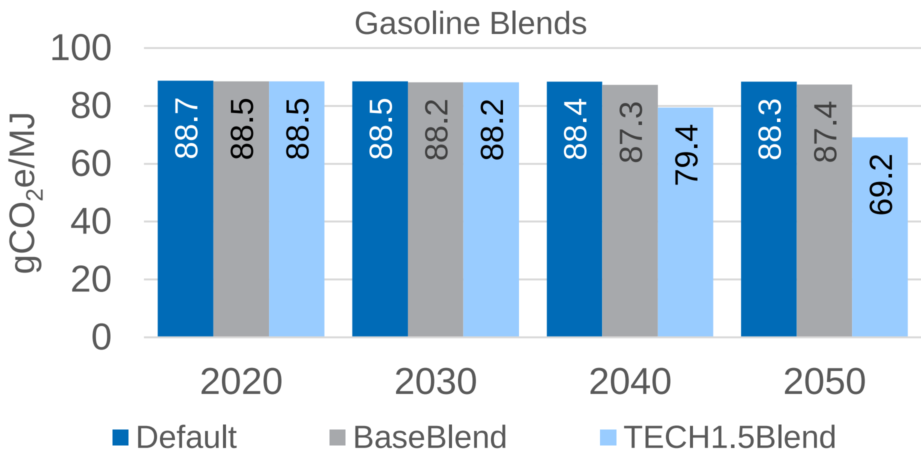


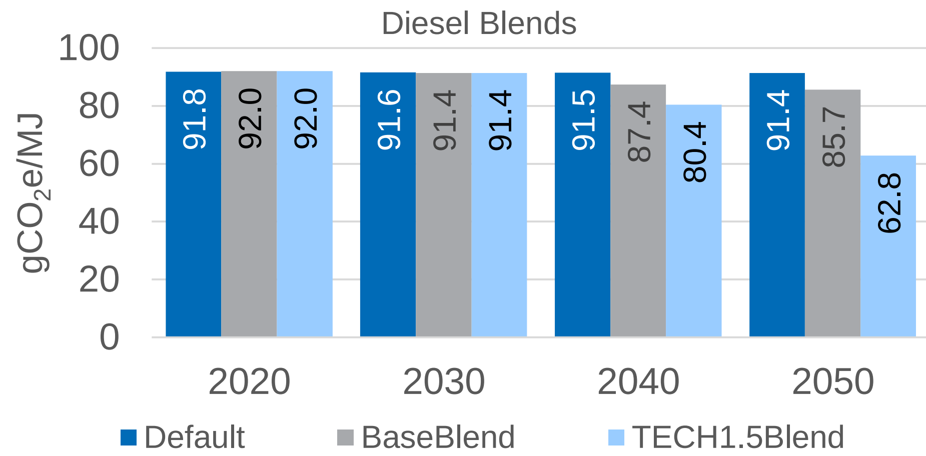
- Blends are indicative: only a subset of the currently available fuels have been modelled

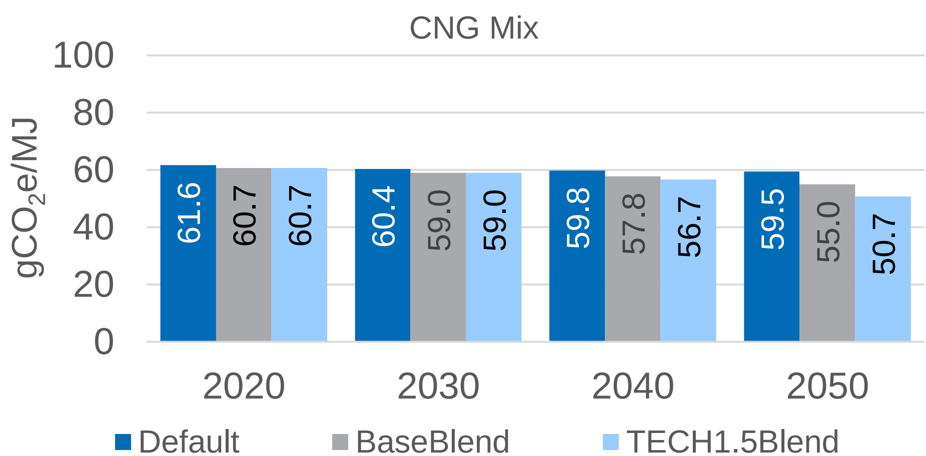
Source:

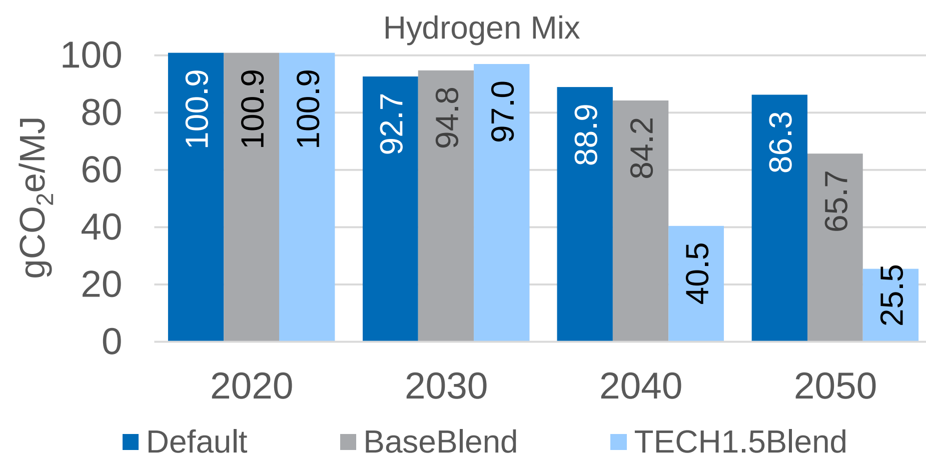
Key assumptions for fuels and electricity: Assumptions on fuel substitution/blends – WTW GWP impacts

Baseline Scenario Fuel Blend assumptions used in the full Vehicle LCA modelling





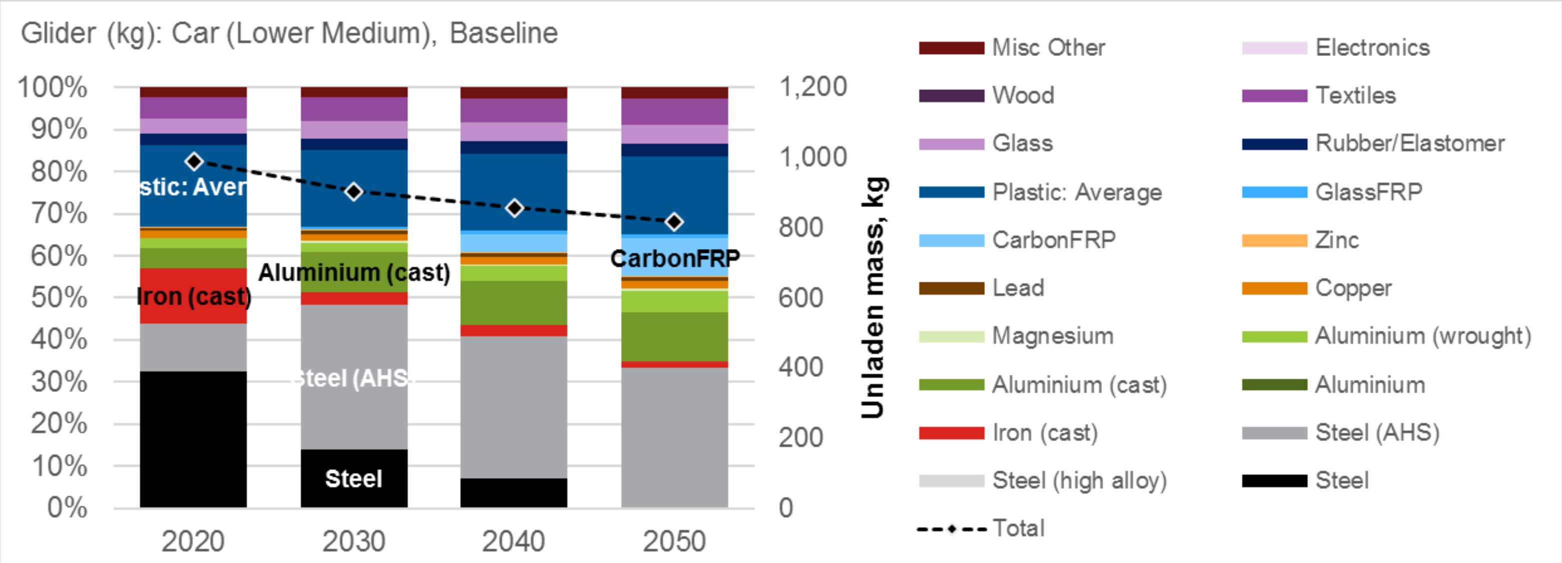




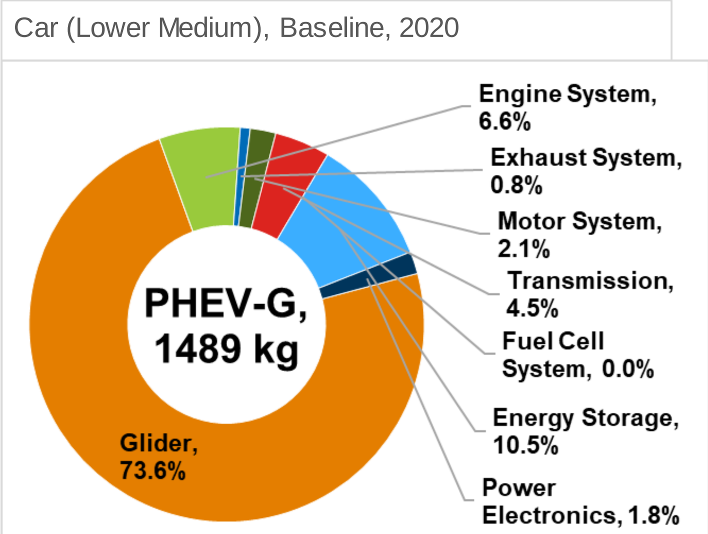
- Blends are indicative: only a subset of the currently available fuels have been modelled

Source:

Key assumptions vehicle specification: Assumptions on vehicle material composition and mass reduction

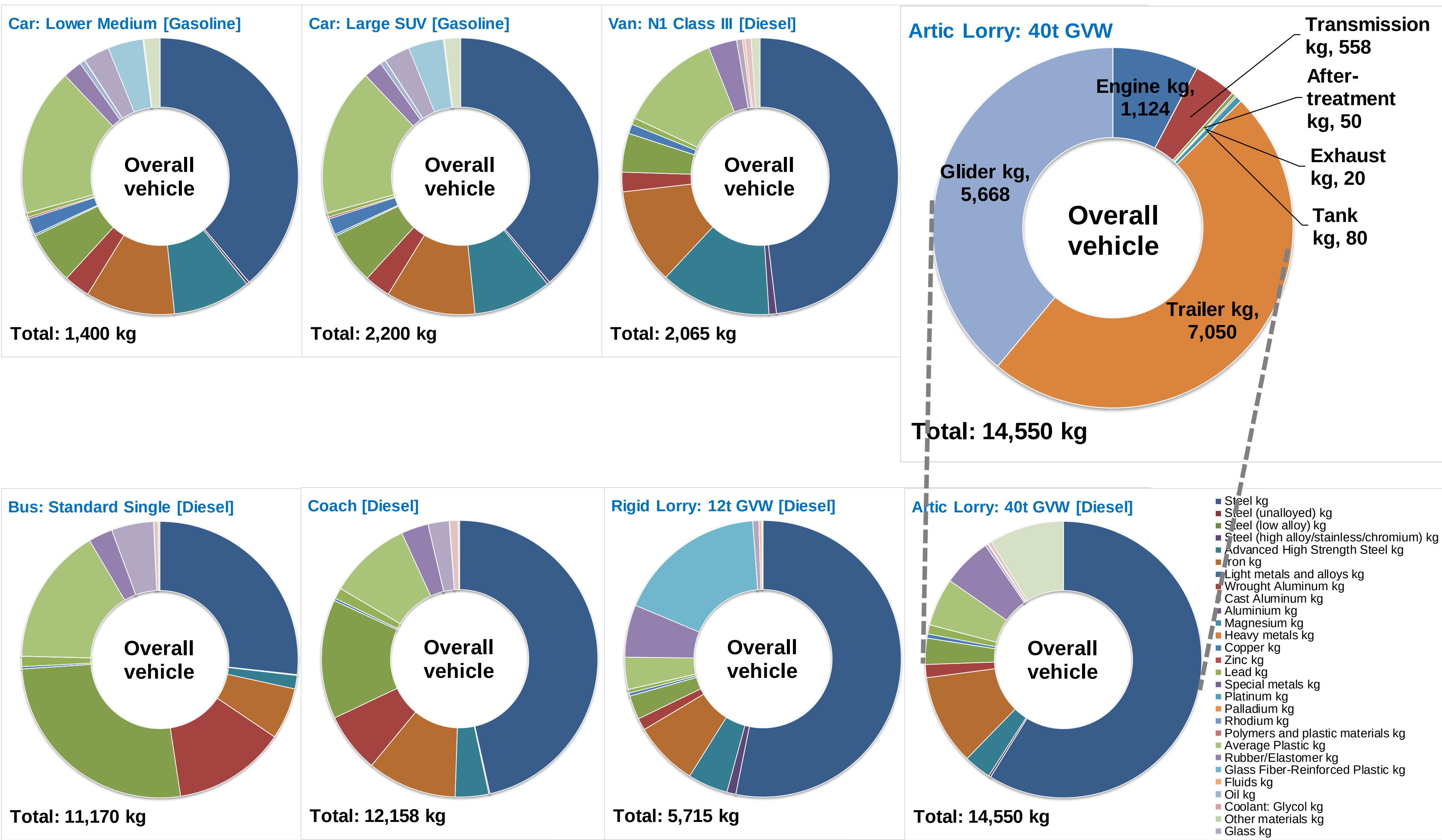


- For the Reference Powertrain by vehicle type
  a. Glider 2020 material shares reviewed with stakeholders
  b. Projections in material mix and mass reduction for (a) Baseline, (b) TECH1.5 scenarios to 2050
- Generic component mass/composition defined separately
- Mass and material composition of alternative powertrains defined based on combination with individual components



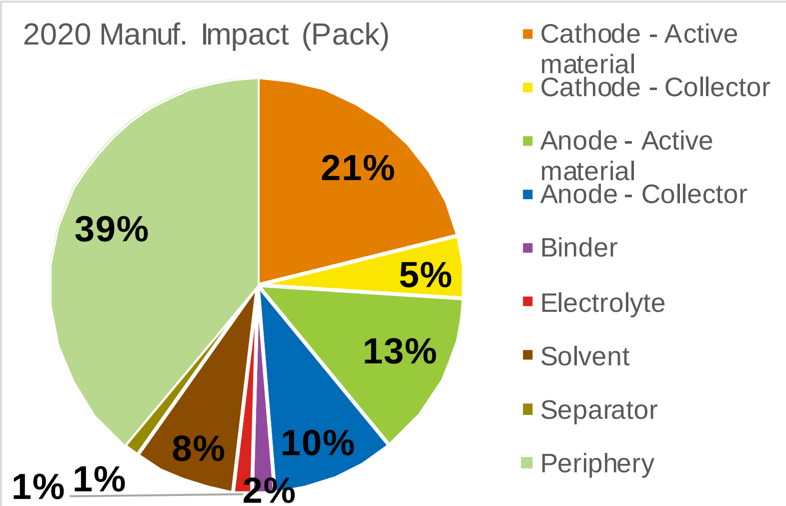
Source: Mass/material mix projections based on a combination of Ricardo's previous analysis for The European Commission, and data on lightweight vehicles from the GREET model (2019)

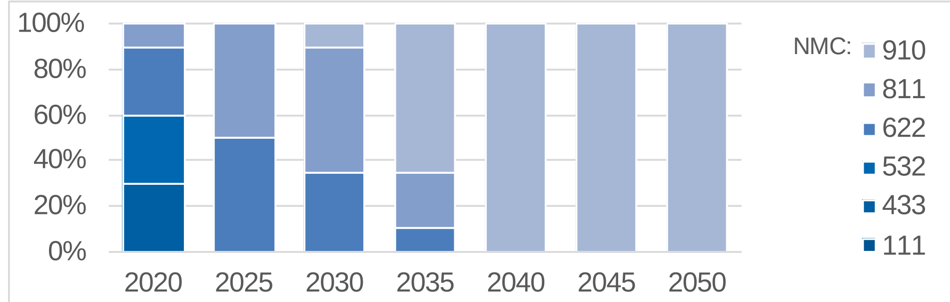
Validation exercise with stakeholders covered assumptions for baseline vehicle / powertrain material composition datasets…

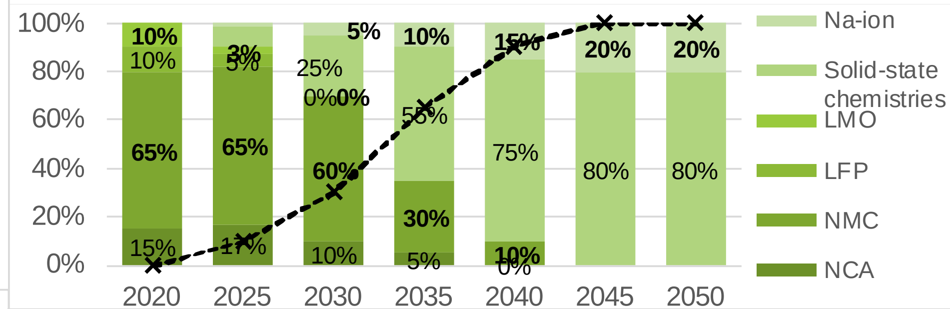


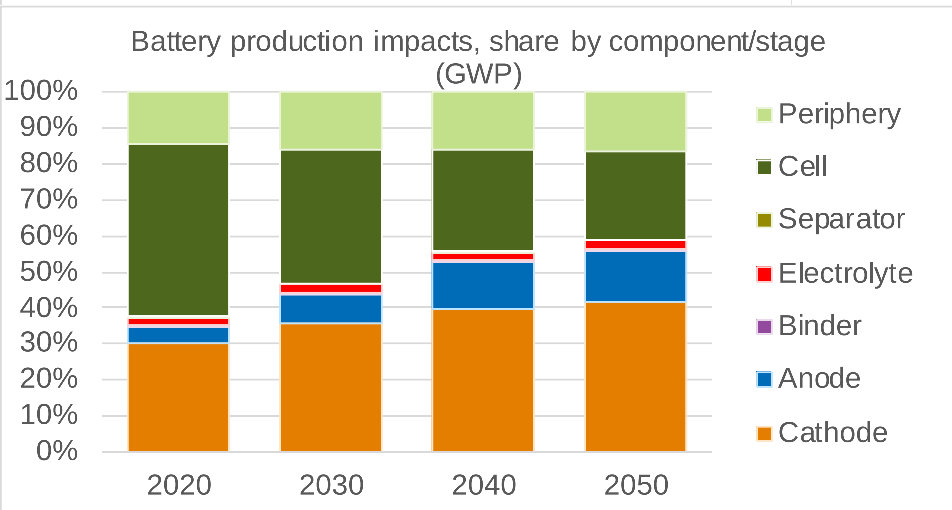
Key assumptions for battery calculations: Summary of key assumptions

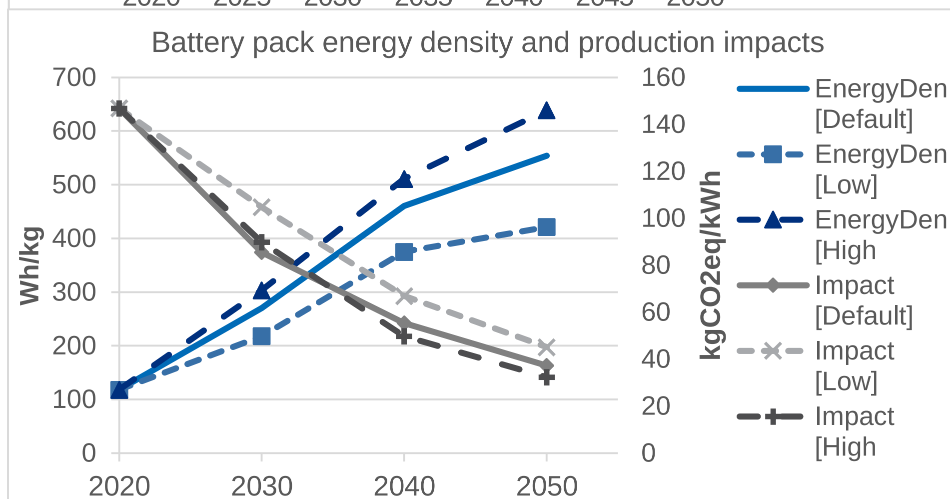
- Manufacture/EoL adapted from GREET





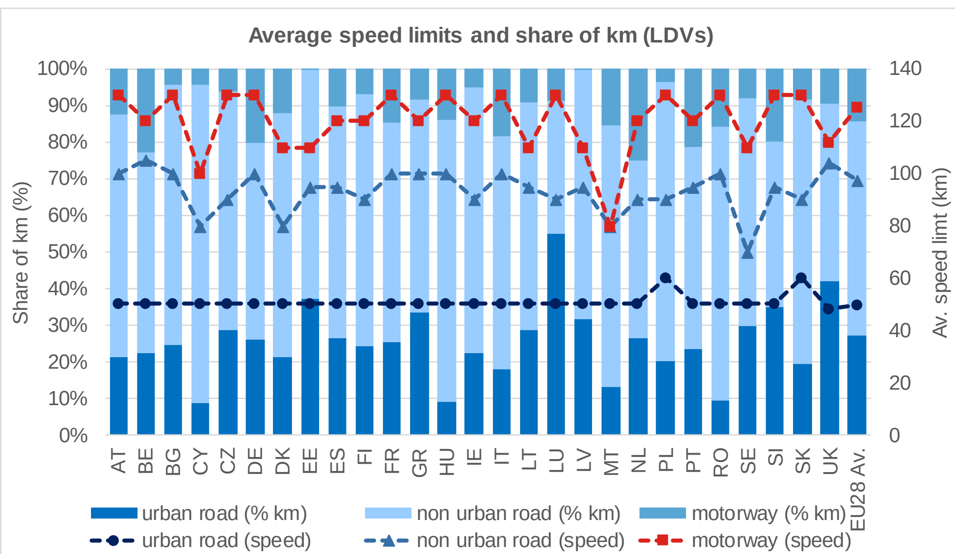


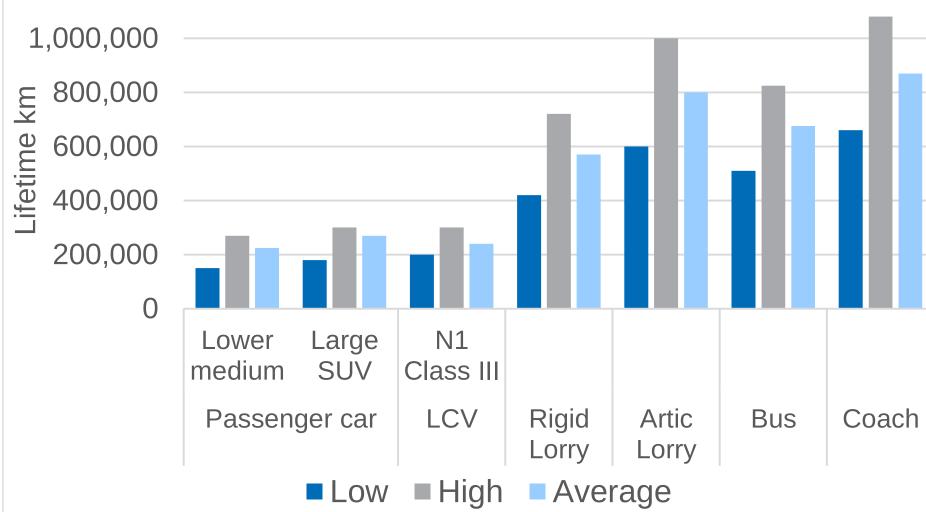




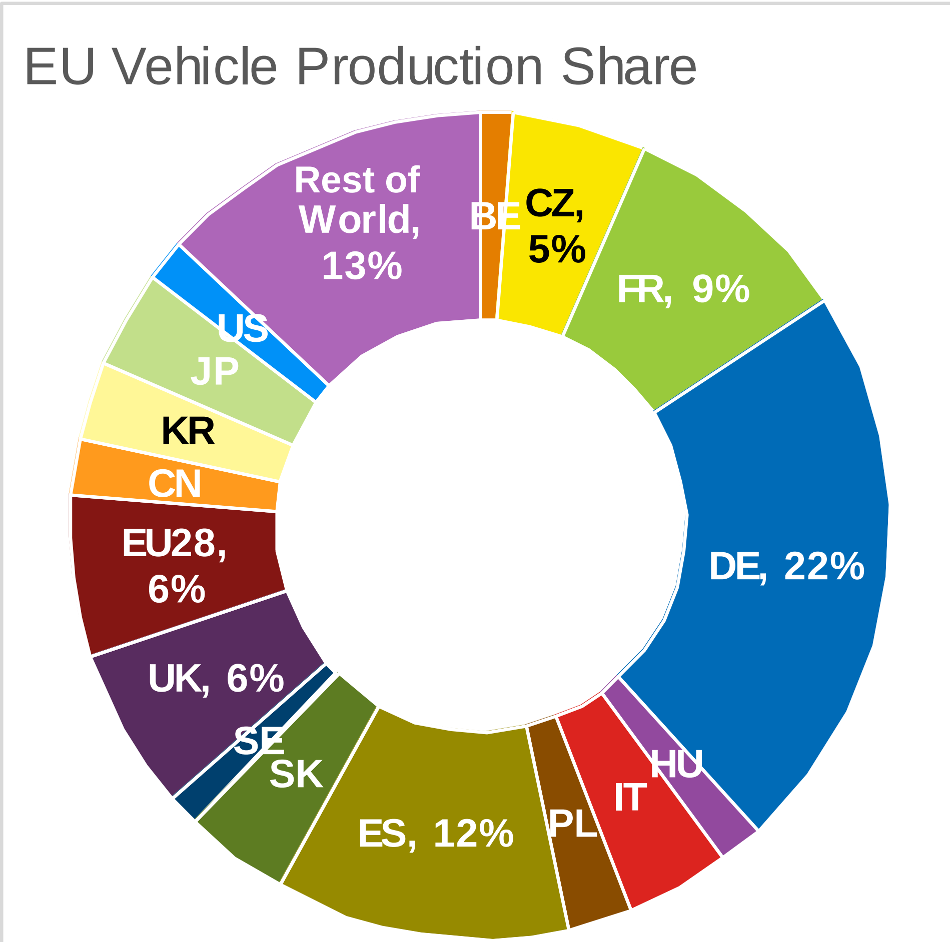
Key assumptions for operational impacts: Assumptions relating to mileage and operation by road type

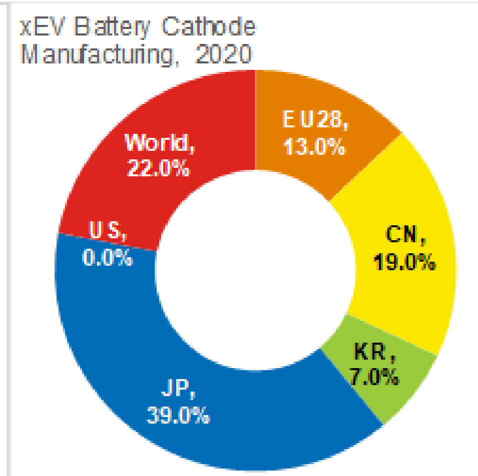
- Share of mileage on different road types varies significantly between EU28 countries
  - Energy consumption and emissions defined based on average speed by road type, based on mainly COPERT factors, Ricardo simulation for relative MJ/km of new powertrain HDVs
  - Average impacts based on calculation using regional share
- Lifetime km and age-dependent annual km profile over time based on recent analysis for EC, and EC transport modelling datasets
  - Low / High sensitivities also applied for lifetime activity

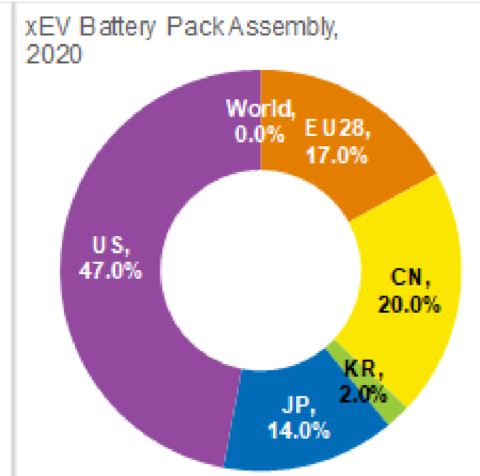


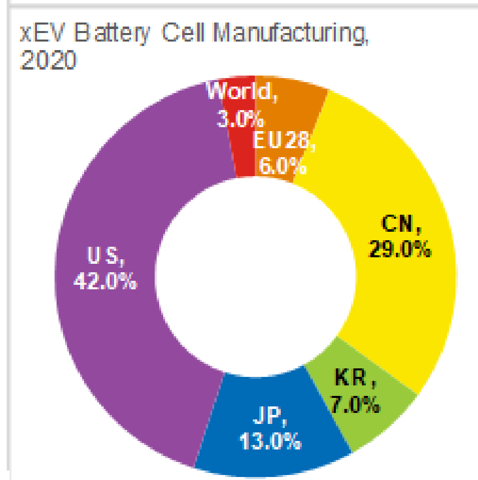


Other assumptions:
Vehicle and battery manufacturing shares









Agenda

- Introduction, background and objectives of the meeting [09:00]
- Overview of the developed methodology [ifeu, 09:30]
- Overall LCA results [Ricardo, 11:00]
  - Results and comparisons for lower medium cars
  - Results for other vehicle types
- Results for energy chains [ifeu / E4tech, 13:30]:
  - Electricity chains [ifeu]
  - Liquid and gaseous fuel chains [E4tech]
- Overall LCA sensitivities [Ricardo, 15:00]
- Other assumptions and general Q&A [Ricardo, 16:15]
- **Initial conclusions & recommendations and wrap-up [Ricardo, 17:00]**

Initial conclusions (overall): Key achievements, strengths and robustness of findings

- A harmonised/consistent comparison of the environmental performance of a sample of vehicles has been developed for all stages of the vehicle life-cycle:
  - Good comparability of overall results
  - Novel methodological development in key areas – particularly to account for future changes in impacts key materials and energy chains, and vehicle mileage
- A key benefit of this study was to concretely try certain methodological approaches and see whether this worked/could be applied in practice and how these impact the results
- Accordance with the general principles of ISO and also other important guidelines (PEF, ILCD) were mostly established
- Stakeholder consultation / engagement predominantly favoured the chosen approaches and on many issues there was almost a consensus on the methodological choice
- Results for a broad scope of products and environmental impacts have been derived on a largely comparable and robust basis
  - Proves the general feasibility of the developed concept and approach
  - Provides a robust evidence base to help dispel common myths, highlights areas of greater variation / uncertainty, indicates potential environmental hotspots

Initial conclusions (overall): Key achievements, strengths and robustness of findings pt2

- Results prove the interesting performance profiles for EVs across all metrics assessed in the study, whilst highlighting key dependencies and hotspots to be addressed:
  - *Hotspots due to electricity*: varies by impact mid-point and generation type. Impacts from biomass generation appear to be particularly large in a number of cases
  - *Hotspots in HTP / ETP_FA / ARD_MM due to materials*: copper, electronics and certain other battery materials (but not cobalt or lithium as low % of total mass)
  - *Hotspots for CED and WaterS for FCEVs/H2*, particularly for electrolysis
- Benefits of BEV, PHEV, FCEV significantly enhanced between 2020 and 2030 due to decarbonisation of electricity/H2, battery improvements
  - No battery replacements after 2020 even for HDVs, based battery cycle life and capacity increases assumed
- The findings for natural (and bio-/synthetic-) gas fuelled vehicle show that these can provide significant benefits vs conventional alternatives across a range of impacts:
  - Some uncertainty remains over WTT components for GHG
  - CH4-slip in dual-fuel gas-diesel vehicles undermines / may eliminate efficiency benefits
- Findings for low carbon fuels are less clear, need further work: questions remain on fossil gas chains, and on novel synthetic fuels, which are further discussed later

Initial conclusions (fuel chains): Key achievements, strengths and robustness of findings

- 59 fuel chains covered for all LCA midpoints + single substances covered
- Novel approach to secondary feedstocks, incl. potential displacement effects (counterfactual) successfully tested. Paves the way for more research and policy work
- Results shall not be taken as face value. Study shows the concrete consequences of certain methodological choices on how fuels are evaluated against each others, in particular:
  - *Importance of the substitution credit chosen*: Our method for selecting was simplistic, for more accuracy would require rigorous modelling – does the co-product typically feed into multiple markets? Is there a more appropriate alternative, etc.
  - *Importance of counterfactual scenarios:* Diverting secondary feedstocks from existing productive uses into liquid fuel production can result in significant environmental impact if that existing use still needs to be supplied. Attributing zero impacts up until the point of collection is only valid for true wastes.
  - Using the same methodology for both secondary fossil and secondary biogenic feedstocks allows fuel produced from mixed feedstocks (e.g. MSW) to be treated as one consignment rather than assessing the fossil and the biogenic fraction separately
  - Weight of Land-Use Change emissions over results for primary biogenic fuels
- Non-GWP impacts provide different trends than GWP for several fuels. Comparability with other WTW studies and RED II remains limited, however.
- IFEU refinery model gives comparable results as CONCAWE's, except for LPG (higher)

Initial conclusions (overall): Uncertainties, limitations and data gaps

- LCA is inherently imprecise/uncertain. The broad scope of the study has also led to trade-offs with level of detail and accuracy in certain areas
- Results are for generic vehicle types, which provide a good basis for further policy decisions and can be assumed to be valid for a representative sample of such vehicles
  - ➲ Validity for specific single vehicle models is naturally limited
  - ➲ Comparisons with more novel fuels/blends needs improved data/methodologies
- Considerably less data/literature is available for certain vehicle types (mainly lorries and buses) and powertrains/fuels (e-fuels, synthetic biofuels and non-conv. fossil fuels)
  - ➲ This may lead to higher uncertainties for these vehicles/energy types
- Broad scope of considered environmental impacts likely leads to differences in data robustness between these impacts due to data uncertainties and asymmetries
  - ➲ Care should be taken in result interpretation, especially for less common/established impacts (and especially for more novel fuel types)
  - ➲ Environmental impact data vary across different LCI datasets: effects absolute result
- Some methodological areas subject to greater debate and could be further investigated:
  - – the extent and application of consequential modelling, end-of-life-modelling as well as the relevance of charging/refuelling infrastructure

Initial conclusions (fuel chains): Uncertainties, limitations and data gaps

- Consistency issues around the combination of attributional LCA (ag. Inputs, crop processing, transport etc.) and consequential LCA (LUC) elements shall be further analysed
- Variable accuracy and reliability of results, primarily stemming from data sets. Some fuels well covered, some scarcely documented. Makes comparability difficult
- A limited number of counterfactual and substitution scenarios were modelled. No economic modelling of counterfactual
- LUC values should be updated for 2020, 2030 and 2050 on the basis of GLOBIOM results, given the dynamic nature of economic modelling. For LUC, a comparison with GTAP should be conducted (not possible within current project timeline)
- A key challenge to the evaluation of secondary feedstocks is to account for / mitigate the risk of indirect impacts from using secondary feedstocks, given the uncertainty in assessing these – is LCA the best tool in order to do this?

Recommendations for future work

Area	Methods	Data	Comment
Vehicle Specification	🙂	🙂	Refine current assumptions based on improved data and/or expand analysis to include other vehicle types
Vehicle / Battery Manufacturing	🙂	🙂	- Improved characterisation of battery manufacturing, particularly for newer and advanced battery chemistries. - More information / data on efficiency improvements in recent years and on effects of future improvements
Electricity Chains	🙂	🙂	- Updated input data on future electricity mix projections - Further review and enhancement of underlying datasets
Fuel Chains	🙂/😐	🙂-☹	- Some methodological areas need further consideration e.g. counterfactual and substitution scenarios, LUC - Development of improved datasets for new processes - particularly for synthetic fuels - Improvements in data/methodological consistency and modelling of additional fuel chains
Vehicle Operation	🙂	🙂	Further enhancement to methodologies to enable capturing of sensitivities due to other effects such as climatic impacts on energy consumption and emissions
Vehicle / Battery End-of-Life	🙂	😐	Improved datasets for certain recycled materials; Further research on of end-of-life recycling and battery second life: LCA methodologies and data

Recommendations for future work

Area	Methods	Data	Comment
Refuelling, recharging, and ERS infrastructure	☹	☹	***- Not covered in this study*** - Methodologies and datasets need developing to characterise existing and new infrastructure - Fleet-level modelling/assessment may be needed to appropriately allocate impacts on a vehicle-basis
Other transport infrastructure	☹	☹	***- Not covered in this study*** - Expansion of boundary to also consider other road infrastructure elements
System/Fleet impacts modelling	☹	☹	***- Not covered in this study*** - Estimation of whole-system/fleet life-cycle impacts using outputs from this study
Effects of new technologies and trends	☹	☹	***- Not covered in this study*** - Estimation of further operational effects due to new technology or trends: e.g. effects of C-ITS / ITS and autonomous vehicle technologies on (a) production/disposal of new systems added to the vehicle, (b) impacts of infrastructure, (c) impacts on vehicle operational efficiency / emissions

Thank you!

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