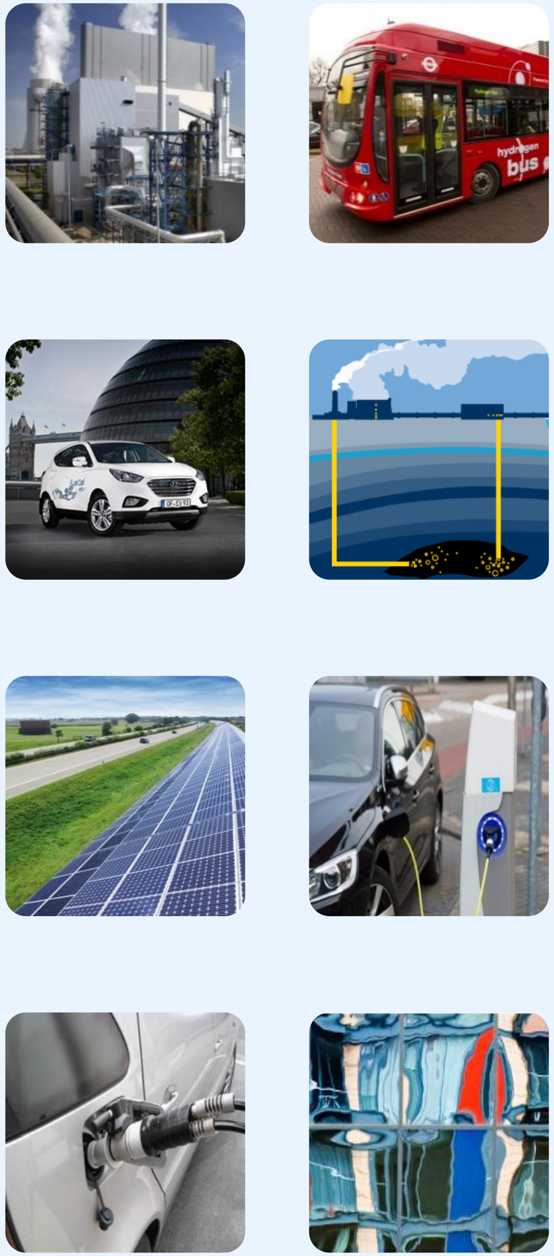

Work Package 1: Net Zero Car in 2030

BEUC – The European Consumer Organisation

Final Results

23th August 2021

elementenergy

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BEUC TCO Extension Project:

Total cost of ownership (TCO) of a net zero CO_2e emission car bought new in 2030

Project Introduction

- Element Energy recently completed TCO results at an EU level and in 9 focus European markets for BEUC – the European Consumer Organisation
- Analysis included modelling CO_2 tailpipe emission for different uptake scenarios of battery electric vehicles (BEVs), from which conclusions were made for European manufacture emission targets
- **Increasing focus within EU regulatory debate is being given to total lifecycle emissions** and it is essential to quantify the cost impact this will have on European consumers
- This pack contains **initial results for the total cost of ownership of a net zero CO_2e emission car bought new in 2030**
- Following work package 1 this project has considered:
  - WP2: battery replacement & additional engine maintenance cost scenarios
  - WP3: battery recycling review

This initial results pack contains the following sections:

1 TCO results & decarbonisation costs

- **TCO comparison between a BEV and ICEV bought new in 2030** with a decarbonised supply chain
- Cost to decarbonise key processes and materials

2 Conclusions on consumer impact

- Conclusions for the **impact on consumers from additional net zero costs** and implications for ongoing EU debate around total lifecycle emissions

3 Scope for a wide-ranging future study

- Review of **data limitations and the outstanding questions** that need to be answered in a more comprehensive future project

4 Review of EE methodology

- Overview of Element Energy's bottom-up approach to estimate life cycle emissions and decarbonisation costs

This report provides a **"pessimistic" top estimate of decarbonisation costs** and aims to outline the **outstanding questions regarding lifecycle emissions that should be considered for future study**

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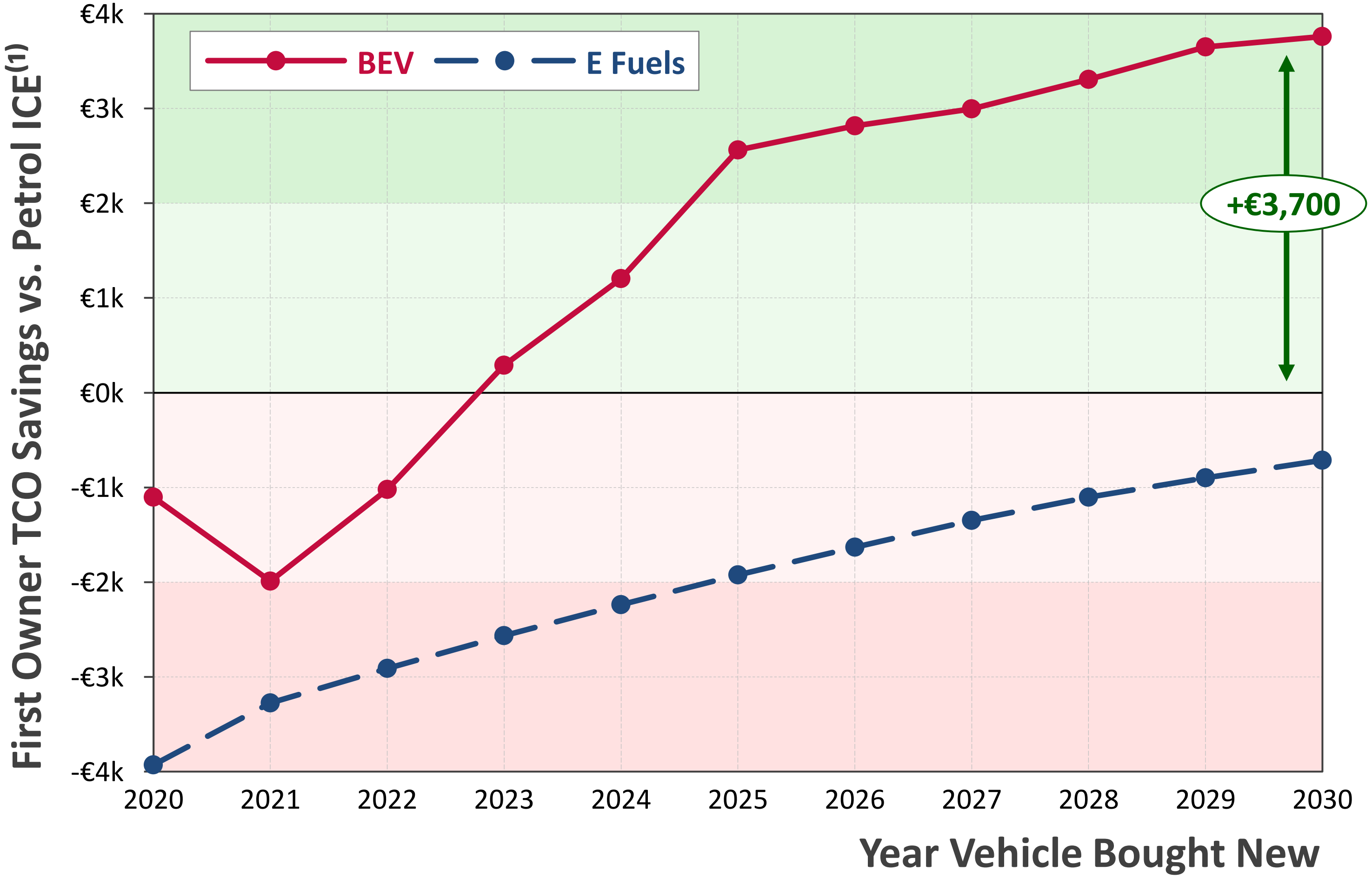
WP1: Net Zero Car in 2030 – Project Introduction & Approach



Proposed EE Approach

- A **BEV bought new in 2030 will save ca. €3,800 for its first owner vs. an equivalent Petrol ICE** (using a "normal supply" chain) or ca. €4,500 vs. an E Fuel powered ICE(1)
- However, **on a purely CAPEX basis**, bought new in 2030, a **medium BEV remains ca. €1,200 more expensive than a Petrol ICE (excluding VAT)**
- EE has analysed whether a BEV still provides substantial savings over a conventional ICE if it had a net zero supply chain
- Analysis will help inform discussion on how to **split decarbonisation costs equitably** between: (1) the consumer, (2) car industry & (3) government spending

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1 – First Ownership = 4 years with average annual mileage of 15,000km. E fuel scenarios based on optimistic Middle East PV scenarios excluding Fuel Duty

WP1: Net Zero Car in 2030 – Car OEMs with commitments to deliver a net-zero car

Growing momentum for OEMs to look beyond tailpipe emissions and focus on net-zero life-cycle emissions

Car OEM	Models	Commitment	Timeframe	Key Actions
	VW ID.3 VW ID.4	• These models are "CO_2 balance sheet neutral", including supply chain, production, use phase and recycling	Current	• Use on-site photovoltaics at Brussels plant for electricity
	One new model	• The new model will be entirely climate-neutral including supply chain and production	2030	• Will run their factory in China on 100% renewable electricity and trace all materials used in their cars
STUTTGART	All models	• All models "CO_2 balance sheet neutral" across entire value chain	2030	• Will require their battery cell suppliers to only use "sustainable energy"
	All "new" models	• CO_2 neutral at all stages of value chain, including development, raw material extraction, production and recycling	2039	• Use of an energy storage system based on reused vehicle batteries at Sindelfingen plant
JAGUAR LAND-ROVER	All models	• Net-zero emissions across supply chain, production and operations	2039	• Will invest in local circular economy supply chains
VOLVO	All models	• Net-zero across supply chain, manufacturing network and wider operations	2040	• Will replace fossil power with energy sources such as wind, solar, biomass and biofuels

Net Zero Car in 2030 – project core archetypes

EE Results focuses on three core archetypes

Baseline →
Petrol ICE with "normal" supply chain

- Baseline Petrol ICE assumptions inline with EE's recent TCO report for BEUC

Scenario A →
ICEV with "net zero" supply chain

- Petrol ICE run on E Fuels bought new in 2030
- Additional costs to decarbonise core material components and processes

Scenario B →
BEV with "net zero" supply chain

- BEV based on EE's bottom up Cost and Performance (C&P) modelling
- Additional cost to decarbonise lithium battery alongside other vehicle materials

Additional sensitivities have considered the impact from green hydrogen costs, E Fuel pricing, net zero distribution costs & changing manufacturing location

Overview of project limitations

Limitations of this study

- Vehicles are typically made up from hundreds of materials, each with their own individual and often complex supply chain → this **study has only considered materials that make up ca. 97% of a vehicle weight** (excluding fluids)
- The “Net Zero” archetype modelled in this study considers a **CO_2e abatement of over 95% lifecycle emissions** of the materials and processes considered
- Distribution emission analysis has only been considered the most substantial components of each material (for example, iron ore for steel)
- Additional exclusions include:
  - Emissions from the construction of processing and manufacturing plants
  - Construction of renewable energy infrastructure
  - “Non-core” plant processes i.e office buildings
  - Emissions produced through factory workers’ travel

EE approach for a “pessimistic scenario”

- Due to the high complexity of vehicle emissions, the aim of this study has been to create **a top estimate of a “pessimistic scenario” for decarbonisation costs**
- As a result we have made the following assumptions:
  - **High cost solar and battery storage system** (without access to large-scale solar plants)
  - **Pessimistic green hydrogen cost forecasting**
  - **CO_2e accounting based off the percentage of recycled material typically available when manufacturing a car** rather than the amount of material in a car that is recycled at end-of-life
  - **High cost “zero carbon” distribution alternatives**
  - No addition of carbon price to China natural gas usage

Contents

In this results section:

Implications for Vehicle TCO & Market Equity

Decarbonisation cost overview

- *Additional “net zero” costs broken out by supply chain process and core materials*

Sensitivity analysis & risk assessment

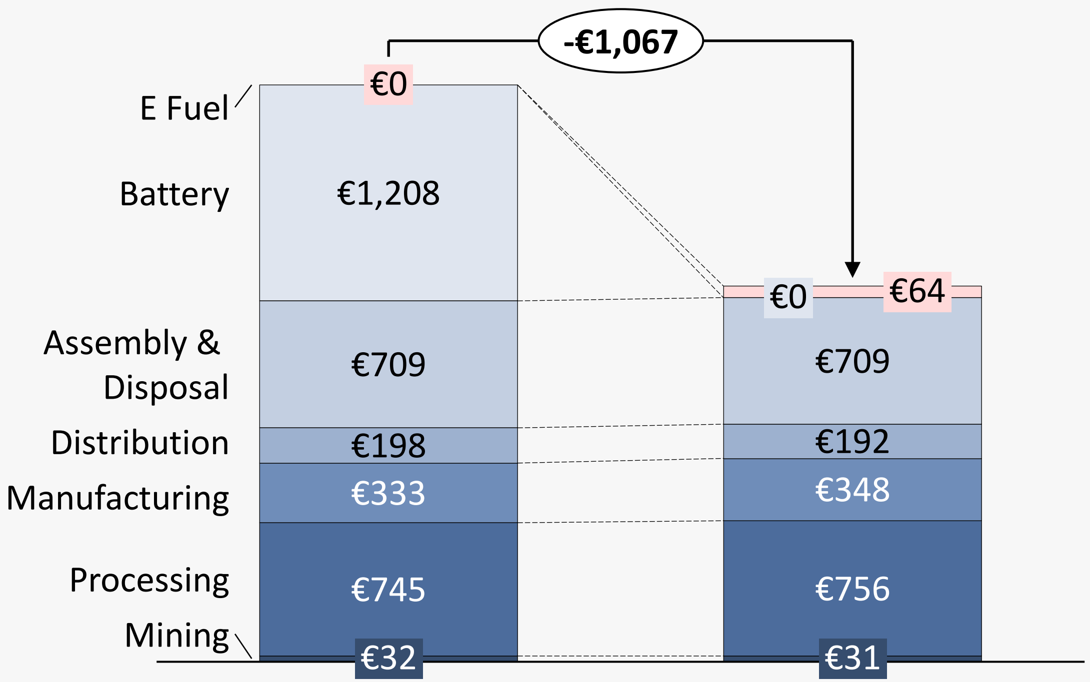
- *Sensitivities including green hydrogen price scenarios, distribution costs & large-scale solar access*

Implications for market equity

- *Comparison of the three archetypes under a low and high E Fuel price scenario*

Additional cost to decarbonise a BEV vs. E Fuel ICE
→ breakdown by supply chain

Additional Cost for a Net Zero Supply Chain(1)



	BEV	E Fuel ICEV
Total Cost	+€3.2k	+€2.1k
Lifetime TCO	**€70.0k**	**€86.1k**
CO2e Abated	*97%*	*97%*

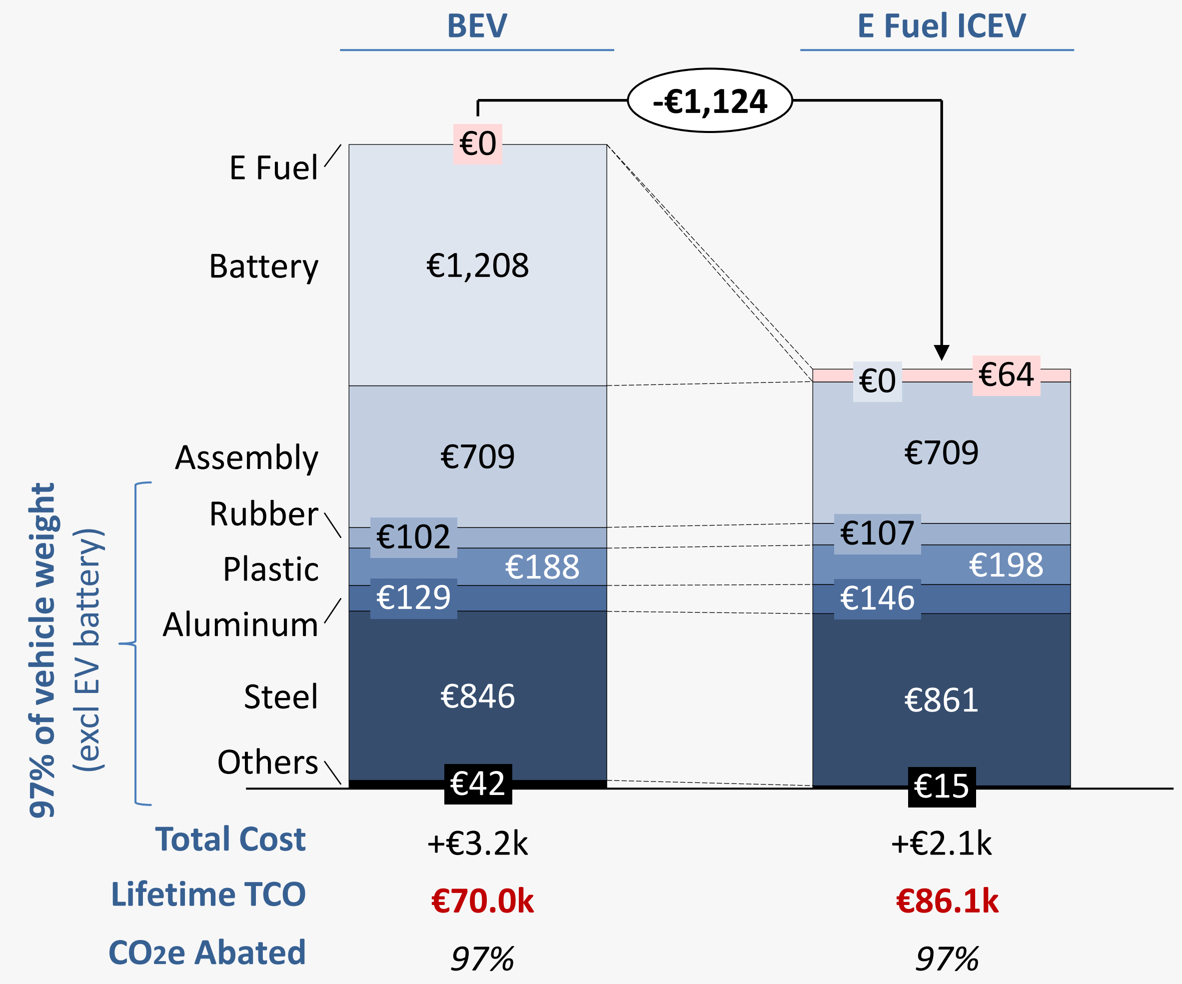
EE Conclusions

- A “net zero” BEVs provides a significantly cheaper option than a “net zero” Petrol ICE on a lifetime TCO basis, **saving consumers over €16k over the vehicles’ lifetime**
- Under a pessimistic case for BEVs and an optimistic E Fuel cost scenario (Middle East PV excluding fuel duty) BEVs cost an additional **€3.0k to decarbonise, compared to €2.1k for an E fuel run ICEV**
- The **most significant difference is the additional battery decarbonisation cost,** which is ca. €1.2k

(1) Assumes a “pessimistic case” for BEVs with a high cost Green Hydrogen, high cost solar PV & net zero distributions costs. Optimistic E fuels scenarios assuming cheap Middle East (excluding fuel duty) – E fuel additional cost over 16 year lifetime

Additional cost to decarbonise a BEV vs. E Fuel ICE → breakdown by material

Additional Cost for a Net Zero Supply Chain(1)



	BEV	E Fuel ICEV
Total Cost	+€3.2k	+€2.1k
Lifetime TCO	€70.0k	€86.1k
CO2e Abated	*97%*	*97%*

EE Conclusions

- **Steel, which makes up ca. 60% of a vehicle's weight, is a significant decarbonisation cost component for both BEVs and ICEV**, with other materials having a more secondary impact
- The materials considered for decarbonisation in this analysis **make up around 97% of a vehicles' weight** (excluding fluids and motor magnet), with **over 95% CO2e abatement achieved** for these materials

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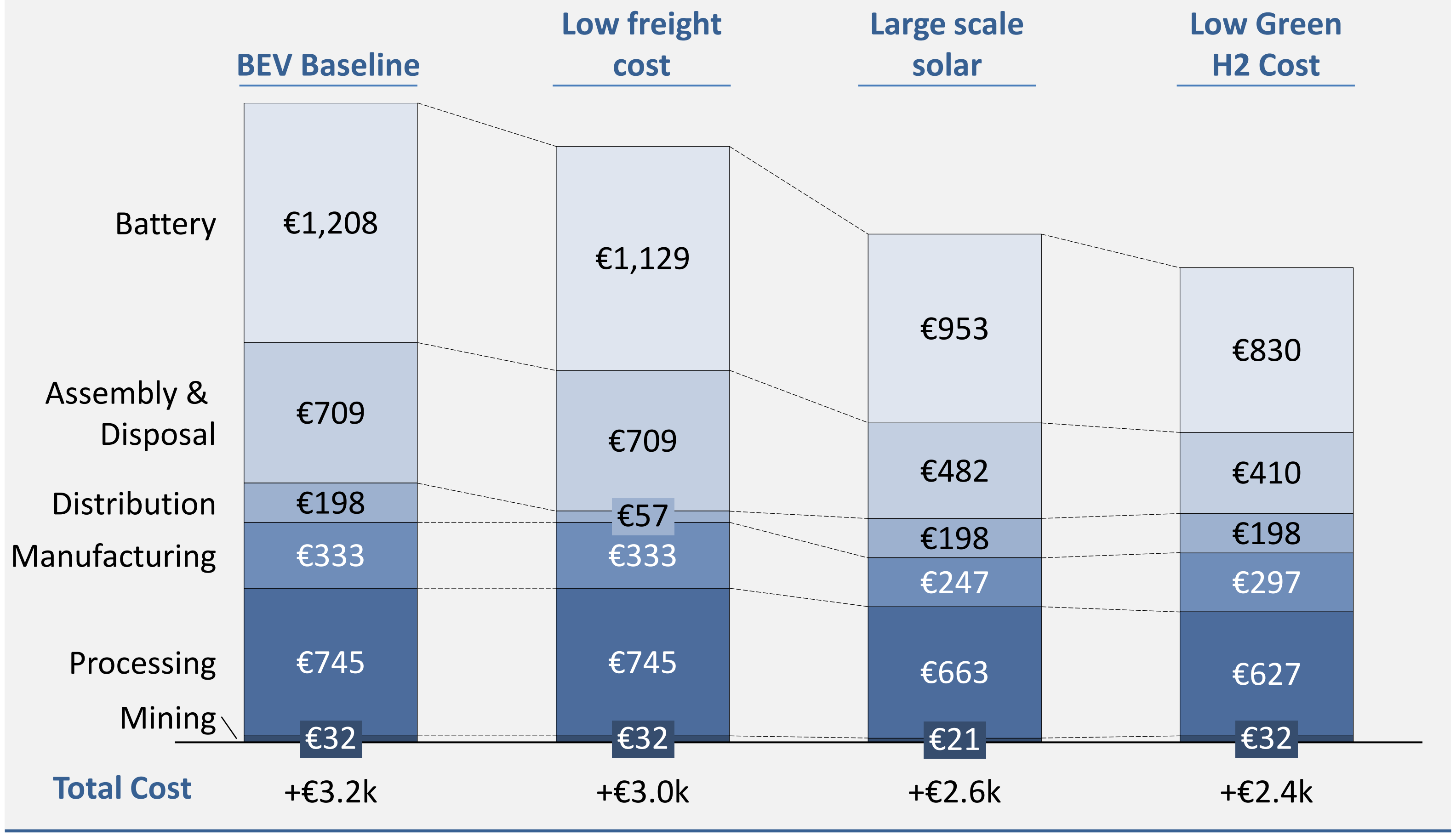
(1) Assumes a "pessimistic case" for BEVs with a high cost Green Hydrogen, high cost solar PV & net zero distributions costs. Optimistic E fuels scenarios assuming cheap Middle East (excluding fuel duty) – E fuel additional cost over 16 year lifetime

Additional cost to decarbonise a BEV vs. E Fuel ICE → modelled sensitivities

Additional Cost for a Net Zero BEV(1)



EE Conclusions

- Green Hydrogen cost, which is used to decarbonise several heating processes, has the greatest impact on BEV decarbonisation cost – **with ca. €800 difference between a low and high cost scenario**
- Distributions costs – which only abate a minimal amount of CO2e – only have a secondary impact on the total decarbonisation cost

Decarbonisation Risk Impact Assessment

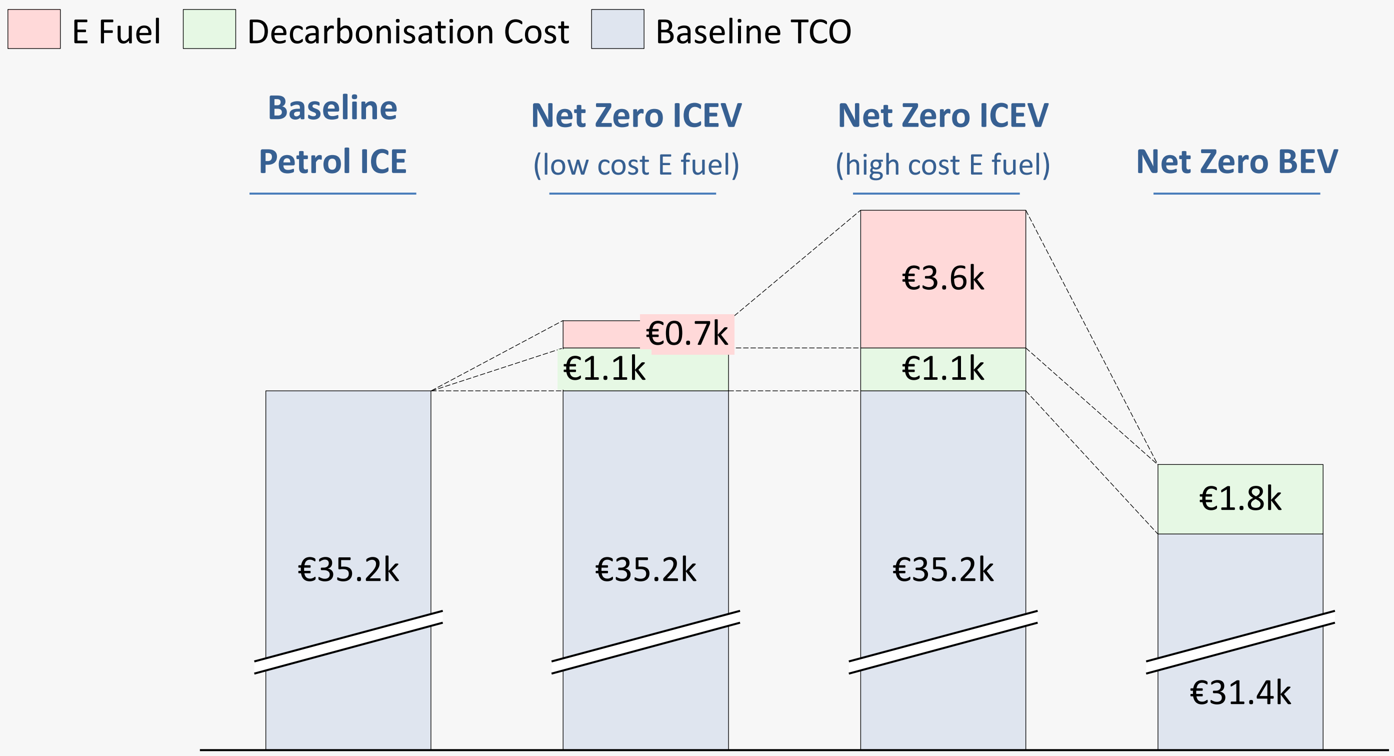
Increased Impact on the BEV Decarbonisation Cost

Increased Risk of Occurring

	Low	Medium	High
Low		**Limited reduction in solar and battery costs →** while this study's estimates for renewable self generation are pessimistic, electricity price remains a core determiner of decarbonisation cost	**Green Hydrogen prices remain high →** Green H2 has been prioritized across a variety of industries with cost forecast to fall significantly. High cost scenario adds ca. €800 compared to low cost case
Medium	**Limited availability of E Fuel to decarbonise mining →** although diesel makes up ca. 30-50% of mining energy usage, mining contribution to decarbonisation cost is secondary	**Limited improvement in reducing cobalt in batteries →** while an NMC 811 battery chemistry has been forecast in 2030, uncertainty still remains. Cobalt is the most expensive battery material & higher concentrations would increase prices	
High	**Limited availability to green electricity at mining sites →** solar PV and battery storage systems may be difficult to guarantee in the DRC and other mining countries		

Consequences of decarbonisation for market equity

First owner TCO for a car bought new in 2030



Total Cost	+€35.2k	+€37.0k	€39.9k	€33.2k
Δ ICEV baseline	-	+€1.8k	+€4.7k	-€2.0k
Equity Index	57%	56%	57%	52%

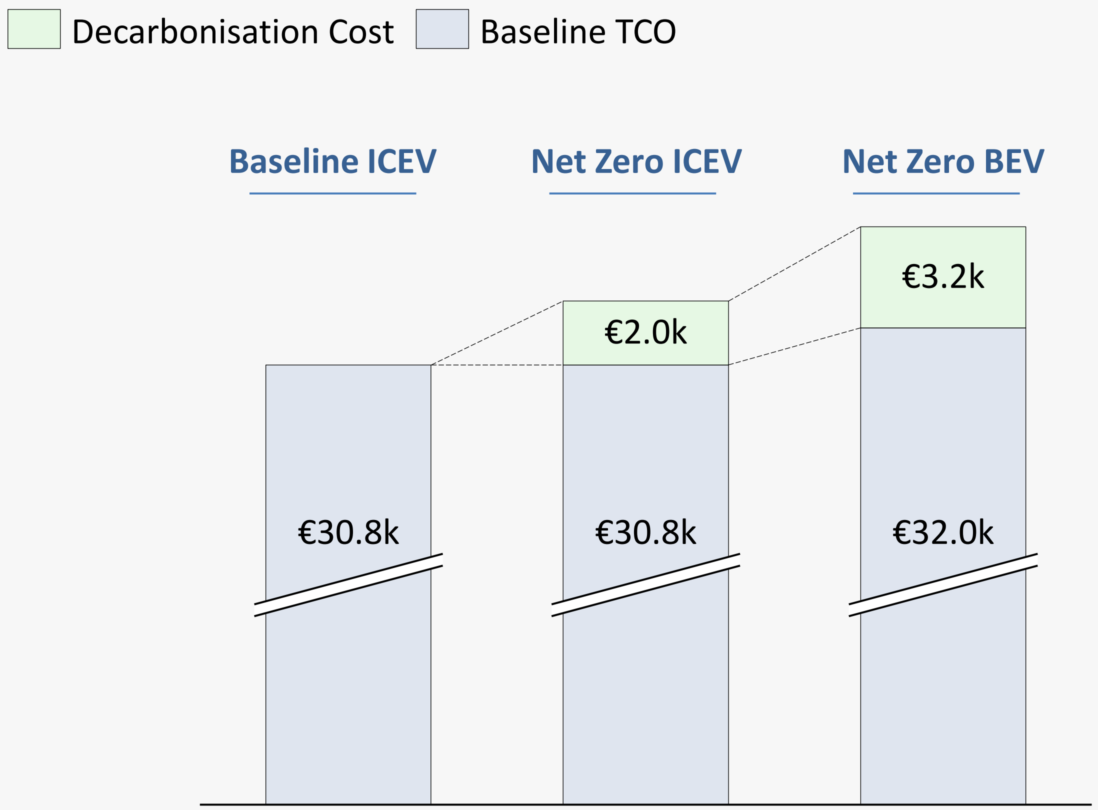
EE Conclusions

- From an **equity index perspective**, which represents the proportion of lifetime TCO paid by the used car buyers, BEVs **provide better value to consumers than ICEVs** – due to a higher proportion of CAPEX paid by the first owner
- Additional ICEV decarbonisation cost varies significantly with E Fuel price scenario
- Under a high cost E fuel scenario – based off North and Baltic Sea wind power – **running costs are increased, which presents a risk to less affluent used car buyers**

Equity index = used car buyer costs / total costs (assumer first ownership of 4 years and used ownerships of 12 years). Assumes a “pessimistic case” for BEVs with a high cost green hydrogen, high cost solar PV & net zero distributions costs. Low cost E fuels based of Middle East PV electricity source

Relative CAPEX costings

CAPEX for a car bought new in 2030 (excl VAT)



	Baseline ICEV	Net Zero ICEV	Net Zero BEV
Total Cost	+€30.8k	+€32.8k	€35.2k
Δ ICEV baseline	-	**+€2.0k**	**+€4.4k**

EE Conclusions

- Although a decarbonised BEV bought new in 2030 provides first owner TCO savings over an ICEV powered by E Fuels, on a **purely CAPEX basis (excluding VAT), a net Zero BEV is ca. +€2.4k more expensive**
- This provides an additional example of how it will become **increasing essential for consumers to have access to financing and lease schemes** to unlock the TCO benefits of BEVs over an entire ownership

Comparisons to other studies:

- In 2021 BCG/WEF estimated manufacturing a net zero car would cost an additional $500 (~**€425**)
- In 2020 Mckinsey estimated that **66%** of emissions from automotive material production could be abated at no extra cost

Equity index = used car buyers costs / first owner costs (assumer first ownership of 4 years and used ownerships of 12 years). Assumes a "pessimistic case" for BEVs with a high cost Green Hydrogen, high cost solar PV & net zero distributions costs. Low cost E fuels based of Middle East PV electricity source

Contents

Consumer TCO savings from BEVs will be impacted by a range of factors in 2030

Additional costs

- As shown in our previous work the introduction of BEVs is expected to benefit consumers through lower TCO for cars
- However, it is very unlikely consumers will fully benefit from all these cost savings. We see a number of places these cost savings could end up:
  - **CAPEX and OPEX saving** - consumers will keep some savings
  - **CAPEX cost** - OEMs will try and keep some of this difference possibly by charging high upfront costs for optional extras, especially software, which can be sold at a higher mark up than the car itself
  - **CAPEX cost** – legislation will force money to be spent on decarbonising supply chains whether the legislation is placed on the car OEM or the material producers. Additionally some emissions will not be reduced but will have to be offset. This will add an additional cost passed on to the consumer
  - **CAPEX cost –** higher CAPEX costs will increase financing costs
  - **OPEX cost** - governments do not want falling fuel prices to encourage more driving as this leads to congestion and road traffic accidents. Governments are likely to replace fuel duty with a new tax on car consumption (vehicle road pricing)

The consumer impact of changes in car taxation and product emissions legislation is beyond the scope of this work but it is a key question to answer in future analysis

Uncertainty in future cost impacts

- In 2030 BEVs, especially net-zero BEVs, will have a higher upfront cost than petrol cars. This means making BEVs or all new cars net carbon neutral in 2030 will reduce the popularity of BEV purchase
- At the same time Governments will wish to increase BEV operating costs to reduce consumption. The price of the tax will be set to reduce consumption and retain tax income. It may therefore not fully incorporate any CAPEX increases when being set
- Avoiding these potentially negative cost impacts for consumers requires that CAPEX costs are shifted to OPEX costs through sharing and service models of car use
- How future car costs for consumers are set will depend on the timeline for policy introduction. For example, government taxation might be set higher if it is introduced before legislation to decarbonise industrial processes
- The different costs will also have different equity impacts as some are CAPEX and some OPEX costs and we know second hand car buyers are much more sensitive to OPEX cost changes. We have a new study starting soon looking at the equity impacts of road pricing scheme to try and understand this change

→ Fully understanding the impacts of these changes in the car market will require more detailed analysis. In the next section we set out the questions we see as being important for future work.

Contents

This was a small study to introduce the topic and highlight the questions which need to be asked and answered in future work

Role of this project

- The role of this project was to better understand if a shift from tailpipe emission targets to life cycle emission targets would change our messaging around the cost benefits of a shift to BEV cars
- We were clear from the outset that this is a very large piece of work and that this study only provides a first indication of the final results with further questions will need to be asked to fully understand this area
- The secondary aim of this study was therefore to also set out the unanswered questions to help BEUC understand what questions and analysis may be needed in the future to fully understand this topic area

The key consumer questions we see as needing further analysis in the future focus around taxation and legislation

Key consumer impact questions for further study

- How are the lifetime emissions of cars best decarbonised with the minimum cost impact on consumers?
- Can these costs be minimised through a change in behaviour e.g. a shift to shared vehicles?
- What are the equity impacts of changes in legislation such as decarbonisation of industrial processes or road user charging

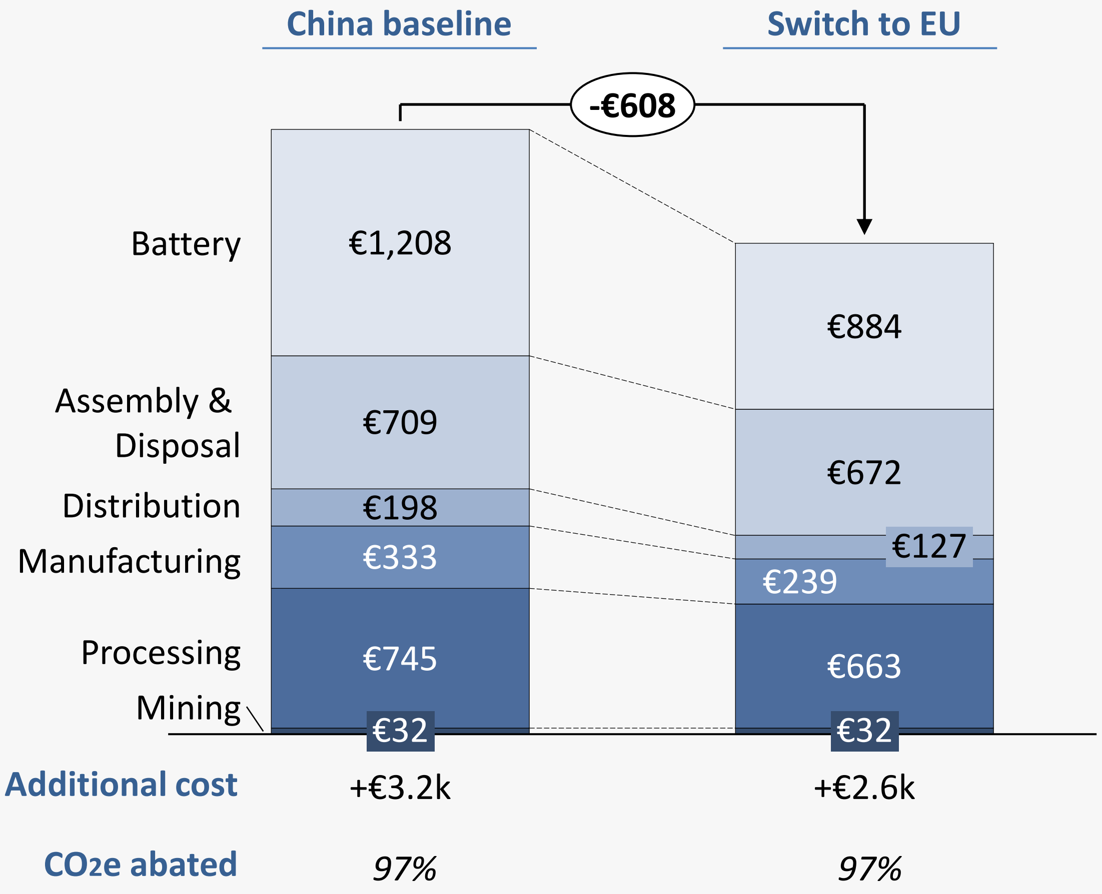
The rest of this section outlines the key technical questions that need to be considered by a wider ranging study

	A **EU based manufacturing**	B **Fluids decarbonisation[1]**	C **Motor magnets**	D **Lightweighting**	E **Improving recycling rates**
Importance	• Transitioning processing & manufacturing from China to the EU is essential to de-risk decarbonisation	• Argonne National Laboratory Greet 2 Model estimates that **fluids make up 10-15% of total vehicle GHGs emissions**	• BEV motor emissions are dominated by a **neodymium permeant magnet**, which has very limited lifecycle emission literature	• Transition to lightweight composite plastics could reduce decarbonisation costs across the supply chain	• Maximising vehicle recycling rates reduces emissions by minimising mining and virgin material processing
Key questions	• Limited information is available to estimate the additional costs of moving manufacturing from China to the EU	• Fluids **have complex supply chains** (consisting of different chemicals) and there is limited data regarding decarbonisation	• It is unclear whether decarbonisation will **focus on the transition to induction magnets** or **aim to minimize neodymium emissions**	• Additional manufacturing costs of lightweight material and near term mass market potential needs further study	• Pathways to boosting recycling rates is unclear and further research is needed to assess mass market potential
	EE has considered a simple sensitivity to compare additional decarbonisation costs in China vs. the EU	*Fluids have been excluded from this EE study*	*Permanent magnets have been excluded from this EE study*	*Significant vehicle light-weighting has been excluded*	*EE has excluded additional emission reductions due significantly boosting material recycling rates*

Fluids include: Engine Oil, Power Steering Fluid, Brake Fluid, Transmission Fluid, Powertrain Coolant, Windshield Fluid, Adhesives, Battery Coolant

A. EU based manufacturing compared to China

Additional Cost for a Net Zero BEV[(1)]



EE Comments

- Moving manufacturing and processing facilities to the EU **reduces the additional cost required for decarbonisation by ca. €600**
- This is primarily driven by the greater additional cost to transition to green electricity sources in China and reduced distribution distances
- There is significantly reduced risk in achieving decarbonisation with a move to EU production, due to more regulated emission accounting & a cleaner energy grid

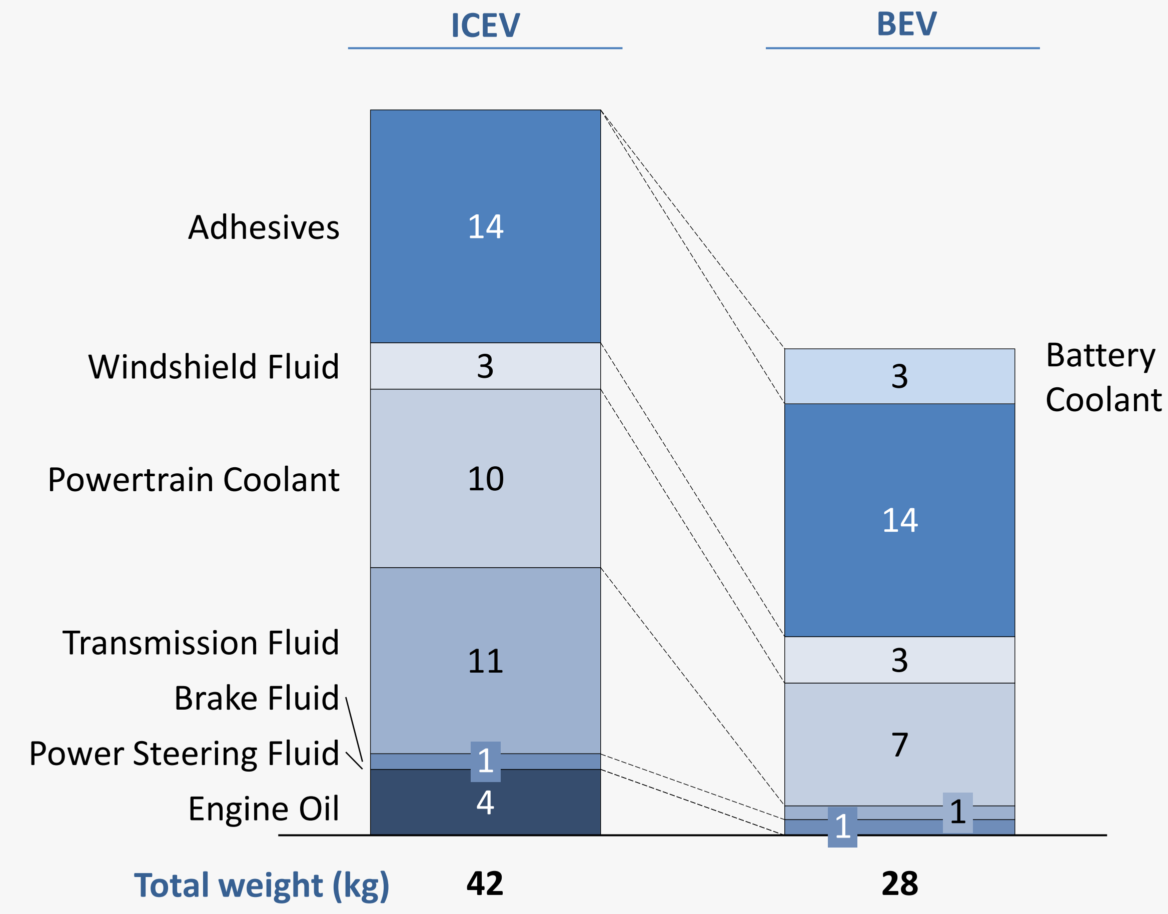
Key questions for wider research:

- **It is important to estimate other additional costs of moving manufacturing from China to the EU** (including lower infrastructure and OPEX cost)
- This will verify if **OEMs that aim to achieve supply chain decarbonisation can make savings by moving production to the EU** (while reducing their decarbonisation risk)

B. Fluids decarbonisation

Lifetime weight of fluids in an ICEV and BEV (kg)

(Greet 2, Argonne National Laboratory)



EE Comments

- EE note that an ICEV contains 6 different major fluids, and a BEV contains 5 - the major difference being the transmission fluid and the engine oil in an ICEV and the battery coolant in a BEV
- Each fluid is a mixture of several chemicals, all with **different and complex supply chains and production processes with varying carbon intensities**
- In addition, the fluid composition can vary significantly from model-to-model
- Data around decarbonisation pathways for every chemicals' supply chain and production is limited, and as such **the cost to decarbonise fluids has not been modelled**

Key questions for wider research:

- Which chemicals within each fluid are the **main sources of emissions?**
- What are the **decarbonisation pathways** for these chemicals and can **substitutes** be found?

C. Decarbonisation of the electric vehicle motor

Overview of electric motors

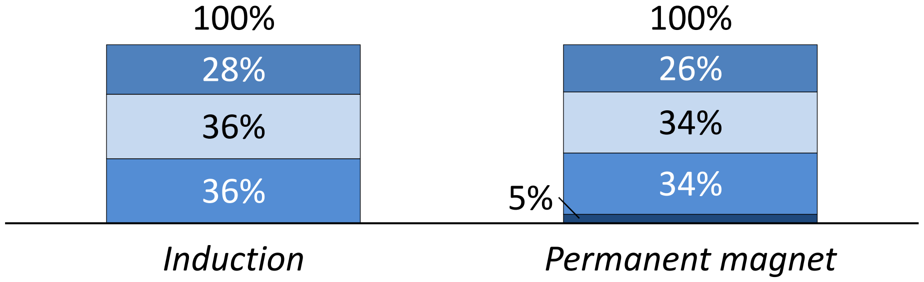
- Greater focus is normally placed on emissions surrounding BEV batteries than motors, however the motor must also be decarbonised to achieve net-zero life-cycle emissions, and **there are significant variances in emissions between motors**
- Motors used in BEVs can be split into two main categories – the far more common **permanent magnet synchronous motor**, and the less common **asynchronous induction motor.** Permanent magnet motors are favoured for their efficiency and robustness
- The key difference between the two is the permanent magnet, normally made of a Neodymium-Iron-Boron alloy (NdFeB)
- The manufacture of the magnet and the mining of the rare earth metal neodymium has significant carbon emissions
- However, **due to the lack of current models using induction motors**, and potential **additional costs and complexities**, **OEMs may instead aim to minimize emissions from Neodymium mining and maximise recycling**

Key questions for wider research:

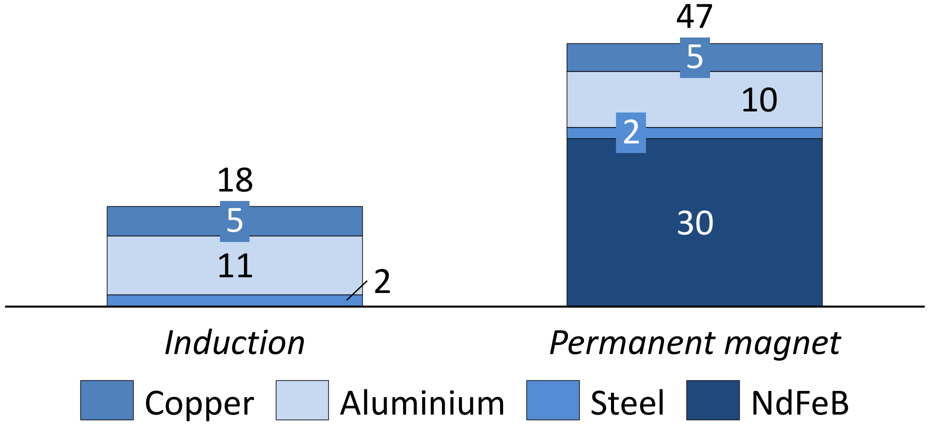
- **Does a transition to induction motors have mass market potential?**
- **How can EV motors' lifecycle emissions (especially with the production of the neodymium permanent magnet) be better understood and detail a clearer pathway towards decarbonisation?**

Motor type	**Example models**
Permanent magnet synchronous	• Nissan Leaf, BWW i3, VW ID.4
Asynchronous induction	• Tesla Model S

Motor weight composition (%)[1]



Emissions by motor material (kgCO2e/motor)[1]



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1 – Electric vehicle traction motors without rare earth magnets (2015): Centre for advanced electrical drives at Newcastle University

D. Lightweighting

Changes in 2030 vehicle mix due to lightweighting

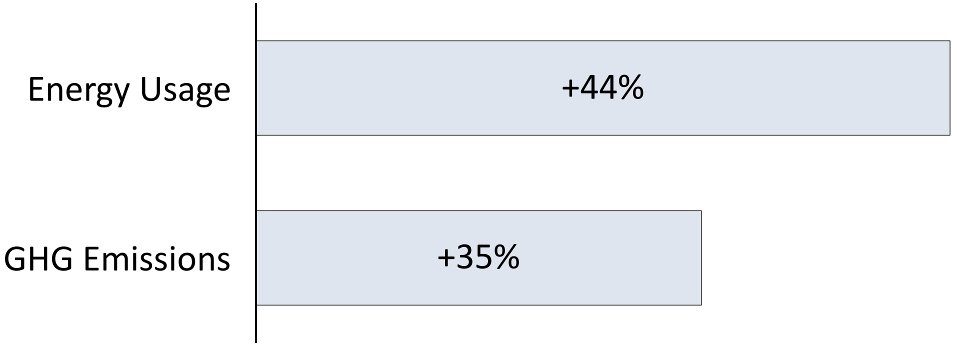
- **Lightweighting** refers to the substitution of heavy materials used for car components (mainly steel) for light weight alternatives such as aluminium and more complex plastic composites
- Benefits of lightweighting include **reduced kerb weight, increased vehicle range** and a **reduction in component wear**
- However, due to the carbon intensity of certain alternative materials, **life cycle vehicle emissions could increase due to lightweighting** (right)
- It is nonetheless expected that by 2030, vehicles will consist of different material compositions to those of 2021
- However, due to the inherent uncertainty of changes in vehicle materials mix, **our modelling has focused on the cost of decarbonising the extraction, processing and manufacturing of materials based on the standard 2021 car mix**

Case Study: Light weighting in practice at Arrival

- **Arrival are embracing innovative lightweighting in their electric 'Arrival Van' in partnership with Uber**
- This brings additional benefits of low repair costs, and no need for an expensive and carbon intensive paint shop, as the body finish colour is mixed in with the resin
- Raised ca. $1.2B worth of orders despite not commencing production until 2022, the logistics and delivery industry see the value in lightweighting

Switch to Lightweight Material

(Greet 2 , Argonne National Laboratory)



- According the Greet 2 model, a move to lightweight materials could **increase GHG emissions and energy usage** due to current processes for composite plastics being emission intensive
- It is essential to ensure that **plastics' supply chains are decarbonised** before switching away from conventional materials

Key questions for wider research:

- **What materials will make up a vehicle in 2030** and will they be **widely available?**
- At what point in the future **will life cycle emissions of a lightweighted vehicle be lower than a conventional vehicle?**

Sources: UK-based Arrival reveals electric panel van with modular battery system, Auto Express, 2021

E. Potential additional recycling processes

Key questions for wider research:

- **What are the additional costs of new recycling processes and do these provide a realistic pathway for mass market OEM adoption?**

		Potential recovery rate improvement in 2030			Process description	Feasibility
10%	**Aluminum**	90%	95%	+5%	Shift away from full shredding of cars to more **selective dismantling** Components designed to be easily **separated and identified by alloy type**	🟢 Modern plants already achieve a 95% reuse or recycle rate according to European Aluminium - it remains for the **rest of the industry to catch-up**
15%	**Plastic**	57%	74%	+17%	**Increased use of thermoplastics** that can be more easily recycled More **selective dismantling** and **improved material separation** from automotive shredder residue	🟠 EuRIC could mandate a minimum of 30% of car plastic be recycled thermoplastic by 2030, however car OEMs remain concerned over **quality** and **expect reduced costs** when using recycled plastic
4%	**Rubber**	52%	95%	+43%	**Increased collection** of worn tyres **Increased mechanical recycling** of tyres and shift away from combustion for energy recovery	🟠 Relatively low **financial incentives restrain the recycling capacity** due to the reduced quality of recycled rubber and unsuitability for use in new tyres
2%	**Glass**	100%	100%	0%	Although automotive glass in cars is already recycled, significant improvement in the quality of the recycled glass is made by **removing all glass before crushing and shredding**	🟠 Already done in some instances however an **estimated cost of €4-5** to remove the glass **from each car** (Glass for Europe) makes profitability an issue

xx = **% vehicle mix** (excluding batteries & fluids)

▭ **2021 rate**

🟩 **2030 rate**

🟢 **Likely to happen without intervention**

🟠 **Unlikely to happen without intervention**

*Recovery rates relate to the percentage of each material recycled at the end of vehicle life

Contents

In this methodology section:

Fuel Decarbonisation Methodology

Heater & boiler assumptions

- *Overview of assumptions to forecast decarbonisation cost for electric & hydrogen heaters and boilers*

Renewable electricity self-generation

- *Review of methodology for a simple solar PV and battery storage self-generation system*

E Fuels forecasting

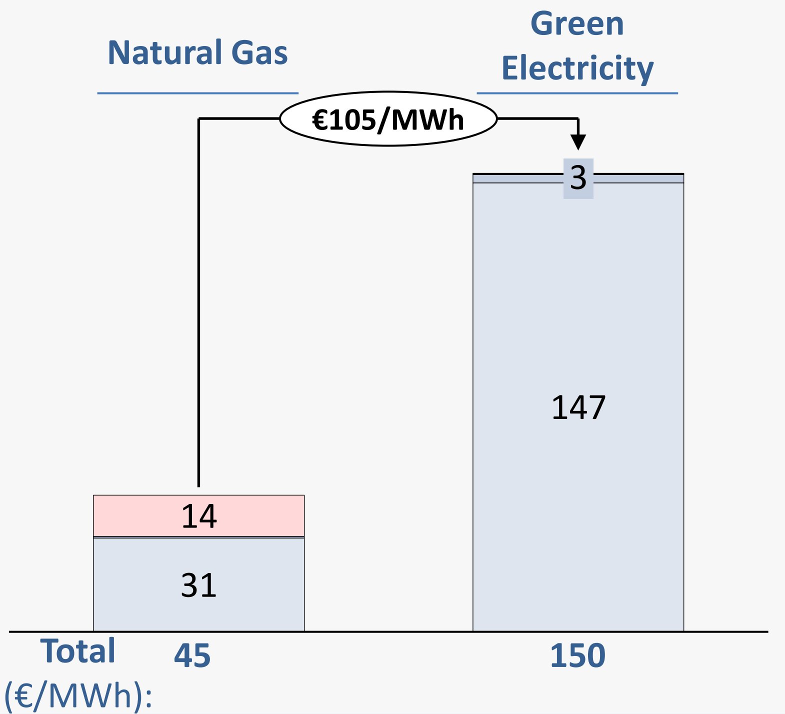
- *High and low cost E Fuel scenarios forecast between 2030-46*

Decarbonising heating processes

▭ Fuel Cost ▭ CAPEX ▭ O&M Fixed ▭ O&M Variable 🟥 Carbon Price

Electric Steam Boiler

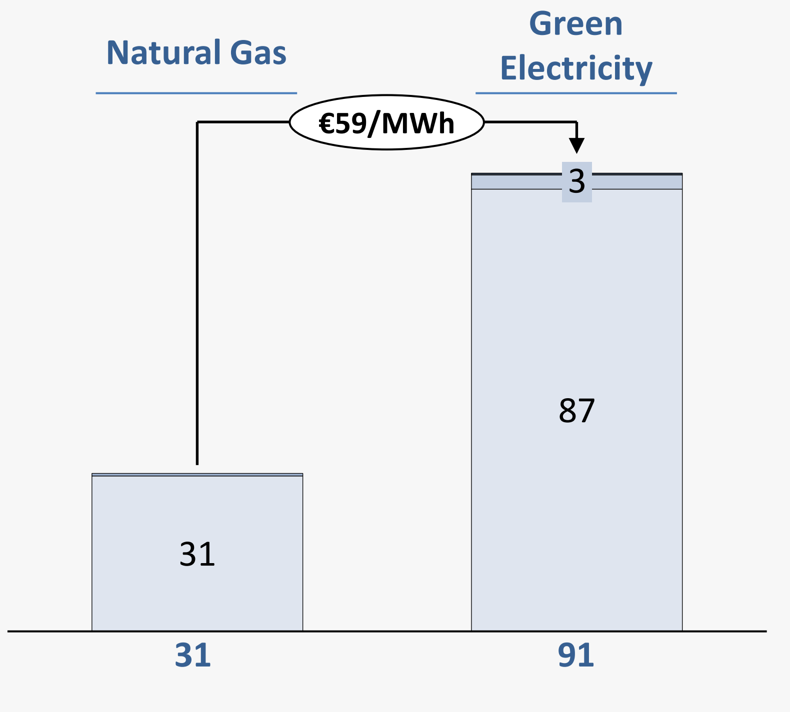
(Germany example, 2030)



- Typical uses – tyre compression moulding and vulcanisation
- **Natural Gas CAPEX excluded to give a 'worst-case' scenario of switching**

Electric Heater

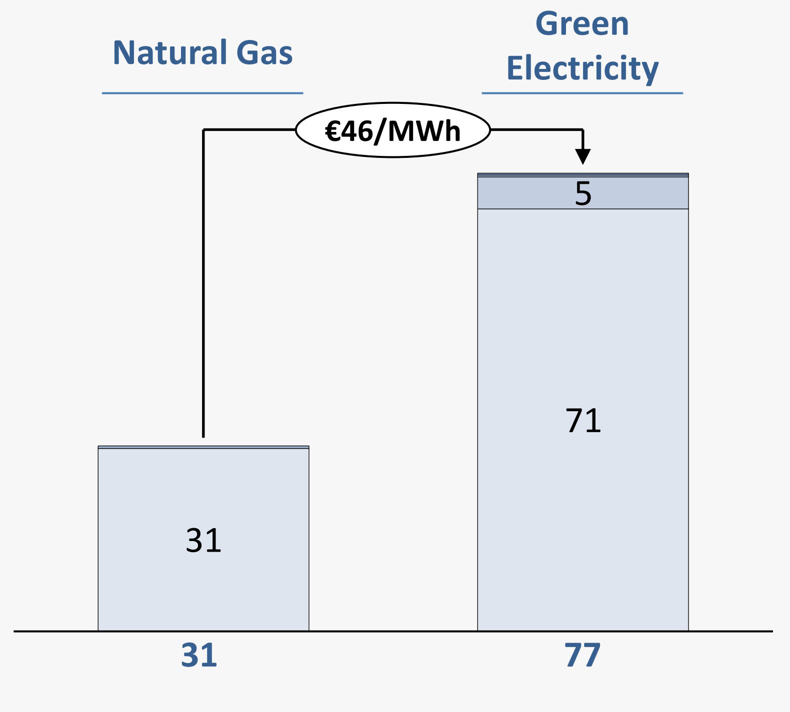
(China example, 2030)



- Typical use – Steel hot rolling
- **Carbon price excluded outside EU due to uncertainty around implementation and value of a carbon price in 2030**

Hydrogen Heater

(China example, 2030)



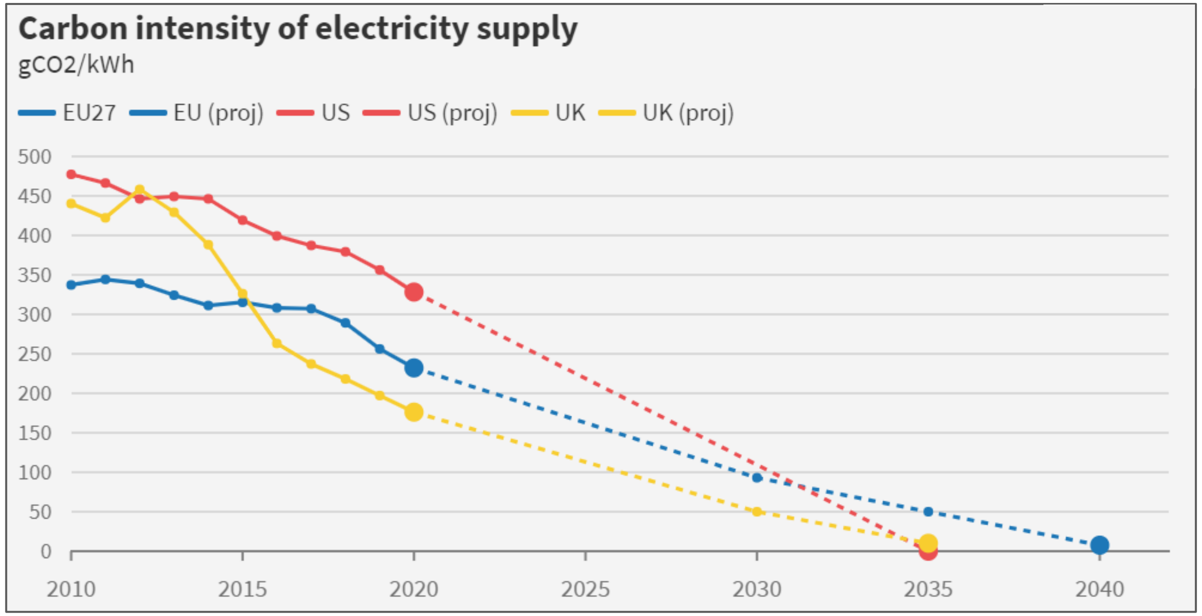
- Typical uses – plastics resin production, alumina and aluminium production, glass melting and refining

Sources: Industrial Fuel Switching Market Engagement Study, Element Energy, 2018

Additional costs from green electricity production

Residential electricity within car daily usage

- In order to achieve overall 2050 EU net zero target in the Green Deal, power generation is forecast to be one of the earliest sectors to net zero. Ember analysis forecast that this is achievable by 2040(1)
- The lifetime of the vehicle bought new in 2030, will last between 2030-46, with the **additional cost of using exclusively renewable sources being negligible**



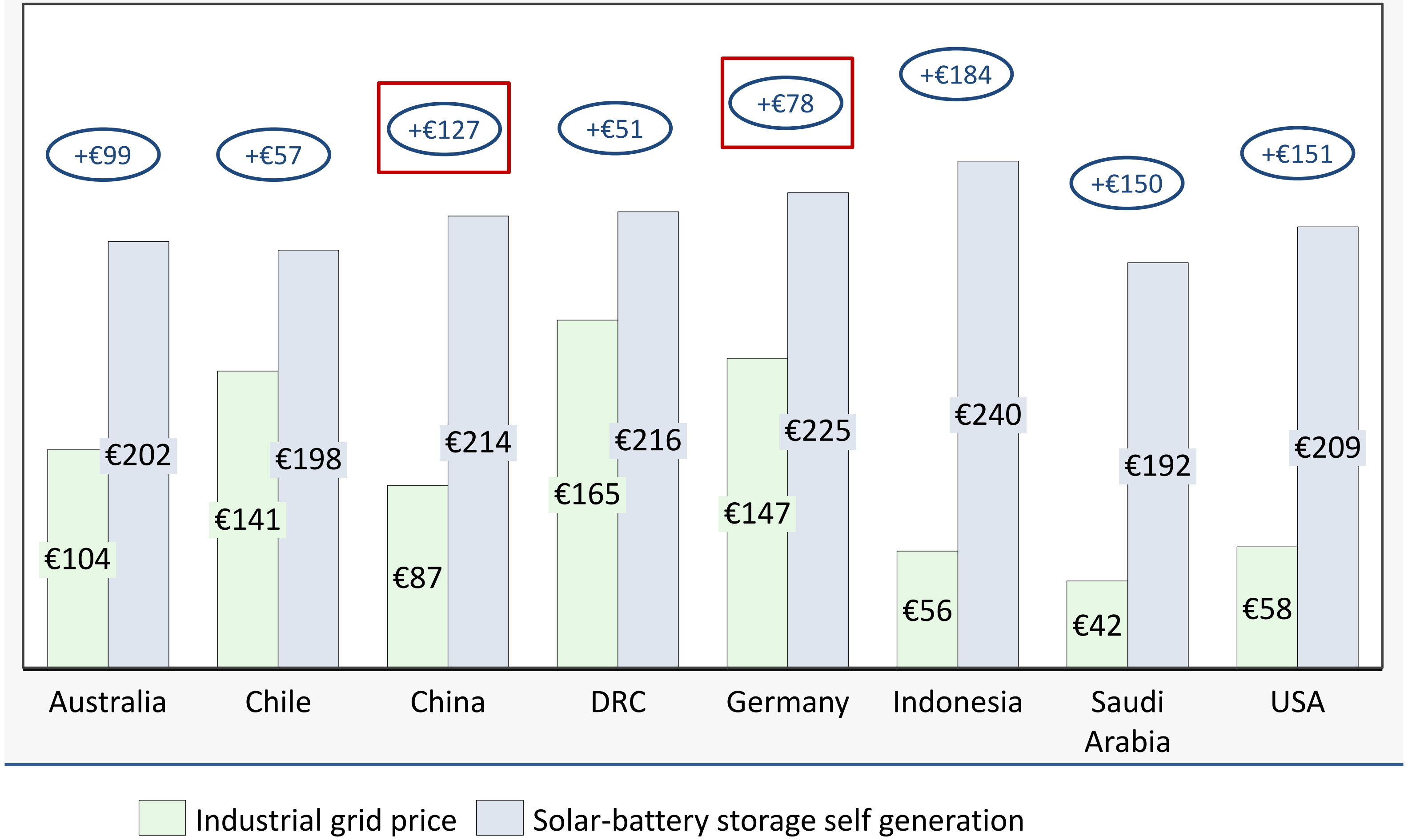
Industrial electricity within manufacturing processes

- While the electricity used within EU manufacturing in 2030 is likely to have minimal carbon load – we have considered **a "risk free" sensitivity that uses "on-site" generated electricity**
- We have focused on a pessimistic **scenario using solar generation and overnight battery storage:**
  - Solar generation forecast based on the UK government's Department for Business, Energy & Industrial Strategy (BEIS) 2020 forecasting
  - Manufacturing plants would not have access to shared large-scale solar (which would significantly reduce costs)
  - Battery storage costs taken from US National Renewable Energy Laboratory (NREL) 2020 cost and performance data
- Electricity costs are compared to forecast 2030 industrial prices, which are based on trending current prices to World Energy Outlook (WEO) stated policies scenario

1 – Ember (2020) Zero-carbon power is a key milestone on the route to net-zero. UK projection: 'Balanced pathway' by the UK Climate Change Committee. EU projection based on Ember analysis of the 'MIX' energy scenario published by the European Commission. The US projection based on Executive Order for a "carbon pollution-free electricity sector no later than 2035"

Additional costs from green electricity production

Additional costs of self-generated green electricity (2030, per MWh)

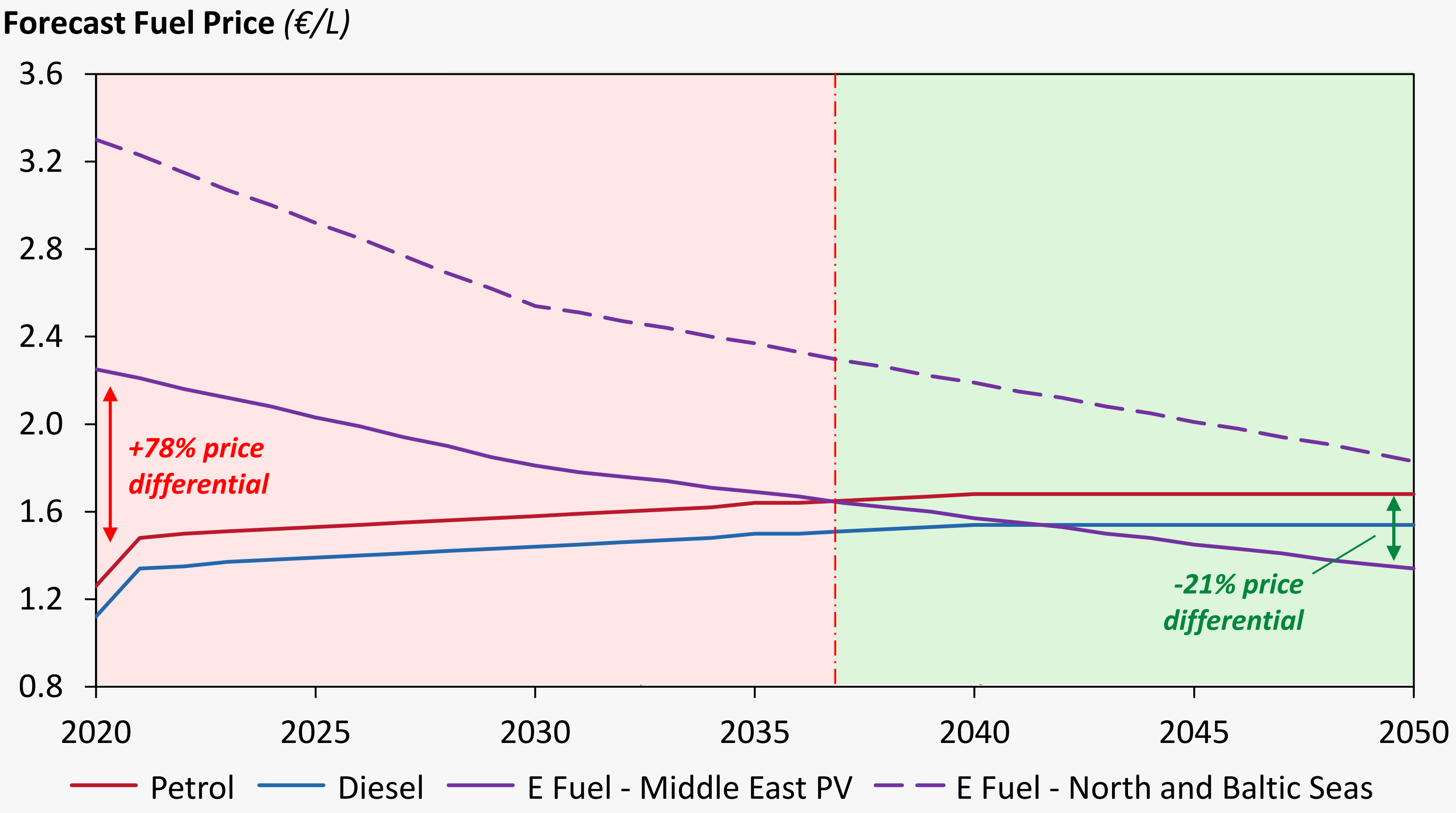


Key Conclusions

- **Additional self-generation cost in Germany ca. €78 per MWh are significantly smaller than China ca. €127 per MWh** due to more expensive industrial grid electricity charges
- **Several OEMs have started integrating on-site electricity production to EU-based manufacturing plants** – including the Audi e-tron plant in Brussels, where the roof of the plant houses the region's largest photovoltaic system with a total area of 107,000 sq meters
- It is important to note **self-generation of electricity may have feasibility risk** in countries such as the DRC and this should be an **area considered for further research**

E-fuels forecasting 2020 to 2050

Retail Price of Fuel *(inc. fuel duty & VAT)*



- E-fuel (Middle East PV scenario) cheaper than Petrol by 2037
- **Currently there is a significant premium**, with E-fuel (Middle East PV scenario) 78% more expensive than Petrol; however, this is driven by low oil prices and will likely narrow post-COVID
- Forecasts predict that E-fuel price continues to fall with an expected **-21% price differential by 2050 compared with petrol**

E-fuel assumption based on “The Future Cost of Electricity-Based Synthetic Fuels” Agora, 2018; no additional fuel duty assumed & retail costs set at €0.15/L

Contents

In this methodology section:

Supply Chain Decarbonisation Methodology

Mining Decarbonisation

- *Overview of approach to decarbonisation of mining raw materials*

Net zero distribution

- *Distribution pathway assumptions and decarbonisation costs*

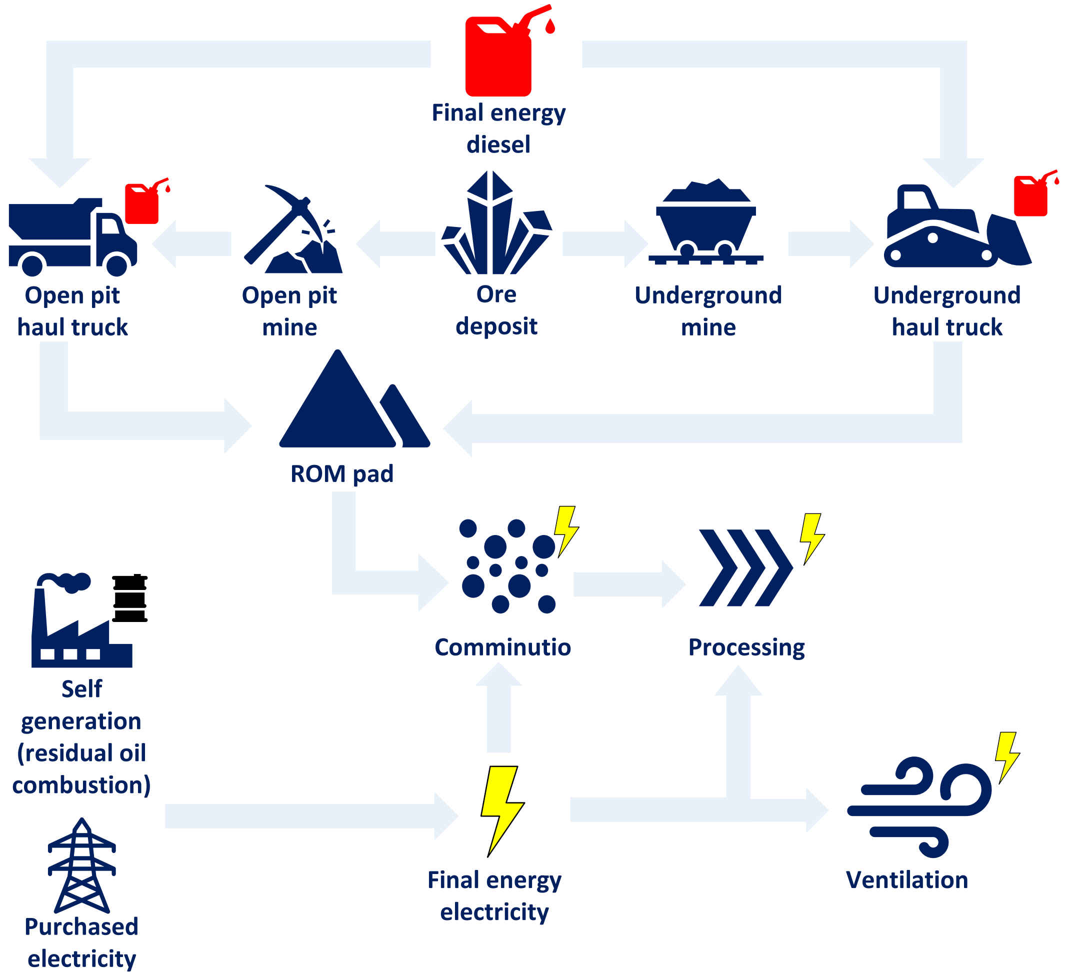
Assembly & disposal

- *Overview of approach to decarbonisation of component and vehicle assembly and disposal*

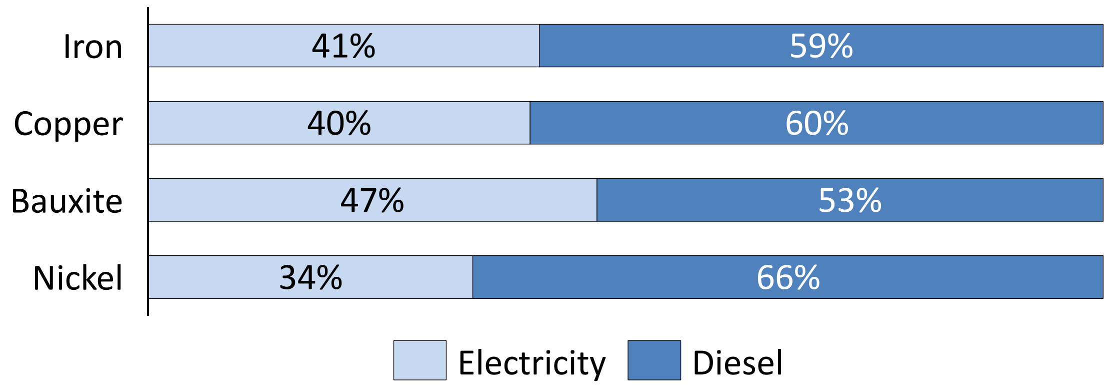
Decarbonisation of processing and manufacturing are discussed on a material by material basis in the next section

Mining decarbonisation

Current typical mining process(1)



Breakdown of emissions by energy source(1)



	Electricity	Diesel
Iron	41%	59%
Copper	40%	60%
Bauxite	47%	53%
Nickel	34%	66%

Key steps to decarbonisation

- **Electricity:** Generate all electricity necessary near the mine-site using renewable sources such as solar, wind and hydroelectric - also removing dependence on **residual oil**
- **Diesel:** Switch to e-fuels for mining vehicles. Hydrogen powered trucks may also be a long-term prospect

Risks:

- E-fuel supply chain and availability is inherently uncertain
- Affordability and availability of renewable energy sources at mine locations in places such as the DRC

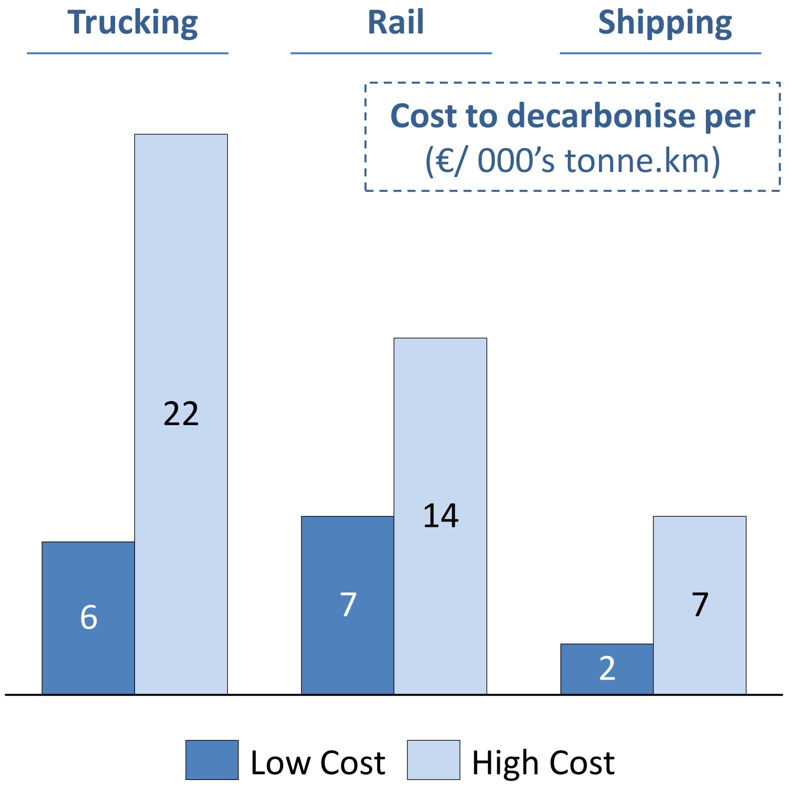
1 – Mining Energy Consumption, Weir, 2021; Environmental Profile Report for the European Aluminium Industry, European Aluminium Association, 2013
*ROM = Run of mine (unprocessed ore)

Decarbonising Car Distribution in 2030

Map of key car components' supply chain

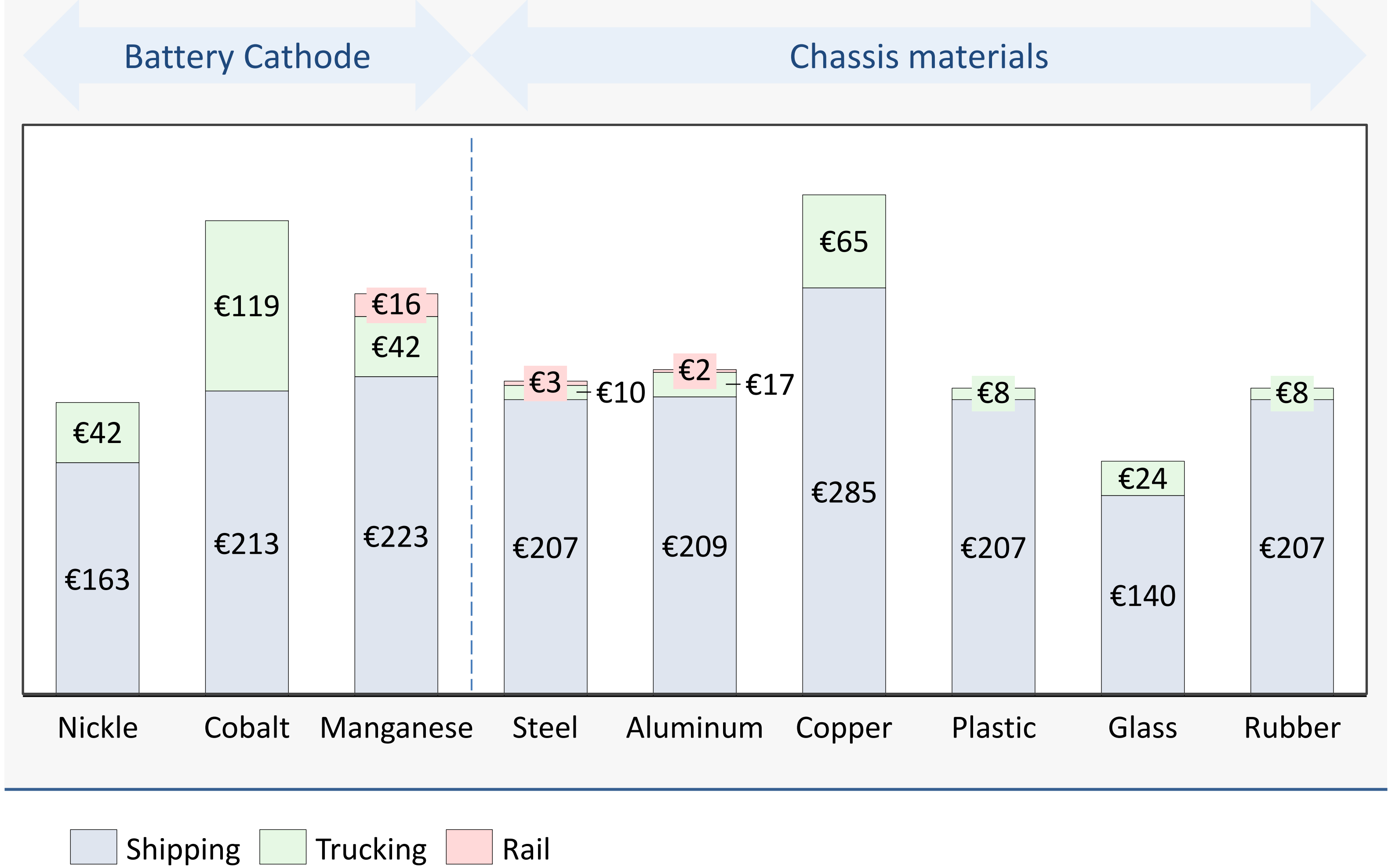
Decarbonisation costs are highly variable on 2030 infrastructure (for example, electrified railways vs. diesel trains)

→ **EE have developed a high and low cost scenario**



Supply chain decarbonisation costs

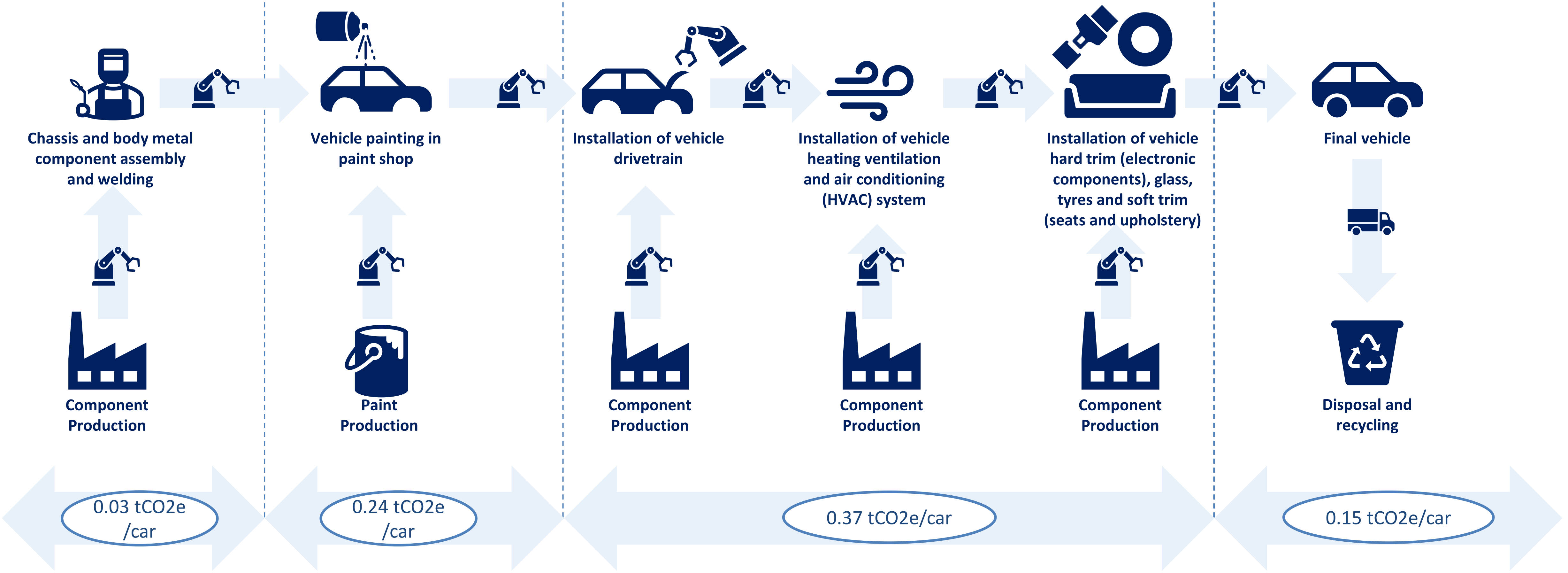
Distribution decarbonisation cost by material (€/tonne material, high-cost scenario)



EE Conclusions

- Shipping is by far the most expensive transport mode to decarbonise, representing **85% of the cost for each material** on average
- High shipping costs are driven by high mileage – over 30,000km per material
- Trucking constitutes most of the remaining decarbonisation cost, but is more varied than shipping cost
- Where mines and factories are close to ports, as with steel/aluminium, trucking (and rail) mileage is relatively low and is thus cheap to decarbonise
- Cobalt's high trucking cost is due to a combination of mine remoteness and the ore being processed outside the DRC

Vehicle assembly processes



Initial assembly

Chassis and body metal component assembly and welding

Component Production

0.03 tCO2e /car

- Switch to green electricity

Painting

Vehicle painting in paint shop

Paint Production

0.24 tCO2e /car

- Switch to green hydrogen for all paint shop heaters

Final assembly

Installation of vehicle drivetrain

Component Production

Installation of vehicle heating ventilation and air conditioning (HVAC) system

Component Production

Installation of vehicle hard trim (electronic components), glass, tyres and soft trim (seats and upholstery)

Component Production

0.37 tCO2e/car

- Switch to green electricity for machinery and green hydrogen for heating

Disposal and recycling

Final vehicle

Disposal and recycling

0.15 tCO2e/car

- Switch to green electricity for car disassembly, crushing and shredding

*Note that the emissions show are purely those for assembly – component production, except paint, has been considered separately

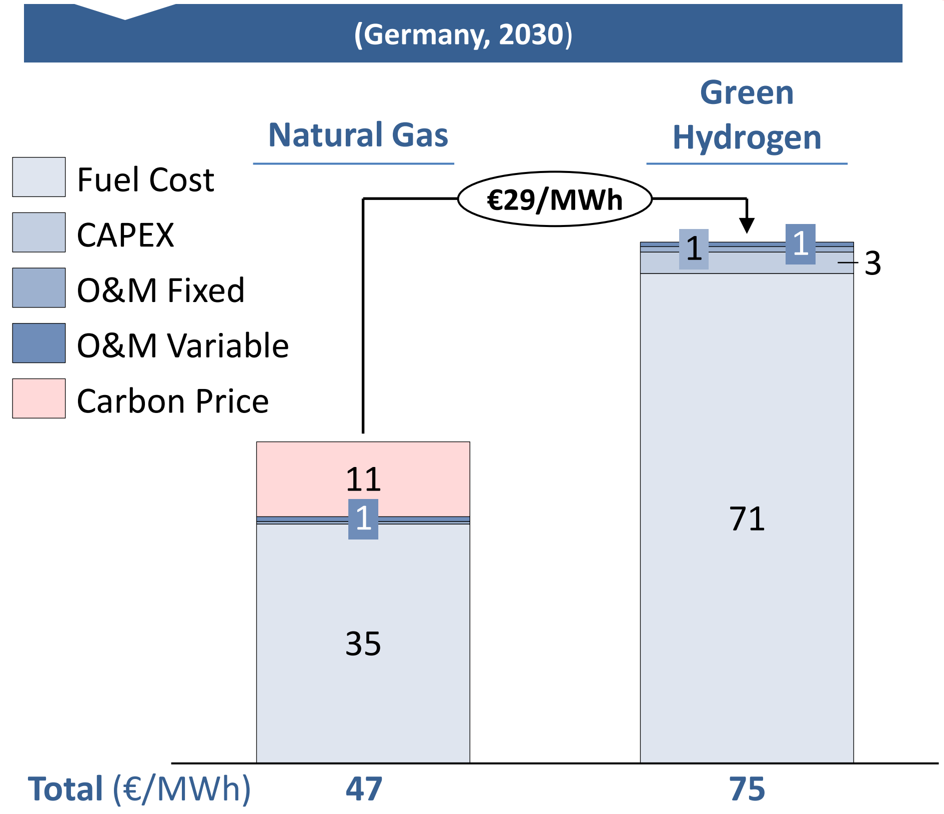
Decarbonised vehicle assembly process

Key Steps to decarbonise

Vehicle Assembly	**Chassis/body assembly and welding**	- Switch to green electricity generated on-site to provide electricity used by machines such as conveyors and robotic arms	**+€37**
	Paint production and painting	- Switch to hydrogen to heat top-coat booth preheater and all ovens	**+€131**
	HVAC and lighting installation	- Switch to green electricity generated on-site for electricity consumed	**+€77**
	Installation of all other components	- Switch to green electricity. Switch to hydrogen heating for heat used in vehicle assembly	**+€185**
End-of-life	**Disposal**	- Switch to green electricity for disassembly, crushing and shredding equipment	**+€117**

XX = **decarbonisation cost** (medium BEV)

Switch to Hydrogen Paint Shop



Natural Gas CAPEX excluded to give a 'worst-case' scenario around the cost of switching to hydrogen

Contents

In this methodology section:

Decarbonisation Modelling Methodology

Battery Lifecycle & Chemistry

- *Overview of current battery lifecycle and forecast chemistry for a BEV bought new in 2030*

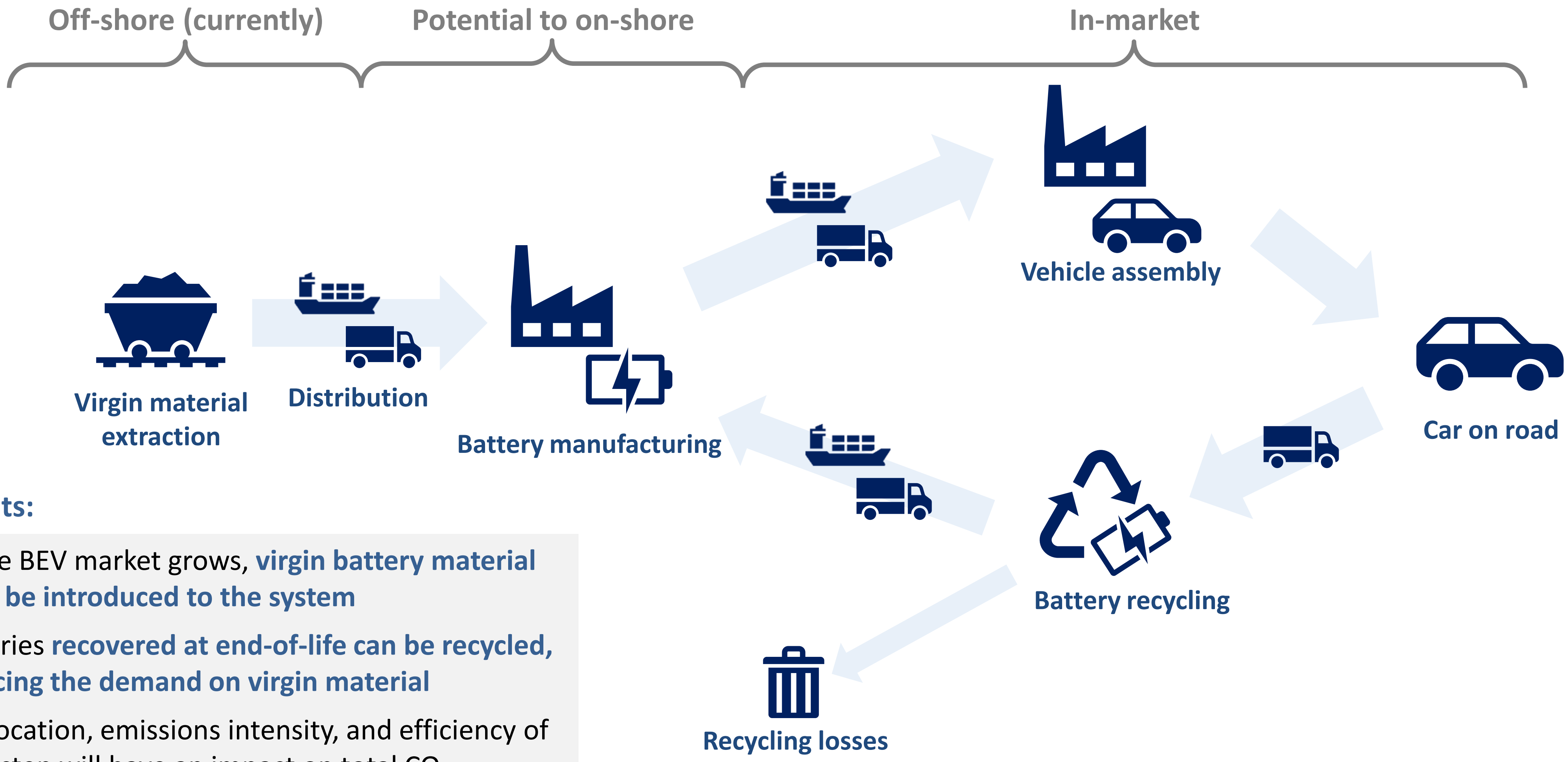
Cell Recycling Assumptions

- *Review of switch to hydrogeological recycling & assumed use of recycled NMC material*

Battery Decarbonisation

- *Decarbonisation results broken down by core battery materials & assembly processes*

We have modelled a partially circular battery supply chain, representing a growing market



Key points:

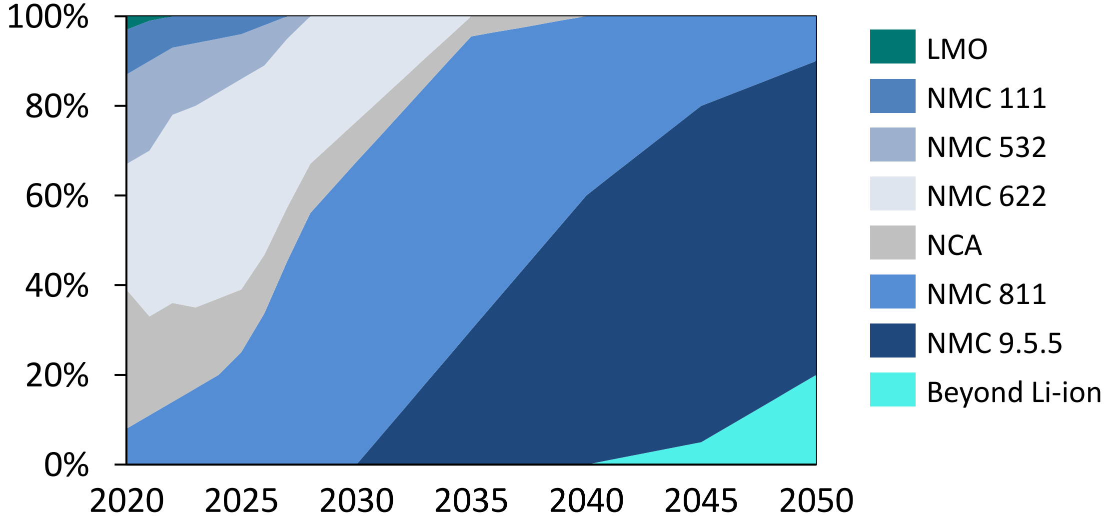
- As the BEV market grows, **virgin battery material must be introduced to the system**
- Batteries **recovered at end-of-life can be recycled, reducing the demand on virgin material**
- The location, emissions intensity, and efficiency of each step will have an impact on total CO_2 emissions of the vehicle

What does a battery look like in 2030?

Chemistry and density control material demand

Share of battery cathode chemistries in new cars

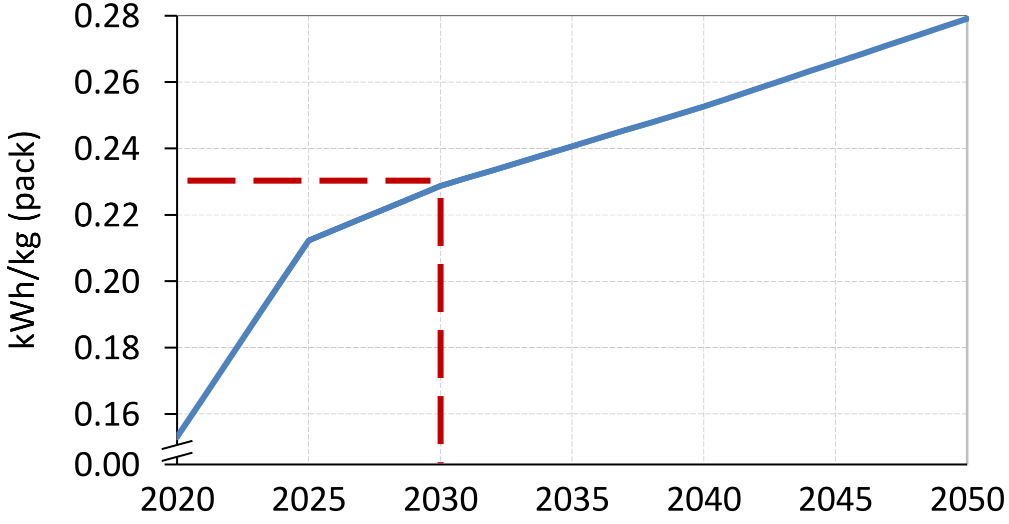
European cars - Source: EE, based on Avicenne projections (2020)



- Battery chemistries are expected to evolve over time as the **industry reduces the cobalt content of batteries**
  - Cobalt is very expensive and prices are volatile, and its extraction is associated with human rights abuses
- Today NMC (nickel manganese cobalt) chemistries are the most common (the numbers indicate the ratio of the 3 metal content)

Energy density of battery packs – 60 kWh segment C

60 kWh (segment C) - Source: EV Push scenario, EE for ETI CVEI (2016)



- As **battery technology improves energy density will increase, meaning more capacity can fit into a battery of the same mass**
- Over time the raw material demand per kWh is expected to decrease
- **Battery capacity in 2030 for a medium car** has been estimated by **EE's bottom up Cost & Performance model(1)**

By 2030, we expect NMC 811 to be the most common chemistry in European cars, **which we have used as the baseline case for our battery modelling**

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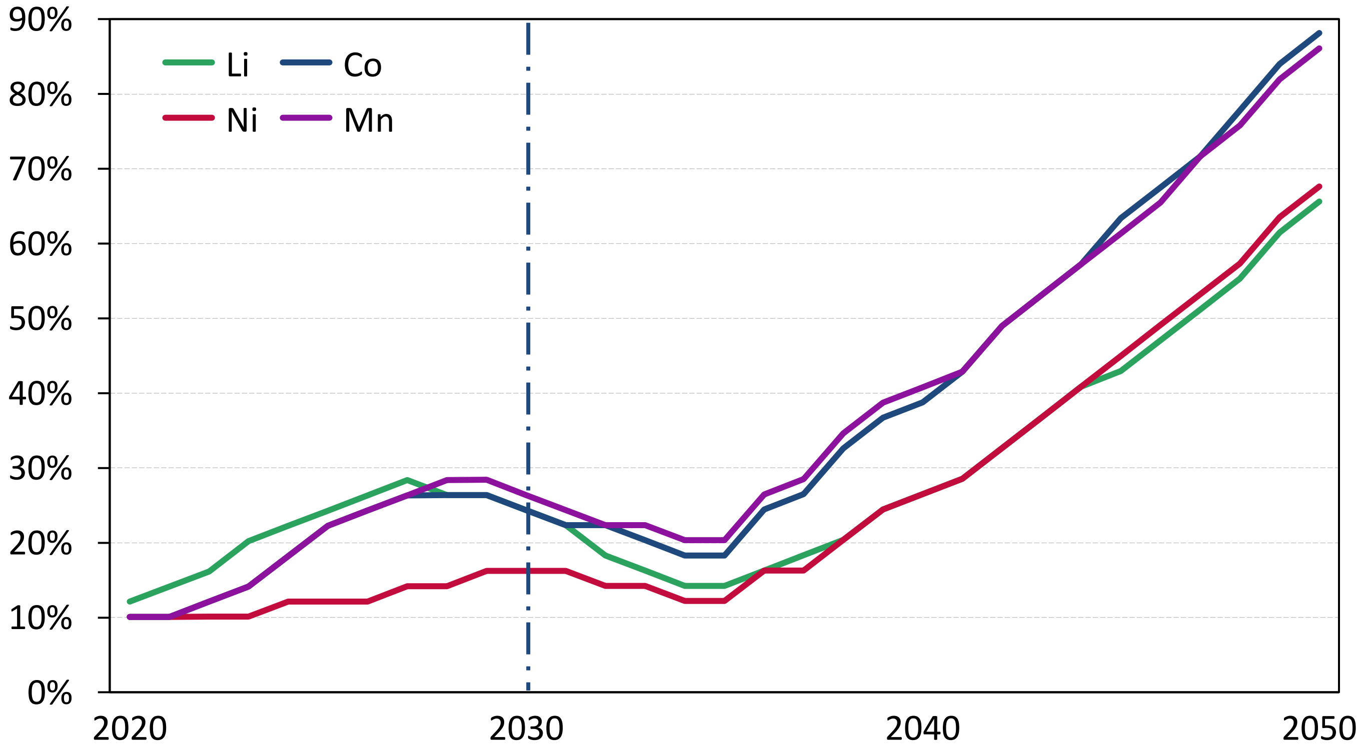
(1) EE Cost & Performance inputs were leveraged within 2020-21 BEUC TCO study

How much material can come from recycling?

A function of feedstock supply and efficiency

Share of material demand that can be met through recycling

Based on EE global battery stock modelling (2020)



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- Whilst the BEV market is growing rapidly, **recycling supply lags behind demand (~15 years – lifetime of the vehicle), with potential circularity low until the market stabilises**

Shift to hydrometallurgical recycling assumed in 2030

- Rare earth metals can be recovered by hydrometallurgy – which uses acid leaching chemical reactions of the battery materials to separate them for re-use
- This has traditionally been done with **inorganic acids** such as nitric and sulfuric acid – these acids are **energy and carbon intensive to synthesise** and are consumed in the leaching process
- Processes that use **organic acids**, such as oxalic and acetic acid, have recently been developed and are expected to be **widely used in 2030**

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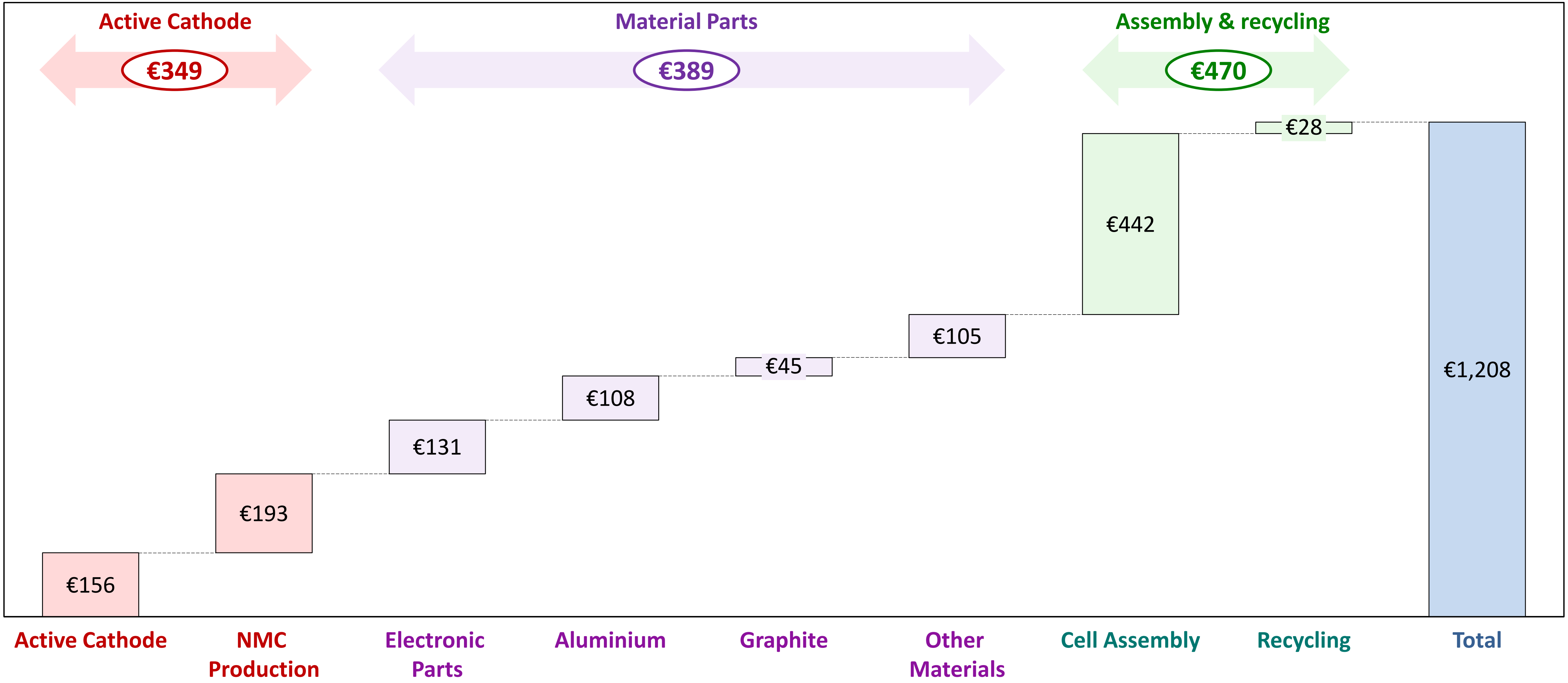
1 – Argonne National Laboratory, Everbatt model – future battery recycling to follow the hydrometallurgical process due to higher recovery rates of lithium.

Cost to decarbonise battery materials & processes

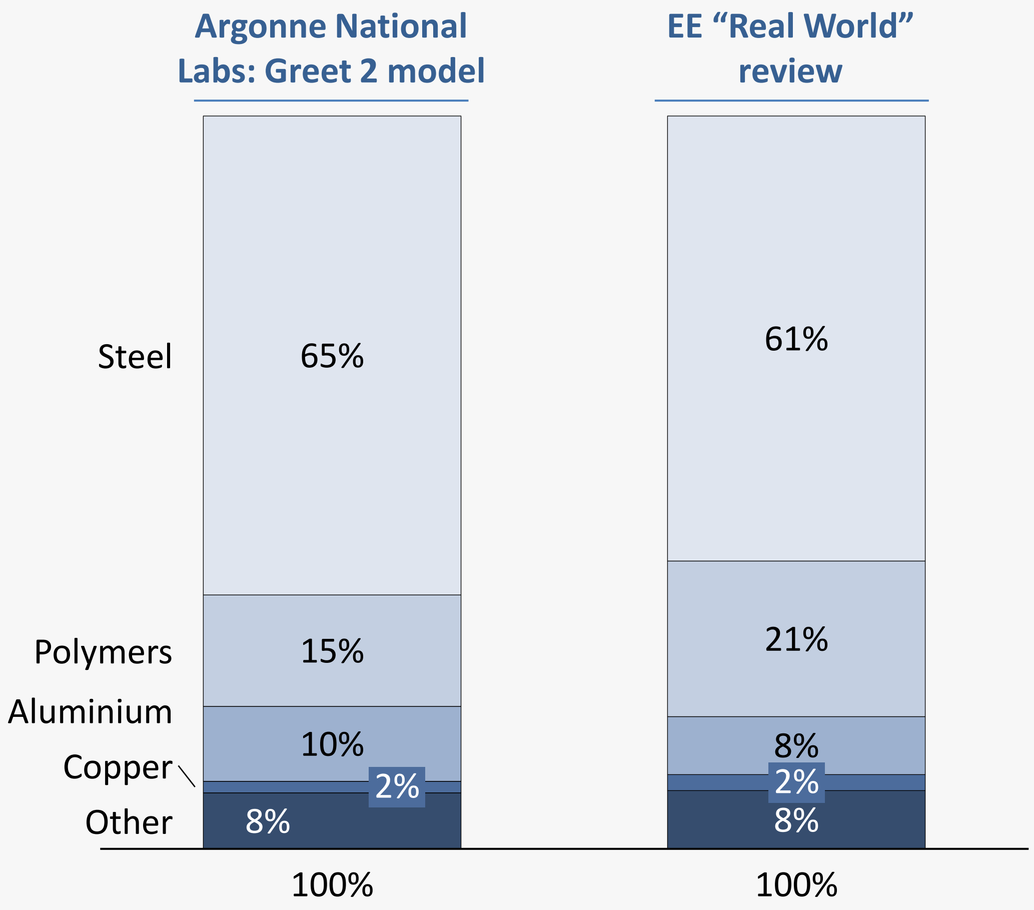


Note: that no additional cost has been assigned for recycling process switch hydrometallurgy (only the decarbonisation of the recycling itself) as this is assumed to be funded from the residual value of the battery

Contents

Decarbonising the materials used in vehicle production

Material Breakdown of a Medium ICEV Chassis(1)



Uses and limitations of the ANL greet 2 MODEL

- Argonne National Laboratory, a US Department of Energy scientific research centre, publish the 'GREET 2' model which calculates the lifecycle emissions of cars
- GREET 2 gives a well evidenced breakdown of:
  - Vehicle composition by material
  - Energy use and emissions of each stage of material and vehicle manufacturing
- EE have calibrated the GREET 2 material breakdown using disassembly data available from car OEMs and noted no significant differences in this "Real World" review
- GREET 2 data has thus been used in our modelling to provide a starting point of what must be decarbonised to achieve a net-zero car in 2030

GREET 2 has several limitations:

- **No material, process or energy cost data** is included in the GREET model – all decarbonisation costs were collated separately by EE, representing one of the main data inputs into our model
- **Key adjustments** to GREET 2 data were also necessary, for example, the **carbon intensity of the electricity grid** shown in GREET was adjusted to represent that forecast for the EU in 2030

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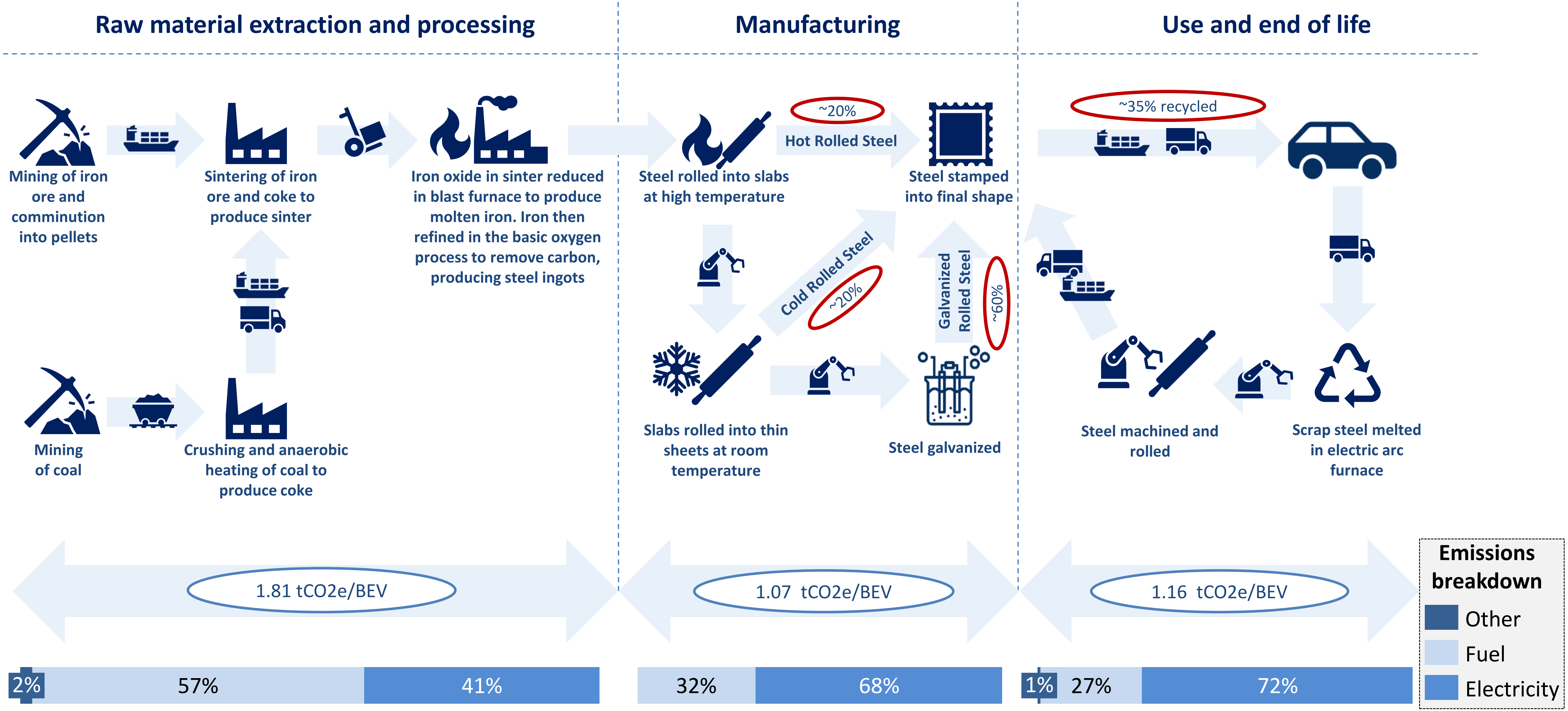
(1) EE "Real World" analysis based on an average of 7 leading ICE models with high market share – excludes: tyres, fluids and glass

Steel → Lifecycle analysis



Raw material extraction and processing

Mining of iron ore and comminution into pellets

Sintering of iron ore and coke to produce sinter

Iron oxide in sinter reduced in blast furnace to produce molten iron. Iron then refined in the basic oxygen process to remove carbon, producing steel ingots

Mining of coal

Crushing and anaerobic heating of coal to produce coke

Manufacturing

Steel rolled into slabs at high temperature

Steel stamped into final shape

Slabs rolled into thin sheets at room temperature

Steel galvanized

Use and end of life

Steel machined and rolled

Scrap steel melted in electric arc furnace

*Recycled percentage relates to the amount of steel in a car that comes from recycled steel in 2020

**'Manufacturing' emissions are those from virgin steel use, while 'Use and end of life' emissions are those from recycled steel use

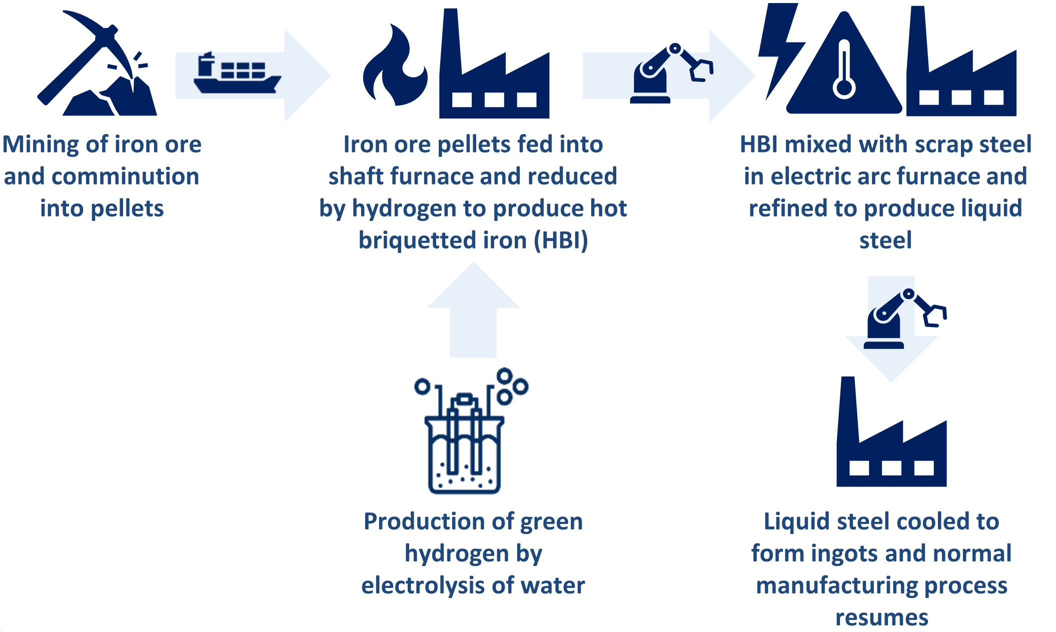
Steel → Decarbonisation Steps

Key Steps to decarbonise

Processing	**Direct reduction of iron ore with hydrogen**	Use of hydrogen instead of coke as the reducing agent for iron oxide, abating all direct processing emissions
Manufacturing	**Cold Rolled** ~20%	Switch to green electricity generated on-site to power cold-rolling machinery
	Hot Rolled ~20%	Use of electric heater to provide heat necessary for hot-rolling (~900˚C)
	Galvanized ~60%	Use of electric heater to provide heat necessary (~ 460˚C) for hot-dip galvanizing
	Recycled ~35%	Use of electric arc furnace (~1,800 ˚C) to melt down scrap steel for recasting and rolling

Case Study – switch to Hydrogen Direct Reduction process

- The Hydrogen Direct Reduction process (H-DR) substitutes hydrogen for coke as the reducing agent and source of heat to extract iron from the iron oxide in iron ore:
- **Blast Furnace** (old process): Iron Oxide + Carbon Monoxide → Iron + Carbon Dioxide
- **H-DR** (new process): Iron Oxide + Hydrogen → Iron + Water
- H-DR results in **zero emissions** when green electricity and hydrogen is used



Mining of iron ore and comminution into pellets

Iron ore pellets fed into shaft furnace and reduced by hydrogen to produce hot briquetted iron (HBI)

HBI mixed with scrap steel in electric arc furnace and refined to produce liquid steel

Production of green hydrogen by electrolysis of water

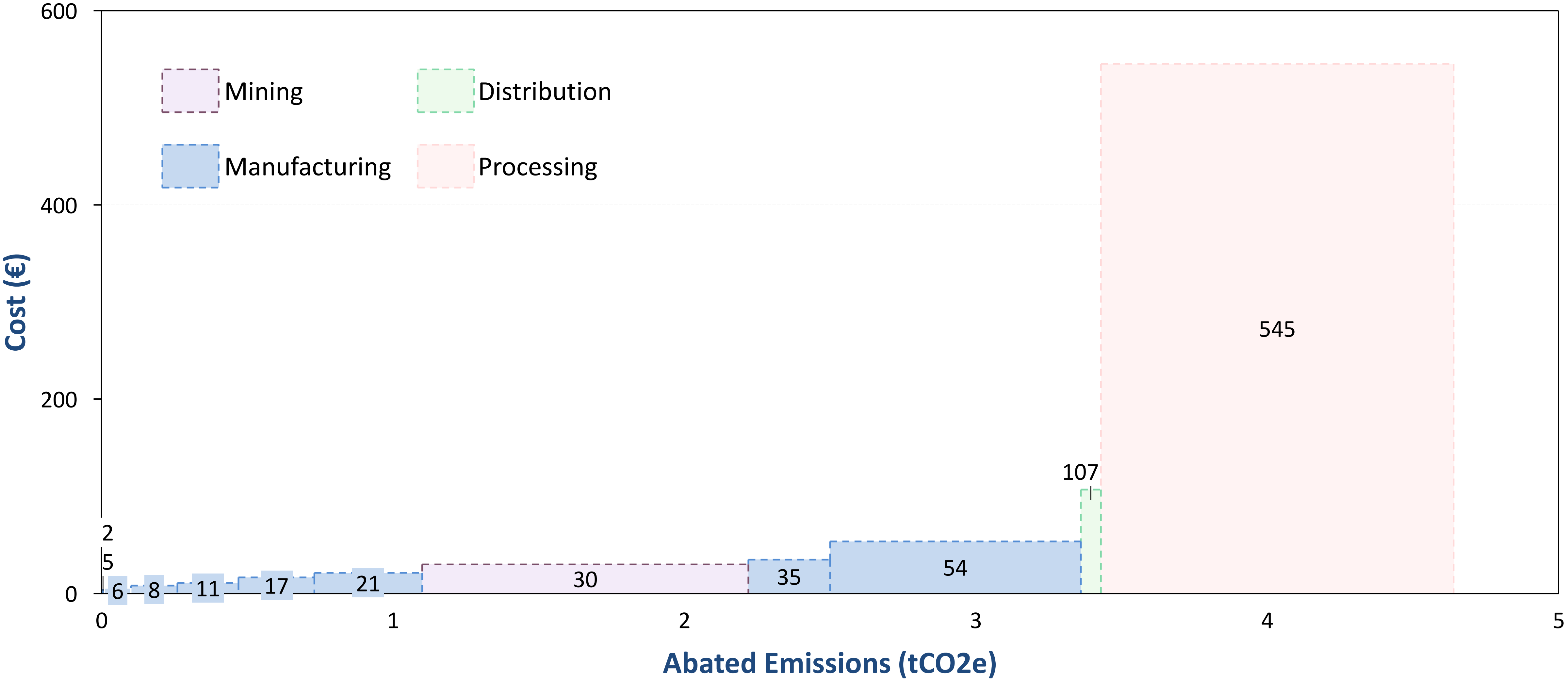
Liquid steel cooled to form ingots and normal manufacturing process resumes

*Relates to % of steel used in car manufactured in 2030 that would be recycled steel

Steel → Decarbonisation Costs

Cost of abating emissions at each stage of steel production

Total: €840 per medium BEV

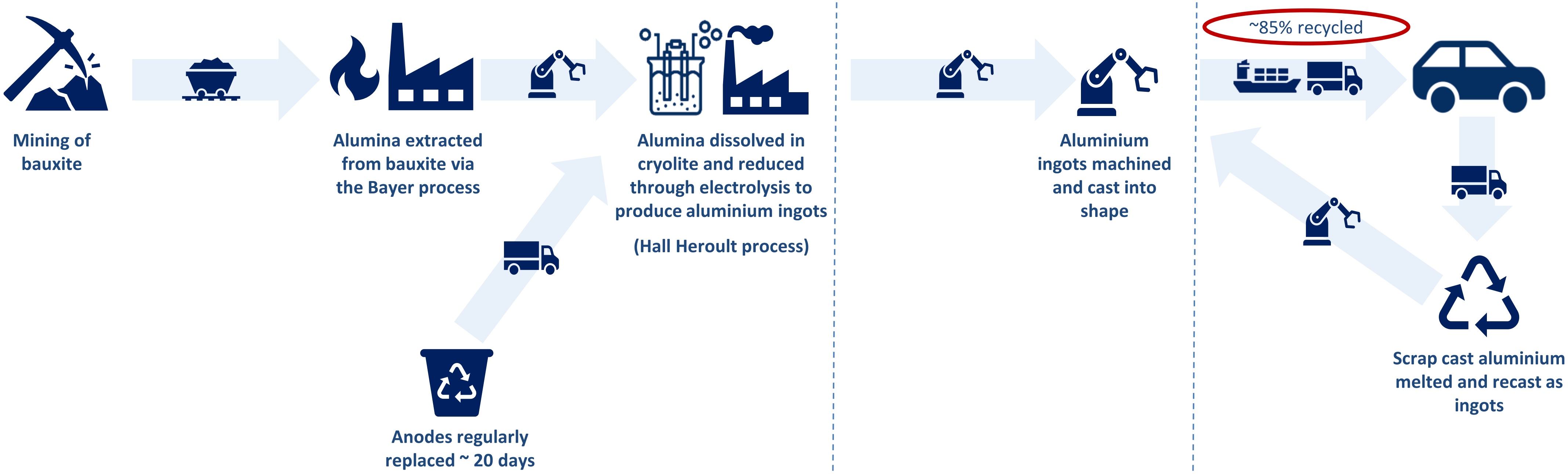


Cast Aluminium → Lifecycle Analysis

Raw material extraction and processing

Manufacturing

Use and end of life



Mining of bauxite

Alumina extracted from bauxite via the Bayer process

Alumina dissolved in cryolite and reduced through electrolysis to produce aluminium ingots

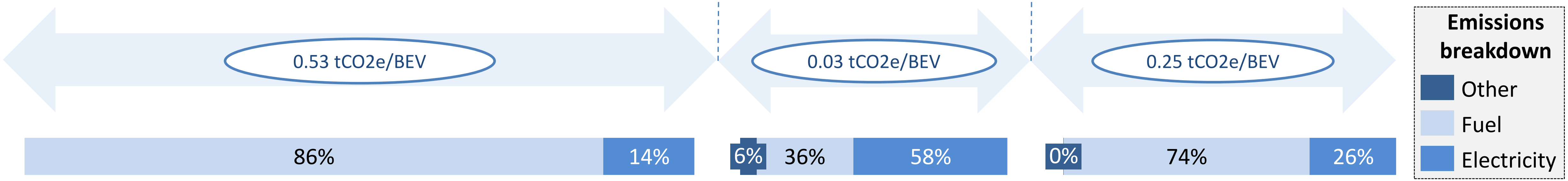
(Hall Heroult process)

Anodes regularly replaced ~ 20 days

Aluminium ingots machined and cast into shape

~85% recycled

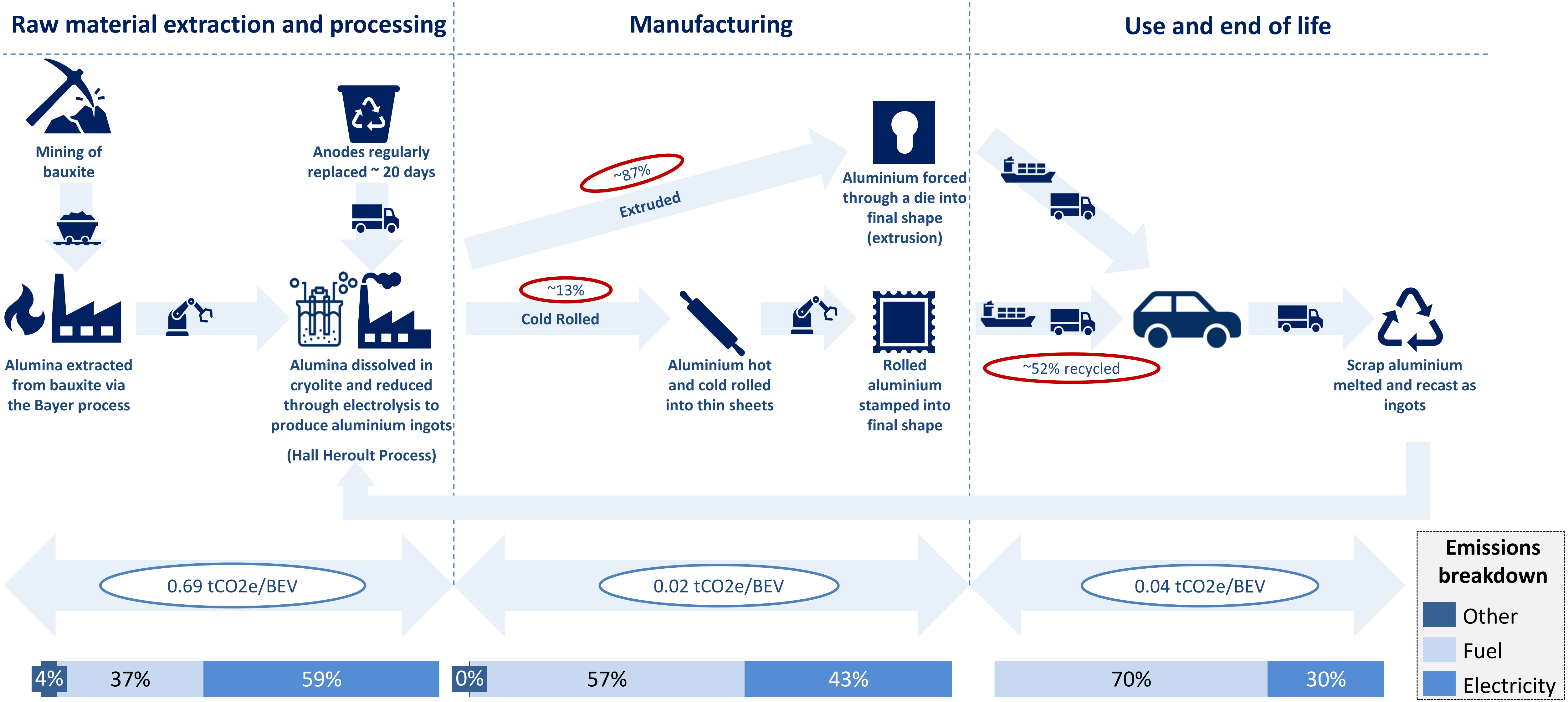
Scrap cast aluminium melted and recast as ingots



*Recycled percentage relates to the amount of cast aluminium in a car that comes from recycled aluminium in 2020

**'Manufacturing' emissions are those from virgin aluminium use, while 'Use and end of life' emissions are those from recycled aluminium use

Wrought Aluminium → Lifecycle Analysis



Raw material extraction and processing

Mining of bauxite

Alumina extracted from bauxite via the Bayer process

Anodes regularly replaced ~ 20 days

Alumina dissolved in cryolite and reduced through electrolysis to produce aluminium ingots

(Hall Heroult Process)

0.69 tCO2e/BEV

4%	37%	59%

Manufacturing

~87% Extruded

Aluminium forced through a die into final shape (extrusion)

~13% **Cold Rolled**

Aluminium hot and cold rolled into thin sheets

Rolled aluminium stamped into final shape

0.02 tCO2e/BEV

0%	57%	43%

Use and end of life

~52% recycled

Scrap aluminium melted and recast as ingots

0.04 tCO2e/BEV

70%	30%

Emissions breakdown

- ▇ Other
- ▇ Fuel
- ▇ Electricity

*Recycled percentage relates to the amount of wrought aluminium in a car that comes from recycled aluminium in 2020

**'Manufacturing' emissions are those from virgin aluminium use, while 'Use and end of life' emissions are those from recycled aluminium use

Aluminium → Decarbonisation Steps

Key Steps to decarbonise

Processing	**Bauxite Refining: Bayer process**	• Use of hydrogen heater in place of natural gas to provide the heat (~1100°C) for final stage of Bayer process
	Alumina Reduction: Hall-Heroult Process	• Implement carbon capture and storage to abate direct CO2 emissions and green electricity for electrolysis
Manufacturing	**Cast** ~70%	• Use of hydrogen heater for primary and secondary ingot casting
	Wrought extruded ~26%	• Use of electric heater to provide heat for aluminium extrusion
	Wrought cold rolled ~4%	• Use of electric heater for initial hot rolling and green electricity for cold rolling machinery

Case Study – inert anodes in the Hall-Heroult Process

- The current process for extraction of aluminium form alumina involves the electrolysis of dissolved aluminium oxide using carbon anodes
- This is a **very carbon intense process** – aluminium oxide reacts with the carbon anode, producing CO2, and the anodes must be replaced every four weeks, causing further emissions
- The best currently available way to abate these emissions is with carbon capture, utilisation and storage which we have **assumed in our modelling**
- However, CCUS for the Hall-Heroult Process is **extremely expensive at €550 per tonne of aluminium** (including the cost of capturing emissions from anode production) and only abates around 87.5% of direct CO2 emissions
- Research is being carried out to develop **inert anodes**, that don't produce CO2 during electrolysis. Focus has been on metal alloys such as Iron-Nickel and Copper-Nickel-Iron, however these are not yet suitable for industrial scale application**
- Inert anodes would also have **significant cost advantages over CCUS** – estimated at €86 per tonne of aluminium - and are likely to be available by 2030, according to MIDDEN

Overall, inert anodes offer an economical and effective decarbonisation pathway for aluminium production, but are not yet ready for industrial scale application

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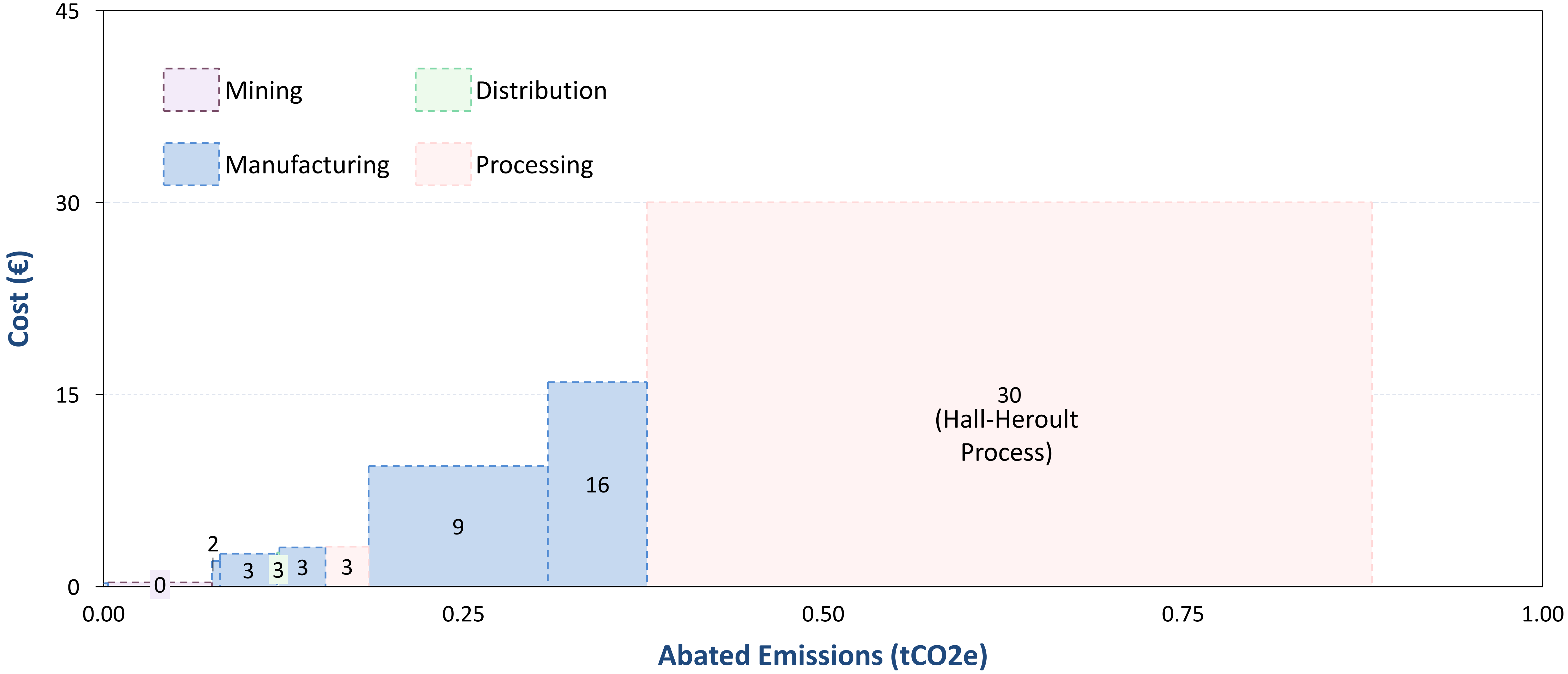
*%s related to mass as a total of all cast and wrought aluminium

** An update on inert anodes for aluminium electrolysis, Siberian Federal University, July 2020

Cast Aluminium → Decarbonisation Costs

Cost of abating emissions at each stage of cast aluminium production

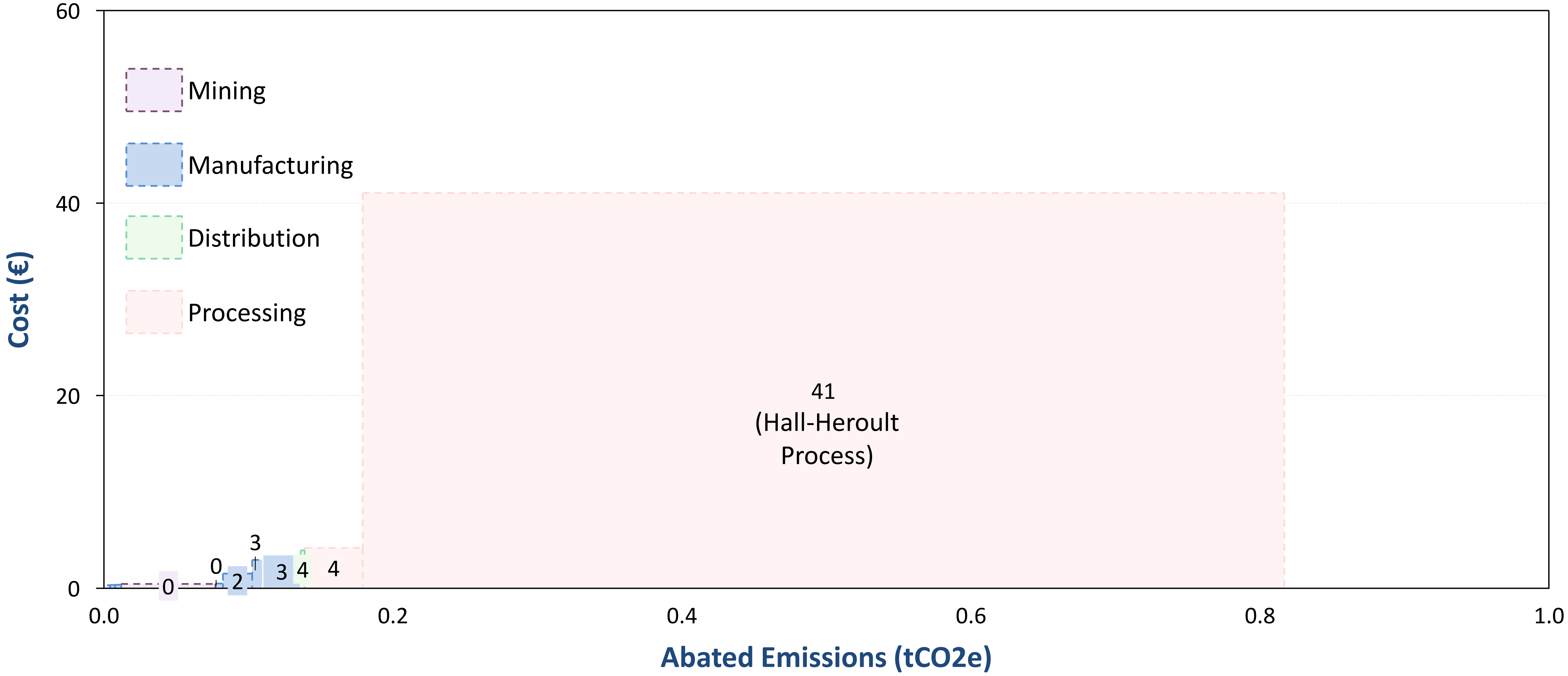
Total: €70 per medium BEV



Wrought Aluminium → Decarbonisation Costs

Cost of abating emissions at each stage of wrought aluminium production

Total: €60 per medium BEV

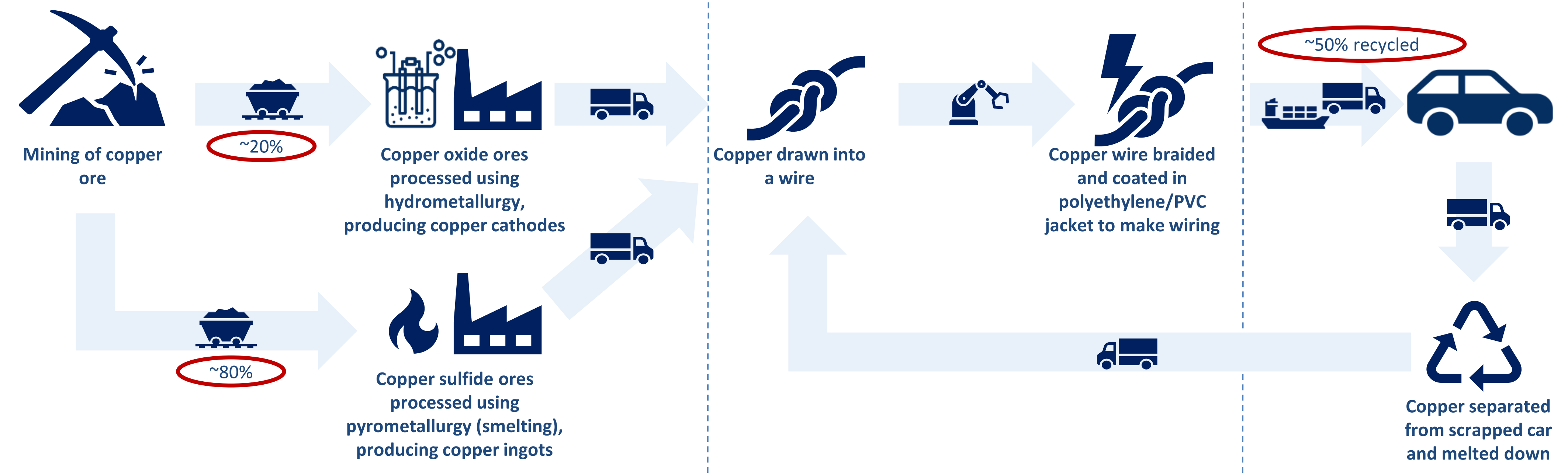


Copper → Lifecycle Analysis

Raw material extraction and processing

Manufacturing

Use and end of life



Mining of copper ore

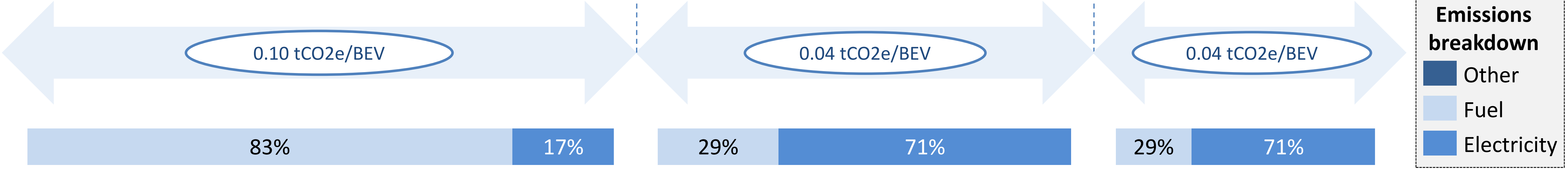
Copper oxide ores processed using hydrometallurgy, producing copper cathodes

Copper sulfide ores processed using pyrometallurgy (smelting), producing copper ingots

Copper drawn into a wire

Copper wire braided and coated in polyethylene/PVC jacket to make wiring

Copper separated from scrapped car and melted down



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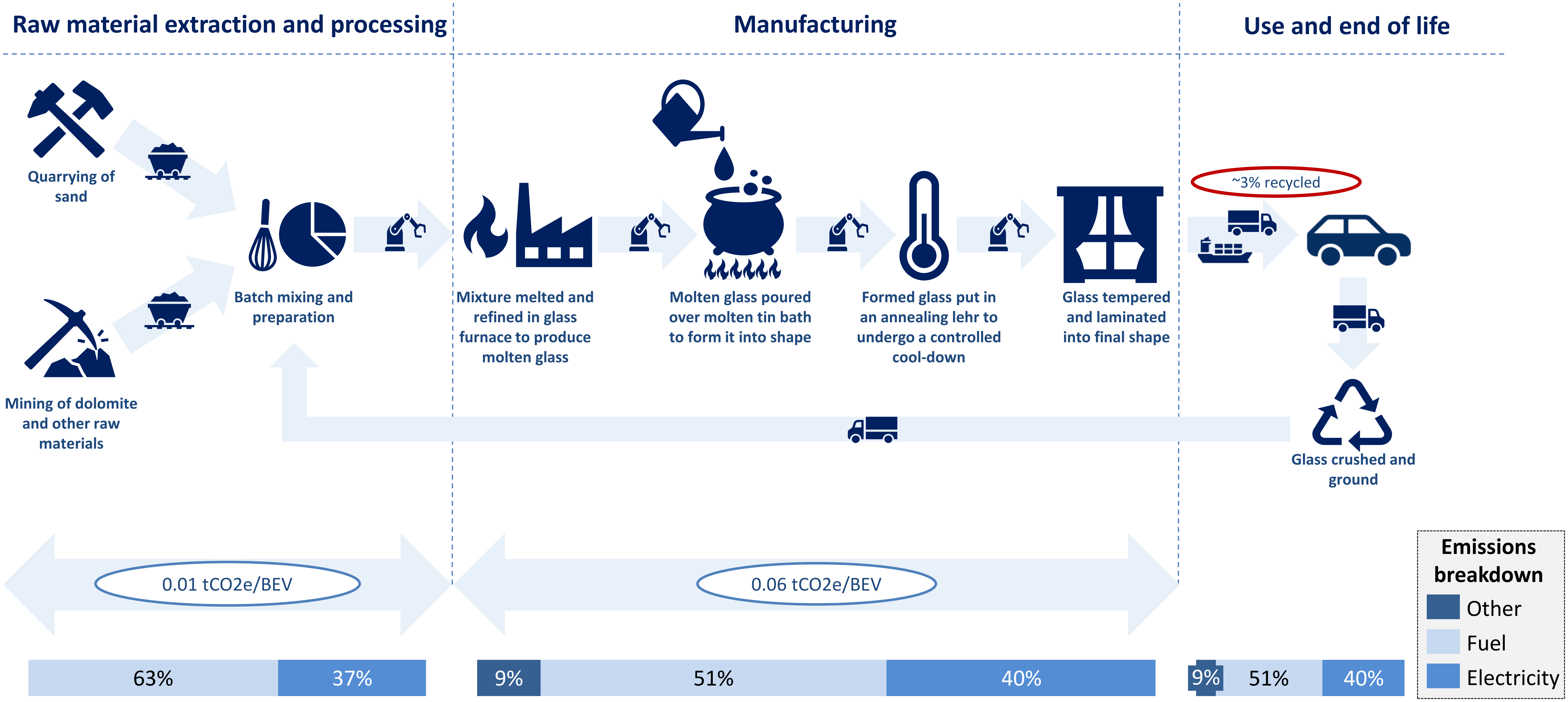
*Recycled percentage relates to the amount of copper in a car that comes from recycled copper in 2020

**‘Manufacturing’ emissions are those from virgin copper use, while ‘Use and end of life’ emissions are those from recycled copper use

Glass → Lifecycle Analysis



Raw material extraction and processing

Quarrying of sand

Mining of dolomite and other raw materials

Batch mixing and preparation

0.01 tCO2e/BEV

63%	37%

Manufacturing

Mixture melted and refined in glass furnace to produce molten glass

Molten glass poured over molten tin bath to form it into shape

Formed glass put in an annealing lehr to undergo a controlled cool-down

Glass tempered and laminated into final shape

0.06 tCO2e/BEV

9%	51%	40%

Use and end of life

~3% recycled

Glass crushed and ground

9%	51%	40%

Emissions breakdown

- ■ Other
- ■ Fuel
- ■ Electricity

---

*Recycled percentage relates to the amount of glass in a car that comes from recycled glass in 2020
**'Manufacturing' emissions are those from virgin glass use, while 'Use and end of life' emissions are those from recycled glass use

Glass and Copper → Decarbonisation Steps

Key Steps to decarbonise - Glass

Processing

Glass batch preparation

- Switch to green electricity generated on-site for batch mixing and preparation

Manufacturing

Melting and refining

- Use of hydrogen to provide heat (~1550^{o}C) in glass furnace

Forming

- Use of green electricity for the compressors that provide air and fans that cool the forming machines

Annealing, tempering and laminating

- Use of hydrogen heater in lehr to control the cool-down of glass, and again for the heat used in tempering and laminating

Key Steps to decarbonise - Copper

Processing

Copper smelting and refining

- Use of a hydrogen heater for heat used (~1200^{o}C) to smelt and refine copper oxide ores

Manufacturing

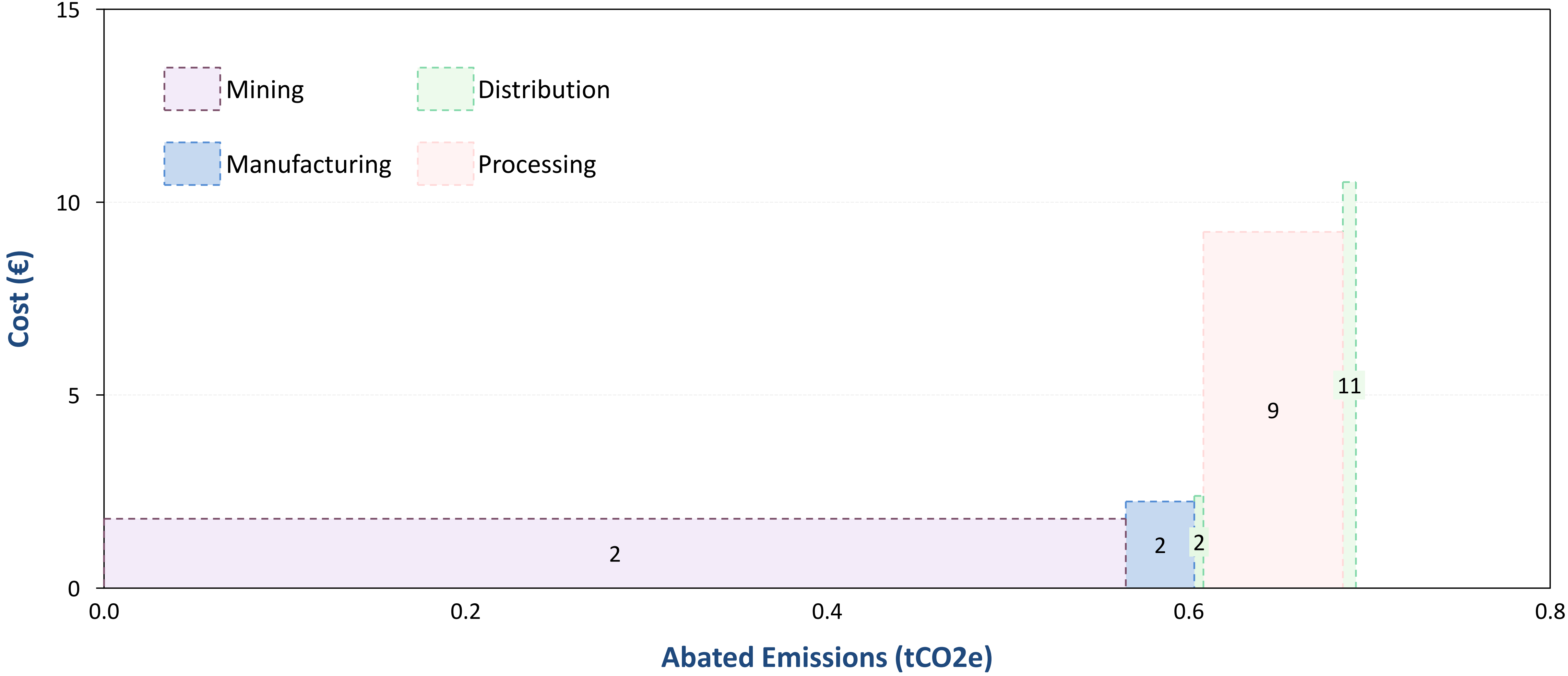
Copper wire drawing

- Switch to green electricity generated on-site to power copper wire drawing machinery

Copper → Decarbonisation Costs

Cost of abating emissions at each stage of copper production

Total: €26 per medium BEV



Glass → Decarbonisation Costs

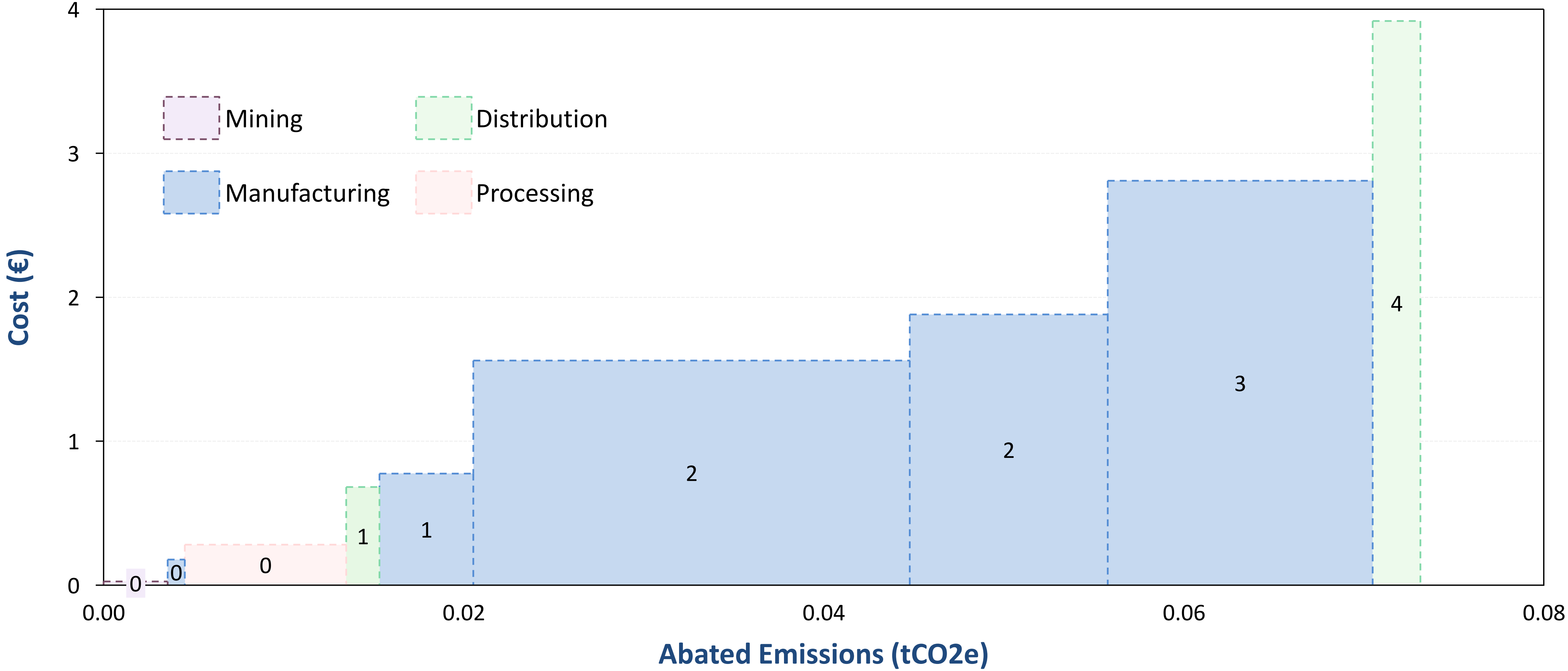
Current life cycle & emissions

Key steps to decarbonisation

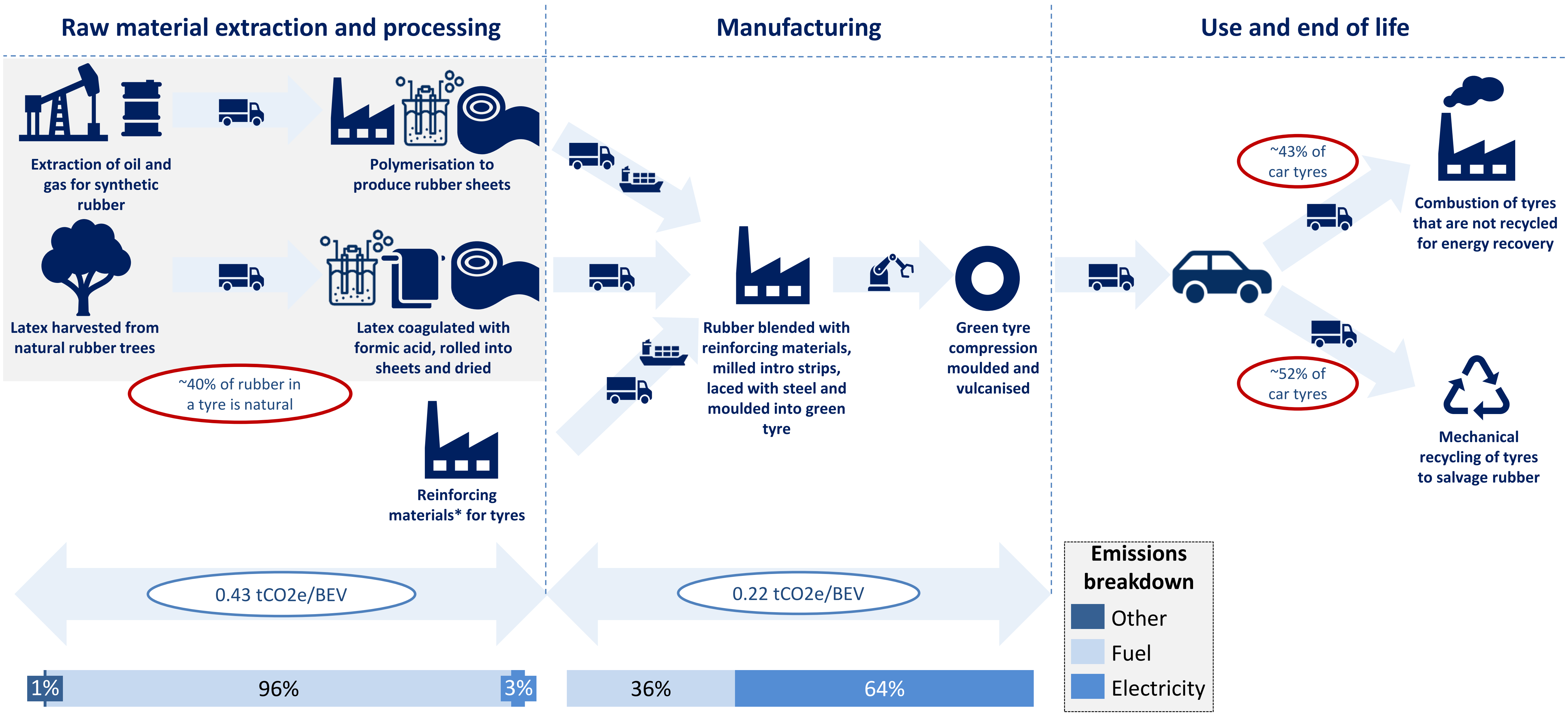
Cost to decarbonise histograms

Cost of abating emissions at each stage of glass production

Total: €12 per medium BEV



Rubber → Lifecycle Analysis



Raw material extraction and processing

Extraction of oil and gas for synthetic rubber

Polymerisation to produce rubber sheets

Latex harvested from natural rubber trees

Latex coagulated with formic acid, rolled into sheets and dried

~40% of rubber in a tyre is natural

Reinforcing materials* for tyres

0.43 tCO2e/BEV

Manufacturing

Rubber blended with reinforcing materials, milled intro strips, laced with steel and moulded into green tyre

Green tyre compression moulded and vulcanised

0.22 tCO2e/BEV

Use and end of life

~43% of car tyres

Combustion of tyres that are not recycled for energy recovery

~52% of car tyres

Mechanical recycling of tyres to salvage rubber

Emissions breakdown

- 🟦 Other
- ▢ Fuel
- 🟦 Electricity

*For the purposes of this study it is assumed tyres are reinforced purely by steel

** Note percentages do not sum to 100% as not all tyres are collected

Rubber → Decarbonisation Steps

Key Steps to decarbonise

Processing

Styrene-butadiene (synthetic rubber) production

- Use of a hydrogen heater for polymerisation of styrene and butadiene to produce synthetic rubber

Manufacturing

Green tyre production

- Use of hydrogen heater to blend reinforcing materials (excluding steel) and for moulding green tyre

Compression Moulding

- Use of an electrode steam boiler to generate steam used in tyre compression moulding and vulcanisation

Case Study – potential for more sustainable natural rubbers

- The rubber used in tyres is currently around 40% natural (from rubber trees) and 60% synthetic (from polymerisation of derivatives of crude oil)
- **Natural rubbers have the benefit of being significantly less carbon intense than synthetic rubbers** at 0.6 kgCO2e/kg and 2.4 kgCO2e/kg respectively, hence increased natural rubber use can significantly lower a car's life-cycle emissions
- However, around 90% of natural rubber is grown in South-East Asia, where **growing concerns over rainforest loss to natural rubber production are constraining supply** - analogous to concerns over palm oil
- Tyre manufactures and car OEMs have thus been working to **produce natural rubber from alternative sources** to reduce life-cycle emissions sustainably
- In 2015 **Bridgestone** announced the production of their first tyre from Guayule-derived natural rubber – a shrub that can be grown in arid locations (e.g. North Mexico), avoiding deforestation
- In May 2019 **GM** committed to using sustainably sourced natural rubber tyres, and **BMW** became the first OEM to use tyres containing certified sustainable natural rubber, produced by Pirelli

Significant CO2e reductions could be achieved from increased natural rubber use, however due to limitations and issues with mass-scale production and cost, this has not been considered in our modelling

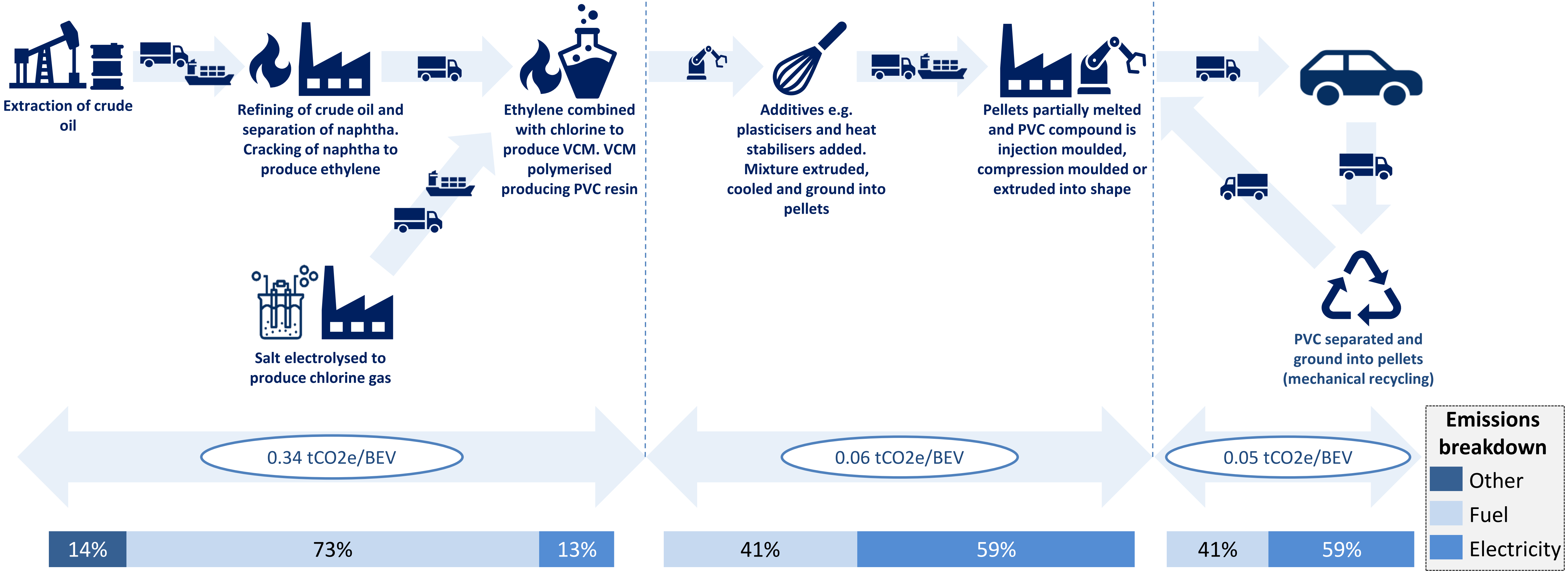
Plastics* → Lifecycle Analysis

Current life cycle & emissions | Key steps to decarbonisation

Raw material extraction and processing

Manufacturing

Use and end of life



Extraction of crude oil

Refining of crude oil and separation of naphtha. Cracking of naphtha to produce ethylene

Salt electrolysed to produce chlorine gas

Ethylene combined with chlorine to produce VCM. VCM polymerised producing PVC resin

Additives e.g. plasticisers and heat stabilisers added. Mixture extruded, cooled and ground into pellets

Pellets partially melted and PVC compound is injection moulded, compression moulded or extruded into shape

PVC separated and ground into pellets (mechanical recycling)

*The lifecycle shown is for PVC - 15 additional plastics were included in the model and all follow analogous life cycles to PVC. The emissions are a total for all plastics

**'Manufacturing' emissions are those from virgin aluminium use, while 'Use and end of life' emissions are those from recycled aluminium use

Plastics → Decarbonisation Steps

Key Steps to decarbonise

Processing

Resin production

- Use of hydrogen heater for crude oil cracking to produce monomers and for heat required to achieve polymerisation reactions*

Manufacturing

Moulding (compression/ injection)

- Use of hydrogen heater to soften/melt plastic pellets sufficiently for compression/injection moulding (e.g. PVC)

Extrusion

- Use of hydrogen heater to provide heat required for plastic extrusion (e.g. High Density Poly Ethylene)

Case Study – potential for increased bioplastics use in cars

- The vast majority of plastics are currently produced from the polymerisation of fossil fuel derivatives
- Although it's possible to decarbonise much of this process, significant energy is required and it paves the way for continued fossil fuel extraction
- Similarly to biofuels, it is possible to create **bioplastics – plastics derived from renewable biomass sources such as corn or castor oil**
- If grown sustainably, bioplastics could play a significant roll in delivering net-zero cars in the future, although **this possibility has not been considered in our modelling**
- Interest is growing amongst car OEMs around bioplastics:
- **Ford** are using soy to develop bio-based polyurethane foams on the seat cushions of 11 vehicle models
- **Renault** have used Mitsubishi Chemicals' bioplastic DURABIO to manufacture the dashboard of the Renault Clio
- **Toyota** have used bio-PET to manufacture interior components of their cars

Bioplastics offer a promising decarbonisation pathway for plastic in cars. However, feedstock availability and meeting vehicle integrity standards must be overcome to achieve widespread use

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*Certain polymers e.g. epoxy resin can be produced with minimal heat and so have not been decarbonised in this way

Contents

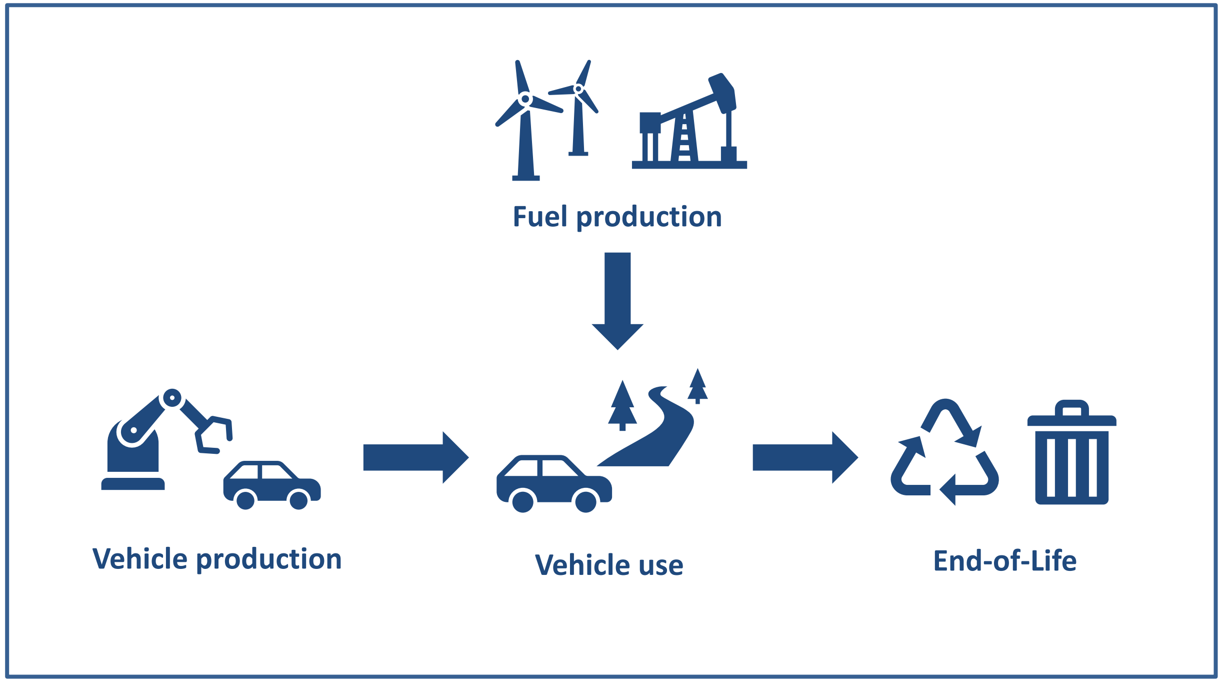
Overview of lifetime emission analysis

Overview of a vehicle lifecycle

A vehicle's life cycle can be broadly split into four stages:

1. **Vehicle production:** Producing the vehicle including extraction of raw materials, processing, component manufacture, logistics, vehicle assembly and painting
2. **Fuel production:** Producing the energy vector from primary energy source to point of distribution (e.g. refuelling station)
3. **Vehicle use:** Driving, maintenance and servicing
4. **End-of-life:** Re-using components, recycling materials, energy recovery and disposal to landfill

Four stages to vehicle lifecycle emissions:

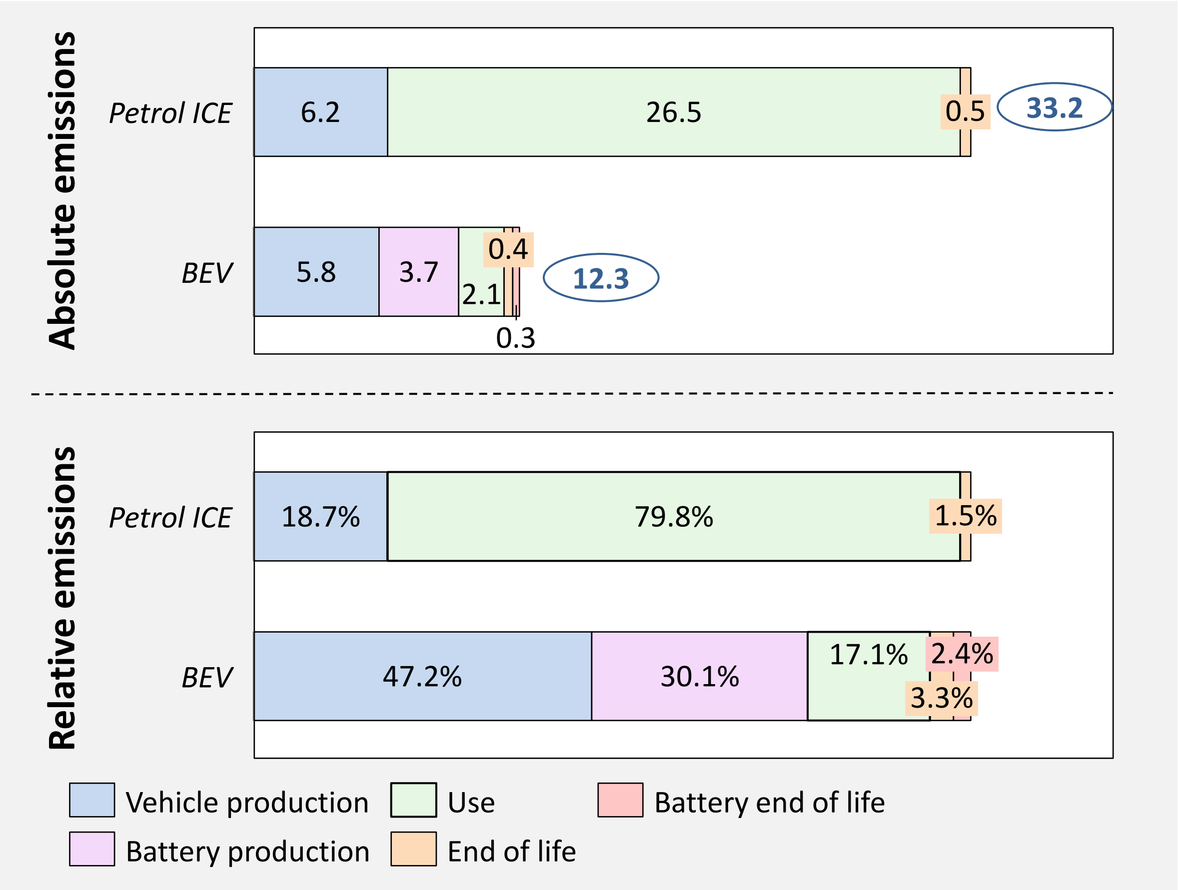


Element Energy will leverage an updated version of our comprehensive literature review of lifecycle emissions

EE have completed a comprehensive literature review of the total life cycle CO_2e emissions of passenger cars

Selected contribution of life cycle stages to total carbon emissions of a small passenger car (tCO_2e)[1]

150,000km functional unit, cradle-to-grave analysis, grid carbon intensity of 300 gCO_2e/kWh assumed



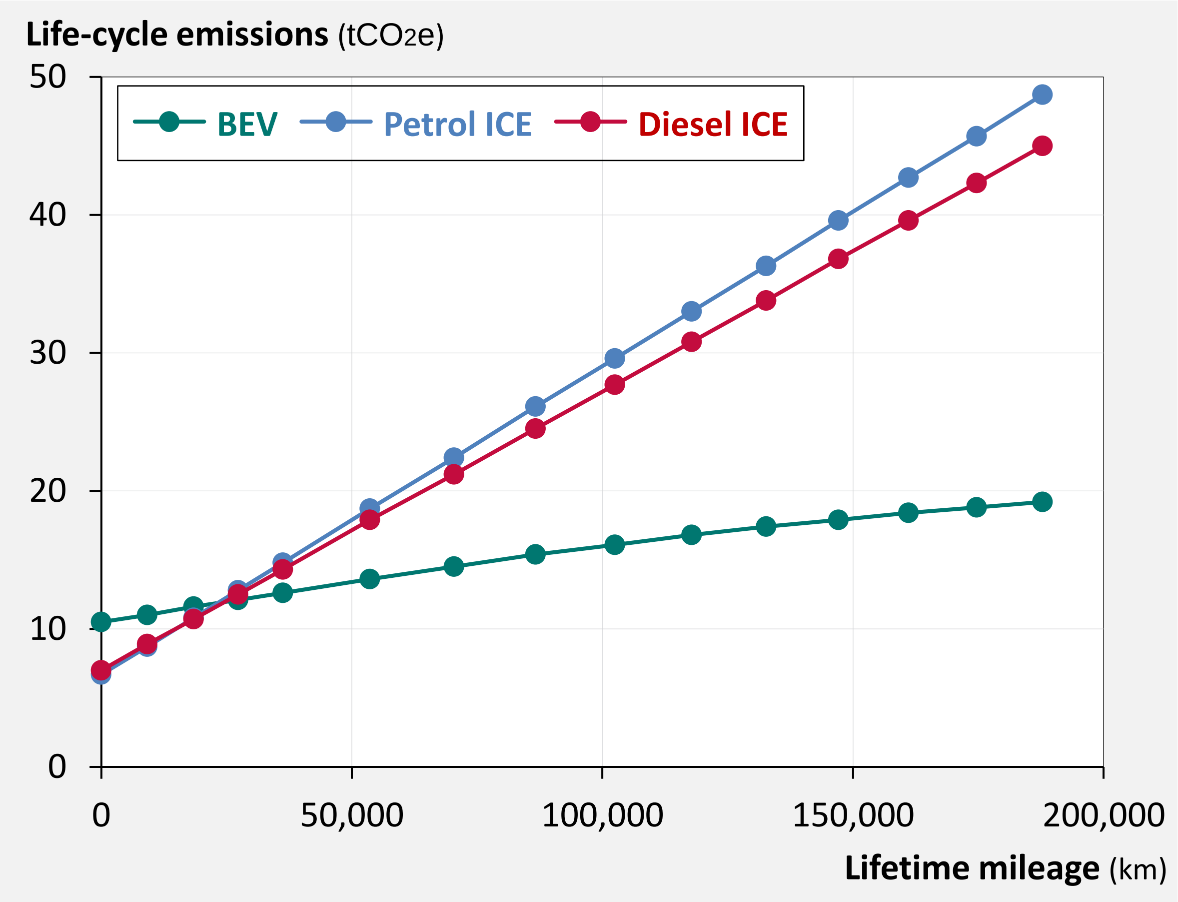
- From published literature, **GHG emissions from the vehicle use stage (WTW) account for between 70-90% of total life cycle emissions for conventional ICEVs**
  - For BEVs, WTW emissions generally make up ca. 15 – 25% of the life cycle emissions, although in extreme scenarios (very high or low electricity carbon intensity) the use stage could result in negligible GHG emissions or may account for over 60% of GHG emissions
- For an average electricity grid carbon intensity, the **embedded emissions of a BEV (battery and vehicle manufacture and end-of life) dominate the life cycle CO_2e emissions**
  - Published studies show that embedded emissions of BEVs account for between 20 – 90% of total GHG emissions. The large variation is due to differences in methodology and assumed electricity grid carbon intensity
  - Embedded emissions are dominated by the vehicle and battery manufacturing stage. Studies generally show that the production stage of a BEV accounts for ca. 50 – 80% of total life cycle CO_2e emissions. End of life accounts for between 1% and 5% of life cycle emissions

Source: 1) How clean are electric cars? T&E's analysis of electric car lifecycle CO_2 emissions, Transport & Environment 2020

EE have completed a comprehensive literature review of life cycle CO_2e emissions

Life-cycle tCO_2e emissions against distance driven[(1)]

EU27 average grid carbon intensity assumed (319 gCO2e/kWh)



- Total life cycle CO_2e emissions increase with distance:
  - BEVs tend to have the highest total CO_2e emissions when 0km have been driven, but after **approximately 20,000km have been driven BEV emissions fall below those of petrol and diesel ICEs**
- That the global warming potential impact of BEVs improves with higher mileage suggest that **BEVs are well suited to a modal shift towards shared mobility**
- BEVs produced today should be treated as **an asset prioritized for high mileage uses to optimize payback of high upfront production emissions**

Total lifecycle emission analysis, and the associated costs to decarbonise, is essential to reduce the high upfront CO_2 emissions associated with BEV production

Source: 1) QUELLE CONTRIBUTION DU VÉHICULE ÉLECTRIQUE À LA TRANSITION ÉCOLOGIQUE EN FRANCE?, Fondation pour la nature et l'homme, 2016

Note: Use stage is well-to-wheel and includes fuel production, driving and maintenance.