Carbon neutral powertrain options - today and tomorrow

Waseda Symposium, October 25, 2022

Prof. Dr. U. D. Grebe

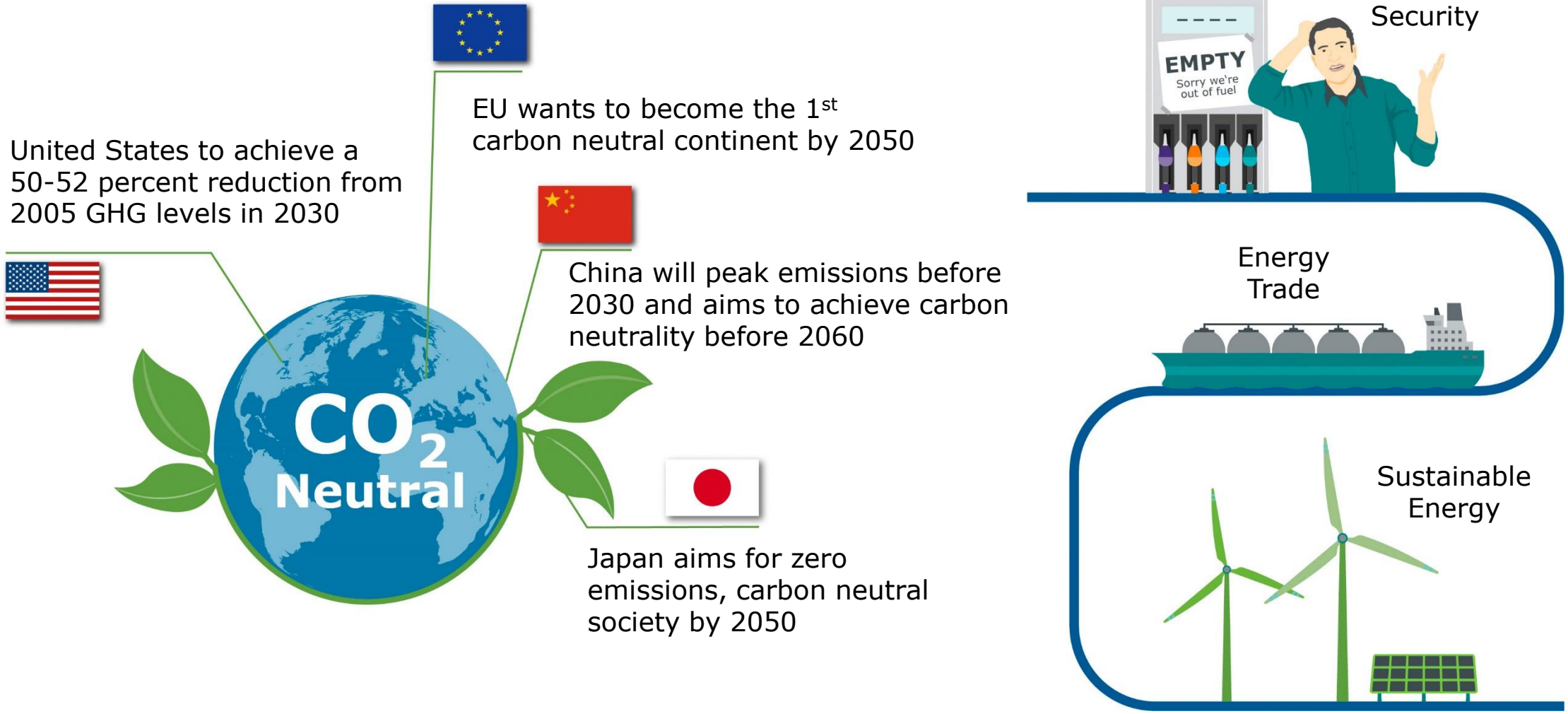
Strive for two goals: Climate-neutrality and energy security

United States to achieve a 50-52 percent reduction from 2005 GHG levels in 2030

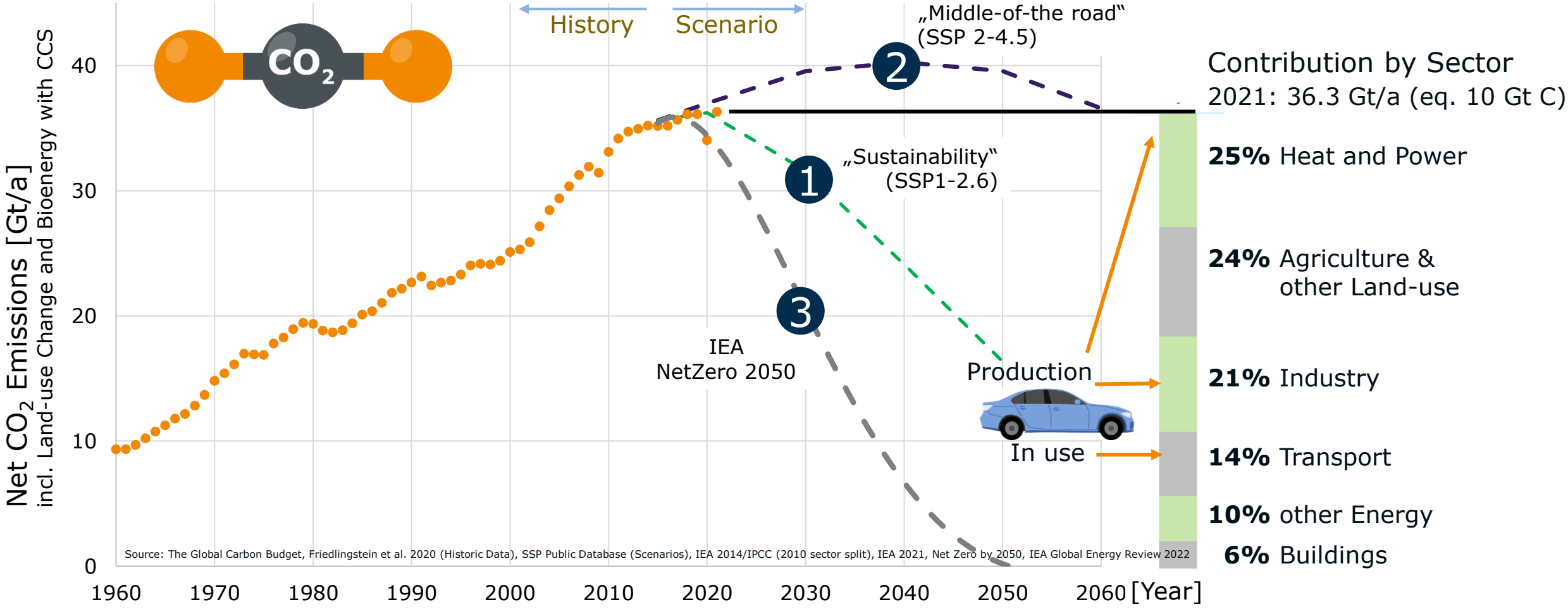
EU wants to become the 1st carbon neutral continent by 2050

China will peak emissions before 2030 and aims to achieve carbon neutrality before 2060

Japan aims for zero emissions, carbon neutral society by 2050



History of Global Human-Made CO_2 Emissions



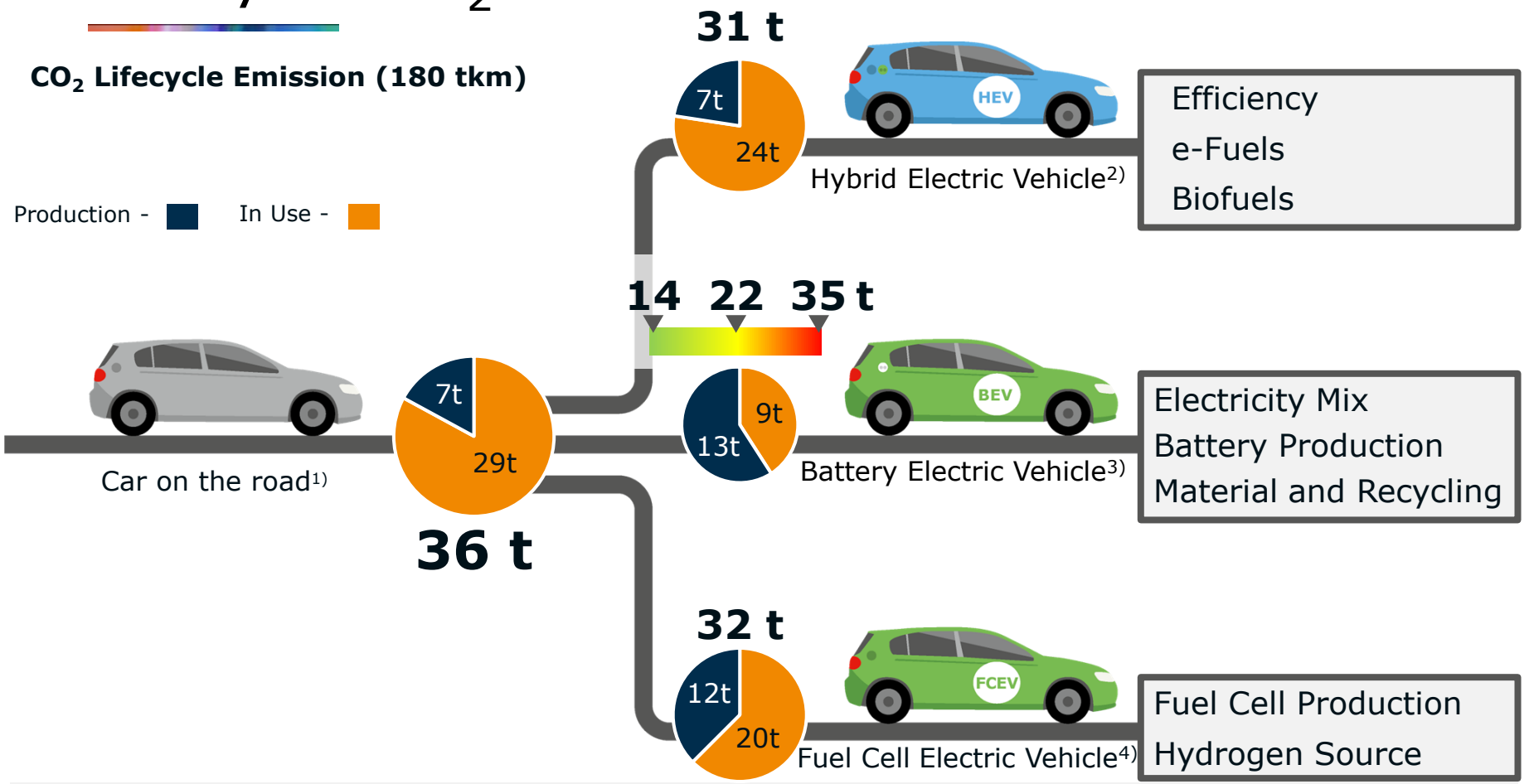
Contribution by Sector
2021: 36.3 Gt/a (eq. 10 Gt C)

- **25%** Heat and Power
- **24%** Agriculture & other Land-use
- **21%** Industry
- **14%** Transport
- **10%** other Energy
- **6%** Buildings

Growth of population and prosperity have been and still are the main drivers for GHG emissions.
Technology progress in all sectors needed for the entire lifecycle including production.

Competition of Powertrains
Lifecycle CO_2 – 2022

CO_2 Lifecycle Emission (180 tkm)



2022: Similar range of CO_2 over lifetime for all powertrains, with potential for future reduction
BEV advantage in case of low CO_2 (renewable or nuclear) electricity
Hydrogen and ICE fuel need to come from renewable sources as well

1)Car on the Road
C-Segment, Diesel 100 kW

2)Hybrid Electric Vehicle
Propulsion 110 kW / Gasoline 85 kW /
Battery 1.2 kWh / Fossil Fuel

3)Battery Electric Vehicle
Propulsion 150 kW / Battery 60 kWh (ca. 330 km range)
Electricity Mix
22t … EU electricity mix 2019
for constant in-use 275gCO2eq/kWh
14t … France electricity mix 2020
for constant in-use 51gCO2e/kWh
35t … Poland electricity mix 2020
for constant in-use 710gCO2e/kWh

4)Fuel Cell Electric Vehicle
Propulsion 110 kW /Fuel Cell 90 kW / Battery 1.6 kWh
Fossil Hydrogen from Natural Gas Reforming
(Steam Methane Reforming)

Sources: AVL, EU EEA, IEA WEO 2021, Fraunhofer ISI, ifeu

Competition of Powertrains
Automobile Roadmap to Zero CO_2

2022 — Road to Zero — 2030+ Target

Production - In Use -

		Potential CO_2 Reduction	
31 t (7t / 24t)	Hybrid Electric Vehicle	Efficiency -10% e-Fuels <10% Biofuels	10 - 26 t
14 22 35 t (13t / 9t)	Battery Electric Vehicle	Electricity Mix -75% Battery Production -50% Mat. and Recycling -30%	5 - 20 t
32 t (12t / 20t)	Fuel Cell Electric Vehicle	Fuel Cell Production -50% Hydrogen Source -90%	6 - 20 t

- Production: Likely to become carbon neutral by 2050
- Efficiency of ICE in HEV: 50% possible
- PHEV: High EV-Range will enable high electric share
- E-fuel unlikely to be available for Pass Car before 2050

- Decarbonizing electricity prod. will significantly improve BEV and PHEV lifecycle emissions
- CO_2 emissions of Battery production will remain a major factor

- Renewable Hydrogen as part of national energy planning will significantly improve lifecycle emissions
- Production CO_2 is higher than ICE but same as BEV
- No known limitations on raw material

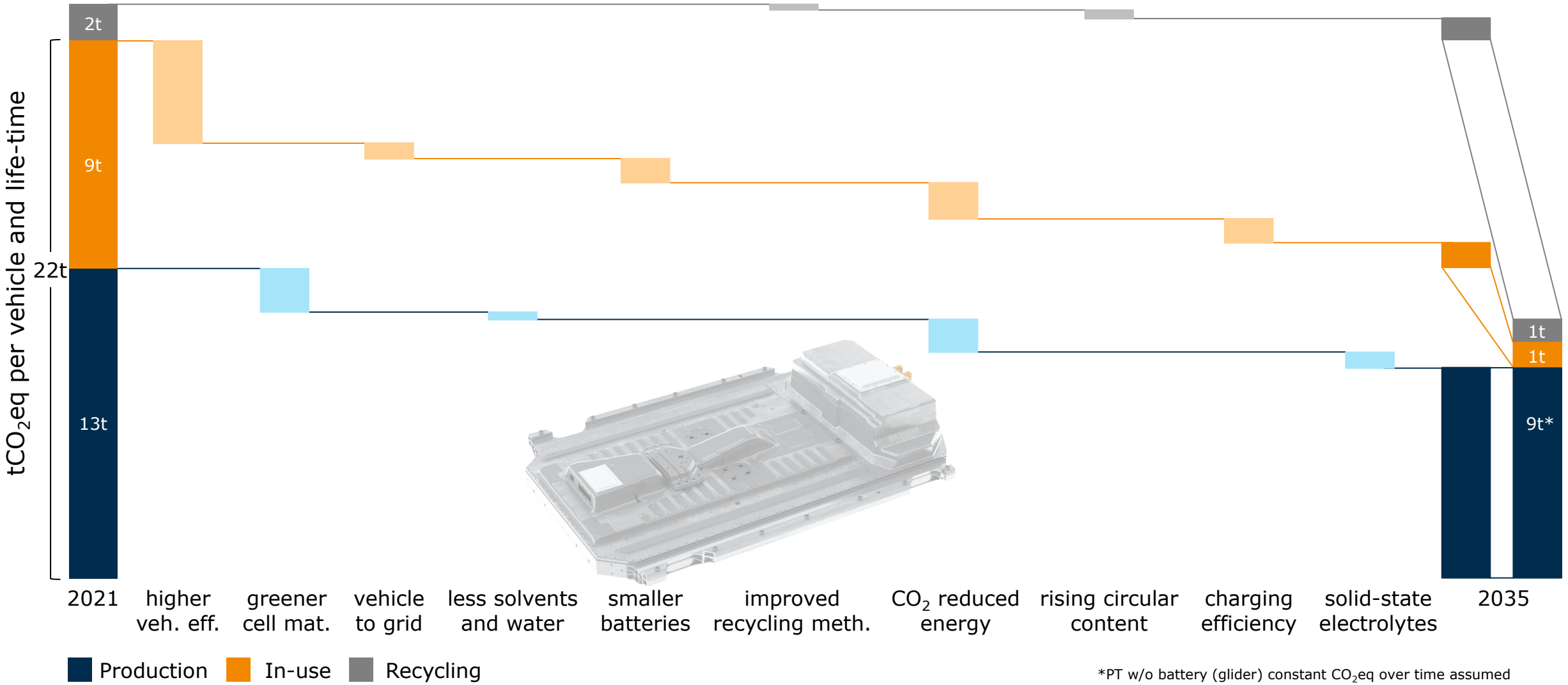
Hybrid Electric Vehicle
Propulsion 110 kW / Gasoline 85 kW / Battery 1.2 kWh / Fossil Fuel

Battery Electric Vehicle
Propulsion 150 kW / Battery 60 kWh (ca. 330 km range)
Electricity Mix
22t … EU electricity mix 2019 for constant in-use 275gCO2eq/kWh
14t … France electricity mix 2020 for constant in-use 51gCO2e/kWh
35t … Poland electricity mix 2020 for constant in-use 710gCO2e/kWh

Fuel Cell Electric Vehicle
Propulsion 110 kW /Fuel Cell 90 kW / Battery 1.6 kWh
Fossil Hydrogen from Natural Gas Reforming (Steam Methane Reforming)

Sources: AVL, EU EEA, IEA WEO 2021, Fraunhofer ISI, ifeu

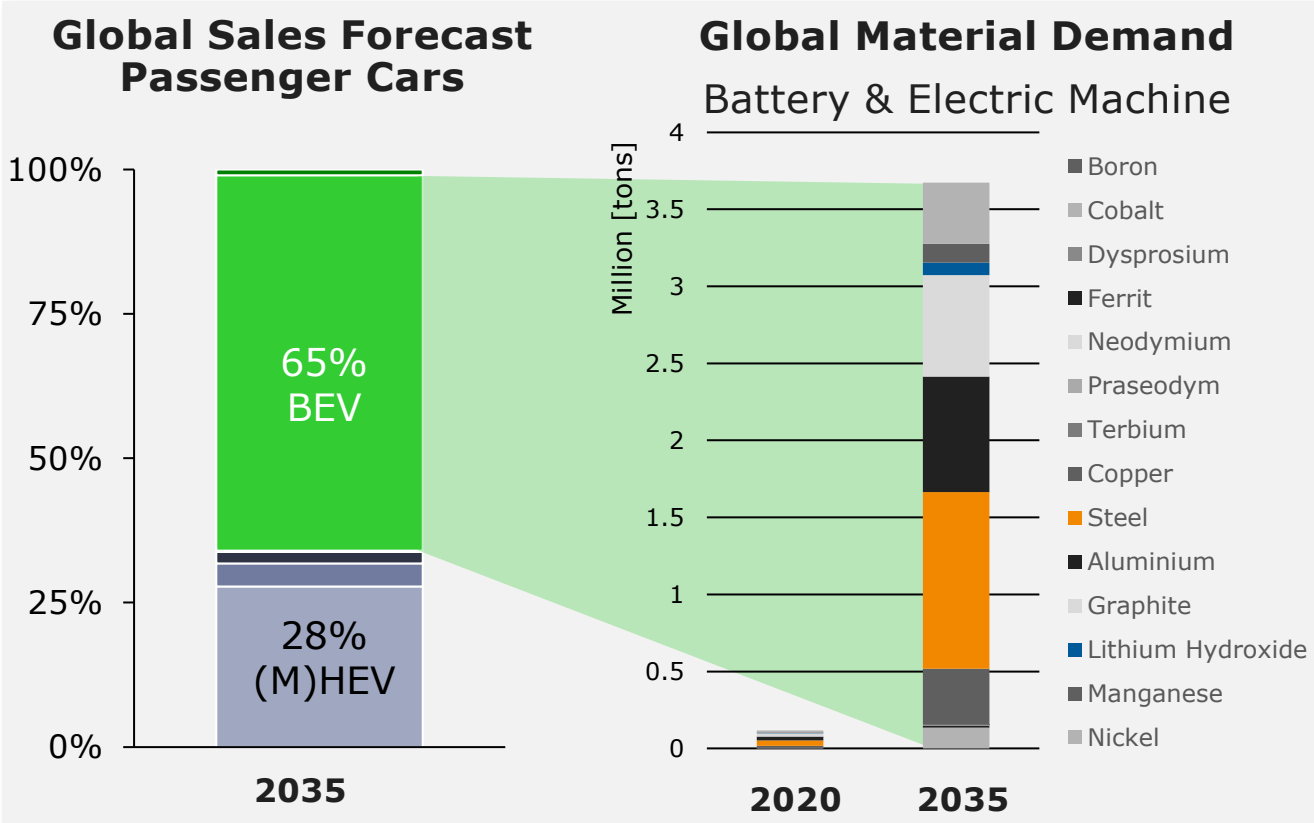
BEV CO_2 walk life-cycle – Battery improvements over time



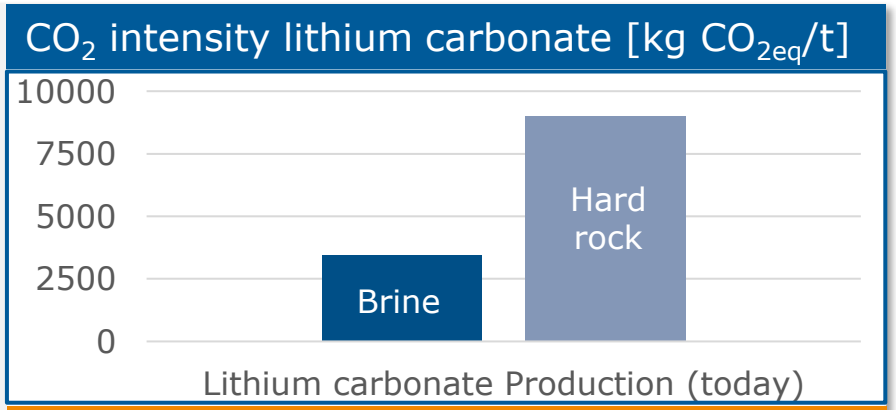
*PT w/o battery (glider) constant CO_2eq over time assumed

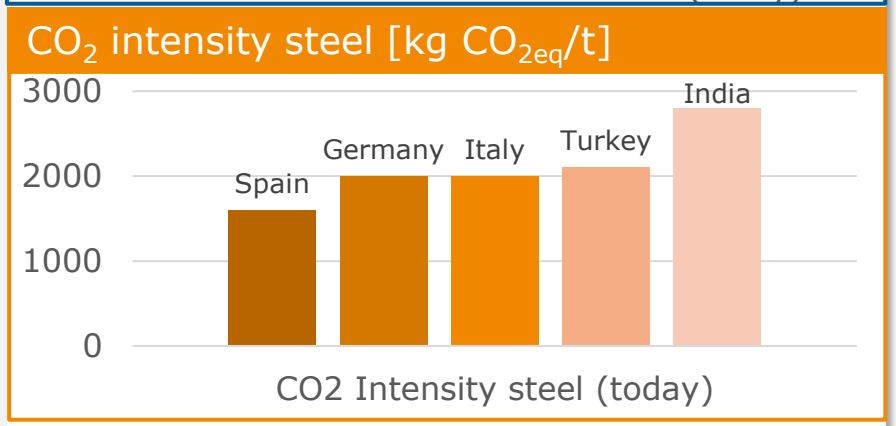
Material demand driving dependency CO_2 footprint

Global BEV passenger car fleet 2035



Sources: AVL, Net Zero Scenario, Powertrain Split (07/2021) | Material demand based on AVL Benchmark data: average of 72kWh battery (470kg), 150kW Peak E-Drive (AVL Design IPM with higher Reluctance)

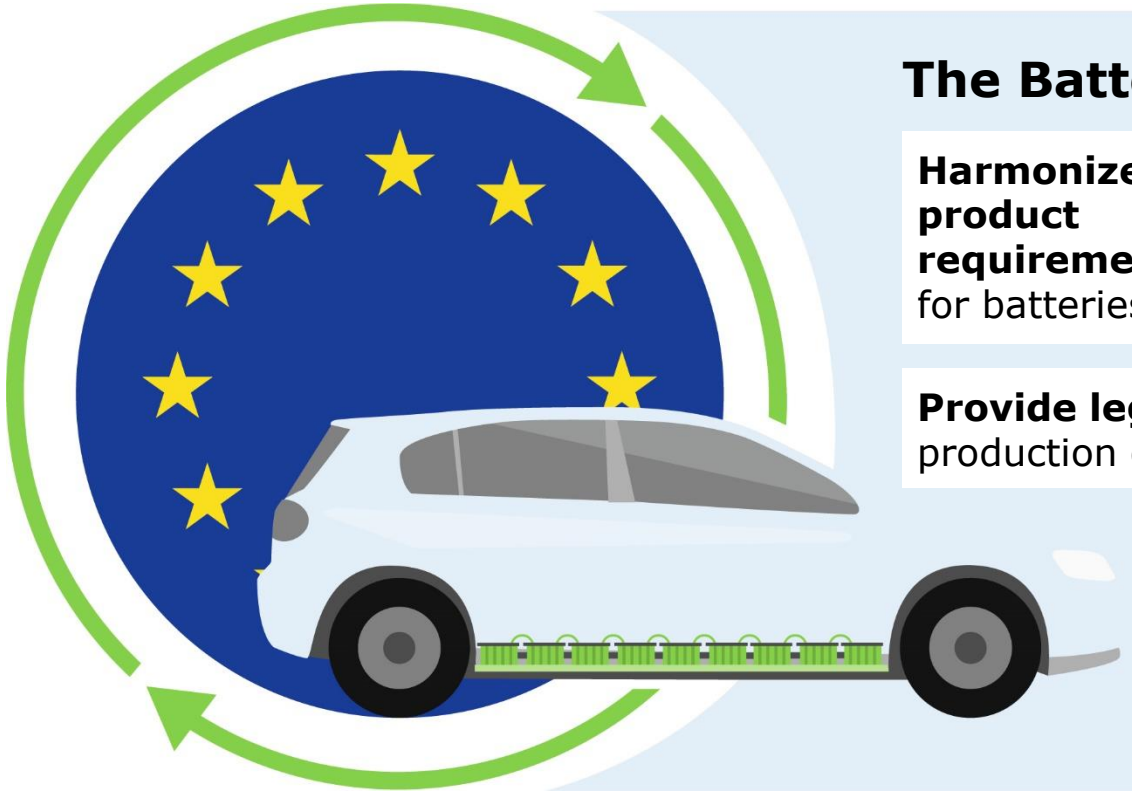




Sources:
GREET: Lithium carbonate Production in Chile (Concentrated Li Brine production as basis)
3450 kg CO2 per ton lithium carbonate |
Roskill: CO2 emissions from lithium production set to triple by 2025 - Green Car Congress Link

Access to raw materials needs to be managed. CO_2 intensity varies by material source.

EU Circular Economy Action Plan and Sustainable Batteries



The Batteries Regulation aims to:

Harmonize product requirements for batteries

Minimize environmental impact of batteries

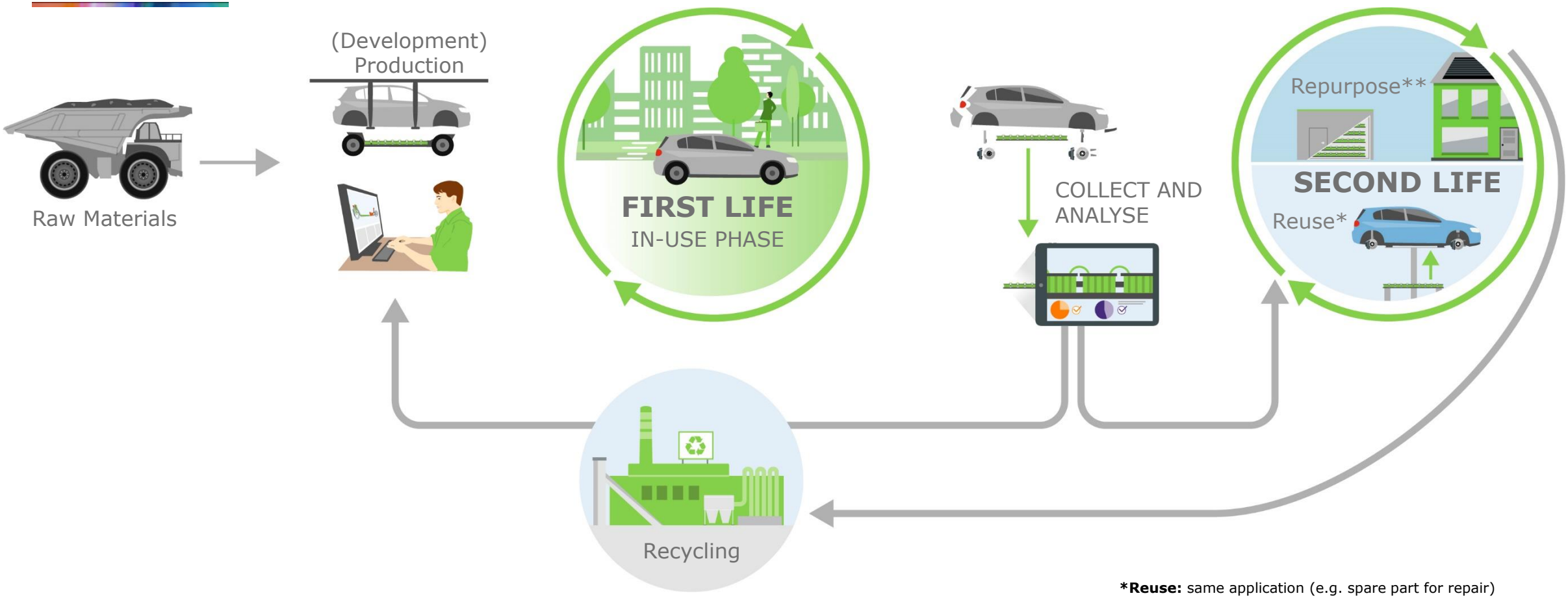
"Close the loop" by encouraging reuse and improving batteries collection and recycling of materials

Provide legal certainty to unlock investments and boost the production capacity for sustainable batteries in Europe and beyond

Proposal from 10 December 2020 | Final legislative act expected end of 2022

Source: Factsheet - Sustainable batteries in their full life-cycle, European Commission, 10.12.2020

Battery life cycle – most cost and CO_2 efficient use of batteries



***Reuse:** same application (e.g. spare part for repair)

****Repurpose:** new application (e.g. stationary storage)

Need for an objective rating of batteries in terms of recyclability and second life capability

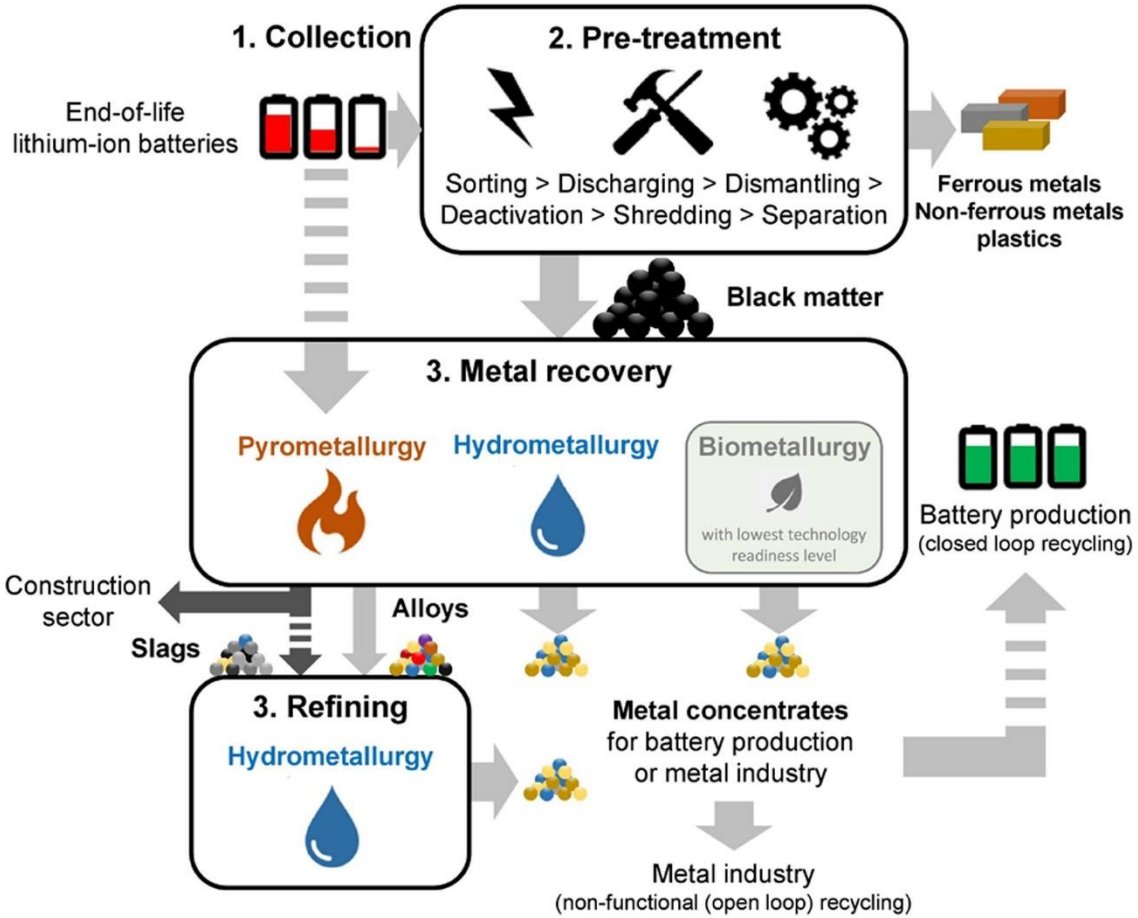
Lithium Ion Battery – Recycling Pathways

Challenges

- Continuous battery development
- Dynamic waste-stream
- Complex recycling-chains

Technologies

- Hydrometallurgy
  - ⊕ Potential recycling of all precious metals
  - ⊖ Low technology readiness level (TRL)
- Pyrometallurgy
  - ⊕ Industrialized process
  - ⊖ Lithium slagging

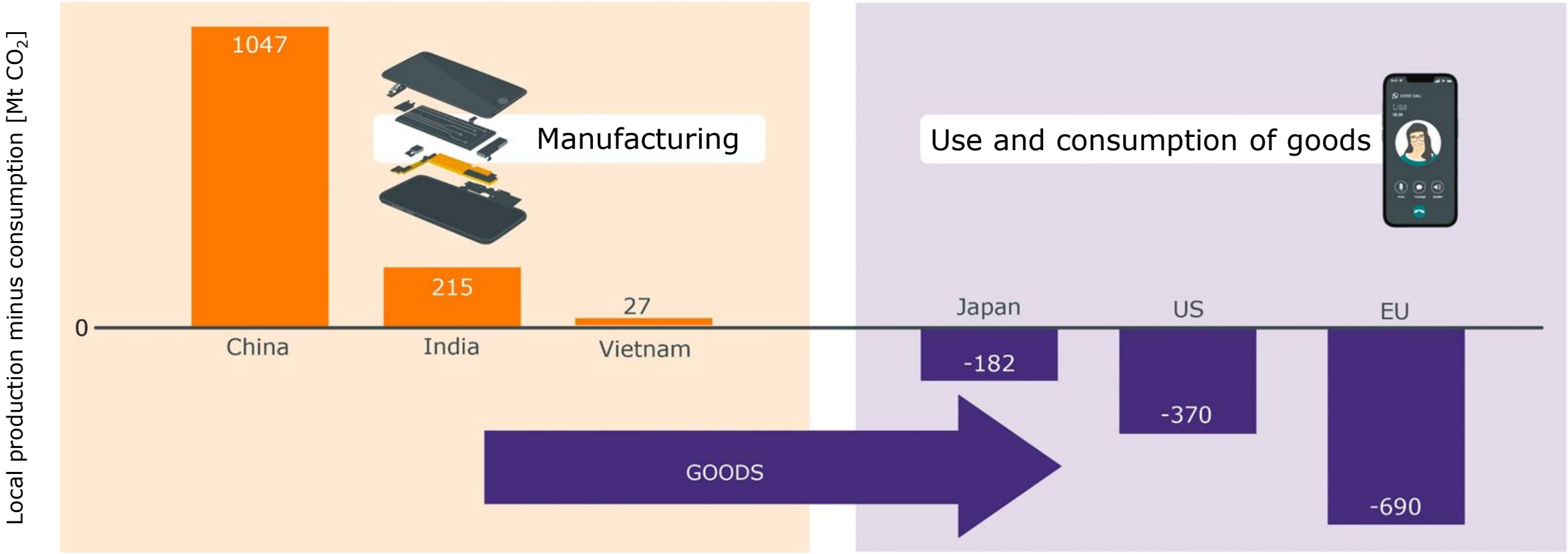


Source: Windisch-Kern et.al., 2022, Recycling chains for lithium-ion batteries, Link

The large number of battery types and their constant developments create an efficiency-challenge of the subsequent recycling processes.

Production CO_2 is allocated to producing country

Net CO_2 Balance in Mt CO_2.



CO_2 emission of consumer goods is shifted.

Sources: Global Carbon Project; S. Tinker, 2021

EU Carbon Border Adjustment Mechanism (CBAM)

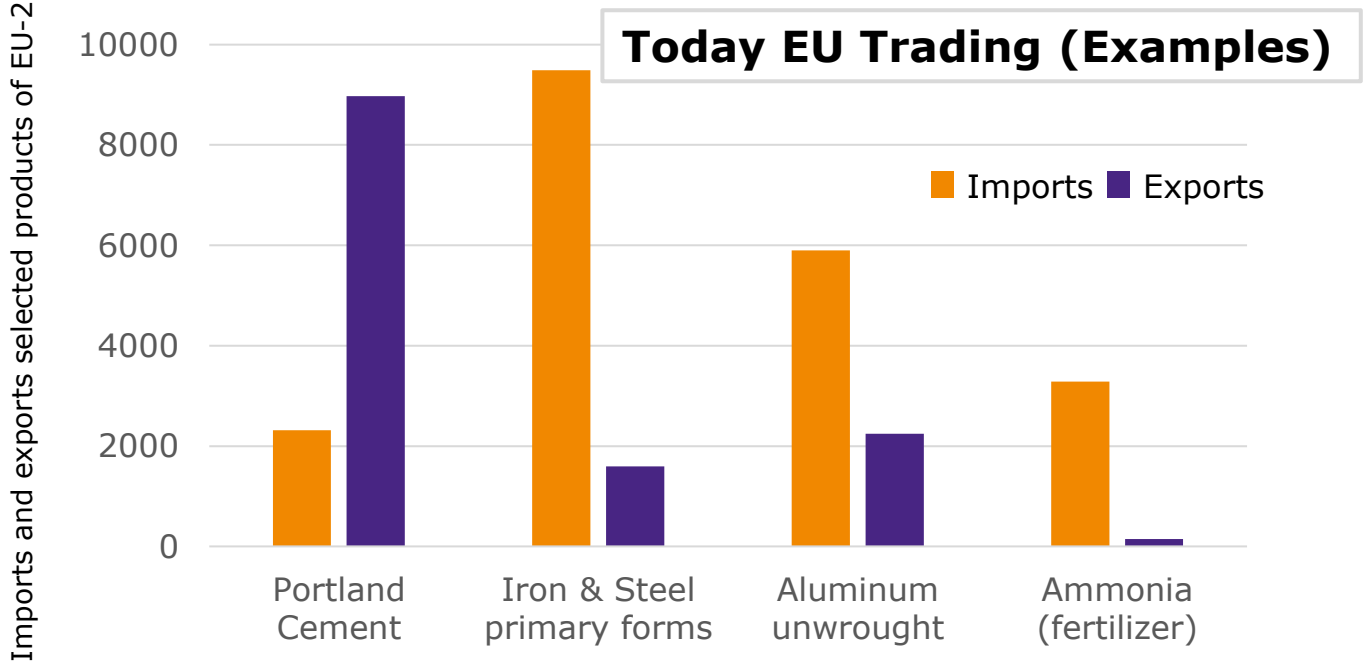
Carbon Import tax for all Carbon intense products imported into EU:

- Focus on global emissions decline
- Equalization of carbon price of domestic products
- Effective from 2026

Applicable Products

Cement | Iron & Steel | Alu-minium | Fertilizer | Electri-city

*Pricing on EU Emission Trading System allowances, today ~ 90 €/t CO_2



Source: EU green taxation, 2022, Link

Global feedback EU CO_2 tax
Conflict with international trade rules

Conflicting items:

Rule of non-discrimination

- In judging WTO members on their climate actions, the European Union will be showing a bias towards certain WTO member states.

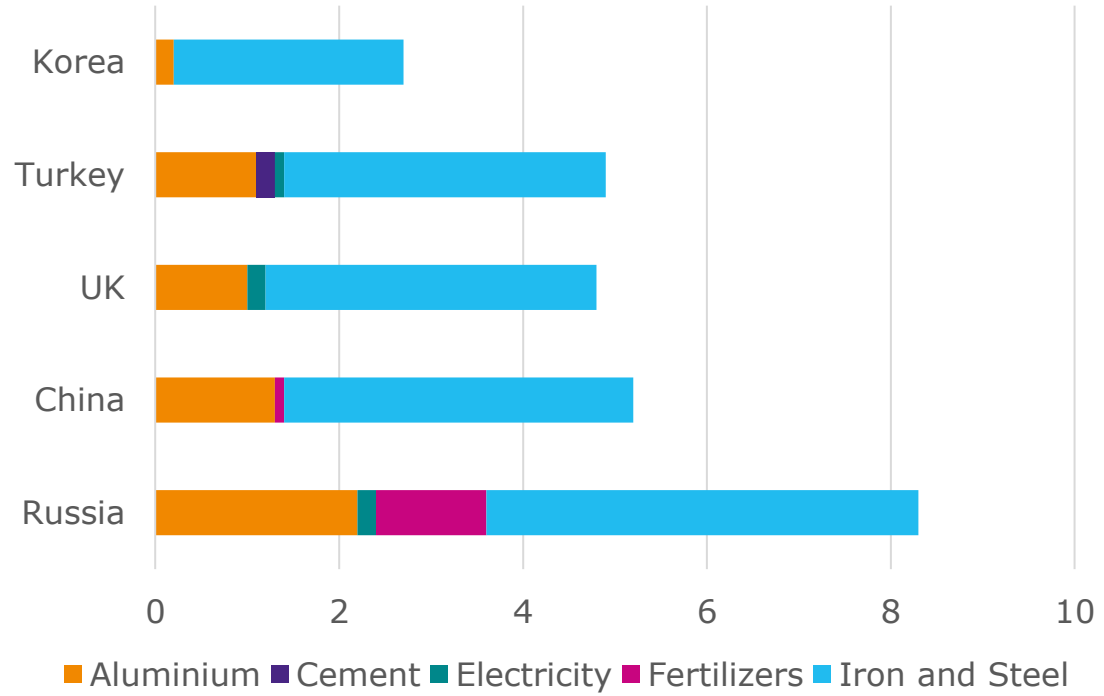
EU's WTO obligations

- CBAM on imported products could be higher than the EU's agreed customs duty.

National treatment rule

- Imported products will be denied an equal opportunity to compete competitively with domestic products within the European market

Top 5 exporters to EU27 of CBAM Goods in 2020 [billion USD]



Russia, India, Brazil, South Africa and China arguing that CBAM is introducing protectionist measures under the pretext of EU's climate policy.

Sources: weforum, Jul. 2021, Link; Rabobank, Jul.2021, Link

Source: UNCTAD (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT) based on UN COMTRADE, KNOEMA, Jul.2021, Link

Life-cycle CO_2 requirements EU regulation vs. OEMs

OEM requirements

- UN Sustainable Development Goals (SDGs)
- Science Based Target Initiative

Basic commitment to sustainability

- Reporting on product level
- Start of max. lifecycle footprint thresholds

CO_2 labeling becomes mandatory at OEMs

- Blockchain encrypted data transfer
- energy measurements converted to CO_2 data

OEM require life-cycle CO_2 data exchange

2020 **2025** **2030** **2035** **2040**

EU border tax for selected raw materials

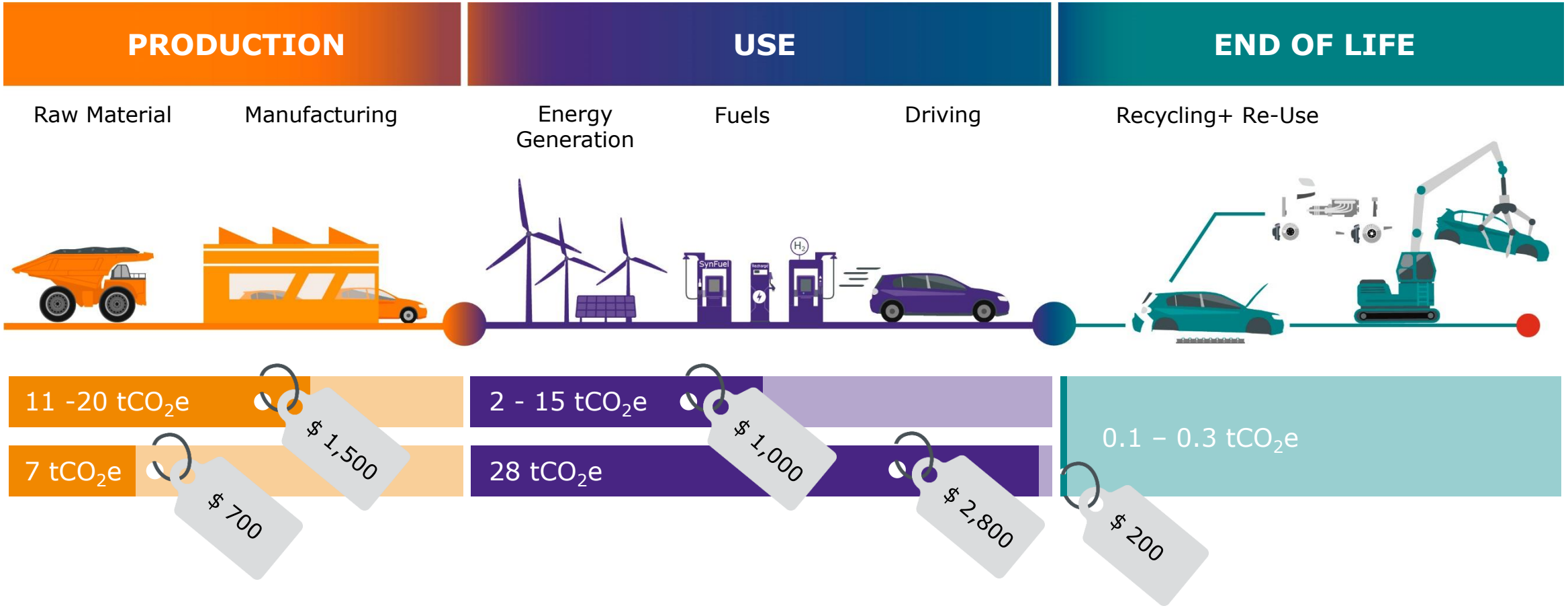
EU CO_2 labeling on product level

EU data exchange on CO_2 data in life-cycle

EU regulation

Green mobility strategy by OEMs will require CO_2 reporting on product level earlier than EU regulation.

Future Vision:
All industries pay the same price per ton CO_2



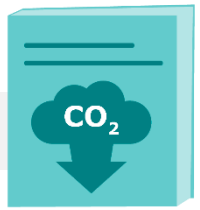
Additional CO_2 costs per phase | Assumption on future CO_2 costs: 100$ / tCO_2
no additional penalties beside CO_2 pricing considered

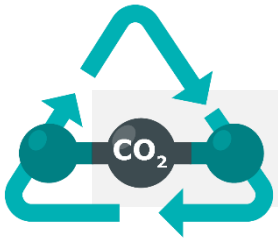
Assumptions: C-segment | HEV: Propulsion 110 kW, Gasoline 85 kW, Battery 1.2 kWh, 42 MPG, 20% CO_2 from WtT, Fossil Fuel | BEV: Propulsion 150 kW, Battery 60 kWh (205 mi. range) | lifetime 110,000 mi.
Electricity mix for production & in-use phase ranges from 105 gCO_2e (France) to 980 gCO_2e (Poland)

Conclusion

Global regulation on CO_2 taxation needed to avoid "CO_2 tourism"

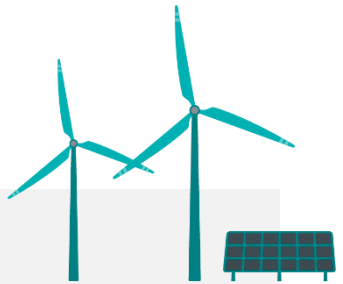
Automotive OEMs will demand product CO_2 reporting ahead of regulation





Life-cycle CO_2 shows large reduction potentials in all steps and powertrain technologies

Global energy situation might slow down pace towards renewables



Thank you

www.avl.com