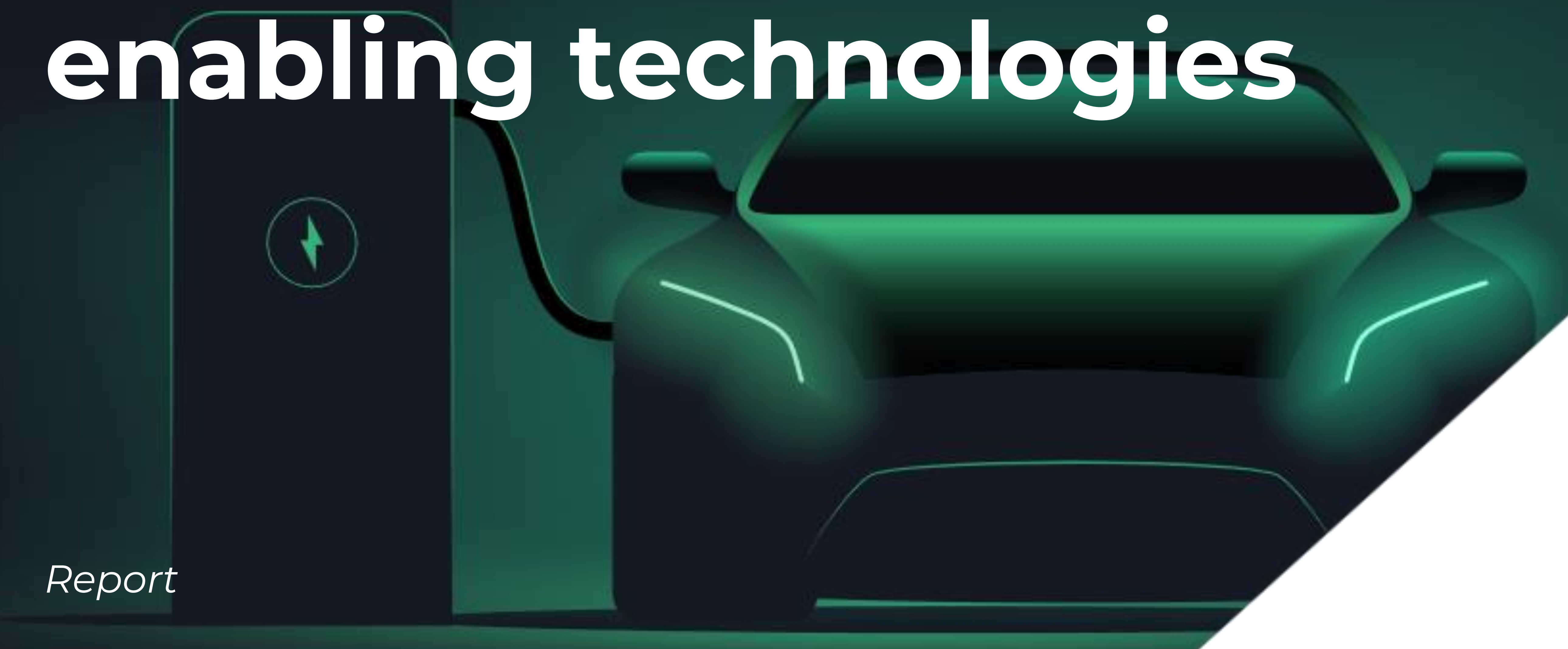
Electric vehicle battery recycling @2050: evolutionary scenarios and enabling technologies



Internal use

Report

March 2023

MOTUS-E
strategy&
Part of the PwC network
POLITECNICO MILANO 1863

www.motus-e.org

Objectives of the report

The report presents a 2050 perspective of battery recycling of electric vehicles in Europe and Italy

Present a scenario to 2050 of the electric vehicle battery recycling market in Europe and Italy in terms of size, required investments, market value, business models and available technologies, while offering a common reference context for all industry operators and policymakers

Sections and areas of analysis of the report

1 Estimated recycling market and investment needs (Europe and Italy)

- Evolution of electric vehicle sales and their battery specifications
- Volumes of batteries for recycling and second-life use
- Investment needed to capture expected recycling volumes
- Materials recovered as an output of recycling processes
- Market value of battery recycling in terms of revenues and margins associated with the sale of the secondary raw material

2 Considerations on business models

- Operational and economic flows along the electric vehicle battery value chain
- Current role and evolutionary scenarios of the different operators involved along the value chain
- Critical factors for successful business models for end-of-life electric vehicle battery management, possible strategies and key market evidence

3 Technological view

- Established and developing recycling processes and technologies
- Technical difficulties along the value chain and potential solutions
- Main industry drivers and expected technology trends for future battery generations and potential impact on recycling processes

Executive Summary (1/3)

Estimation of the recycling market and necessary investments

1

Estimation of the recycling market and necessary investments

- The introduction of lithium-ion batteries on the market is driven by the **sale of electric vehicles**, expected to **grow sharply in the coming years** (CAGR 2020-2030 +23% in Europe and +32% in Italy), also stimulated by regulatory developments at European level
- At the end of a battery's first life cycle, "**second life**" solutions can be developed through **reuse and reconditioning** strategies that **extend its use by ~10 years**
  - To date, carmakers and other supply chain operators in Europe are experimenting with **stationary applications** with end-of-life batteries
  - The "second-life" battery **capacity proposal** is expected to increase and will reach **~647 GWh in Europe** by 2050, of which **~77 GWh will be in Italy**, also supported by the increase in devices for proper diagnosis of the health status of used batteries as well as the increasing energy density of registered batteries
- **Recycling volumes**, consisting of damaged end-of-life batteries, "second-life" batteries and production waste, will reach **~3.4 million tonnes in Europe** by 2050, of which **~0.4 million tonnes in Italy**
- To date, in Europe, the first generations of used batteries are treated in plants designed for different batteries (e.g. lead-acid), with a total capacity of ~80 ktonne/year, while in Italy there are no plants suitable for recycling electric vehicle batteries; to intercept all the volumes generated in Europe, **investments of ~€2.6 billion** will be required, **of which ~€0.3 million will be for the Italian market**
- A typical **hydrometallurgical recycling process recovers ~60% of input materials** through the disassembly, pre-treatment and treatment stages, so that by 2050 it will be possible to recover up to **~2.1 million tonnes of materials in Europe, of which ~0.2 million tonnes will be in Italy**
- **Nickel, cobalt and lithium**, which are contained in the cathode within the cell, account for **~13% of the recycled volumes** and may allow **margins** to be generated through sales for new production processes; referring to the *economics* of running a recycling plant:
  - **The operating** and **amortisation** costs for nickel, cobalt and lithium processing by 2050 will be **~€2.9 billion in Europe, of which ~€0.3 billion will be in Italy**
  - The achievement of the **new European targets on the minimum recycled content** in batteries for electric vehicles as of 2030 has a strong impact on the **selling price** of recycled material, which has been estimated by applying a price discount on virgin material based on a demand-supply analysis to meet the targets; the proposed investments will allow all ambitious targets to be reached by 2040
  - **Revenues generated from the sale** of recycled nickel, cobalt and lithium will amount to **€4.1 - 6.1 billion in Europe, of which €0.4 - 0.6 billion will be in Italy**, with a **margin of €1.2 - 3.2 billion in Europe, of which €0.1 - 0.3 billion in Italy**

Executive Summary (2/3)

Considerations on business models

2 **Considerations on business models**

- The **value chain of** batteries for electric vehicles is structured in **two macro-phases**: (i) **production and use** and (ii) **end-of-life management**, which includes the stages of collection, transport, possible second-life usage and battery recycling and ends with the sale of recycled material
- The **operational and economic flows** for end-of-life management are **organised by Extended Producer Responsibility (EPR) systems**:
  - **Today**, EPR systems **bear a cost for each end-of-life phase**, including recycling, for which they make a payment to recycling companies
  - In the **future**, the achievement of adequate scale and cost optimisation could allow for a **reversal of the economic flow**, i.e. the recognition of a payment to EPR systems, as is already the case in other more developed supply chains (e.g. lead batteries)
- The opportunities arising from the management of end-of-life batteries are already starting to incentivise **traditional operators** in the value chain to **extend their expertise** into adjacent roles and in particular:
  - **Battery manufacturers** complement **recycling activities** by developing plant capacity to also process their own production waste
  - **Electric vehicle manufacturers** investigate **"second life" opportunities** for batteries to utilise their remaining capacity
  - Manufacturers' **access to end-of-life batteries** is also supported by **innovation in electric vehicle sales models**, so that battery **ownership** remains with the manufacturers themselves and **collection points** are more concentrated on the territory
- The **success of business models** for managing the end-of-life of batteries depends on **6 critical factors** that affect the entire value chain:

1. **Evolution and adaptation of regulations**, currently being developed at European level, to provide incentives for appropriate end-of-life management
2. **Appropriate scale for economic sustainability**, to justify the investment in recycling infrastructure
3. **Optimisation of logistics**, whose costs are influenced by the classification of used batteries, distribution of collection points and infrastructure capacity in the area
4. **Technological efficiency of recycling**, assessed by level of technological sophistication, material recovery capacity and associated operating costs
5. **Demand for recycled material**, supported by the new European targets, the risk of which can be reduced by diversifying the outlet markets
6. **Stability in the supply of raw materials**, through the development of a local recycled material supply chain to mitigate the sources of instability affecting the supply chain of virgin materials for EV batteries, which is characterised by poor availability and accessibility

Executive Summary (3/3)

Technological view

3 **View technology**

- The **recycling process** for electric vehicle batteries is structured in **4 main steps**:
  1. **Pre-selection and discharge**, functional for isolating the battery from the vehicle and securing it by removing residual energy
  2. **Disassembly**, which frees the modules and cells that make up the battery from the superstructure that encases them, and allows the other components of the battery system to be allocated to dedicated recovery chains
  3. **Pre-treatment** (mechanical/thermal/chemical or a combination of these), with the aim of releasing and pre-concentrating the target metals in a mix of anodic and cathodic powders named "*black mass*".
  4. **Treatment**, which allows the recovery of chemical compounds containing the target metals, via:
     - **Pyrometallurgical processes for the extraction of metals**, which stimulate chemical and physical reactions through high temperatures and enable the recovery of cobalt, copper and nickel
     - **Hydrometallurgical processes for the extraction of metals**, using organic acids, inorganic acids, ammonia or microorganisms to recover lithium, cobalt and nickel at high rates
     - **Processes for the regeneration of anode and cathode** ("*direct recycling*"), which avoid the transition from chemical precursors
- **4 technological trends** could affect new generations of batteries with potential impacts on the configuration of recycling processes:
  1. **The circulation of prismatic cells** and **battery designs** characterised by modular solutions and standardised joints will facilitate the automation of disassembly processes
  2. **The evolution of the cathode** towards a **gradual reduction of cobalt** in favour of nickel or low grade materials such as sulphur and oxygen will support the use of hydrometallurgical or *direct recycling* treatments as opposed to pyrometallurgical treatments, which are mainly based on cobalt recovery
  3. **Replacing graphite within the anode** with materials such as **graphite-silicon composite, silicon or lithium metal** will not have any particular impact on recycling processes, minus the adaptation in the pre-treatment phase to ensure that the active material is inert when using lithium metal
  4. **The transition of the electrolyte from a liquid to a solid state** (ceramic or polymer) will not have a significant impact on recycling processes, but the use of ceramic material may contaminate the *black mass* by reducing the concentration of target metals

Agenda

Estimation of the recycling market and necessary investment

- Europe
- Italy

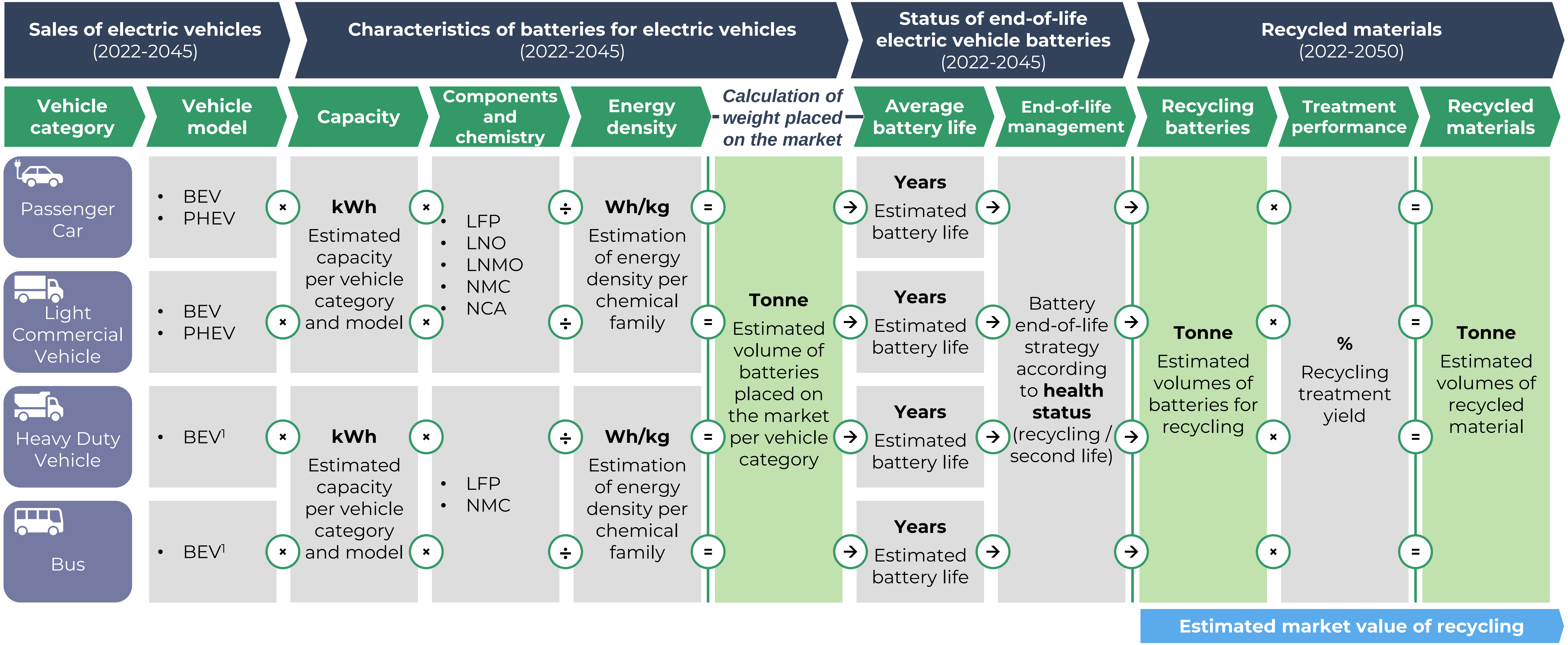
Considerations on business models

Technological view

Agenda

Model for estimating volumes of recycled material

The model estimates the volumes of recycled material from end-of-life electric vehicle batteries



Sales of electric vehicles (2022-2045)			**Characteristics of batteries for electric vehicles** (2022-2045)								**Status of end-of-life electric vehicle batteries** (2022-2045)				**Recycled materials** (2022-2050)				
Vehicle category	**Vehicle model**		**Capacity**		**Components and chemistry**		**Energy density**		***Calculation of weight placed on the market***		**Average battery life**		**End-of-life management**		**Recycling batteries**		**Treatment performance**		**Recycled materials**
Passenger Car	BEV PHEV	×	**kWh** Estimated capacity per vehicle category and model	×	LFP LNO LNMO NMC NCA	÷	**Wh/kg** Estimation of energy density per chemical family	=	**Tonne** Estimated volume of batteries placed on the market per vehicle category	→	**Years** Estimated battery life	→	Battery end-of-life strategy according to **health status** (recycling / second life)	→	**Tonne** Estimated volumes of batteries for recycling	×	**%** Recycling treatment yield	=	**Tonne** Estimated volumes of recycled material
Light Commercial Vehicle	BEV PHEV	×		×		÷		=		→	**Years** Estimated battery life	→		→		×		=	
Heavy Duty Vehicle	BEV[1]	×	**kWh** Estimated capacity per vehicle category and model	×	LFP NMC	÷	**Wh/kg** Estimation of energy density per chemical family	=		→	**Years** Estimated battery life	→		→		×		=	
Bus	BEV[1]	×		×		÷		=		→	**Years** Estimated battery life	→		→		×		=	

Estimated market value of recycling

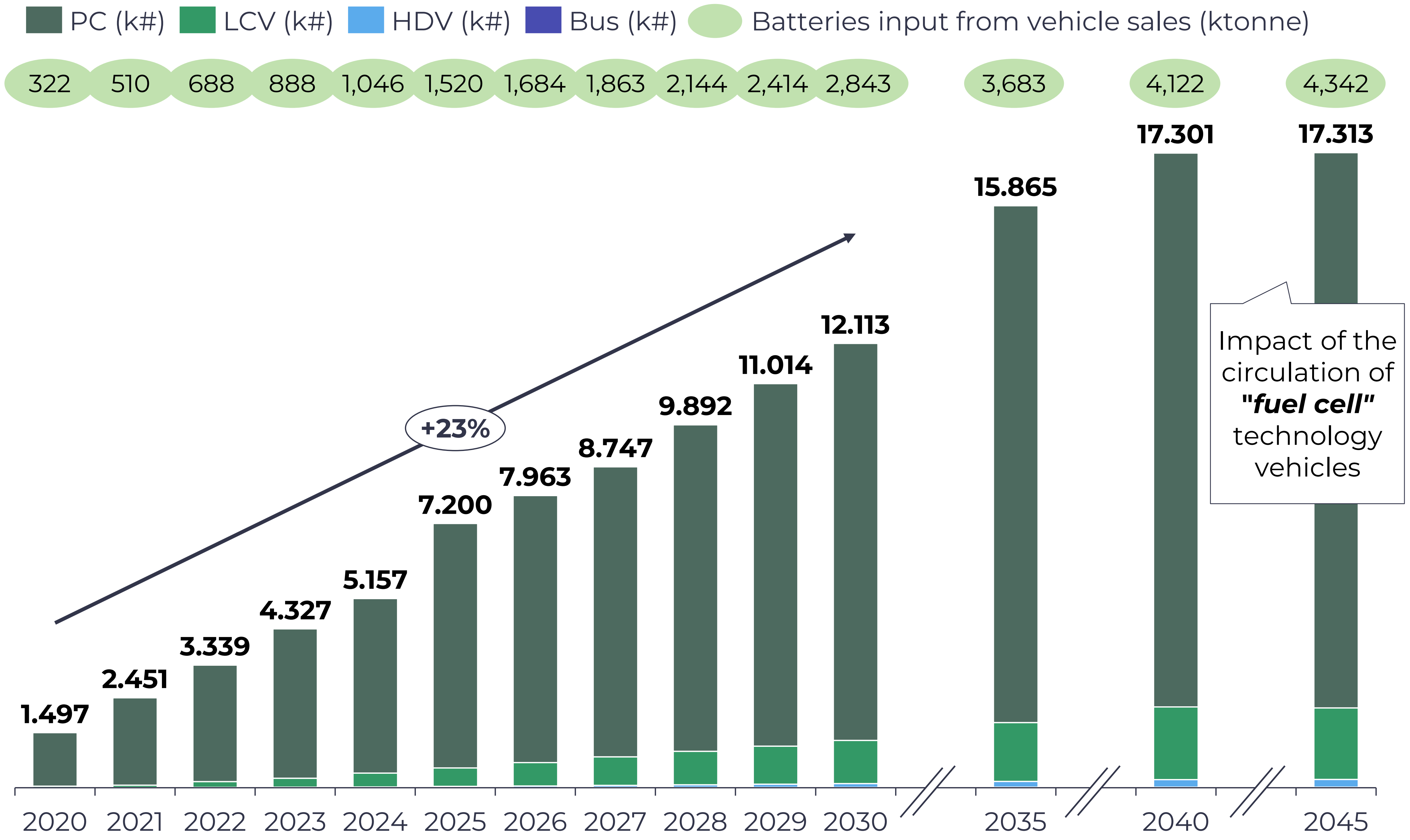
▨ Input 🟩 Output

Notes: 1) The scenario considered includes only Heavy Duty Vehicles and Buses with BEV technologies
Source: PwC Strategy&

Evolution of electric vehicle sales in Europe

Sales of electric vehicles in Europe are expected to grow rapidly (CAGR 2020-2030 +23%)

Annual sales of electric vehicles in Europe (k#, ktonne)



Impact of the circulation of ***"fuel cell"*** technology vehicles

Hypotheses and considerations

The market introduction of lithium-ion **batteries** is driven by the sale of **electric vehicles**, which is expected to grow strongly in the coming years

The circulation of electric vehicles is **stimulated** by **regulatory developments** at European level. In particular, the new ***"Fit for 55"*** climate package envisages a 55% reduction in greenhouse gas emissions by 2030, and sets the goal of producing only **zero-emission** cars and light commercial vehicles from **2035**

The **growth in the volume** of batteries placed on the market in terms of **weight** (tonnes) is driven by the progressive circulation of **large electric vehicle categories**, whose high capacity impacts their weight

Post 2040, development of the technology of **hydrogen combustion cells** ("*fuel cell technology*") **will stabilise sales levels** of electric vehicles with **lithium-ion** for all categories

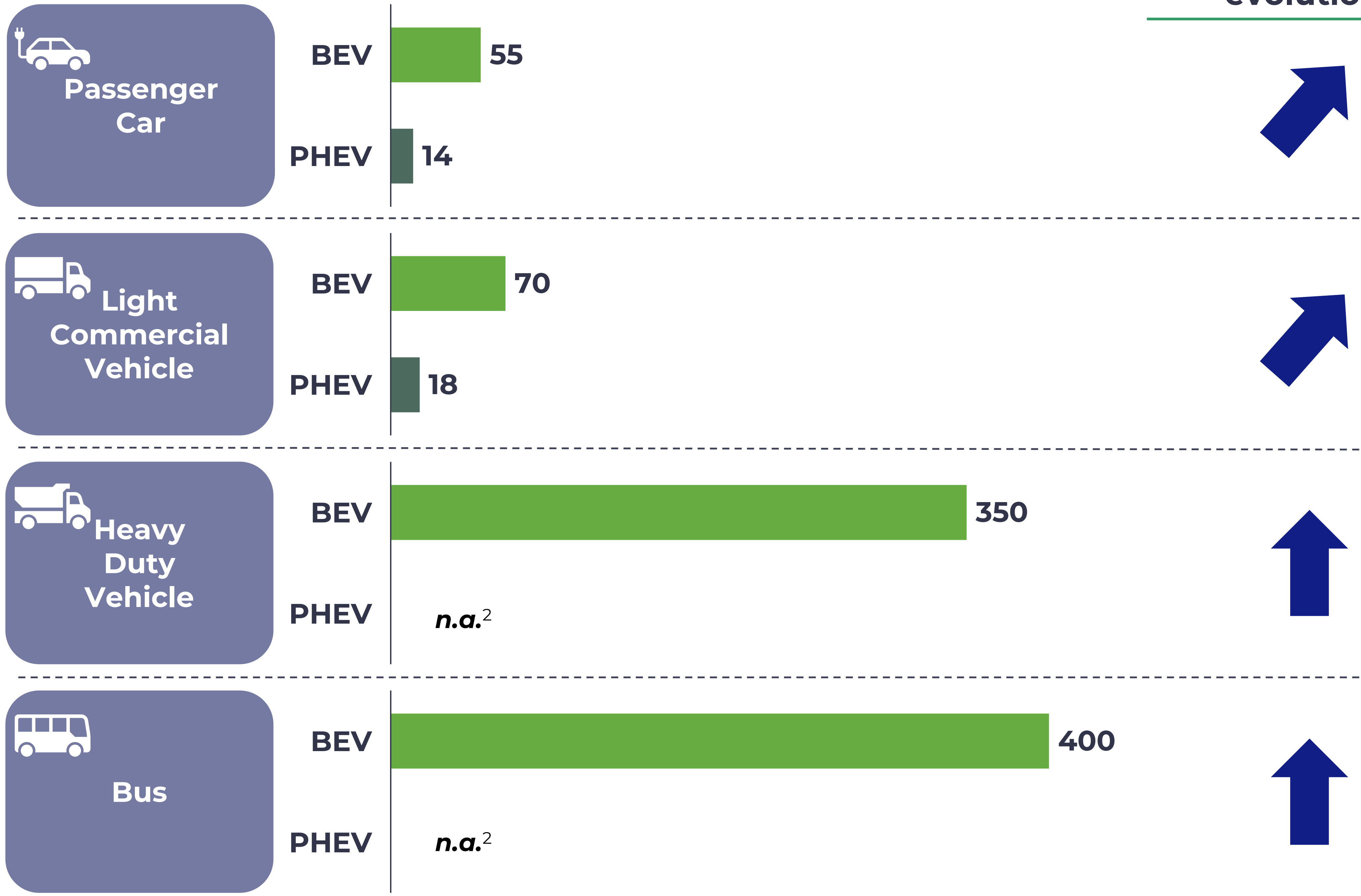
Source: BloombergNEF, Motus-E, PwC Strategy&

Vehicle battery capacities per model

Capacity is diversified by vehicle category and model, with specific evolution drivers

Average capacity per vehicle category and model (2021, kWh)

Expected evolution[1]



Drivers of evolution

Consumer demand for **greater vehicle autonomy** to maintain driving habits similar to those achieved with **conventional vehicles**

More **scope for improvement** expected **given the early stage** of technology development for large vehicles

Mitigating factors

Expected **improvement** in battery range **performance** due to increased **efficiency** (km/kWh)

Increased possibility and frequency of battery charging thanks to the development of charging infrastructures across the country

Notes: 1) Period 2022 - 2050; 2) The scenario considered includes only Heavy Duty Vehicles and Buses with BEV technologies
Source: Politecnico di Milano, Cobat, Global EV Outlook, PwC Strategy&

⬆ Growth ⬇ Degrowth ➡ Building

Battery components and materials

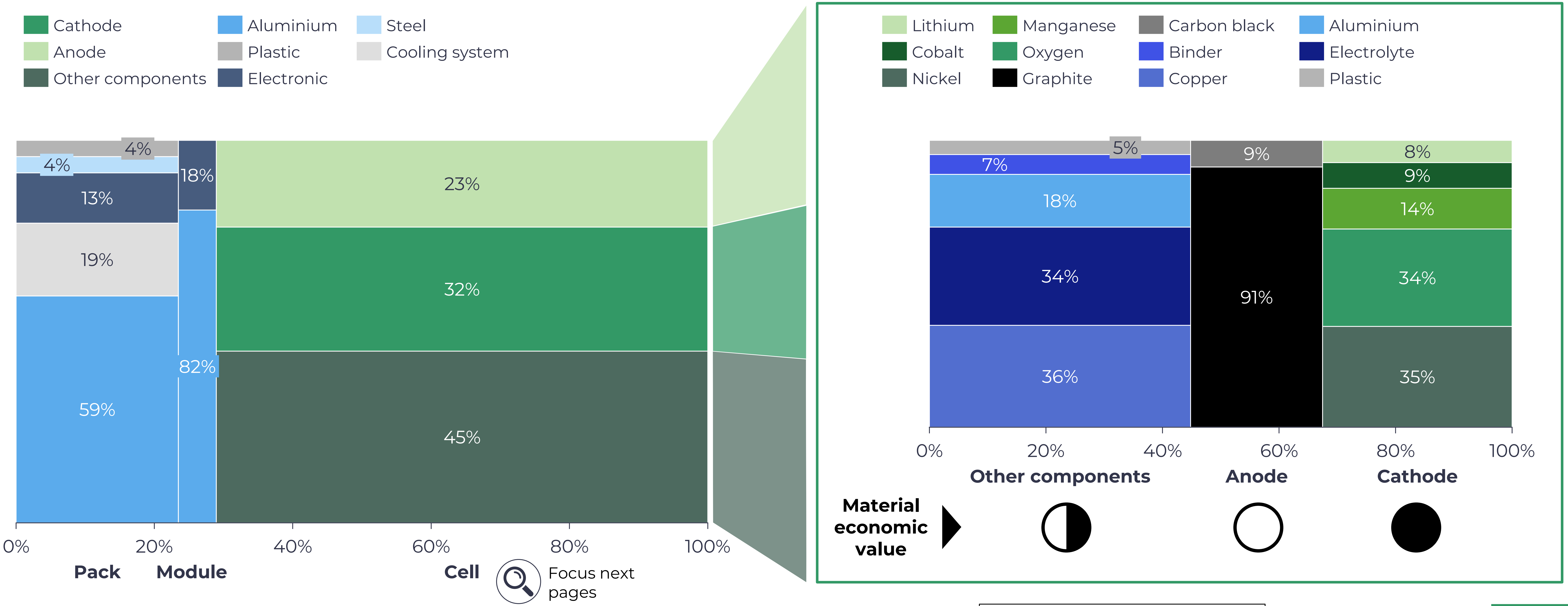
Inside the cell, the cathode contains the battery's most valuable materials

Figure[1]

The weight of materials and components varies according to vehicle category, model and chemical composition

Battery components (% of battery weight)

Focus: cell materials (% of cell weight)



○ Low value ● High value

Notes: 1) Selected example: PC category, BEV model, NMC chemistry
Source: Argonne National Laboratory, PwC Strategy&

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Chemical composition of cells

The 5 families of chemical compositions have different applications per vehicle category

Families of chemical compositions

① **LFP**
(Iron phosphate and lithium)

② **LNMO**
(Lithium nickel manganese oxide)

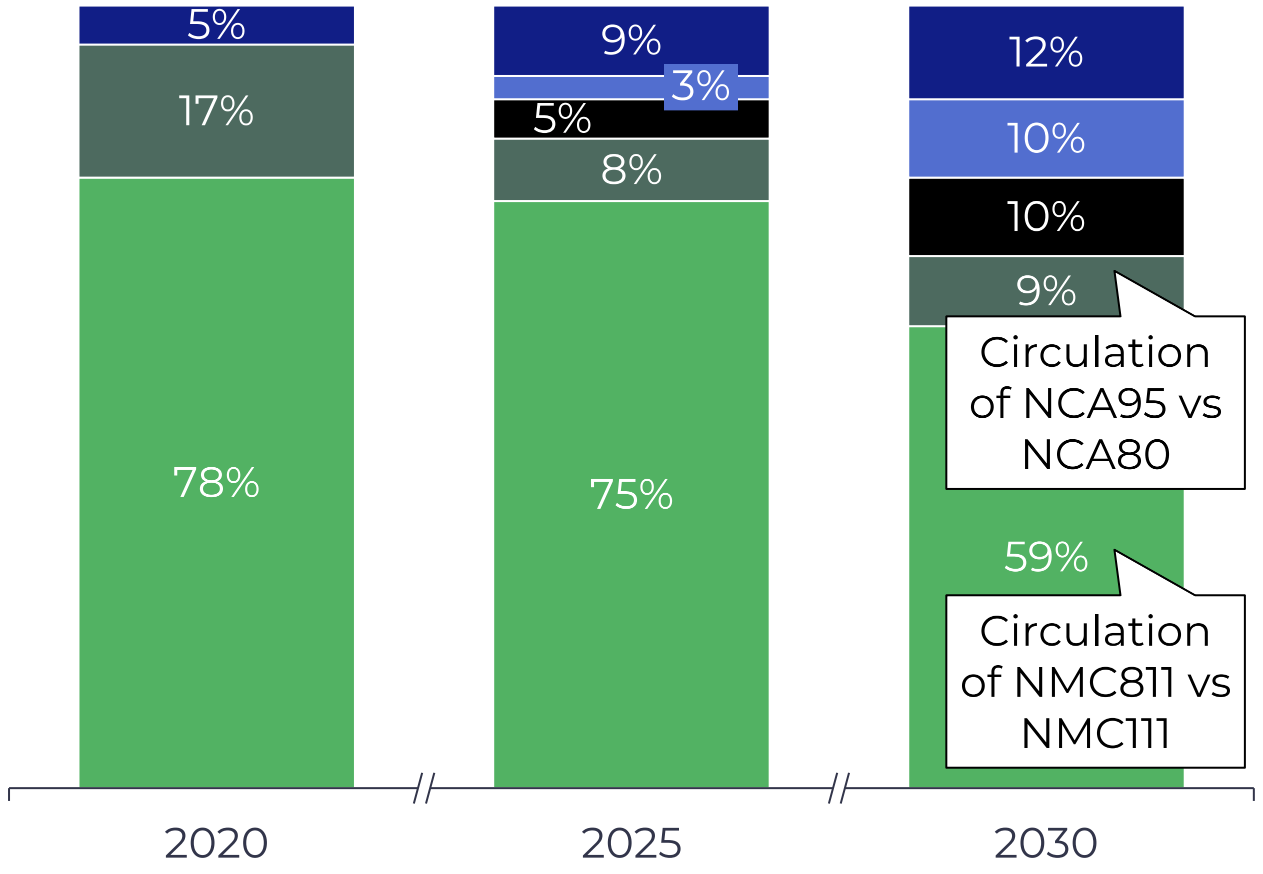
③ **LNO**
(Lithium nickel oxide)

④ **NCA**
(Lithium oxide, nickel, cobalt and aluminium)

⑤ **NMC**
(Lithium oxide, nickel, manganese and cobalt)

Passenger Car and Light Commercial Vehicle

- The PC and LCV categories are subject to a **high variety of chemical families** used
- The trend to 2030 is characterised by a gradual **reduction of cobalt**, a **high-cost** material characterised by **critical supply** issues, which manifests itself both between and within families (NCA and NMC)

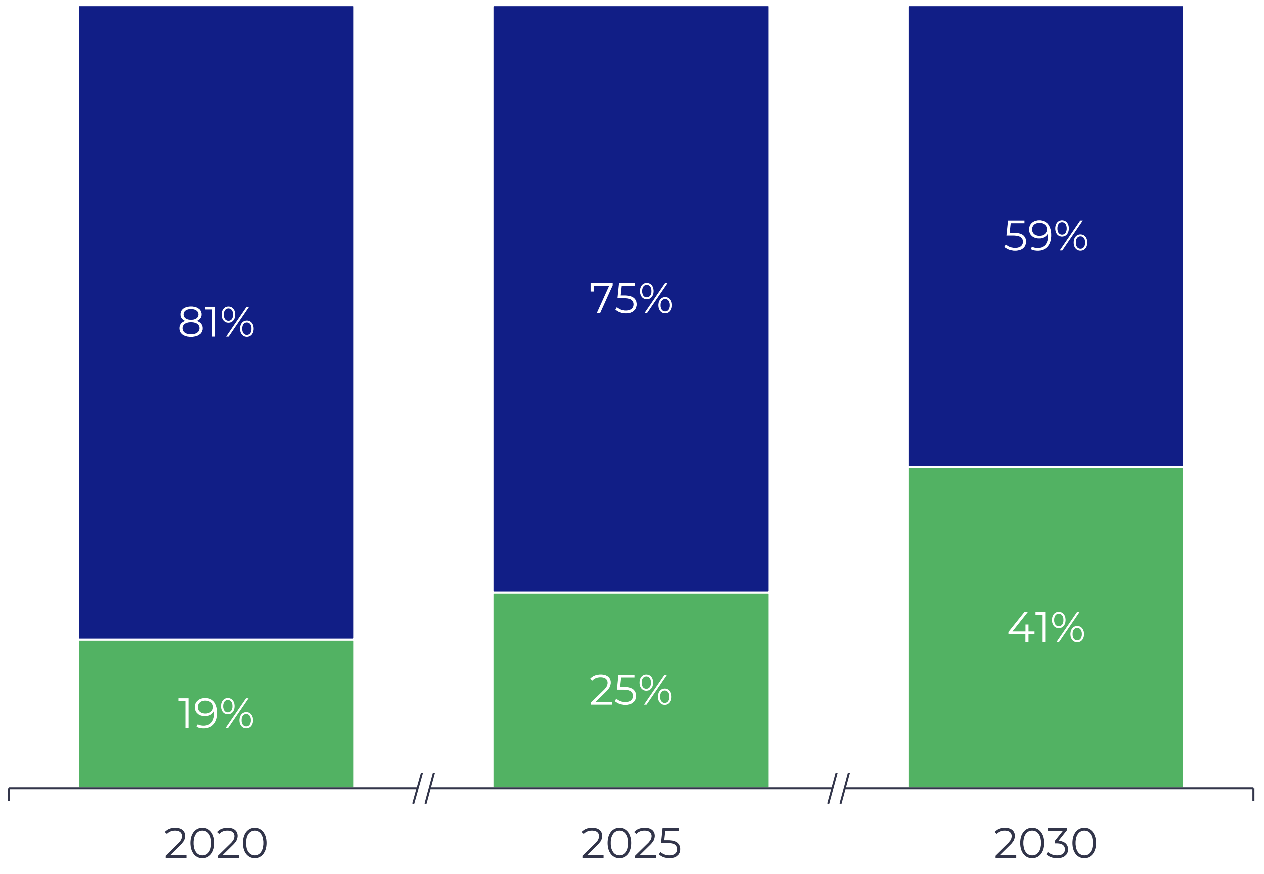


Circulation of NCA95 vs NCA80

Circulation of NMC811 vs NMC111

Heavy Duty Vehicle and Bus

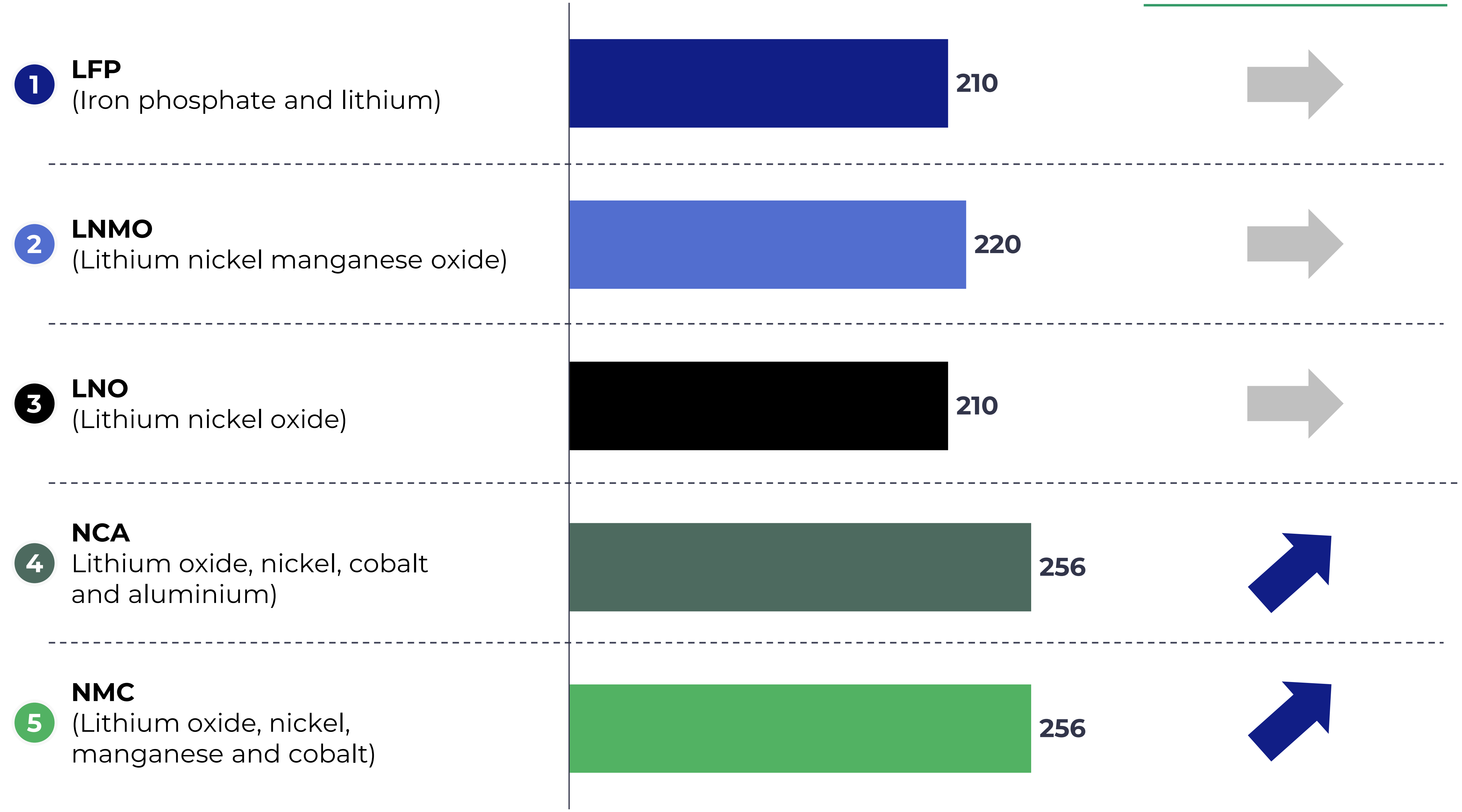
- The HDV and Bus categories use **two main chemical families** (LFP and NMC)
- The adoption of **LFP will remain prominent** due to:
  - **Thermal and chemical stability** maintained in the event of short circuit / overload
  - **Limited need** for **energy-dense** chemicals for large vehicles



Source: Bloomberg NEF, Cobat, PwC Strategy&

Energy density of the cells

Cell energy density and its evolution depend on chemical composition



Energy density by chemical composition (2021, Wh/kg)		Expected evolution[1]
① **LFP** (Iron phosphate and lithium)	210	➡
② **LNMO** (Lithium nickel manganese oxide)	220	➡
③ **LNO** (Lithium nickel oxide)	210	➡
④ **NCA** Lithium oxide, nickel, cobalt and aluminium)	256	↗
⑤ **NMC** (Lithium oxide, nickel, manganese and cobalt)	256	↗

Drivers of evolution

No innovation expected for the chemical composition of the **LFP, LMNO and LNO** families

Change in chemical composition characterised by an **increase in the use of Nickel** in future generations at the expense of Cobalt

⬆ Growth ⬇ Degrowth ➡ Building

Notes: 1) Period 2022 - 2050
Source: Argonne National laboratory, Politecnico di Milano, Cobat, PwC Strategy&

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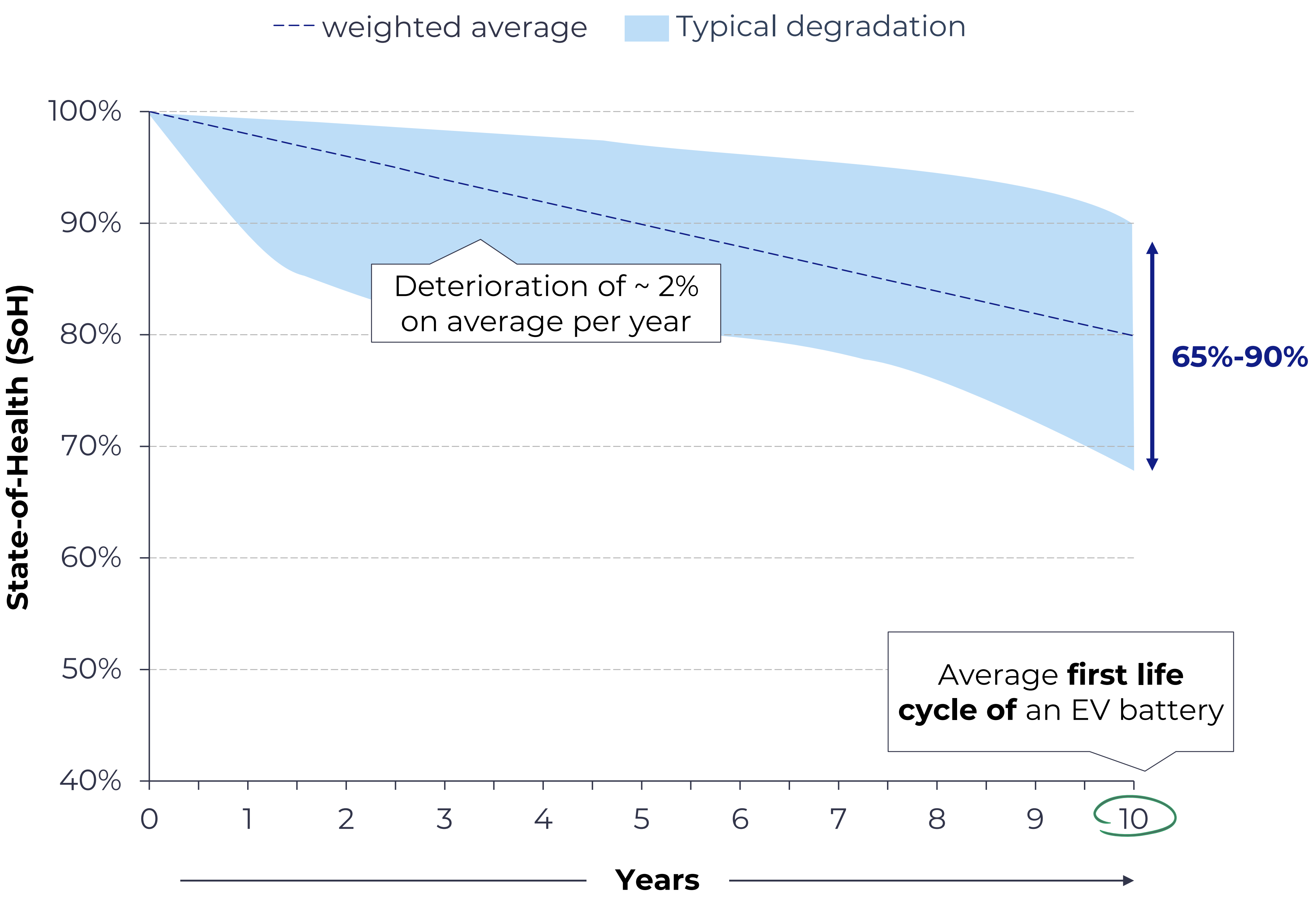
The *State-of-Health (SoH)* associated with batteries

The level of performance guaranteed by the batteries deteriorates over time and is measured by the SoH[1]

Evolution of SoH[1] in the first battery life cycle



Deterioration of ~ 2% on average per year

Average **first life cycle of** an EV battery

Main factors impacting SoH[1]

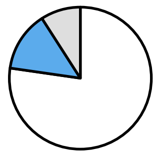
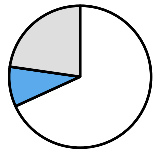
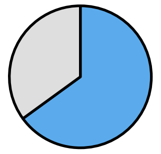
Habits of charge	Regular battery charging **above 80% charge** causes wear and tear battery advance
Recharging fast	**Prolonged use of fast charging** causes a state of stress that can lead to premature cell failure
Depth of discharge	Reaching a **charge level below 20%** damages the cells
Mileage	A high **number of charging cycles** accelerates battery degradation mechanisms
Extreme temperatures	Exposure **to extreme temperatures**, high or low, affects the chemical reactions that develop in the battery and its performance

Note: 1) SoH (State of Health) = state of health
Source: BloombergNEF, Geotab, University of California, PwC Strategy&

End-of-life battery management strategies

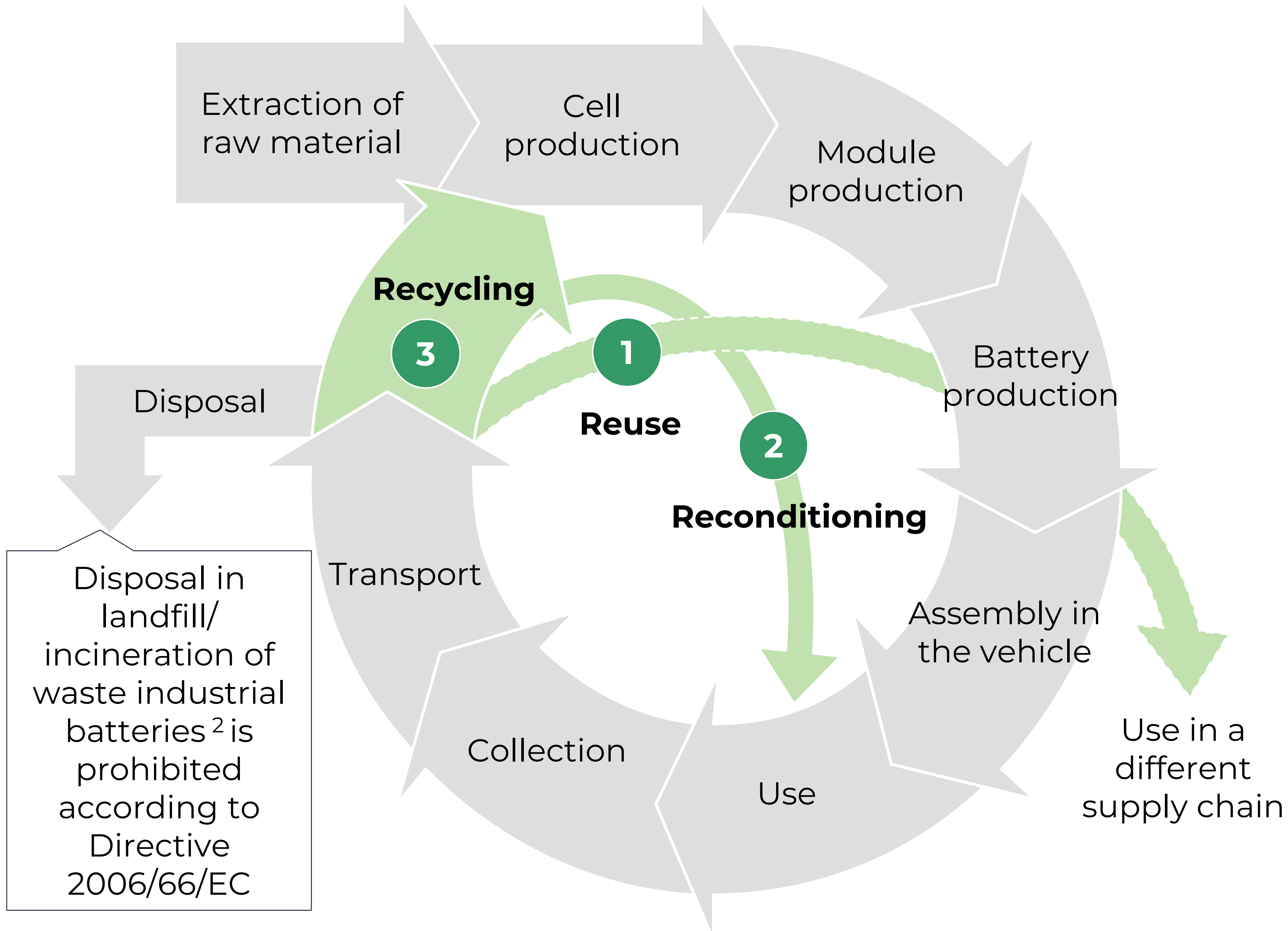
According to SoH[1], end-of-life batteries can be managed with 3 main strategies

End-of-life battery management strategies

			SoH[1]
1	**Reuse**	**Re-use** of the battery in **applications** typically **other than** automotive (e.g. storage systems), by **testing** and **assembling** the packs	 *75%-90%*
2	**Reconditioning**	**End-of-life battery disassembly** at module or cell level and **replacement** of damaged parts to at least partially **restore initial capacity**	 *65%-75%*
3	**Recycling**	**Recovery** of the **raw material** contained in the battery at the end of its life through a series of mechanical, thermal or chemical **treatments**	 *<65%*

Impact of strategies on the supply chain

🟩 Circular business model
▨ Linear business model



Extraction of raw material

Cell production

Module production

Battery production

Assembly in the vehicle

Use

Collection

Transport

Disposal

Disposal in landfill/ incineration of waste industrial batteries[2] is prohibited according to Directive 2006/66/EC

Recycling 3

1 **Reuse**

2 **Reconditioning**

Use in a different supply chain

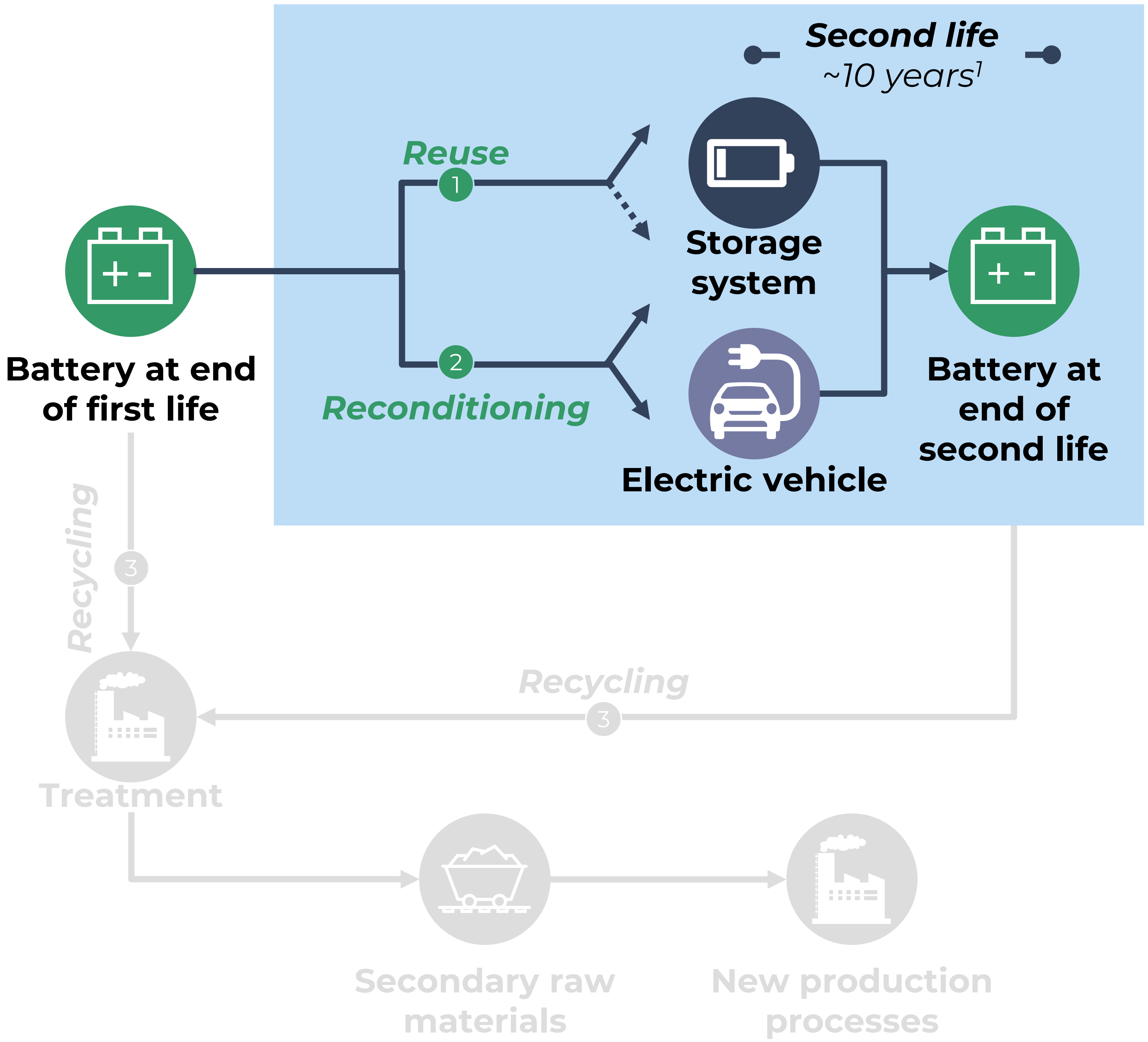
Notes: 1) State of Health = state of health; 2) Electric vehicle traction batteries fall into the category of industrial batteries within the meaning of Directive 2006/66/EC
Source: PwC Strategy&

The "second life" of batteries

Battery use can be extended by ~ 10 years thanks to "second life" opportunities

- 1 **Reuse**
- 2 **Reconditioning**
- 3 **Recycling**

End of life of batteries



"Second life" opportunities

Storage system	**Accumulation for use private**	**Storage of energy from renewable sources** in private buildings to maximise self-consumption
	Accumulation for public use	**Creation of renewable energy storage facilities** to decouple production and consumption
	Balancing the network	**Stabilisation of the electricity grid** to ensure service flexibility
	Prevention of blackouts	**Countering energy peaks** to prevent blackouts in energy-intensive buildings
	Charging for electric vehicles	**Energy storage in the charging infrastructure** during low-demand periods for future use
Vehicle	**Other vehicle applications**	Application in vehicles with **lower energy performance** requirements (e.g. ferries/lift trucks)

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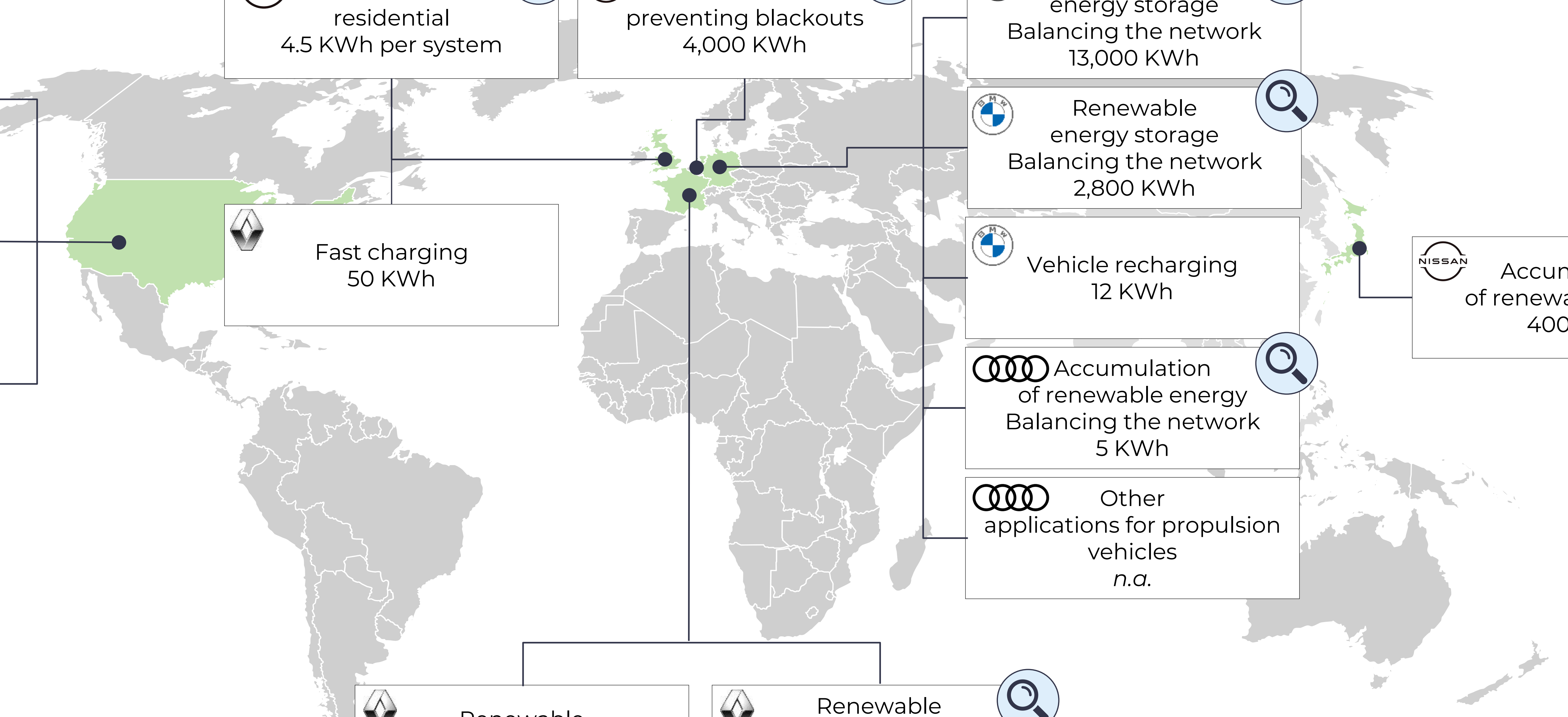
Notes: 1) The lifetime varies depending on the application (e.g. small stationary systems have a warranty period of about 5 years, while large storage systems have a lifetime of 10-15 years); this estimation model considers an average lifetime of 10 years
Source: PwC Strategy&

Focus next pages

Main "second life" applications in existence...

Car makers are experimenting with stationary applications with end-of-life batteries

Non-exhaustive



GM
Balancing
of the network
50 KWh

GM
Accumulation
of renewable energy
n.a.

Accumulation
of renewable energy
160 KWh

NISSAN
Accumulator
residential
4.5 KWh per system

NISSAN
Plants for
preventing blackouts
4,000 KWh

Fast charging
50 KWh

Renewable
energy storage
Balancing the network
13,000 KWh

Renewable
energy storage
Balancing the network
2,800 KWh

Vehicle recharging
12 KWh

Accumulation
of renewable energy
Balancing the network
5 KWh

Other
applications for propulsion
vehicles
n.a.

NISSAN
Accumulation
of renewable energy
400 KWh

Renewable
energy storage
66 KWh

Renewable
energy storage
Balancing the network
60.000 KWh

Case studies on
next slide

🟩 Countries with pilot projects
⬜ Countries without pilot projects

Source: Join Research centre, Sustainable Chemistry; PwC Strategy&

…developed through industrial partnerships

Projects leverage diversified skills enabled by industrial partnerships

Non-exhaustive

NISSAN

Blackout prevention

System made from used batteries of the Nissan Leaf model, providing **emergency power** in case of **blackouts**, **peak shaving services** and **storing** part of the energy produced by solar panels

Partner	Capacity (MWh)
EATON THE MOBILITY HOUSE	4

BMW

Energy storage

System with 700 battery packs from BMWi3, coupled with **wind turbines** and connected to the grid, stores energy for **grid stability** and **balancing demand**

Partner	Capacity (MWh)
BOSCH VATTENFALL	3

Energy storage

System made with 1024 Daimler batteries, stores **energy** from **wind and photovoltaic sources**

Partner	Capacity (MWh)
THE MOBILITY HOUSE REMONDIS® GETEC ENERGIE	13

Energy storage

System made from discarded Audi e-tron batteries for **stationary energy storage**, compensates for fluctuations in renewable energy availability and **stabilises the grid**

Partner	Capacity (MWh)
RWE	5

Energy storage

System made from used batteries in Renault Zoe, generates or absorbs large amounts of energy to **react** to **major grid loads**

Partner	Capacity (MWh)
THE MOBILITY HOUSE	60

NISSAN

Residential accumulator

System (xStorage) made with Nissan Leaf batteries, **stores residential energy** to **provide back-up power** and reduce the cost of energy

Partner	Capacity (MWh)
EATON	*n.a.* (4.5 KWh for each System)

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Source: Join Research centre, Sustainable Chemistry; PwC Strategy&

The proposal of "second life" batteries in Europe

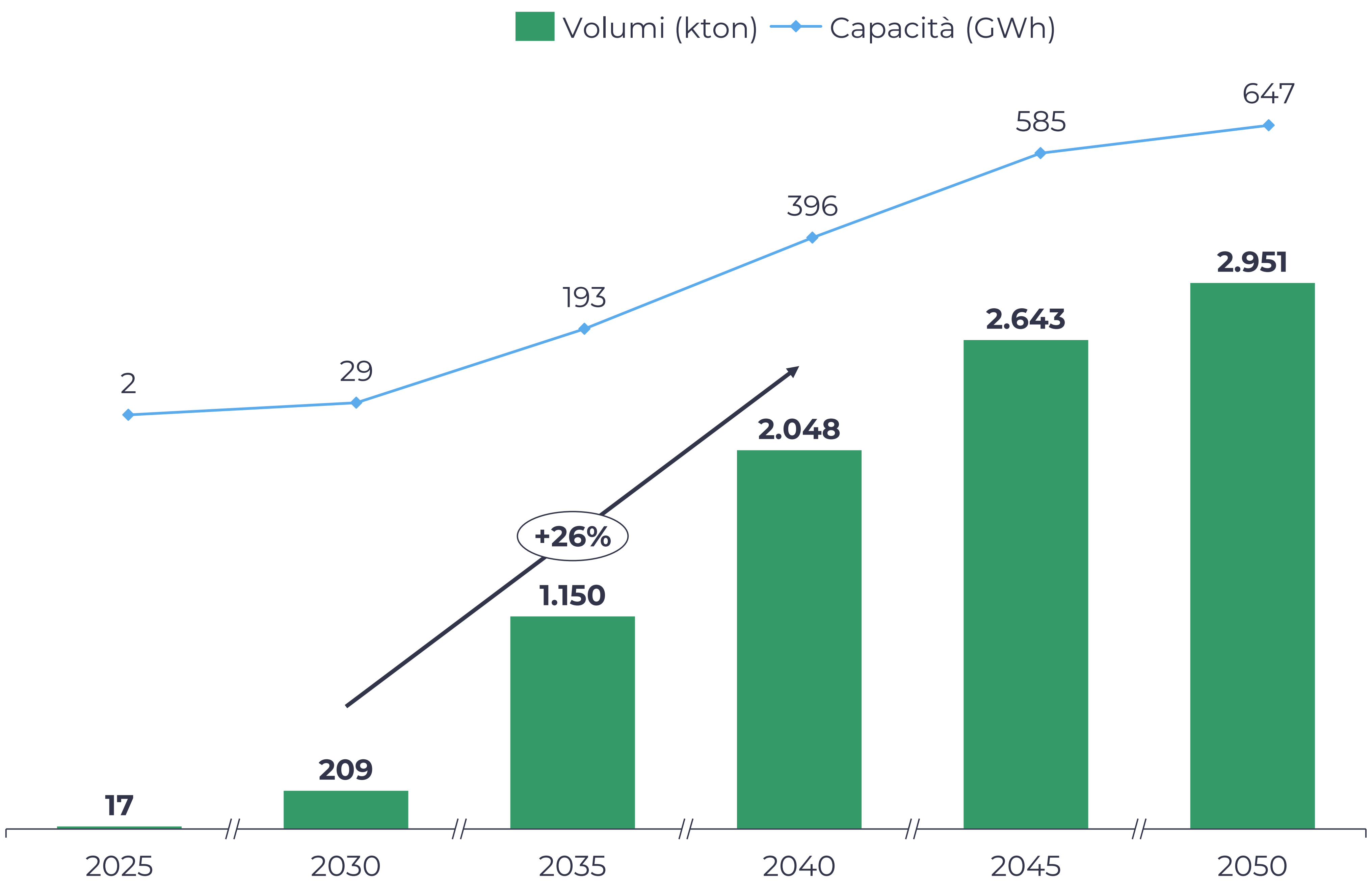
Capacity for "second life" applications is growing and will reach 647 GWh by 2050

1 **Reuse**

2 **Reconditioning**

3 Recycling

EV batteries destined for "second life" (ktonne, GWh)



Hypotheses and considerations

The circulation of "second-life" applications makes it possible to **exploit the remaining capacity** of batteries reaching the **end of their life**, which is expected to increase significantly after 2030 (+26% CAGR 2030-20240)

In the coming years, the increased use of devices for **correct** battery **health diagnosis** will allow a **greater circulation** of second-life applications, reducing the risk of recycling batteries with high residual capacity

Batteries reaching end-of-life are characterised by **increasing energy density**, which justifies an **increase in expected capacity more than proportional** to the increase in volumes

Source: Cobat, Politecnico di Milano, PwC Strategy&

Recycling opportunities for end-of-life batteries

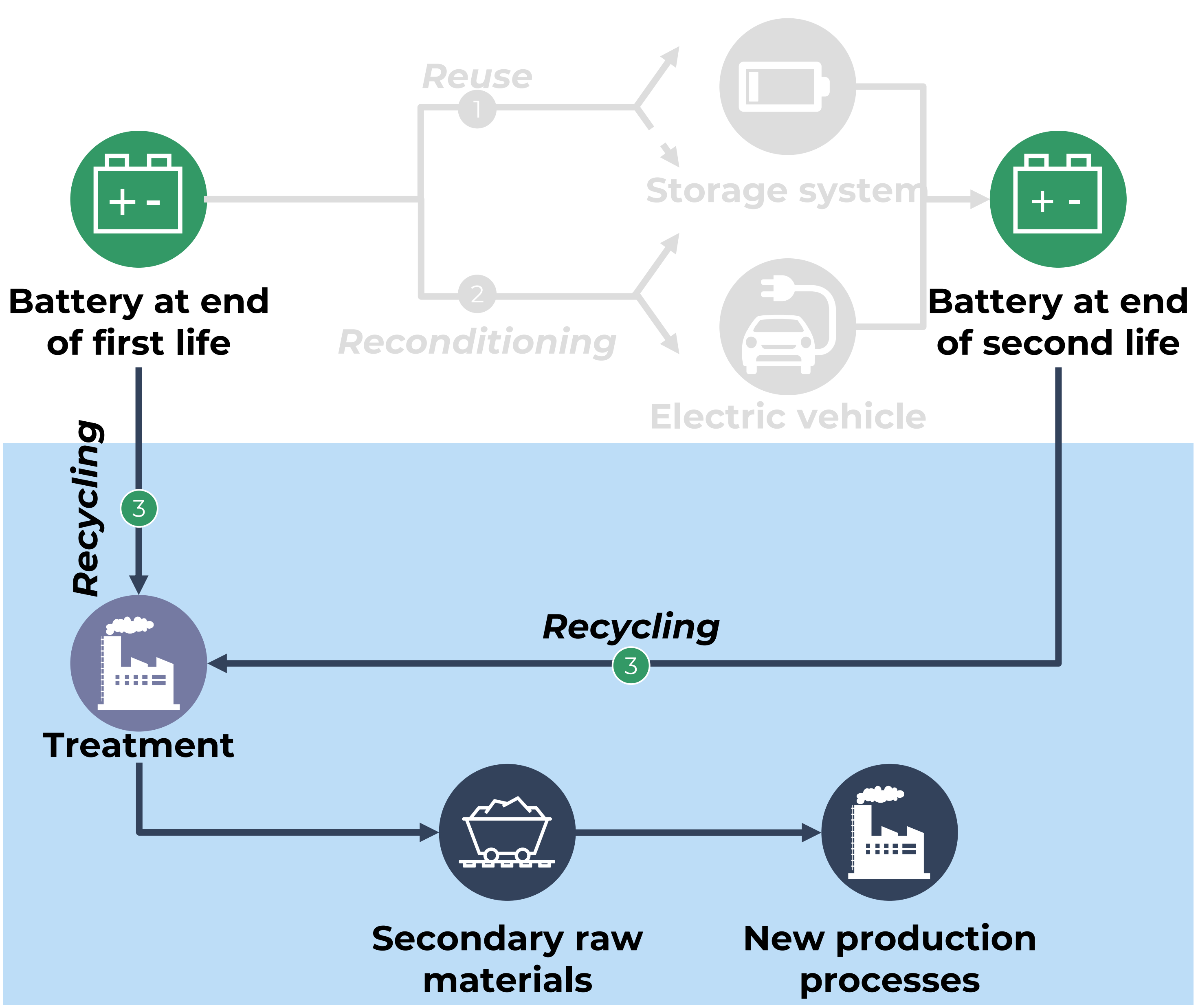
Recycling enables the generation of secondary raw materials for new production processes

1 Reuse

2 Reconditioning

3 **Recycling**

End of life of batteries



Opportunities for "recycling"

Raw materials and production processes	**Resilience of the supply chain**	**Reducing the risk** of **market shocks** through the creation of a new supply chain
	National independence	**Sourcing raw materials** from a **local supply chain** at the expense of imports
	Coverage of demand	Supporting the **coverage of raw material demand**, even in case of **reduced availability of virgin materials**
	Cost of raw materials	Availability of secondary raw materials at **potentially lower prices** than virgin materials
Treatment	**Environmental Impact**	Reducing **energy requirements and greenhouse gas emissions** associated with **mining and refining** operations
	Social impact	Creation of **new jobs** in the processing industry at national and European level

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Source: Politecnico di Milano, PwC Strategy&

Volumes of batteries for recycling in Europe

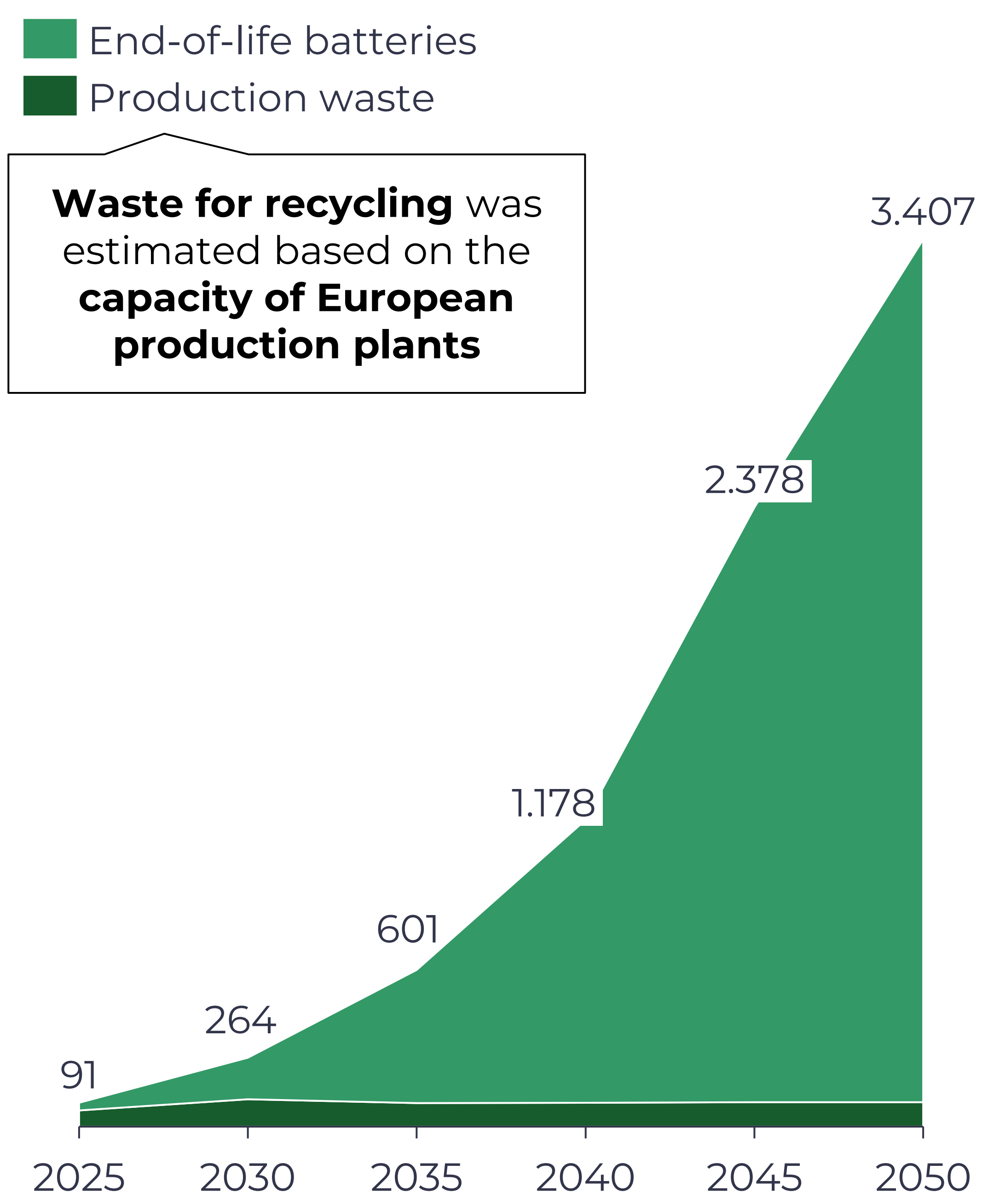
Volumes of batteries for recycling in Europe will reach ~3.4 Mtonne by 2050

1 Reuse

2 Reconditioning

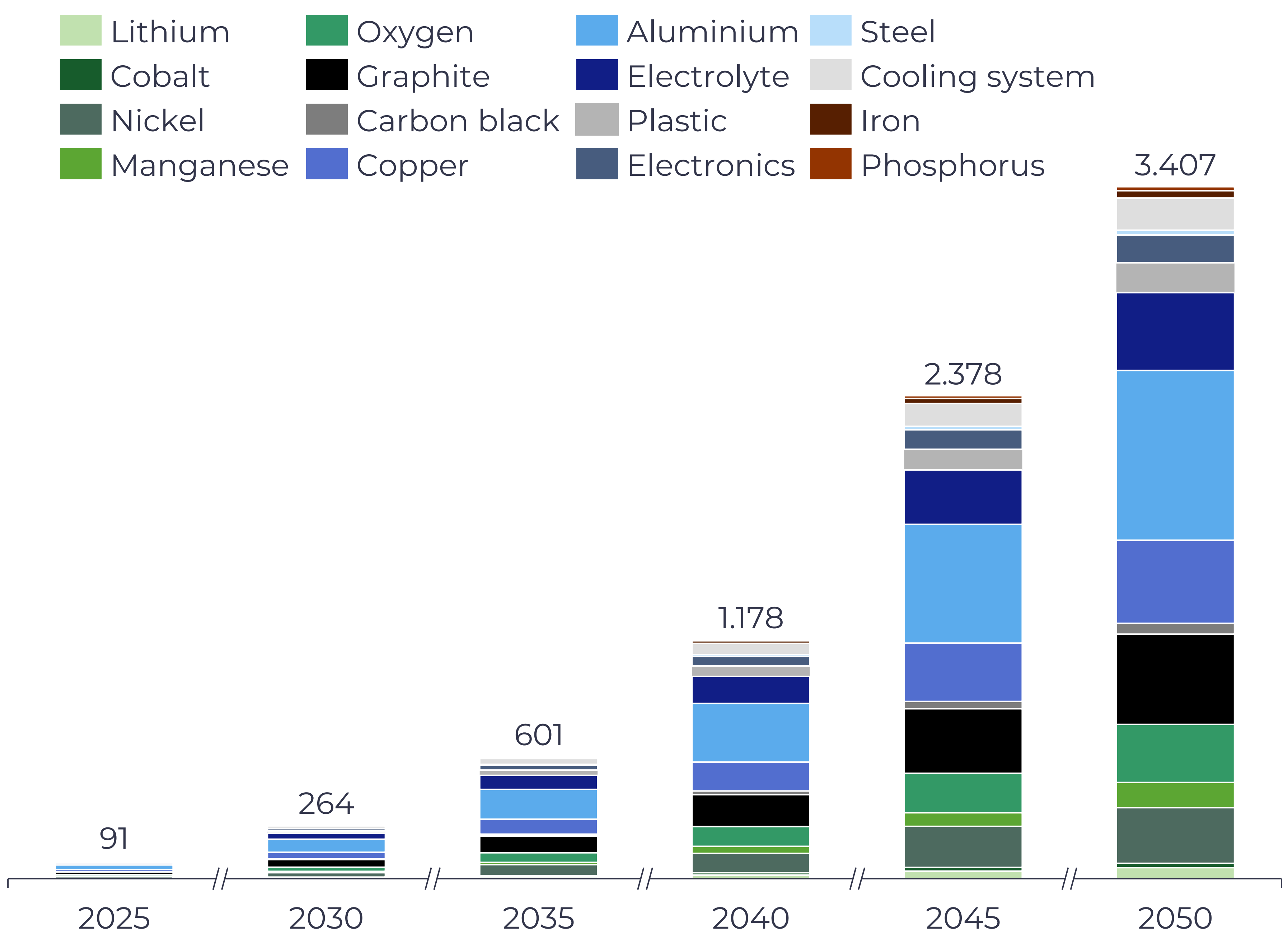
3 Recycling

Total volumes recycled (ktonnes)



Waste for recycling was estimated based on the **capacity of European production plants**

Material flows for recycling (ktonnes)



Source: Cobat, Politecnico di Milano, PwC Strategy&

Assumptions for estimating the market value of recycling

The market value of recycling is estimated based on key assumptions on Capex, Opex and revenues

1 Reuse

2 Reconditioning

3 **Recycling**

Parameter				Hypothesis		Limits of the hypotheses and potential evolutionary scenarios
Capex	**Investment capacity**		=	**Additional annual investments** to capture **all end-of-life battery volumes** generated in the reporting year	▶	The development of the recycling infrastructure will be a **gradual and less timely process** so that, at least in a first phase, volumes will continue to be **transferred abroad**
	Type of treatment		=	**Hydrometallurgical**	▶	The recycling infrastructure will be characterised by the **combination of several different** treatment types
	Investment cost		=	**~ 770 €/tonne** for a medium-sized plant (5-10 ktonne per year)	▶	The cost may vary depending on the **size** of the plant and the **type** of treatment
	Plant service life		=	**10 years**	▶	Useful life may vary depending on **rate of use**
Opex	**Pre-treatment and treatment**		=	**~ 7,850 €/tonne** for a medium-sized plant (5-10 ktonne per year)	▶	The cost may vary depending on the **size** of the plant and the **type** of treatment
Revenues	**Demand for recycled material**		=	**Allocation of all recycled material**, through demand for EV batteries and other industrial supply chains	▶	To **date**, the recycled market for EV battery materials **is undeveloped**; however, there are **growing applications** supported also by European regulatory targets
	Selling price of recycled material	**Nickel Cobalt Lithium**	=	**Discount vs. virgin 20%**; **0%** in case of material **shortage** to meet **EU minimum recycled content targets**	▶	**Virgin material** prices are characterised by high **volatility** with strong impacts on the recycled market, potentially influenced by **additional exogenous factors**
		Other	=	**= Opex**	▶	**Efficient treatment processes** could generate **margins** for all recycled materials
	EPR payment systems (*"gate fee"*)		=	**= 0** throughout the time span considered	▶	Today, EPR systems recognise a **payment to recyclers** to support their economic viability; in the future, market development may **reverse the economic flow**

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Source: Cobat, Erion, Politecnico di Milano, PwC Strategy&

Investment needed in Europe

In Europe, the investment to intercept volumes for recycling by 2050 is €2.6 billion

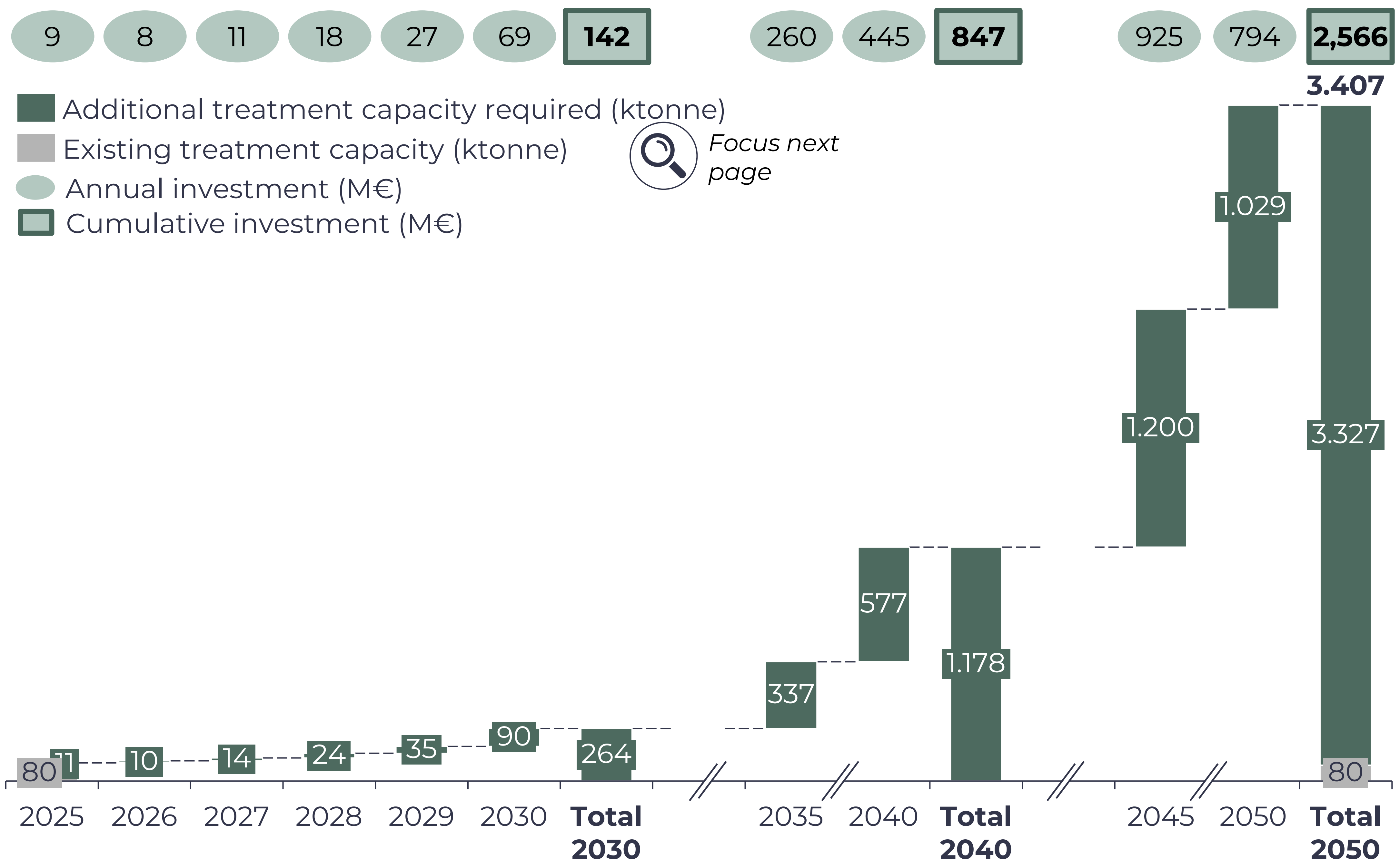
1 Reuse

2 Reconditioning

3 **Recycling**

Capex **Hydrometallurgical treatment**

Capacity and investment needed (ktonne, M€)



Hypotheses and considerations

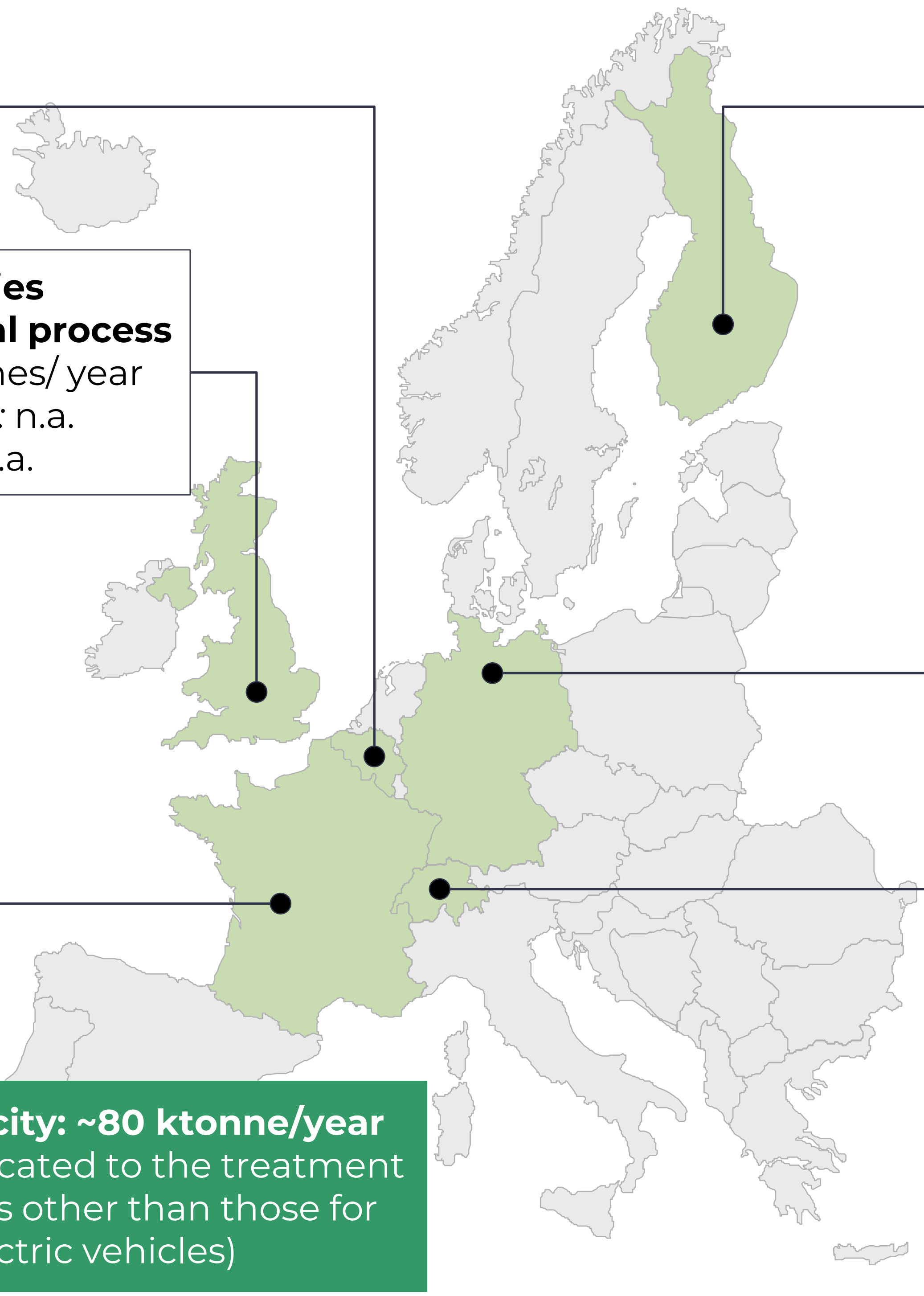
- **There are battery recycling plants in Europe** with a total capacity of ~ **80 ktonne/year**; however, today these plants mainly process **batteries other than** those for electric vehicles
- The **treatment capacity** has been sized to **annually intercept all volumes** of end-of-life EV batteries generated in Europe
- Investment costs (Capex) are estimated for a **medium-sized hydrometallurgical plant** (~5-10 ktonne/year); the cost can **vary** significantly depending on the **size of the plant** and the **type of treatment**

Source: Politecnico di Milano, PwC Strategy&

Battery recycling plants in Europe

In Europe, there are a few recycling plants with a total capacity of ~ 80 ktonne/year

Non-exhaustive



Umicore
Pyrometallurgical process
Capacity: 7,000 tonnes/year
Recovery rate: > 90%
Materials: Li, Co, Ni, Cu

AEA Technology
Hydrometallurgical process
Capacity: n.a.
Recovery rate: > 90%
Materials: Li, Co, Ni, Cu

G&P Batteries
Hydrometallurgical process
Capacity: 145 tonnes/ year
Recovery rate: n.a.
Materials: n.a.

SARP
Mechanical process
Capacity: 400 tonne/ year
Recovery rate: n.a.
Materials: *black mass*

Recupyl
Hydrometallurgical process
Capacity: 110 tonne/ year
Recovery rate: n.a.
Materials: Mn, Li, Co, Ni

SNAM
Mechanical process
Capacity: 300 tonnes/ year
Recovery rate: n.a.
Materials: *black mass*

! **Total capacity: ~80 ktonne/year** (mainly dedicated to the treatment of batteries other than those for electric vehicles)

Akkuser LTD
Mechanical process
Capacity: 4,000 tonnes/ year
Recovery rate: n.a.
Materials: *black mass*

Accurec
Pyrometallurgical process
Capacity: 4,000 tonnes/ year
Recovery rate: n.a.
Materials: Co, Fe, Cu, Al

Grs batteries
Pyrometallurgical process
Capacity: n.a.
Recovery rate: n.a.
Materials: n.a.

Nickelhutte Aue
Pyrometallurgical process
Capacity: n.a.
Recovery rate: n.a.
Materials: Co, Ni, Cu, Fe

Lithorec
Hydrometallurgical process
Capacity: n.a.
Recovery rate: 75%
Materials: n.a.

Battery resources
Hydrometallurgical process
Capacity: n.a.
Recovery rate: n.a.
Materials: Co, Mn, Li

Xstrata (Glencore)
Pyrometallurgical process
Capacity: 7,000 tonnes/ year
Recovery rate: n.a.
Materials: Co, Ni, Cu

Batrec
Pyrometallurgical process
Capacity: 200 tonne/ year
Recovery rate: n.a.
Materials: n.a.

Source: Politecnico di Milano, PwC Strategy&

Yield of a typical recycling process

A typical recycling process recovers ~ 60% of the input materials

Figure[1]

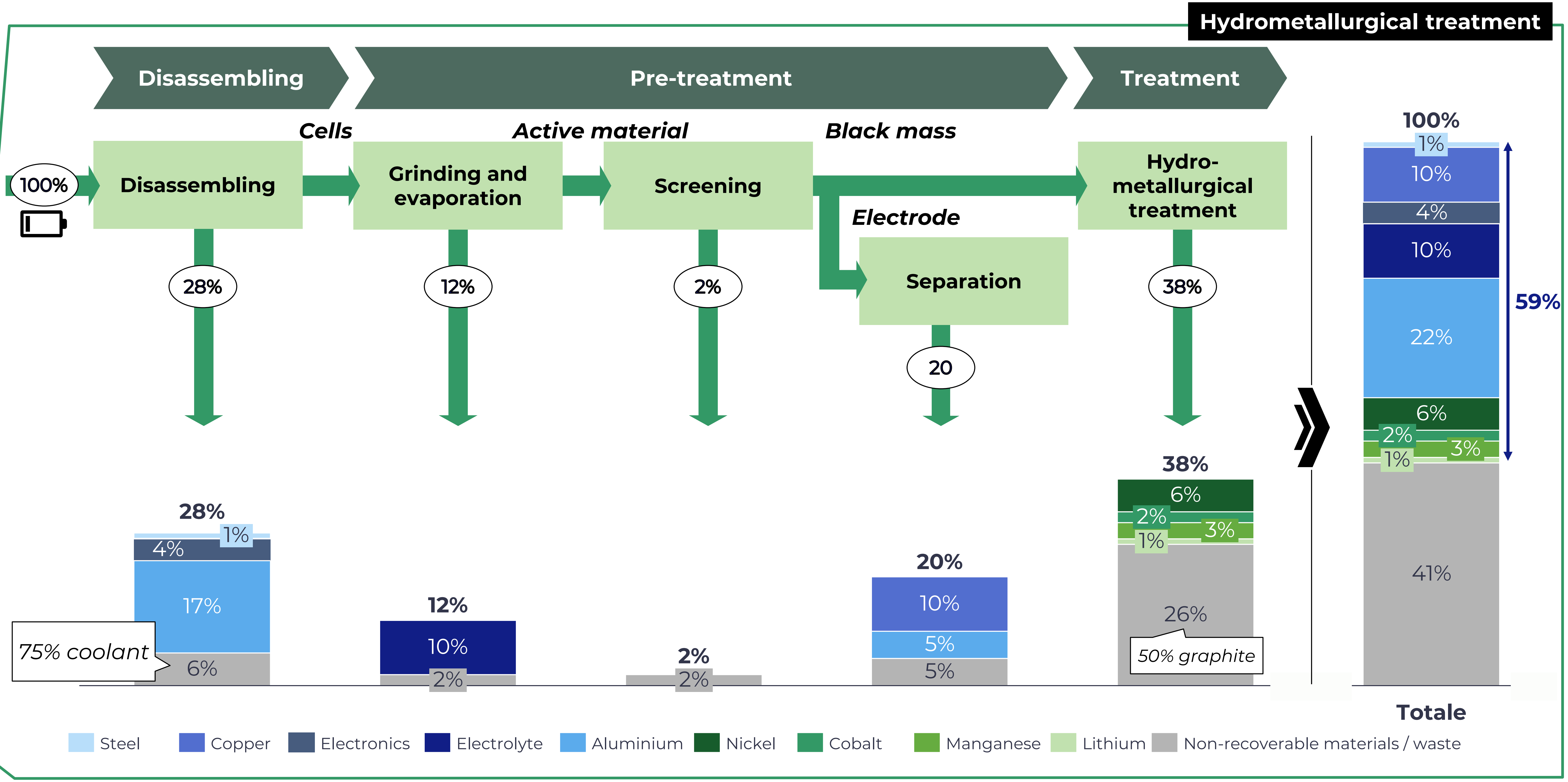
The share of recovered materials varies according to vehicle category and chemical composition

1 Reuse

2 Reconditioning

3 **Recycling**

Hydrometallurgical treatment



Notes: 1) Selected example: PC category, NMC chemistry
Source: Politecnico di Milano, PwC Strategy&

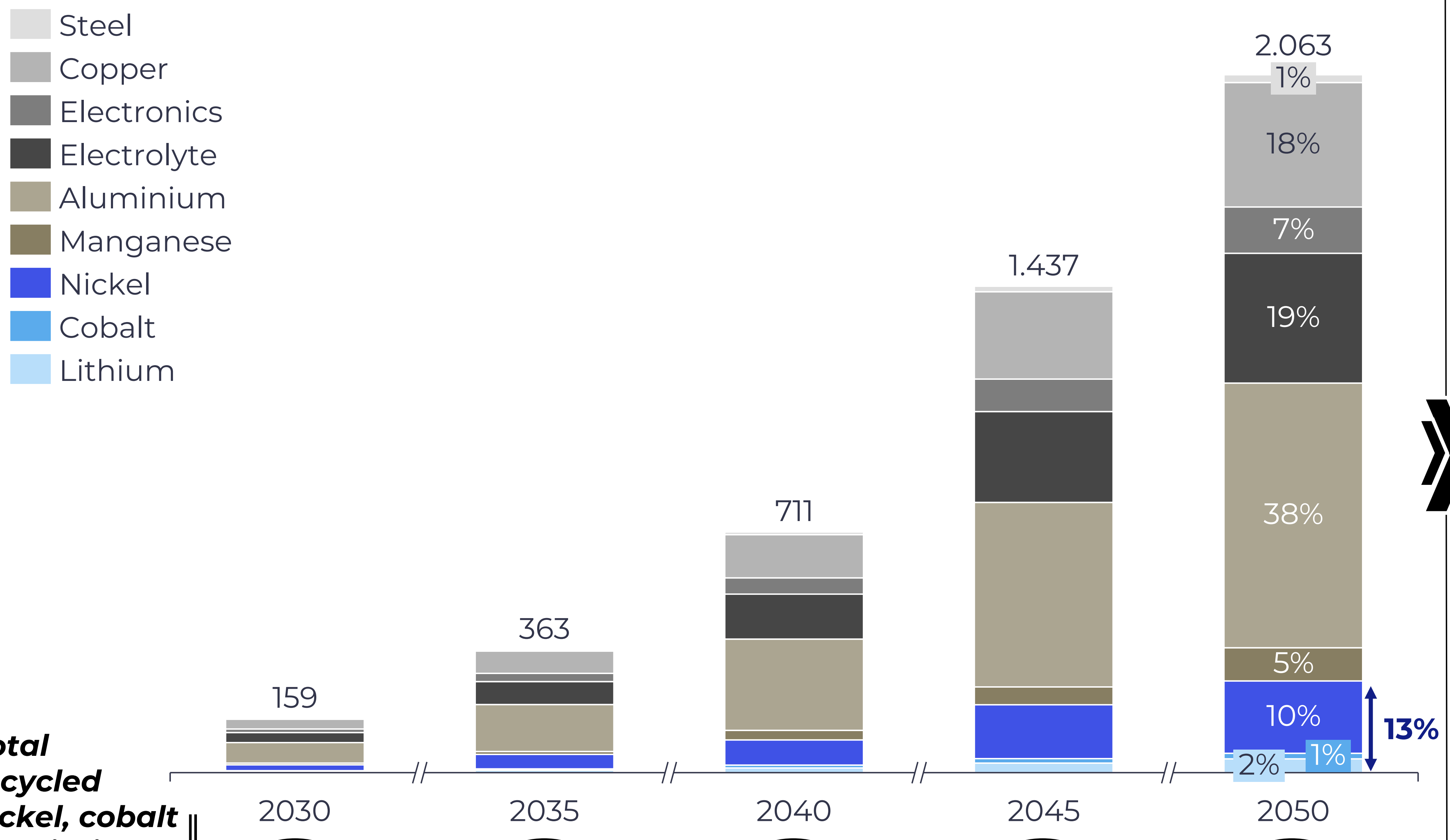
Volumes of recycled material in Europe

Nickel, cobalt and lithium cover ~ 13% of recycled volumes and offer margin opportunities

- 1 Reuse
- 2 Reconditioning
- 3 **Recycling**

Opex **Revenues** **Hydrometallurgical treatment**

Volumes of recycled material (ktonne)



Total recycled nickel, cobalt and lithium (ktonne)	2030	2035	2040	2045	2050
	23	54	97	200	271

Economic considerations

Recycled material	Hypothesis of marginality
Steel	✗
Copper	✗
Electronics	✗
Electrolyte	✗
Aluminium	✗
Manganese	✗
Nickel	✓
Cobalt	✓
Lithium	✓

Analysis in subsequent slides

✗ Revenue from sales ≈ Opex treatment
✓ Revenue from sales > Opex treatment

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Source: Politecnico di Milano, PwC Strategy&

Operating costs and amortisation

Operating costs for nickel, cobalt and lithium processing in 2050 will be ~ € 2.9 billion

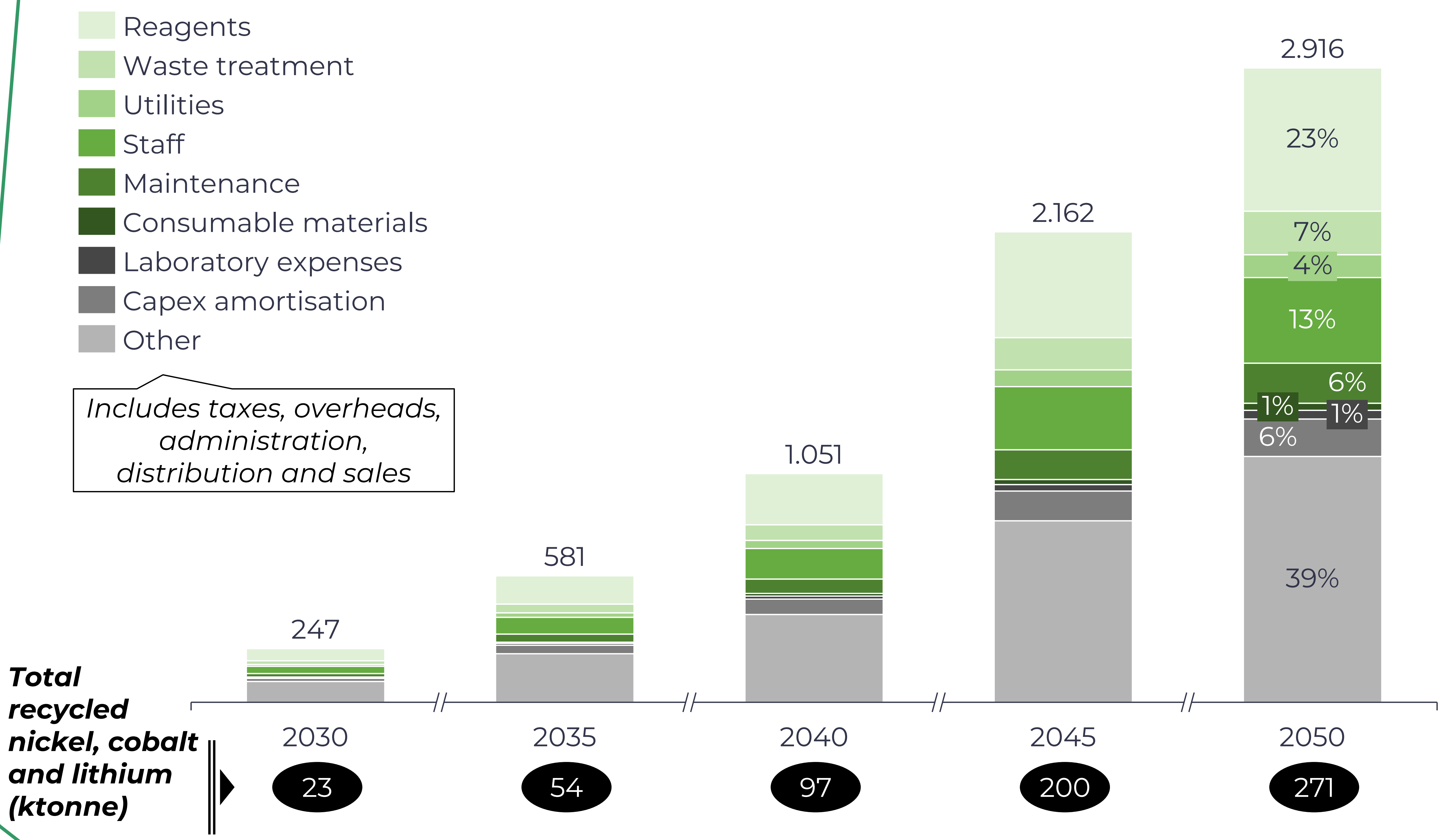
Opex **Hydrometallurgical treatment**

1 Reuse

2 Reconditioning

3 **Recycling**

Operating costs[1] for nickel, cobalt and lithium and amortisation (M€)



Includes taxes, overheads, administration, distribution and sales

Hypotheses and considerations

- Operating costs (Opex) include all activities required for **disassembly, pre-treatment and treatment** of batteries, excluding preliminary transport, testing and discharging activities
- The **amortisation** of investment costs (Capex) is estimated assuming an **average useful life** of the plants of **10 years**
- The operating (Opex) and investment (Capex) costs are estimated for a **medium-sized hydrometallurgical** plant (~5-10 ktonne/year); the cost can **vary** significantly depending on the **size of the plant** and the **type of treatment**

Notes: 1) Operating costs are calculated on the material entering the treatment plant (for nickel, cobalt and lithium, this corresponds to ~1.3x of the recycled material)
Source: Politecnico di Milano, PwC Strategy&

Impact of EU Targets on recycled prices

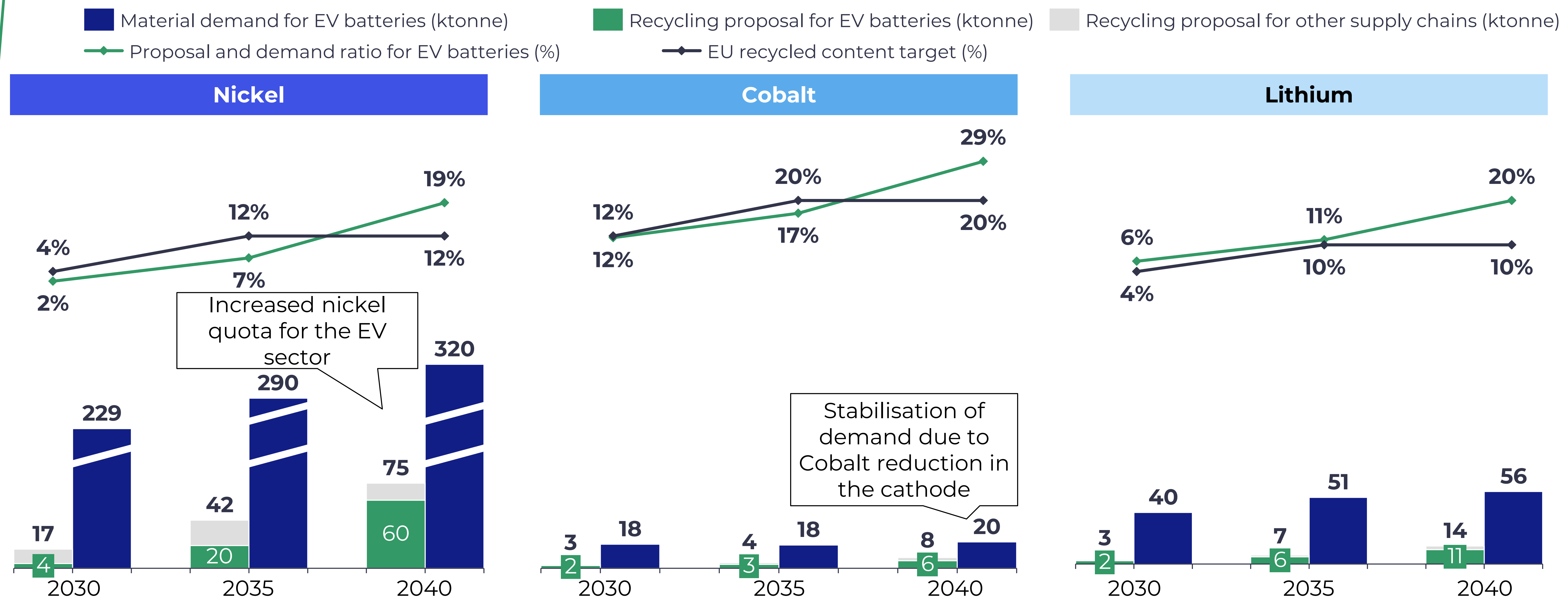
The price of recycled material compared to virgin material depends on the ability to meet EU targets

1 Reuse

2 Reconditioning

3 **Recycling**

Revenues **Hydrometallurgical treatment**



Increased nickel quota for the EV sector

Stabilisation of demand due to Cobalt reduction in the cathode

Below target	***Below target***	***Above target***	***Below target***	***Below target***	***Above target***	***Above target***	***Above target***	***Above target***
*Recycled price = **100%** virgin*	*Recycled price = **100%** virgin*	*Recycled price = **80%** virgin*	*Recycled price = **100%** virgin*	*Recycled price = **100%** virgin*	*Recycled price = **80%** virgin*	*Recycled price = **80%** virgin*	*Recycled price = **80%** virgin*	*Recycled price = **80%** virgin*

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Source: Proposal for a regulation of the European parliament and of the council concerning batteries and waste batteries, Avicenne, PwC Strategy&

The market value of recycling in Europe

By 2050, revenues generated by recycling will be €4.1-6.1 billion with a margin of €1.2-3.2 billion

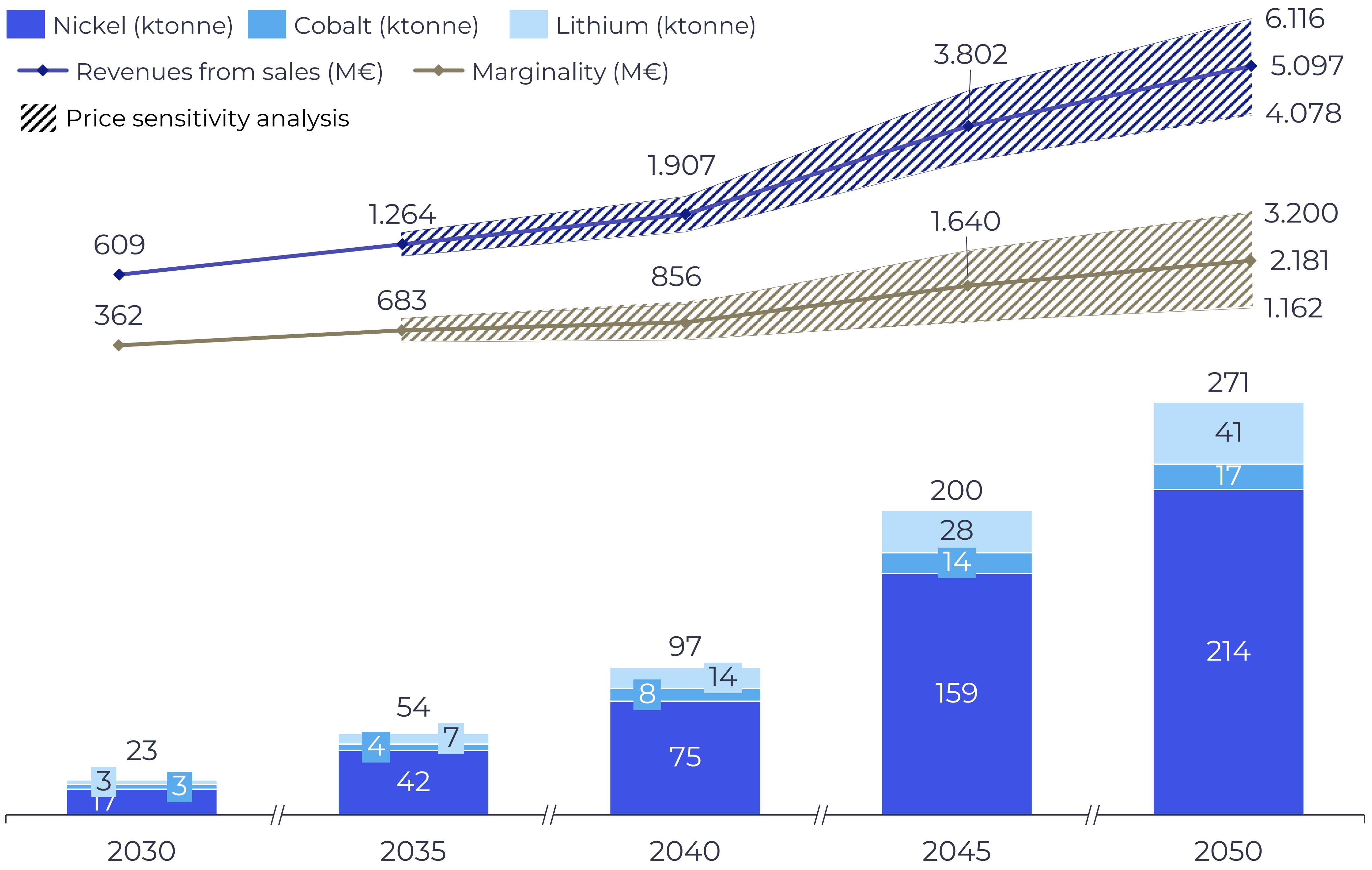
Capex **Opex** **Revenues** **Hydrometallurgical treatment**

1 Reuse

2 Reconditioning

3 **Recycling**

Volumes and market value of nickel, cobalt and lithium (ktonne, M€)



Hypotheses and considerations

- The **prices of recycled material** are estimated by applying a **discount** on the prices of virgin **material based on the recycled material** coming out of treatment processes compared to **demand to meet the EU minimum content targets**:
  - 0% if demand exceeds the proposal
  - 20% if demand is lower than the proposal
- **Virgin material prices** are estimated on the basis of the past 10-year **history** and **forecasts to 2030**, with a **profitability** analysis starting in 2035
- The calculated **marginality** considers, for the recycling phase only: **sales revenue, operating costs** and **amortisation**

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Source: Politecnico di Milano, Wood Mackenzie, London Metal Exchange, PwC Strategy&

Agenda

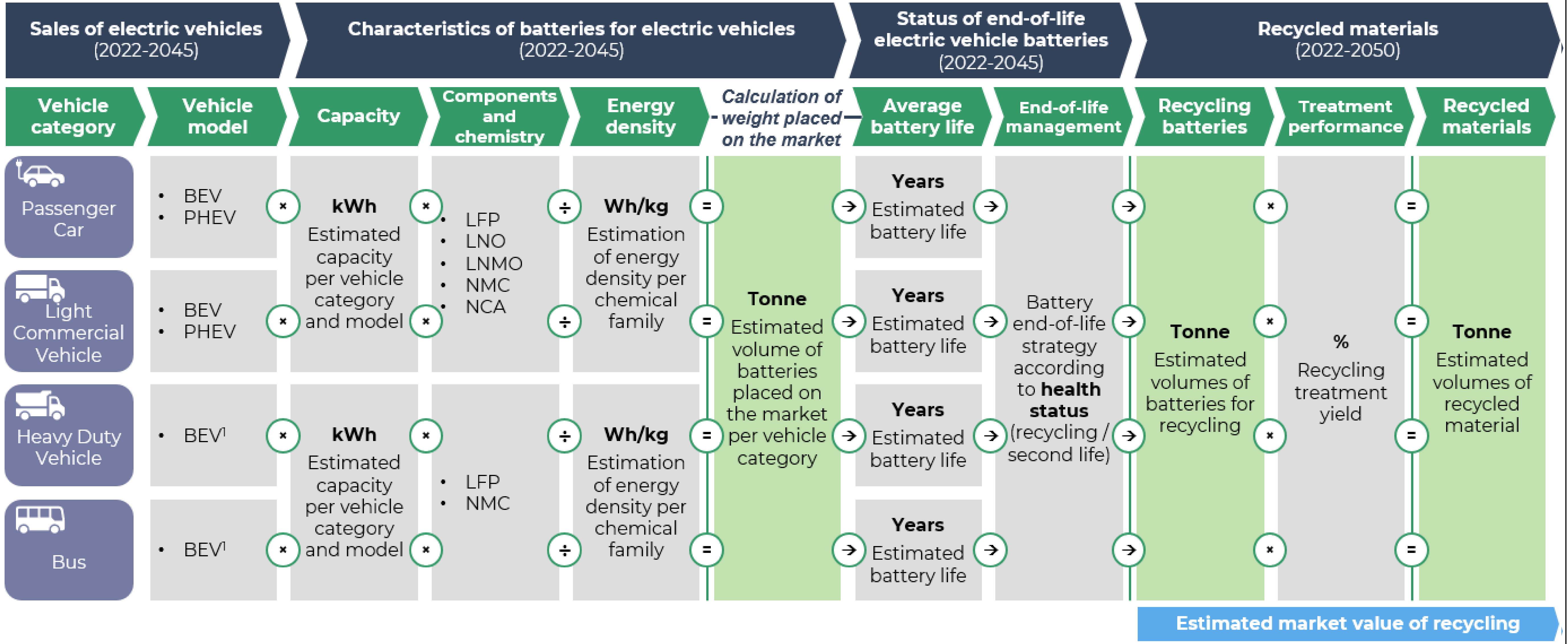
Methodological approach

Methodological approach for estimating market and investment needs in Italy

- The **model for estimating volumes of** recycled material developed for the analysis at the European level was **replicated for the analysis in Italy**, taking into account **key differences** in EV **sales**, **production and treatment capacity**
- The following pages illustrate the **main results** of the estimate and in particular:
  - Annual sales of electric vehicles and volumes of batteries released
  - Battery volumes and "second life" capacities
  - Volumes of batteries for recycling
  - Investment needed
  - Volumes of recycled material
  - Market value of recycling (revenues and margins)

Model for estimating volumes of recycled material

The model estimates the volumes of recycled material from end-of-life electric vehicle batteries



Sales of electric vehicles (2022-2045)		**Characteristics of batteries for electric vehicles** (2022-2045)				**Status of end-of-life electric vehicle batteries** (2022-2045)		**Recycled materials** (2022-2050)		
Vehicle category	**Vehicle model**	**Capacity**	**Components and chemistry**	**Energy density**	*Calculation of weight placed on the market*	**Average battery life**	**End-of-life management**	**Recycling batteries**	**Treatment performance**	**Recycled materials**
Passenger Car	BEV PHEV	**kWh** Estimated capacity per vehicle category and model	LFP LNO LNMO NMC NCA	**Wh/kg** Estimation of energy density per chemical family	**Tonne** Estimated volume of batteries placed on the market per vehicle category	**Years** Estimated battery life	Battery end-of-life strategy according to **health status** (recycling / second life)	**Tonne** Estimated volumes of batteries for recycling	**%** Recycling treatment yield	**Tonne** Estimated volumes of recycled material
Light Commercial Vehicle	BEV PHEV					**Years** Estimated battery life				
Heavy Duty Vehicle	BEV[1]	**kWh** Estimated capacity per vehicle category and model	LFP NMC	**Wh/kg** Estimation of energy density per chemical family		**Years** Estimated battery life				
Bus	BEV[1]					**Years** Estimated battery life				

Estimated market value of recycling

▨ Input 🟩 Output

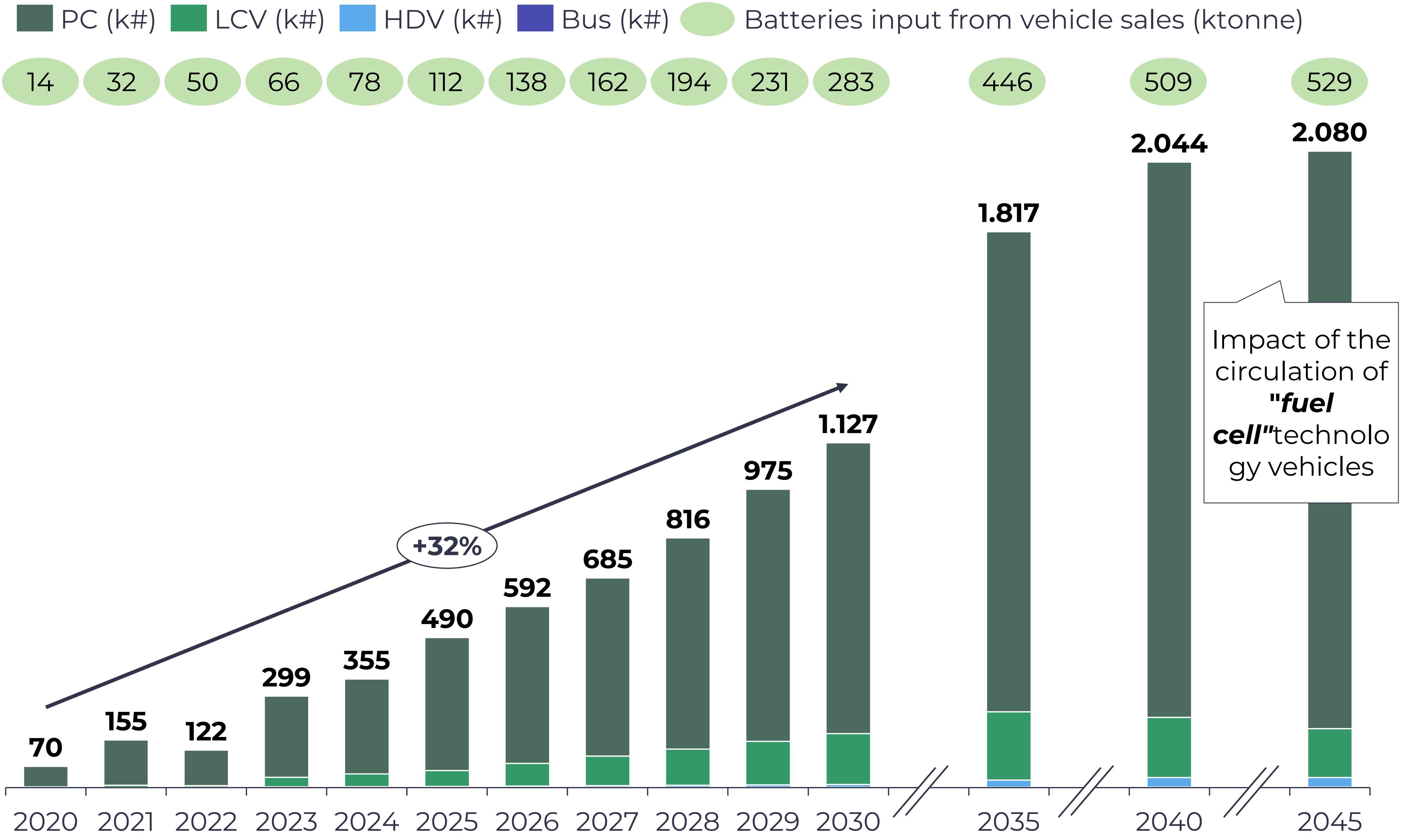
Notes: 1) The scenario considered includes only Heavy Duty Vehicles and Buses with BEV technologies
Source: PwC Strategy&

Source: PwC Strategy&

Evolution of electric vehicle sales in Italy

Sales of electric vehicles in Italy are expected to grow rapidly (CAGR 2020-2030 +32%)

Annual sales of electric vehicles in Italy (k#, ktonne)



Impact of the circulation of ***"fuel cell"***technology vehicles

Hypotheses and considerations

The market introduction of lithium-ion **batteries** is driven by the sale of **electric vehicles**, which is expected to grow in the coming years, after a slight decline to 2022

The circulation of electric vehicles is **stimulated** by **regulatory developments** at European level. In particular, the new **"*Fit for 55*"** climate package envisages a 55% reduction in greenhouse gas emissions by 2030, and sets the goal of producing only **zero-emission** cars and light commercial vehicles from **2035**

The **growth in the volume** of batteries placed on the market in terms of **weight** (tonnes) is driven by the progressive circulation of **large electric vehicle categories**, whose high capacity impacts their weight

Post 2040, the development of **hydrogen** *fuel cell technology* **will stabilise sales levels of** electric vehicles with **lithium-ion** batteries for all categories

Source: BloombergNEF, Motus-E, PwC Strategy&

The proposal of "second-life" batteries in Italy

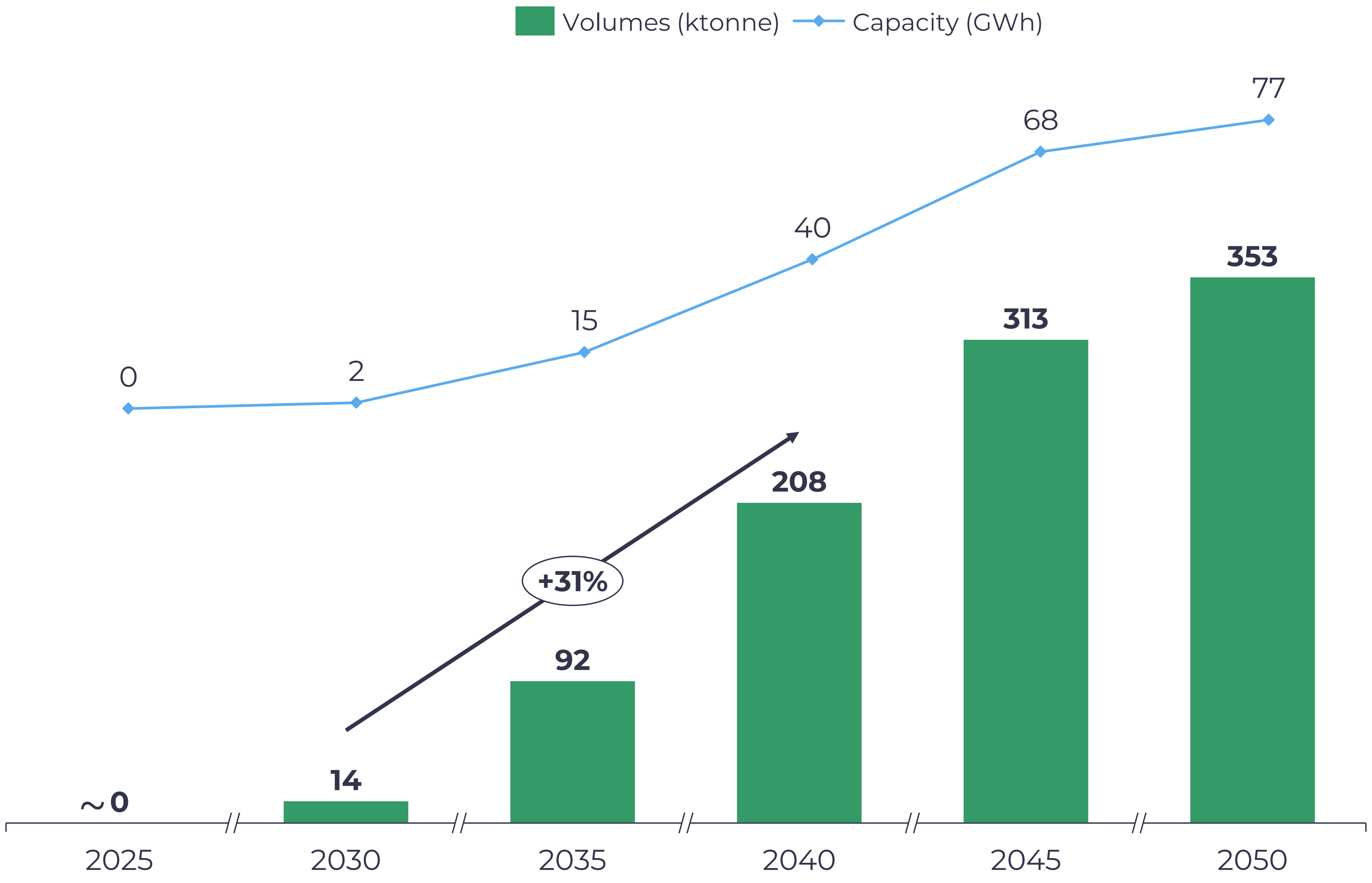
Capacity for "second life" applications is growing and will reach 77 GWh by 2050

1 **Reuse**

2 **Reconditioning**

3 **Recycling**

EV batteries destined for "second life" (ktonne, GWh)



Hypotheses and considerations

The circulation of "second-life" applications makes it possible to **exploit the remaining capacity** of batteries reaching the **end of their life**, which is expected to increase significantly after 2030 (+31% CAGR 2030-2040)

In the coming years, the increased use of devices for **correct** battery **health diagnosis** will allow a **greater circulation** of second-life applications, reducing the risk of recycling batteries with high residual capacity

Batteries reaching end-of-life are characterised by **increasing energy density**, which justifies an **increase in expected capacity more than proportional** to the increase in volumes

Source: Cobat, Politecnico di Milano, PwC Strategy&

Volumes of batteries for recycling in Italy

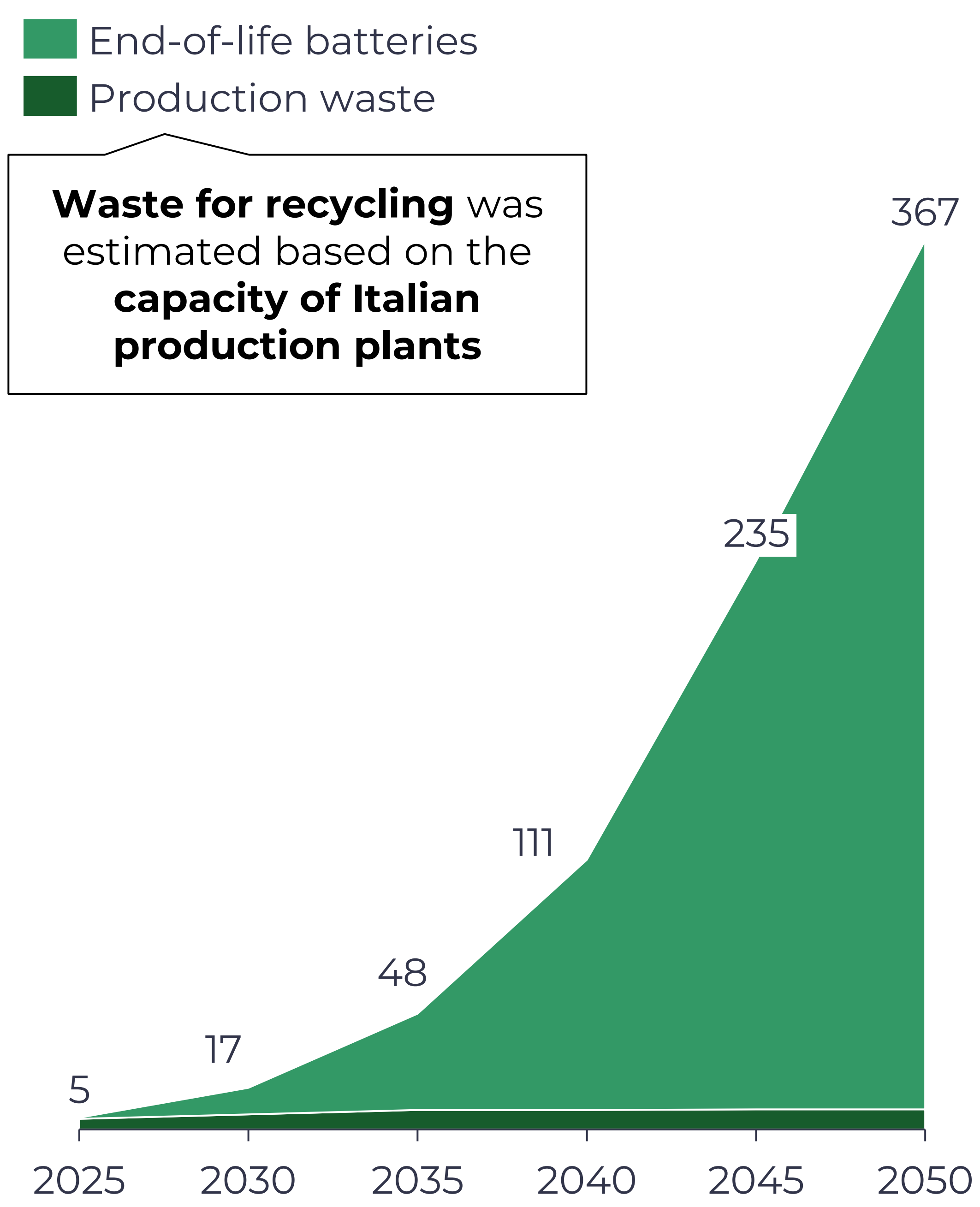
Volumes of batteries for recycling in Italy will reach ~ 367 ktonnes by 2050

1 Reuse

2 Reconditioning

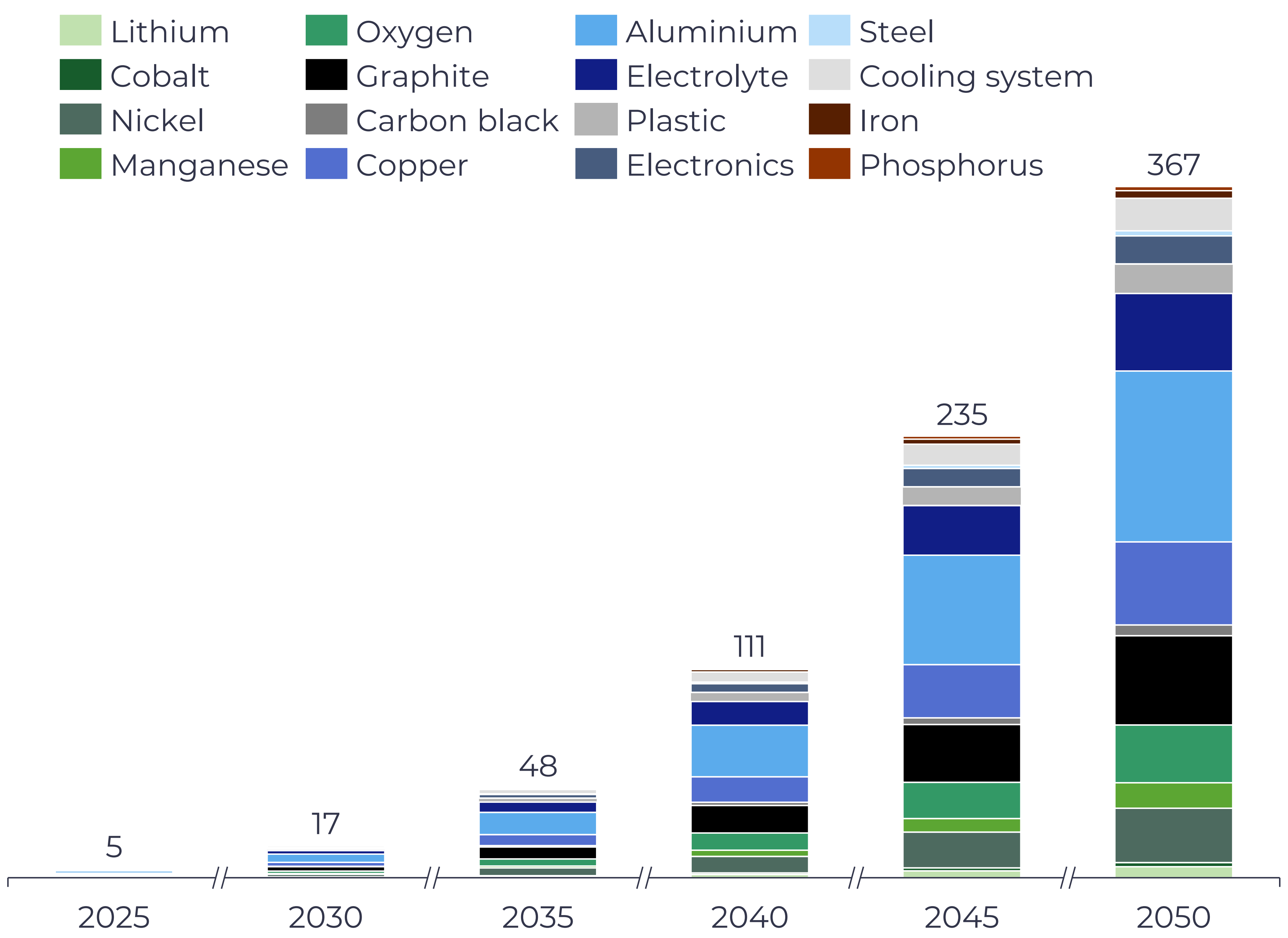
3 **Recycling**

Total volumes recycled (ktonnes)



Waste for recycling was estimated based on the **capacity of Italian production plants**

Material flows for recycling (ktonnes)



Source: Cobat, Politecnico di Milano, PwC Strategy&

Investment needed in Italy and associated costs

In Italy, the investment to intercept volumes for recycling by 2050 is €283 M

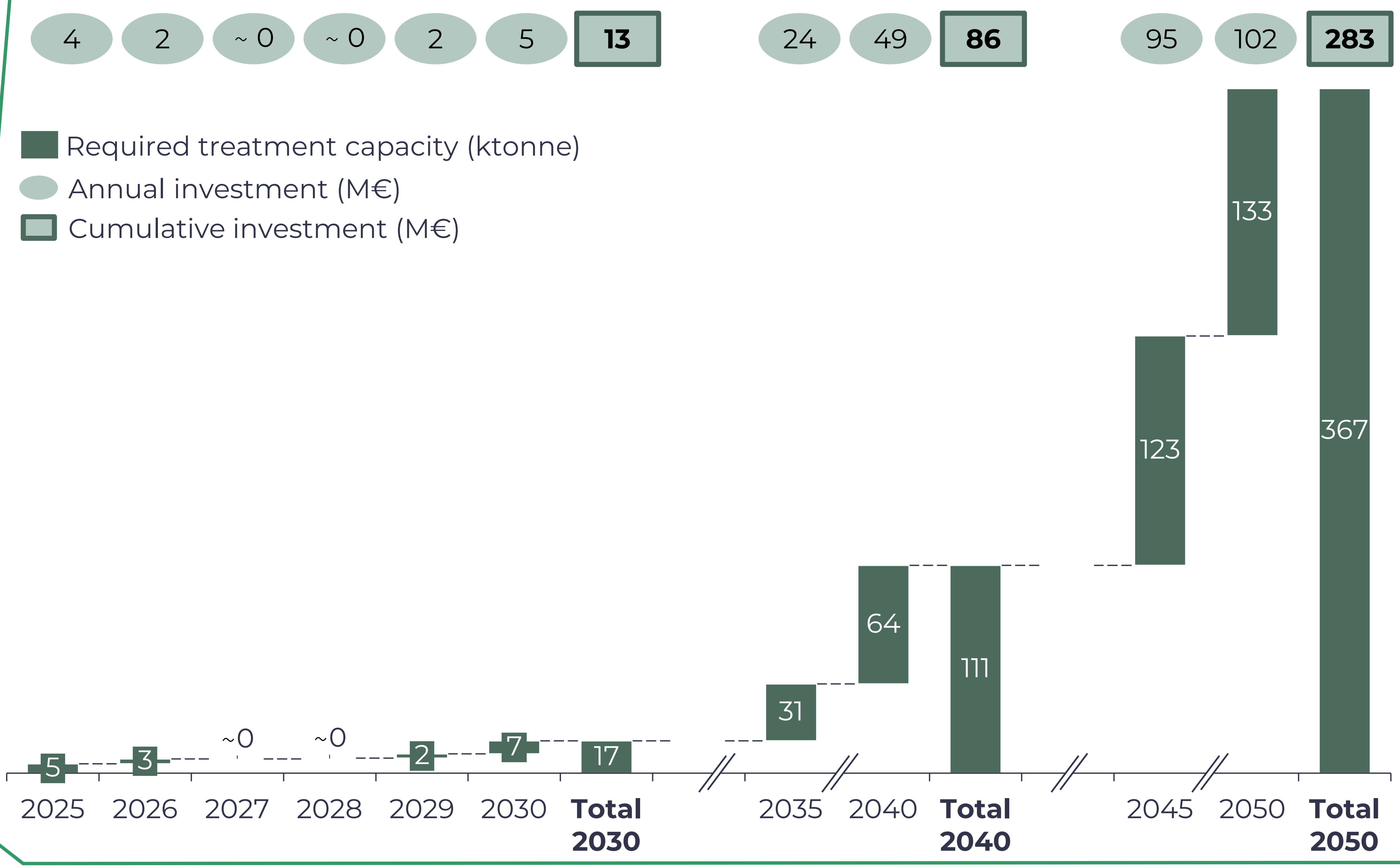
1 Reuse

2 Reconditioning

3 Recycling

Capex **Hydrometallurgical treatment**

Capacity and investment needed (ktonne, M€)



Hypotheses and considerations

To date, **there are no lithium-ion battery recycling facilities in Italy**, so at the end of their life they are typically **transferred abroad**

The **treatment capacity** has been sized to **annually intercept all volumes** of end-of-life EV batteries generated in the country

Investment costs (Capex) are estimated for a **medium-sized hydrometallurgical plant** (~5-10 ktonne/year); the cost can **vary** significantly depending on the **size of the plant** and the **type of treatment**

Source: Politecnico di Milano, PwC Strategy&

Volumes of recycled material in Italy

Nickel, cobalt and lithium cover ~ 13% of recycled volumes and offer margin opportunities

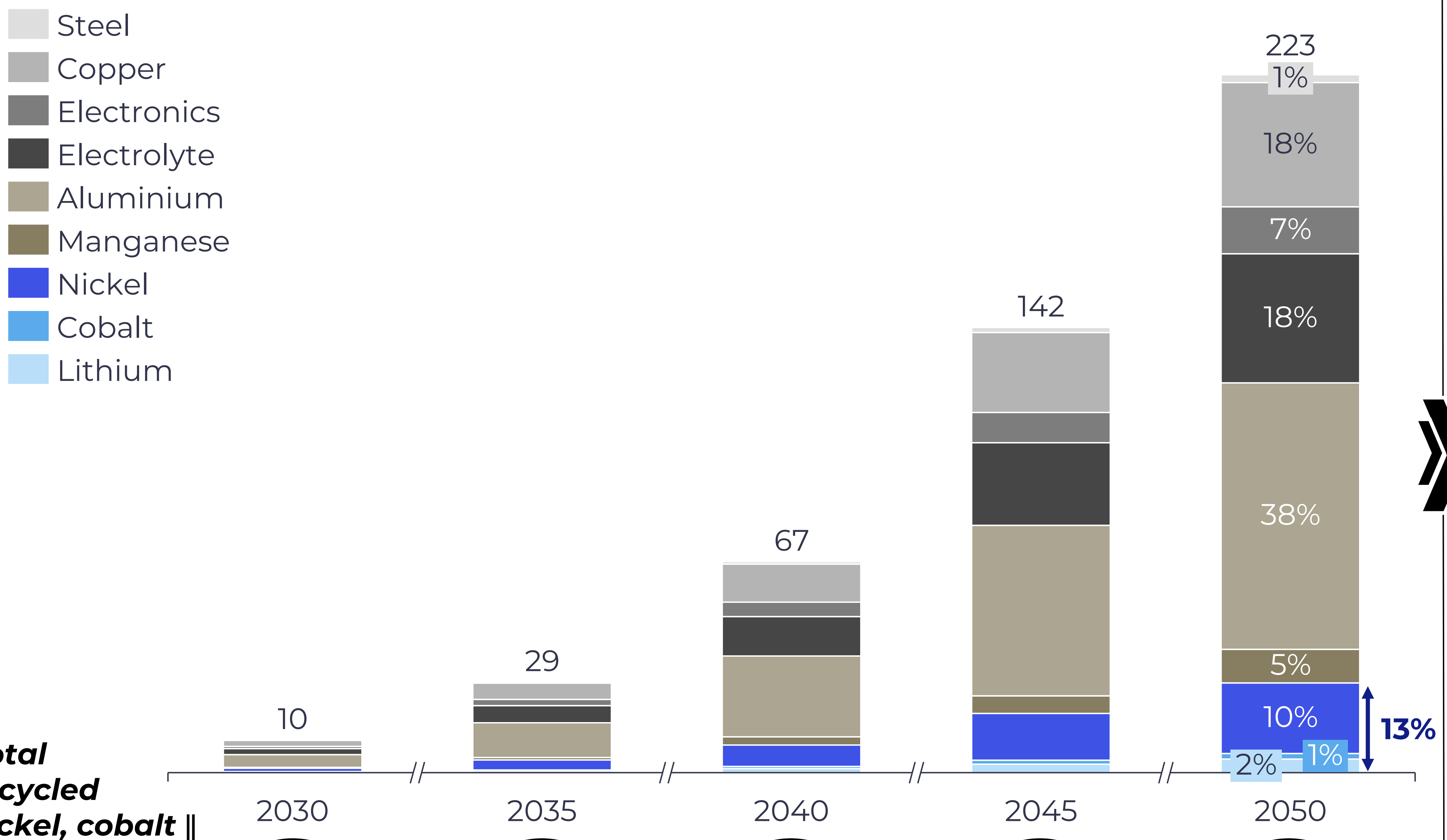
1 Reuse

2 Reconditioning

3 Recycling

Opex **Revenues** **Hydrometallurgical treatment**

Volumes of recycled material (ktonne)



Total recycled nickel, cobalt and lithium (ktonne)

2030	2035	2040	2045	2050
1	4	9	19	29

Economic considerations

Recycled material	Hypothesis of marginality
Steel	✗
Copper	✗
Electronics	✗
Electrolyte	✗
Aluminium	✗
Manganese	✗
Nickel	✓
Cobalt	✓
Lithium	✓

Analysis in subsequent slides

✗ Revenue from sales ≈ Opex treatment

✓ Revenue from sales > Opex treatment

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Source: Politecnico di Milano, PwC Strategy&

Operating costs and amortisation

Operating costs for nickel, cobalt and lithium processing in 2050 will be ~ €309 M

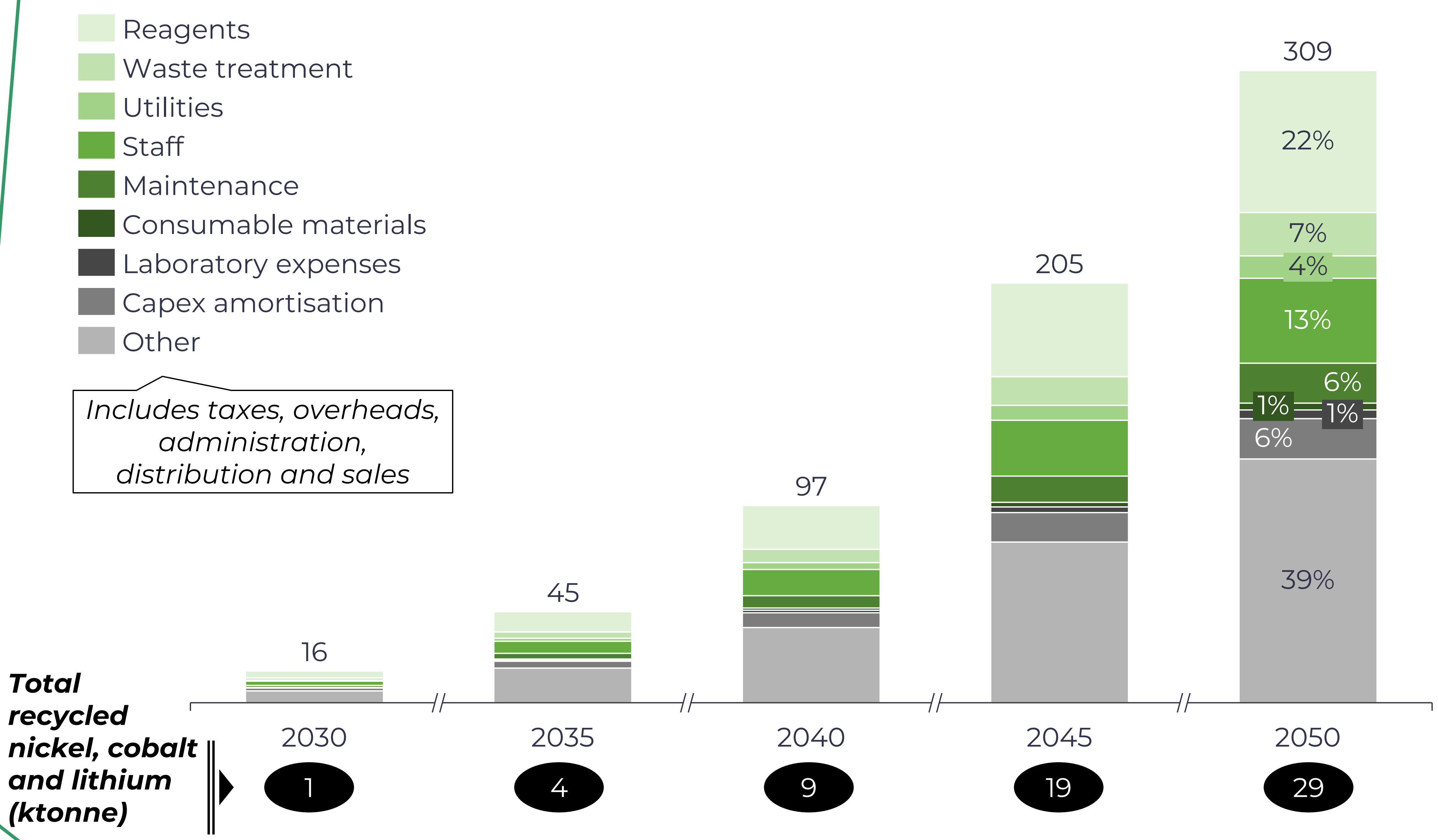
1 Reuse

2 Reconditioning

3 Recycling

Opex **Hydrometallurgical treatment**

Operating costs[1] for nickel, cobalt and lithium and amortisation (M€)



Hypotheses and considerations

- Operating costs (Opex) include all activities required for **disassembly, pre-treatment and treatment** of batteries, excluding preliminary transport, testing and discharging activities
- The **amortisation** of investment costs (Capex) is estimated assuming an **average useful life** of the plants of **10 years**
- The operating (Opex) and investment (Capex) costs are estimated for a **medium-sized hydrometallurgical** plant (~5-10 ktonne/year); the cost can **vary** significantly depending on the **size of the plant** and the **type of treatment**

Notes: 1) Operating costs are calculated on the material entering the treatment plant (for nickel, cobalt and lithium, this corresponds to ~1.3x of the recycled material)
Source: Politecnico di Milano, PwC Strategy&

The market value of recycling in Italy

By 2050, revenues generated by recycling will be €431-646 million with a margin of €121-337 million

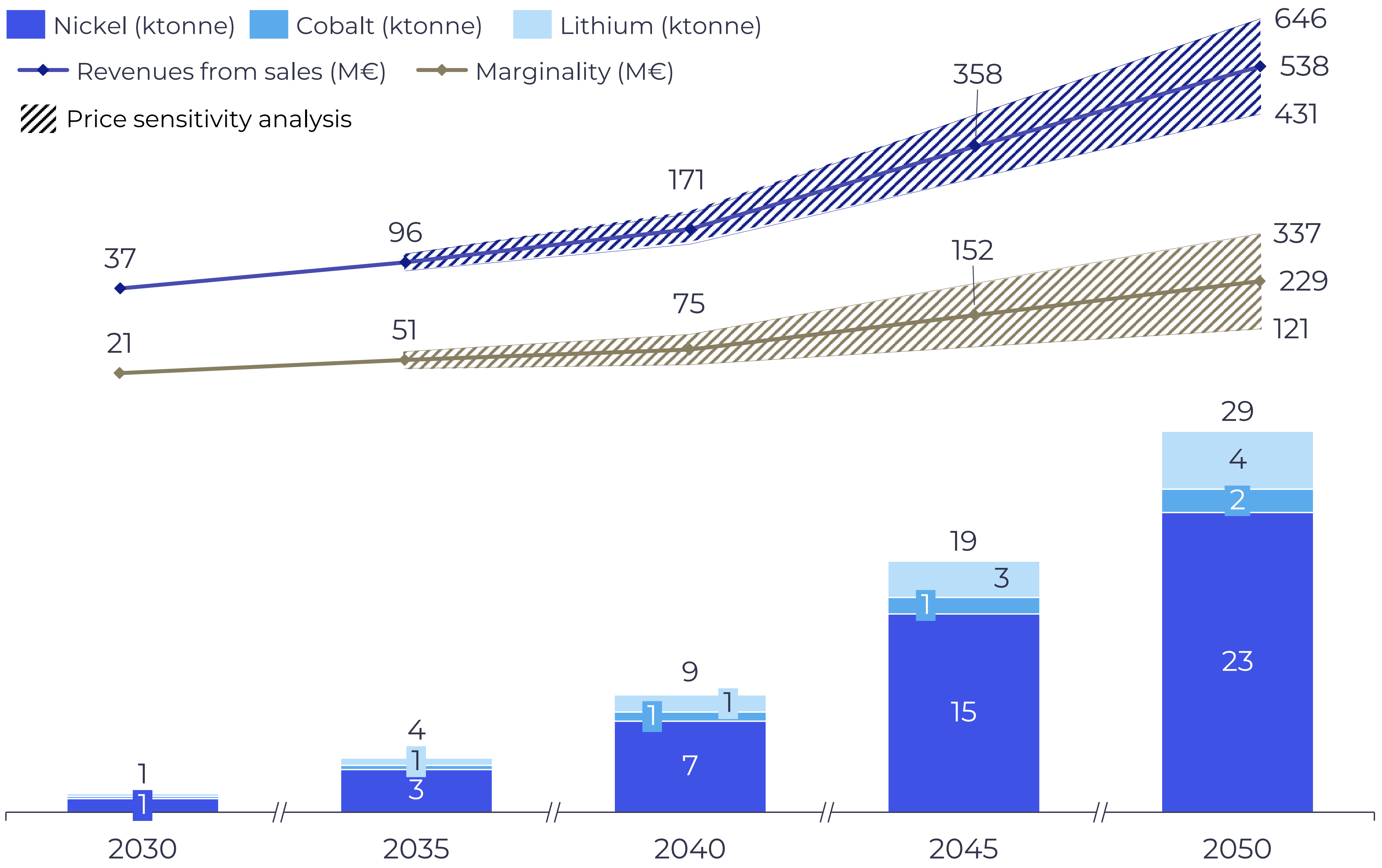
1 Reuse

2 Reconditioning

3 **Recycling**

Capex **Opex** **Revenues** **Hydrometallurgical treatment**

Volumes and market value of nickel, cobalt and lithium (ktonne, M€)



Hypotheses and considerations

- The **prices of recycled material** are estimated by applying a **discount** on the prices of virgin **material based on the recycled material** coming out of treatment processes compared to **demand to meet the EU minimum content targets**:
  - 0% if demand exceeds the proposal
  - 20% if demand is lower than the proposal
- **Virgin material prices** are estimated on the basis of the past 10-year **history** and **forecasts to 2030**, with a **profitability** analysis starting in 2035
- The calculated **marginality** considers, for the recycling phase only: **sales revenue, operating costs** and **amortisation**

Source: Politecnico di Milano, Wood Mackenzie, London Metal Exchange, PwC Strategy&

Agenda

Estimation of the recycling market and necessary investments

Considerations on business models

- Main stages and operators in the value chain
- Factors to success

Technological view

Agenda

Estimation of the recycling market and necessary investments

Considerations on business models

Main stages and operators in the value chain

Factors to success

Technological view

Electric vehicle battery value chain

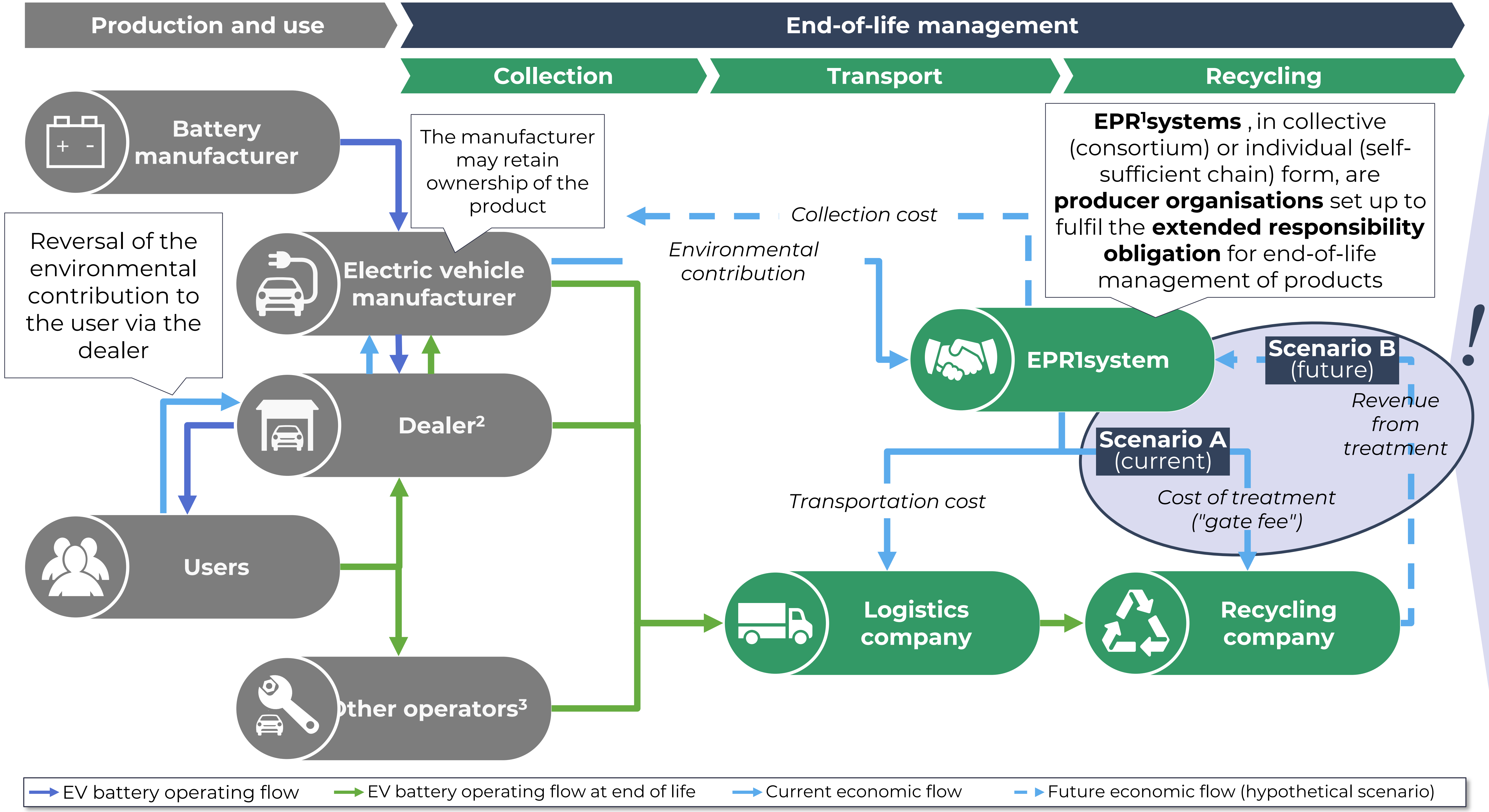
The value chain of batteries for electric vehicles is structured in 2 macro-phases

Phase II Production and use	**Extraction of raw material**	Extraction and refining of **virgin material** (e.g. cobalt, nickel, copper, aluminium, lithium etc.)
	Battery production	**Electrode** manufacture and assembly of **cells, modules** and **battery packs,** including components such as cables, BMS[1], cooling system
	Assembly in the vehicle	Battery assembly inside the **vehicle**
	Using the battery with the vehicle	Use of the battery inside the electric vehicle for a period of **~ 8-10 years**
Phase II End-of-life management	**Battery collection**	Removal and collection of the battery from the vehicle of the battery at the **end of its life**
	Transporting the battery	Transporting the battery **safely** to **specialised end-of-life battery treatment centres**
	Possible second life application	Re-use or reconditioning of the battery for **second life applications**, after which the battery is sent for recycling
	Battery recycling	End-of-life battery treatment for recovery of contained **raw materials**
	Sale of recycled material	Sale of **recycled material** for use in **industrial processes** in different supply chains

Notes: 1) Battery management system
Source: PwC Strategy&

Operating and economic flows of EV batteries

Operational and economic flows for end-of-life management are organised by EPR [1] systems



Production and use

End-of-life management

Collection | **Transport** | **Recycling**

Battery manufacturer

The manufacturer may retain ownership of the product

EPR[1]systems , in collective (consortium) or individual (self-sufficient chain) form, are **producer organisations** set up to fulfil the **extended responsibility obligation** for end-of-life management of products

Reversal of the environmental contribution to the user via the dealer

Electric vehicle manufacturer

Collection cost

Environmental contribution

EPR1system

Scenario B (future)

Revenue from treatment

Scenario A (current)

Cost of treatment ("gate fee")

Dealer[2]

Transportation cost

Users

Logistics company

Recycling company

Other operators[3]

→ EV battery operating flow | → EV battery operating flow at end of life | → Current economic flow | - - → Future economic flow (hypothetical scenario)

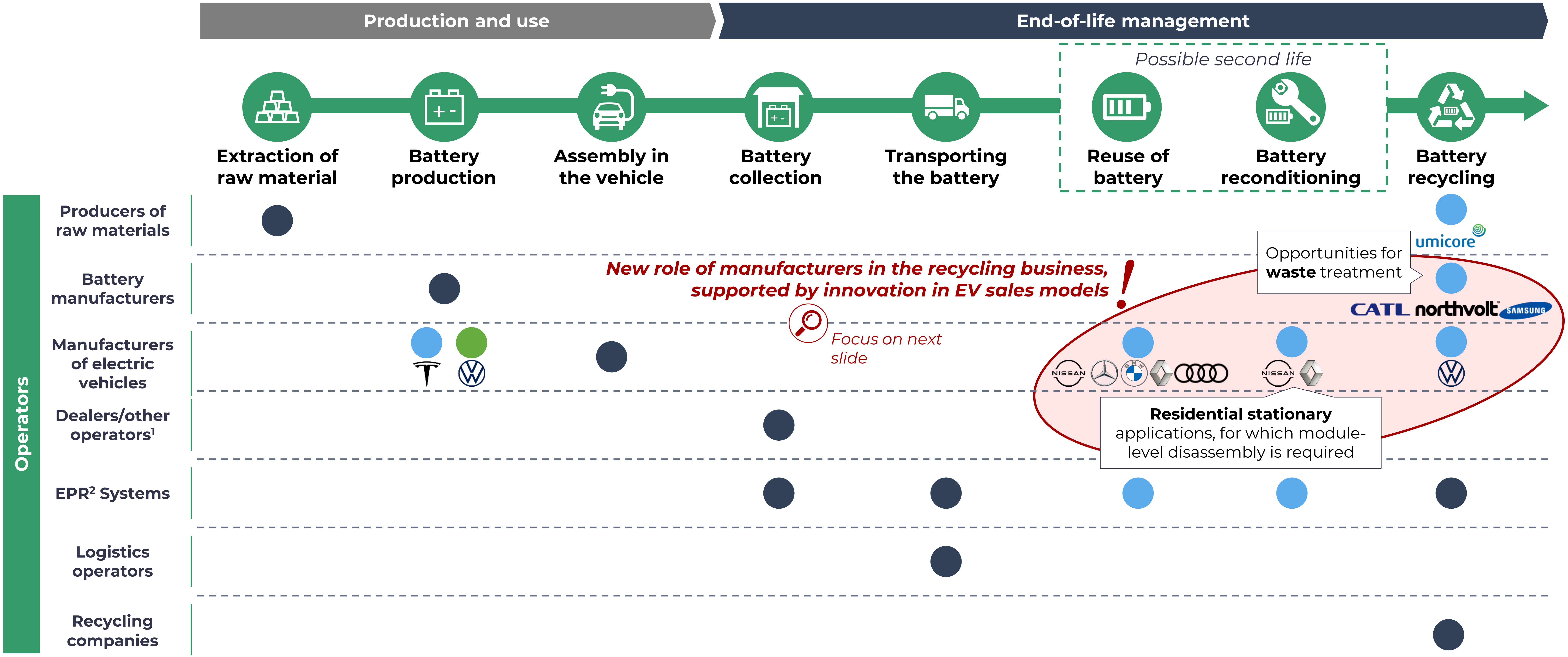
- To date, **EPR[1] systems** incur a cost for each end-of-life phase, including recycling, for which **they make a payment to recycling companies** (Scenario A, "gate fee")
- In the future, an **improved scenario** is assumed in which, due to the achievement of the **appropriate scale** and therefore the **optimisation of recycling costs**, EPR[1] systems will deliver products for recycling in **return for payment by recycling companies** (Scenario B). Such a scenario, demonstrating the cost-effectiveness of end-of-life management, could also imply:
  - The **resolution** of the problem of **"orphan batteries[4]"**, the cost of managing which is currently redistributed over the average environmental contribution
  - The incurring of a **collection cost** by EPR[1] **systems**, as is already the case today in other more developed supply chains (e.g. lead batteries)

Notes: 1) EPR = Extended Producer Responsibility; 2) In the future, it may also include rental cars; 3) Car repair shops, car wrecks, new actors; 4) "Orphan batteries" are defined as batteries for which the producer cannot be recognised on the market
Source: Cobat, Erion, PwC Strategy&

Operators and roles along the value chain

Non-exhaustive

Traditional operators in the value chain are expanding into different roles



Operators	Extraction of raw material	Battery production	Assembly in the vehicle	Battery collection	Transporting the battery	Reuse of battery	Battery reconditioning	Battery recycling
Producers of raw materials	●							🔵 umicore
Battery manufacturers		●						🔵 CATL northvolt SAMSUNG
Manufacturers of electric vehicles		🔵 🟢	●			🔵 NISSAN	🔵 NISSAN	🔵
Dealers/other operators¹				●				
EPR² Systems				●	●	🔵	🔵	●
Logistics operators					●			
Recycling companies								●

New role of manufacturers in the recycling business, supported by innovation in EV sales models **!**

Focus on next slide

Opportunities for **waste** treatment

Residential stationary applications, for which module-level disassembly is required

● Traditional expertise 🔵 Extended expertise
🟢 Expertise planned / being explored

Notes: 1) Electric car, workshops, auto wrecks; 2) EPR (Extended Producer Responsibility)
Source: PwC Strategy&

Innovation of EV sales models

New EV sales models support manufacturers' access to end-of-life batteries

\- *Degree of innovation* +

Sales models of electric vehicles	**Vehicle sale + Battery sale**	**Vehicle leasing + Battery leasing**	**Vehicle sales + Battery leasing**	**Vehicle Sales + Battery as a Service**	**Vehicle sale + Battery Swap**
Battery properties	User	Electric vehicle manufacturer	Electric vehicle manufacturer	Electric vehicle manufacturer Battery manufacturer	Electric vehicle manufacturer Battery manufacturer
Player	All	All	NISSAN HYUNDAI	NIO[1]	NIO CATL
Country	All	All	All	🇨🇳	🇨🇳 🇳🇴
Average duration of the contract	n.a.	2-5 years	Monthly subscription	Monthly subscription	Monthly subscription
End-of-life battery collection points	Other operators[2]	Dealer	Dealer	Dealer	Swap Station
Easy access to end-of-life batteries for manufacturers	◔	●	●	●	◕

Notes: 1) Partnership between NIO and battery manufacturers; 2) Car repair shops, auto wrecks
Source: PwC Strategy&

● High ○ Low

Agenda

Estimation of the recycling market and necessary investments

Considerations on business models

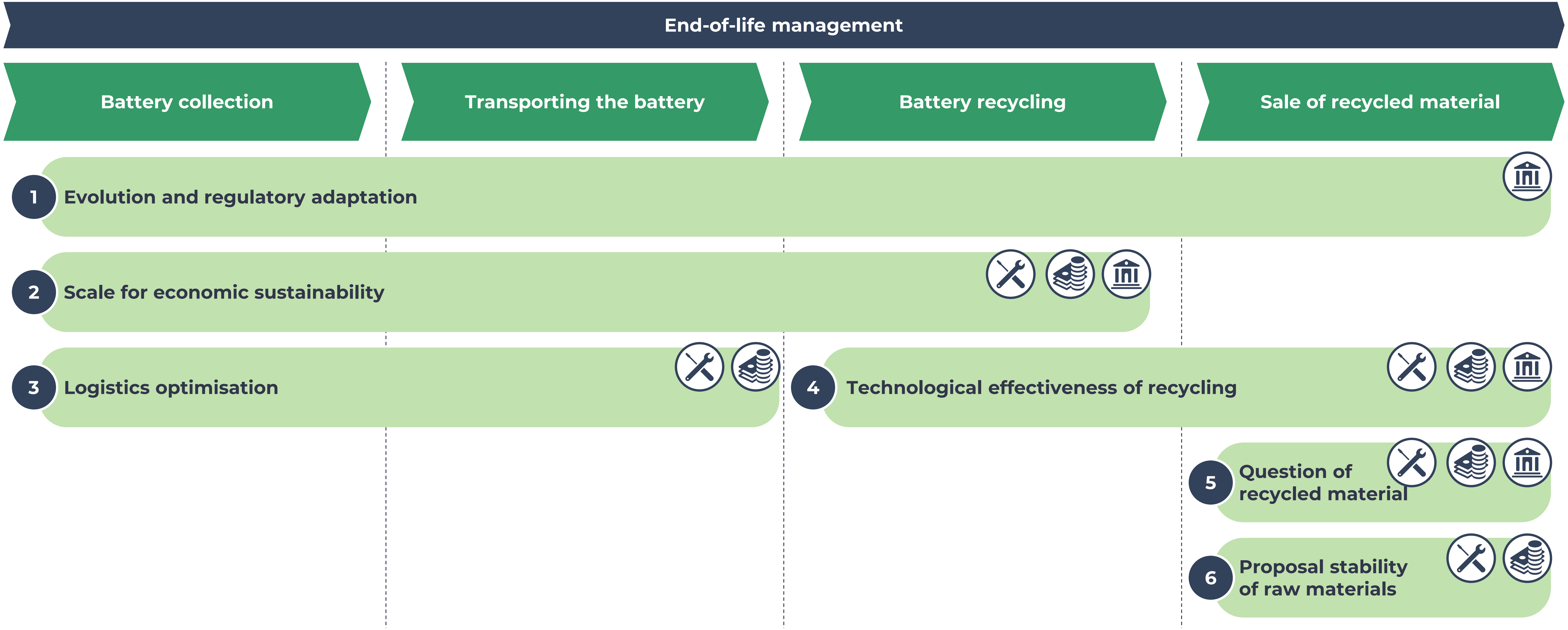
- Main stages and operators in the value chain
- **Factors to success**

Technological view

Success factors of business models

! *The success factors are strongly interrelated, so they should not be considered in isolation*

Six success factors for end-of-life management of batteries have been identified



End-of-life management

Battery collection → **Transporting the battery** → **Battery recycling** → **Sale of recycled material**

1 **Evolution and regulatory adaptation** 🏛

2 **Scale for economic sustainability** 🛠 💰 🏛

3 **Logistics optimisation** 🛠 💰

4 **Technological effectiveness of recycling** 🛠 💰 🏛

5 **Question of recycled material** 🛠 💰 🏛

6 **Proposal stability of raw materials** 🛠 💰

Source: PwC Strategy&

Type of factors 🛠 Technological / Infrastructural 💰 Financial 🏛 References

① Evolution and regulatory adaptation

Evolving European legislation supports end-of-life management of batteries

End-of-life management

Battery collection → **Transporting the battery** → **Battery recycling** → **Sale of recycled material**

Success factors and possible strategies

Regulatory

- The objectives and requirements defined at the regulatory level are key **incentives** for proper end-of-life management
- The regulatory intervention for EV batteries, currently limited, is being defined at Regulatory intervention for EV batteries, **so far limited, is being defined** at **European level**

- Participate in working tables for legislative proposals to ensure **coherence** with **end-of-life vehicle** legislation
- Supporting initiatives to **regulate international material exchanges** in terms of requirements and impacts
- Design **new recycling plants / adapt existing plants** to meet efficiency targets and enable the production of batteries **from high-quality recycled material**

Example of market evidence

Proposal for a European regulation on waste batteries[1]

EPR[1]	Definition of **extended liability obligations for manufacturers** of batteries for electric vehicles
Recycled material content	Definition of **minimum recycled content targets** for specific materials (Lithium, Cobalt, Nickel)
Efficiency of recycling processes	Definition of **minimum recycling efficiency targets** for specific materials (Lithium, Cobalt, Nickel, and Copper)
Exchange of information	Information sharing through an **electronic exchange system** and ***battery passport***
Standardisation	Introduction of **standards** for battery **design** and SoH[2] analysis from a **second life** perspective

Note: 1) EPR = Extended Producer Responsibility; 2) SoH = state of health
Source: Proposal for a Regulation of the European Parliament and of the Council on batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation 2019/1020, 10/12/2020, PwC Strategy&

🟩 Factors to success
🟦 Possible strategies
➡ Impacted phase
➡ Non-impacted phase

❷Scale for economic sustainability

High expected volumes justify investment in recycling infrastructure

End-of-life management

Battery collection | **Transporting the battery** | **Battery recycling** | **Sale of recycled material**

Success factors and possible strategies

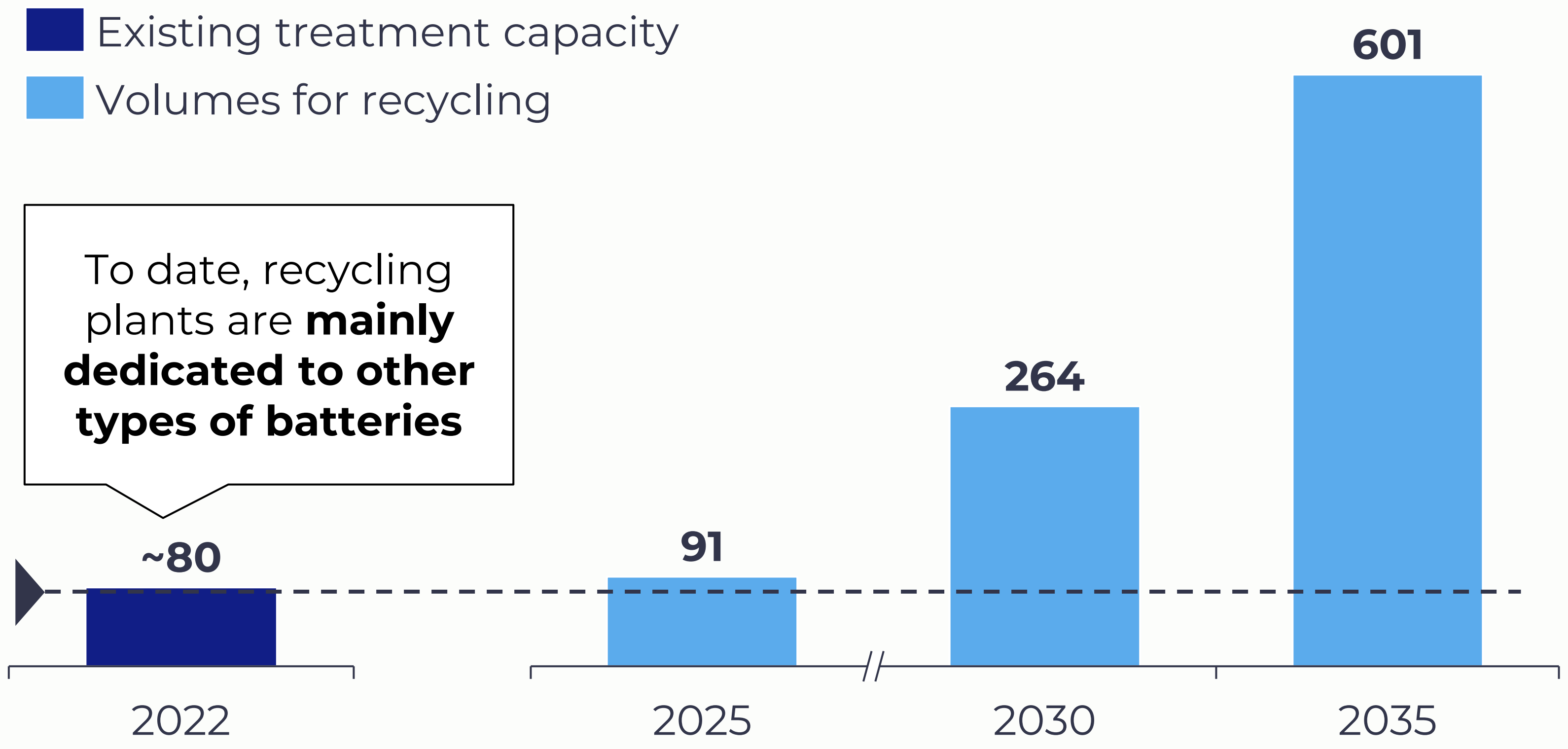
Technological / Infrastructural   Economic   Regulatory

- Collection, transport and recycling activities require **significant input volumes to** ensure the economic sustainability of the model
- **Increasing volumes** of used batteries, exceeding existing treatment capacity, will achieve the scale needed to **justify the infrastructure investment**

- Promote the development of **partnerships** involving **operators along the supply chain** (battery manufacturers, car manufacturers, dealers, logistics operators and recyclers) to **optimise the collection and transport** of end-of-life batteries in terms of:
  - Quality (state of health)
  - Homogeneity of chemical composition
  - Place of collection

Example of market evidence

Evolution of recycling volumes and European capacity *(ktonne)*



To date, recycling plants are **mainly dedicated to other types of batteries**

Source: Politecnico di Milano, PwC Strategy&

🟩 Factors to success
🟦 Possible strategies
▶ Impacted phase
▷ Non-impacted phase

❸ Logistics optimisation

The logistical costs of transporting used batteries are influenced by many factors

End-of-life management

Battery collection → **Transporting the battery** → **Battery recycling** → **Sale of recycled material**

Success factors and possible strategies

Technological / Infrastructural | Economic | Regulatory

- Transport logistics represent **one of the main costs** of battery management at end-of-life and depend on **3 factors**:
  - **Appropriate classification** of used batteries collected according to physical condition (critical vs. non-critical)
  - **Distribution** of used battery **collection** points
  - **Infrastructure capacity** in the territory

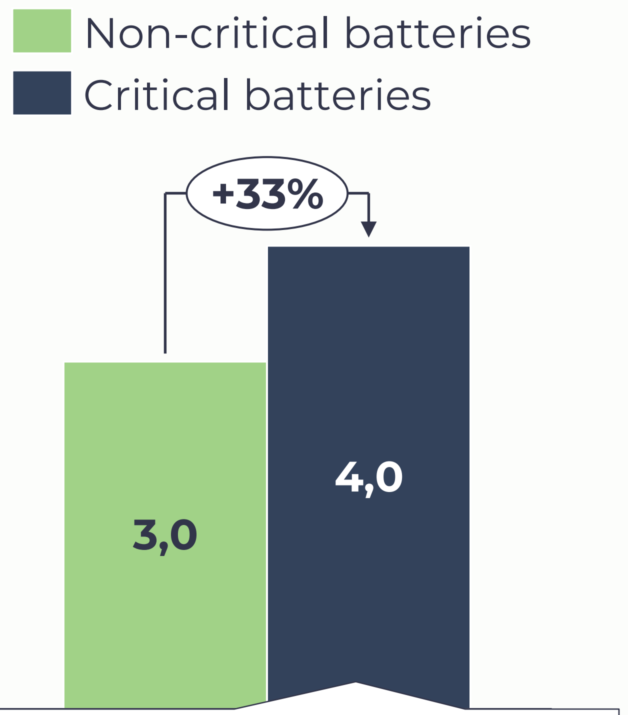
- Developing **procedures and training programmes for** operators involved in the **classification** of used batteries (e.g. *dealers*)
- Promoting, at least in a first phase, EV **sales models** that favour the **concentration of collection points**
- Developing an adequate urban and industrial **infrastructure** in the **territory**, reducing the need for transport abroad

Example of market evidence

Cost of transporting EV batteries by classification *(€/kg)*

Batteries classified as **critical**[1] require that during transport:

- The temperature of the outer surface of the packaging does not exceed 100°C
- No flame can develop on the outside of the packaging
- No projectiles can exit the package
- The structural integrity of the packaging is maintained
- The packaging has a gas management system



These requirements also imply that packages may not be overlapped

Notes: 1) Can rapidly degrade, react dangerously, produce flame, heat, toxic, corrosive or flammable gases, vapours
Source: Cobat, PwC Strategy&

🟩 Factors to success
🟦 Possible strategies
➡ Impacted phase
⇨ Non-impacted phase

❹ Technological effectiveness of recycling

Innovative recycling processes are flanking established treatment solutions

End-of-life management

Battery collection → Transporting the battery → **Battery recycling** → **Sale of recycled material**

Success factors and possible strategies

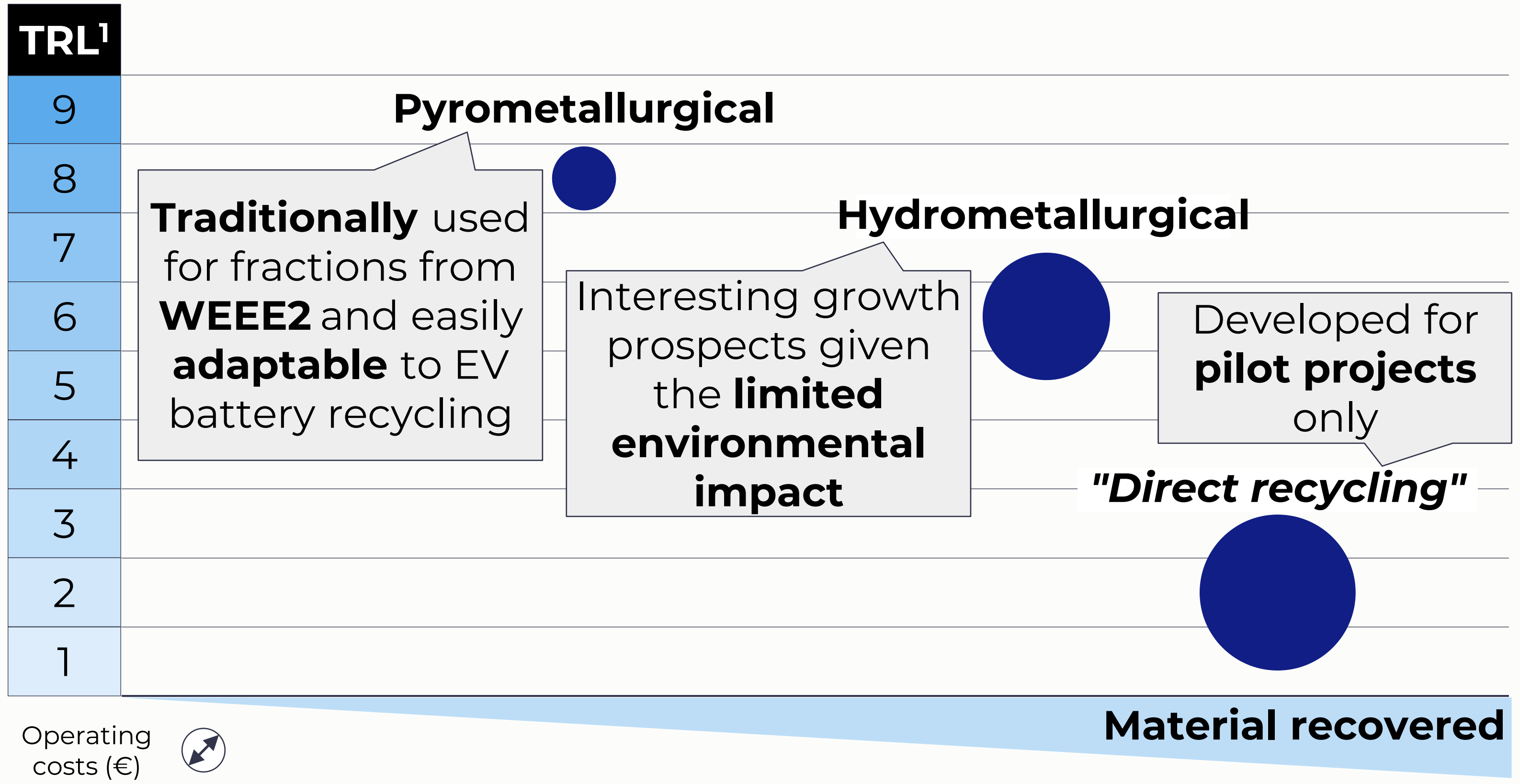
Technological / Infrastructural | Economic

- Recycling processes are evaluated according to their **level of technological maturity** (TRL[1]), **material recovery capacity** and associated **operating costs**

- Promoting the **development** and **adoption** of new technologies that enable efficient and sustainable treatment at economic, environmental and social levels
- Develop **pilot projects** for innovative treatment processes in order to demonstrate their **technical feasibility** and support their **application on a large scale**, optimising the material yield
- Supporting **research projects** with companies, start-ups and universities with the aim of developing **new solutions** and/or **adapting existing solutions**

Example of market evidence

Main processes for battery recycling



Traditionally used for fractions from **WEEE2** and easily **adaptable** to EV battery recycling

Interesting growth prospects given the **limited environmental impact**

Developed for **pilot projects** only

Notes: 1) TRL (Technology Readiness Level) = Level of technological maturity; 2) WEEE = Waste electrical and electronic equipment
Source: Politecnico di Milano, PwC Strategy&

🟩 Factors to success
🟦 Possible strategies
▶ Impacted phase
▷ Non-impacted phase

❺Demand for recycled material

The allocation of recycled material is ensured by demand on different industrial supply chains

End-of-life management

Battery collection

Transporting the battery

Battery recycling

Sale of recycled material

Success factors and possible strategies

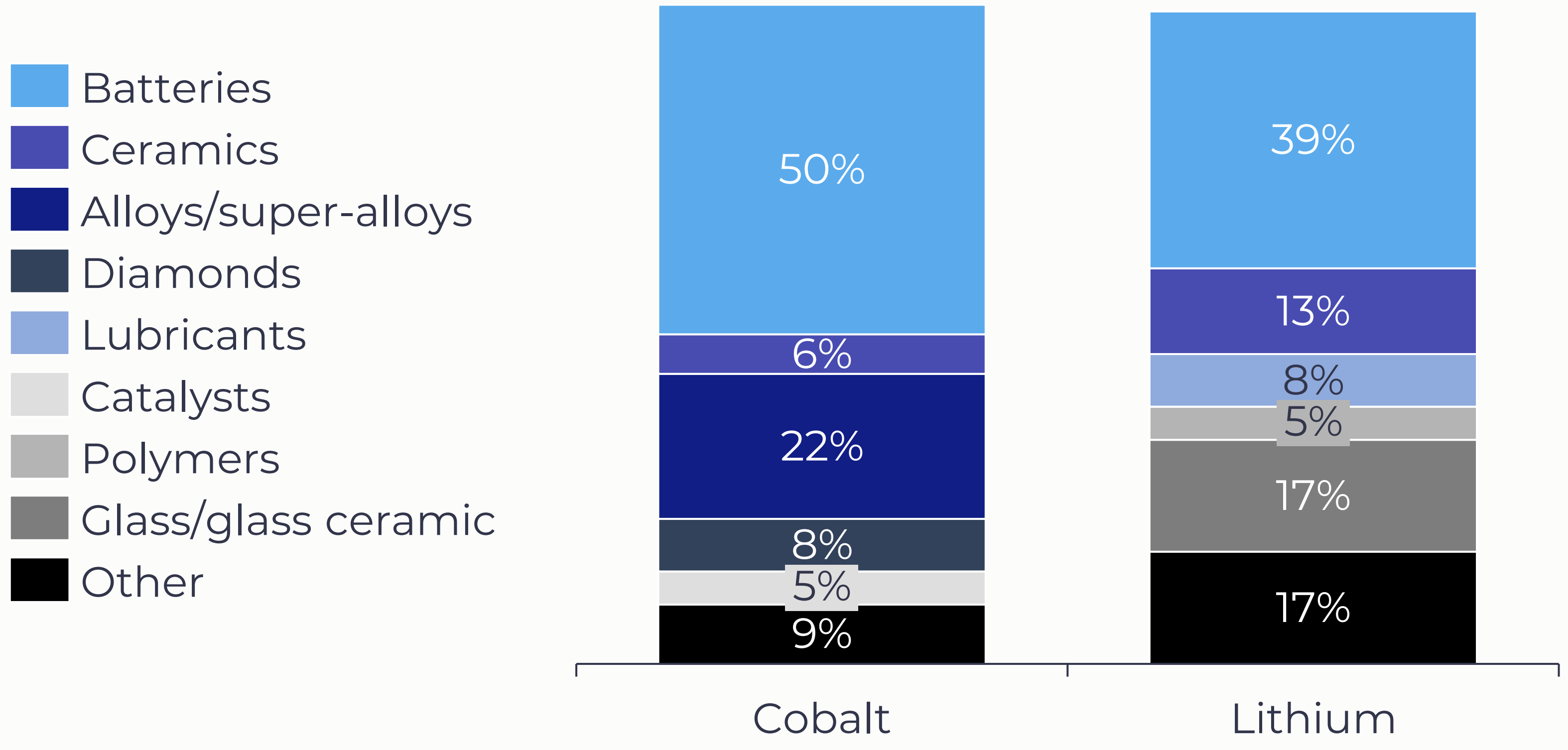
Technological / Infrastructural   Economic   Regulatory

- The effective development and implementation of a supply chain for end-of-life EV batteries requires an **established demand** for **recycled material** from recycling processes, supported by the new European targets
- The **market risk** associated with the allocation of recycled material can be **reduced by diversifying** the **outlet markets**

- **Promote the use of recycled material** for the production of **EV batteries** in order to meet new **European targets**
- Support the development of **certifications** for recycled material to facilitate its application in **industrial supply chains other than** EV batteries, to promote the **replacement** of the current demand for **virgin material** for major battery components (e.g. cobalt, lithium)

Example of market evidence

Distribution of demand among supply chains *(% of total tonnes, 2020)*



Source: Join Research Centre, PwC Strategy&

🟩 Factors to success
🟦 Possible strategies
Impacted phase
Non-impacted phase

❻Stability of raw material proposals

Recycling of end-of-life batteries enables the development of a local and stable proposal of raw materials

End-of-life management

Battery collection → Transporting the battery → Battery recycling → **Sale of recycled material**

Success factors and possible strategies

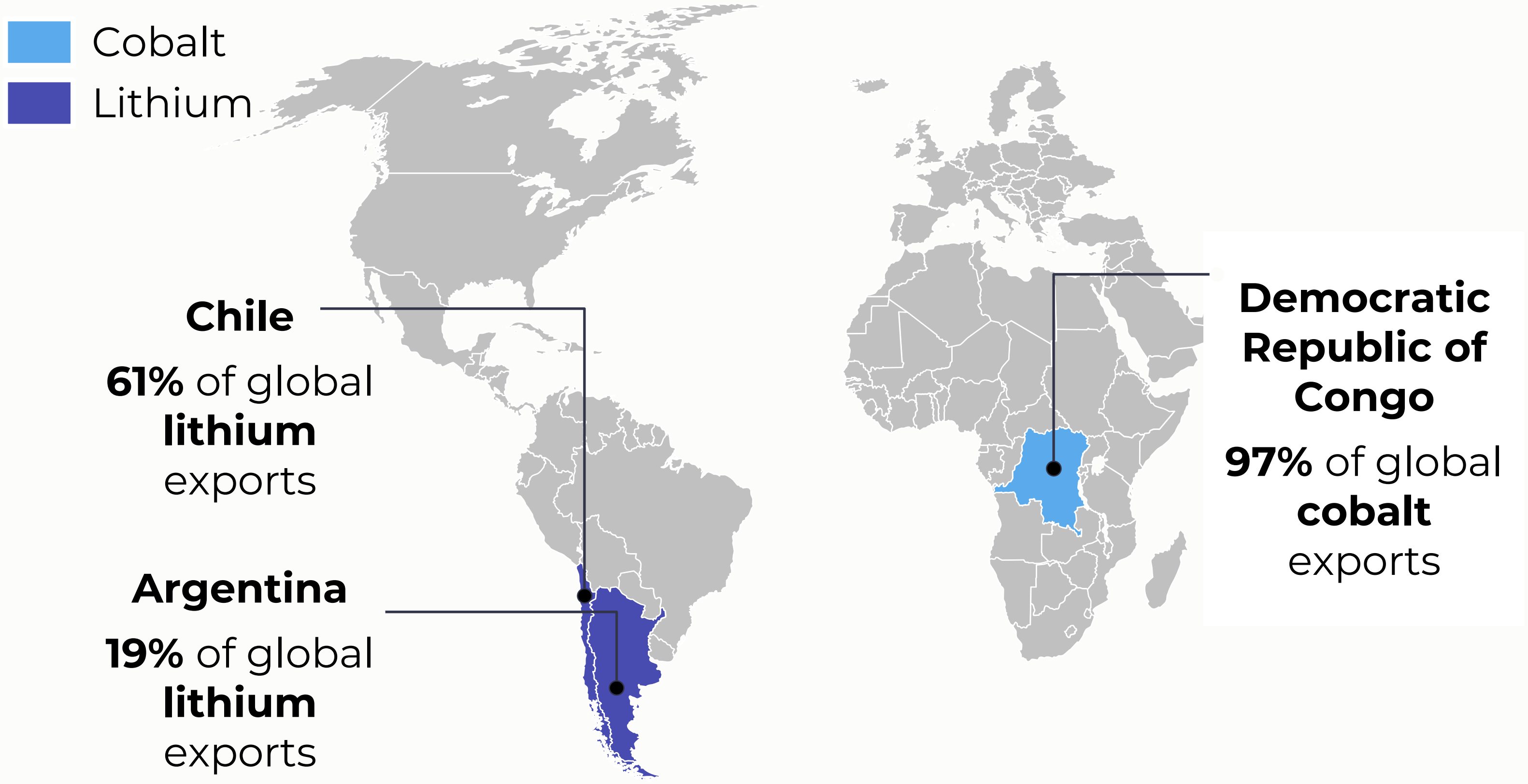
Technological / Infrastructural · Economic

- The development of a **local recycled material supply chain** can **mitigate** the main **sources of instability** in the supply chain of virgin materials for EV batteries, whose **limited availability and accessibility** (price increase and volatility) is due to:
  - **Geographical concentration of mining** in third countries, with environmental and social risks linked to work practices
  - **Demand competitiveness** on other industries

- Support investments in **treatment capacity** at **national** level generate **secondary raw material** for EV batteries
- Promote EV **battery production** in Europe and at home by favouring the use of **recycled material**, also encouraged by the new European targets

Example of market evidence

Share of global export value by country *(% of total, 2020)*



Chile
61% of global **lithium** exports

Argentina
19% of global **lithium** exports

Democratic Republic of Congo
97% of global **cobalt** exports

Source: Join Research Centre, PwC Strategy&

🟩 Factors to success
🟦 Possible strategies
Impacted phase
Non-impacted phase

Agenda

- Estimation of the recycling market and necessary investments
- Considerations on business models
- **Technological view**
  - Recycling processes and technologies
  - Technological trends with impact on recycling processes

Agenda

Estimation of the recycling market and necessary investments

Considerations on business models

Technological view

Recycling processes and technologies

Technological trends with impact on recycling processes

Overview of the recycling process

The recycling process for EV batteries is designed to handle a complex product

Introduction to recycling processes

The battery system

- The **battery** is the main component for cost, volume and weight of the electric vehicle
- Battery **cells** contain precious metals, often in the form of oxides (e.g. cobalt, lithium, manganese), embedded **in a complex layered structure** necessary for the electrochemical reactions that generate the electrical charge and discharge
- The cells are assembled in series and in parallel in a modular structure to form **battery packs**, complemented by structural and electronic support components

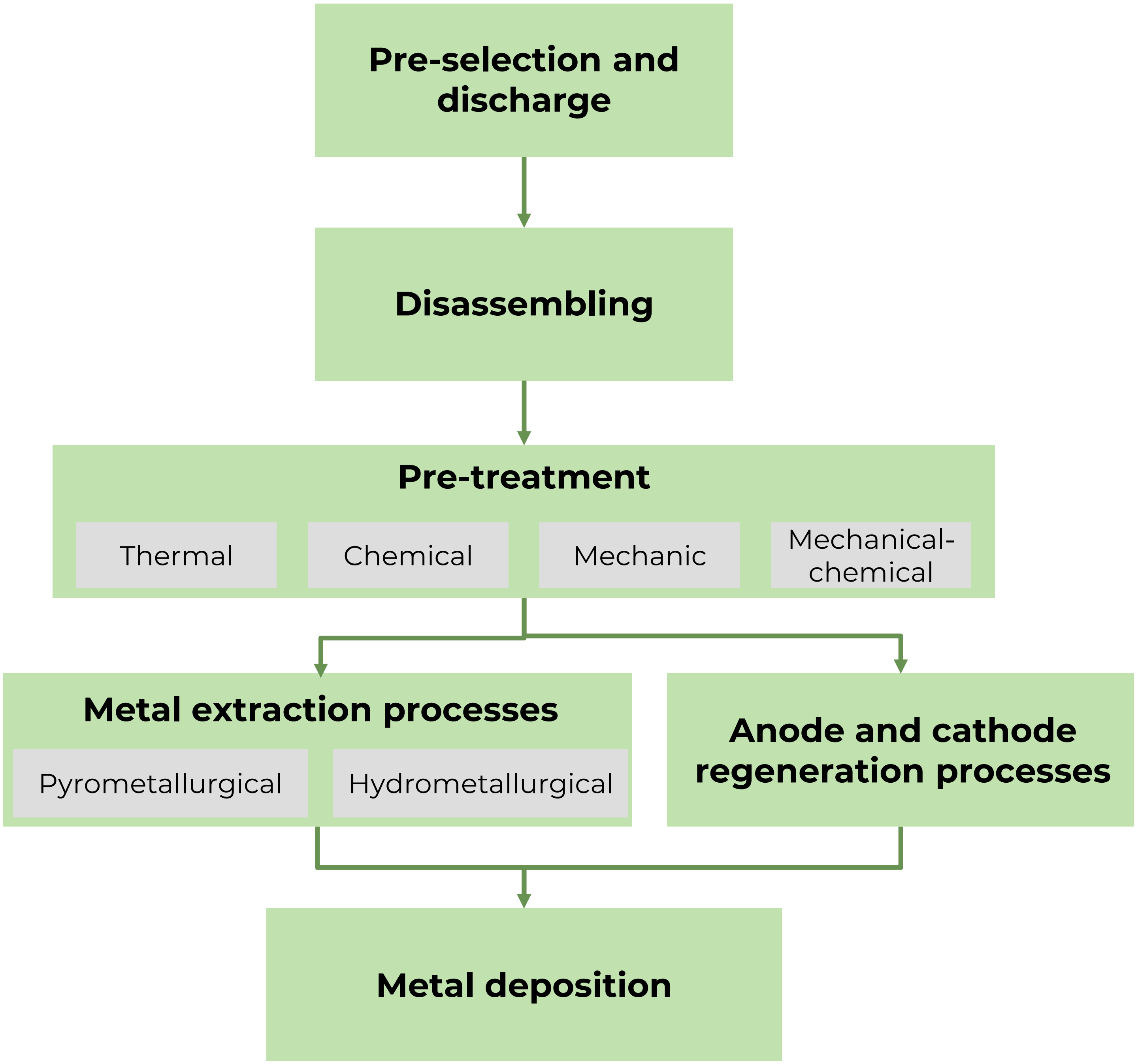
Challenges for the circular economy

- The **complex battery system** is difficult **to treat** in circular value chains
- Recyclers must ensure the proper **safety and preparation** of recycling treatments
- Recycling processes must be designed to **efficiently recover** the high value embodied in batteries

Recycling processes

- The structure of recycling process chains **is not yet consolidated**, but it is possible to outline **4 macro-phases of the treatment**:
  - **Pre-selection and discharge**, to isolate the battery and remove residual energy
  - **Disassembly** of the modules and cells
  - **Pre-treatment** of cells to release and concentrate target metals
  - The **recycling of metals** to obtain secondary raw materials of a quality suitable for industrial use
- Industrial and academic operators are active in **investigating innovative technological solutions** and new operating conditions for recycling processes

Macro-phases of the recycling process



Pre-selection and discharge

Disassembling

Pre-treatment

Thermal

Chemical

Mechanic

Mechanical-chemical

Metal extraction processes

Pyrometallurgical

Hydrometallurgical

Anode and cathode regeneration processes

Metal deposition

Source: Politecnico di Milano

The main steps in the recycling process

The recycling process is structured in 4 main steps

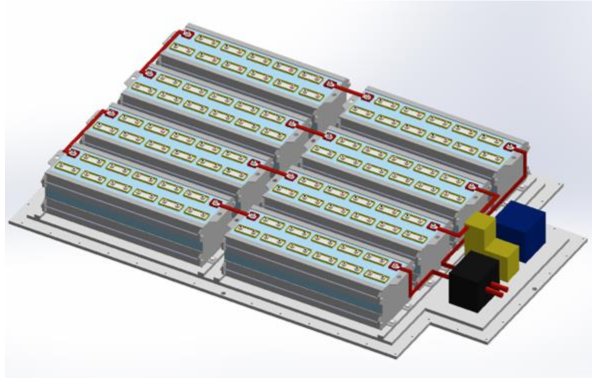
Description

Output

1 Pre-selection and discharge

- The treatment of the battery requires dedicated management, starting with **isolating** it from the rest of the vehicle
- **The safety** of the battery is carried out by means of a **controlled electric discharge**, to dissipate, or recover, the residual energy available in the system

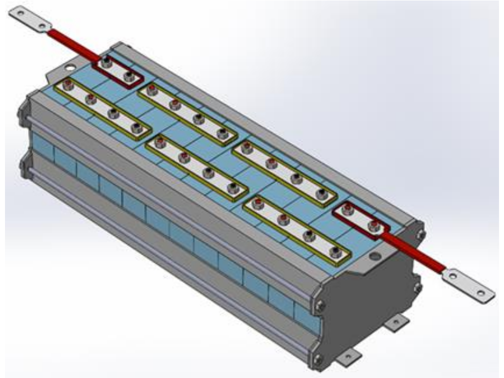
Isolated and secured battery pack



2 Disassembling

- The **disassembly** releases the cells or modules from the superstructure that encases them, so that they can be processed in subsequent process steps
- Battery **components** (e.g. structural elements, cooling electronics) can be allocated to dedicated and consolidated **recovery chains**

Modules and/or cells



3 Pre-treatment

- The **pre-treatment** enables the **and pre-concentration of materials**
- There are **multiple technological strategies** for pre-treatment, whose different efficiency rates impact the overall sustainability of the recycling chain

Mix of cathode and anode powders (black mass)

4 Treatment

- Using **thermal and chemical processes**, the elements inside lithium-ion batteries **are concentrated and isolated**
- Processes vary by **factors:** recovered materials, reagents and operating conditions, efficiency and recovery rate, environmental and economic sustainability

Chemical compounds containing target metals

3 **Li** Lithium

25 **Mn** Manganese

27 **Co** Cobalt

28 **Ni** Nickel

29 **Cu** Copper

strategy& Part of the PwC network

POLITECNICO MILANO 1863

Source: Politecnico di Milano

Pre-selection and discharge

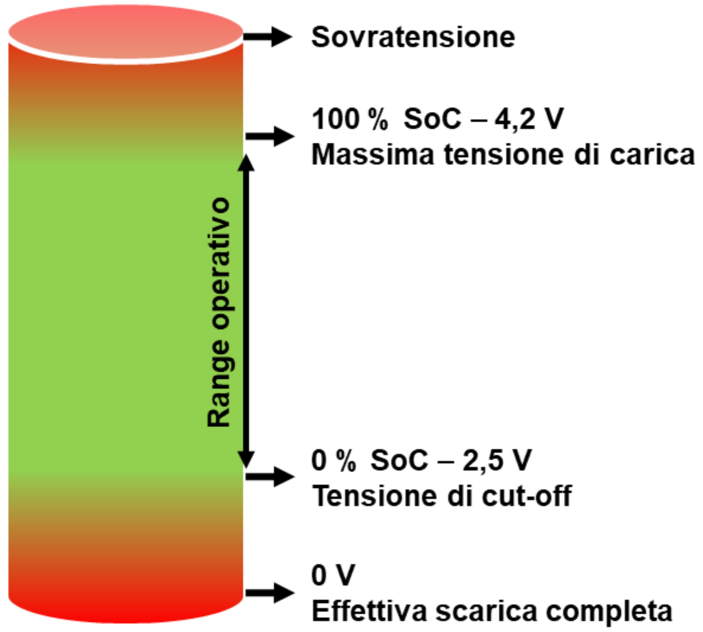
The pre-selection and discharge phases prepare the battery for treatment

Pre-selection

- The pre-selection **isolates the battery from the vehicle**, disassembling it from the vehicle's structural and functional components as a whole
- There are several **accessibility points**:
  - Car bottom for full electric model
  - Boot compartment for hybrid models
- It is necessary to **remove the electronics and liquid cooling circuits** to isolate the battery

Discharge

- The **discharge dissipates or recovers the battery's residual energy**, as during the usage phase, lithium-ion batteries remain in a state of charge (SOC[1]) which never reaches full discharge, with zero voltage and residual energy
- The **latent electrochemical potential** in the battery results in a **risk of electric shock** or possible thermal drift during disassembly and treatment



Examples and applications

- The pre-selection of the battery from the vehicle is often **carried out by experienced car dismantlers and** requires specific precautions:
  - **Isolate the work area** from the risk of electrical shock
  - **Use PPE[2]** (e.g. gloves, dielectric tools and helmets with visor)
  - **Check** the possibility **of propagation of stray** currents in the vehicle and in the battery itself

- Discharge of high capacity batteries can occur:
  - **Applying constant resistance**, through high resistance or medium
  - **Generating constant currents** controlled by electronic equipment, which sometimes allows for the recovery of residual energy
- Industrial-size regenerative discharge systems are currently being developed and constitute an **important cost** item in the profitability of processes

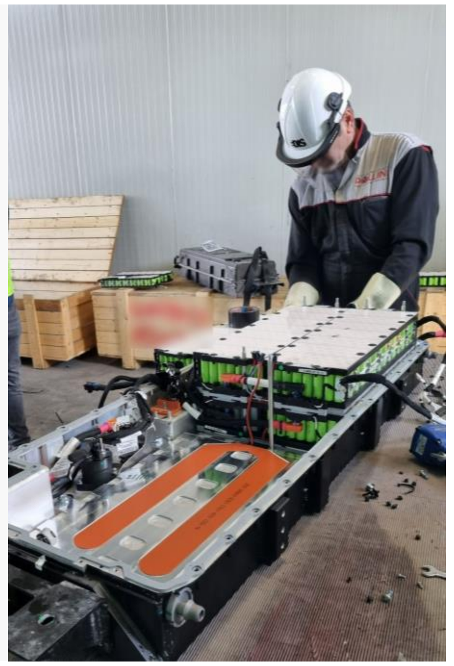
Notes: 1) SoC State of Charge; 2) Personal protective equipment
Source: Politecnico di Milano

Disassembling

Disassembling the battery makes it possible to obtain individual modules and cells

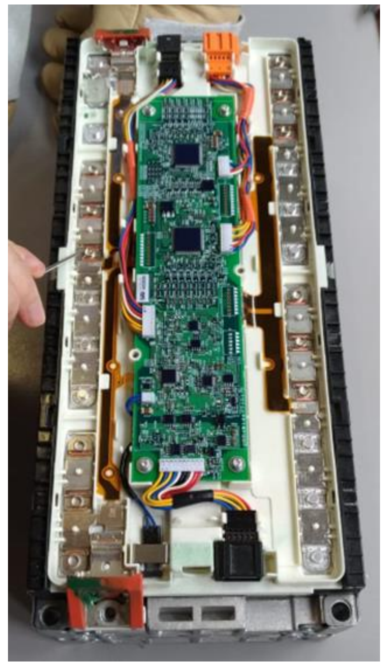
Disassembly at module level

- The **disassembly of the modules from the package** isolates the lithium-ion cells from the complex battery superstructure
- The activities can be formalised and shared by batteries of different architectures and components, through the removal of **external metal cover** , **cooling liquid** (if present), **plugs and safety fuses, power connection block, electronic control devices** and **modules**
- The **joints** between the different components are of a **mechanical** type

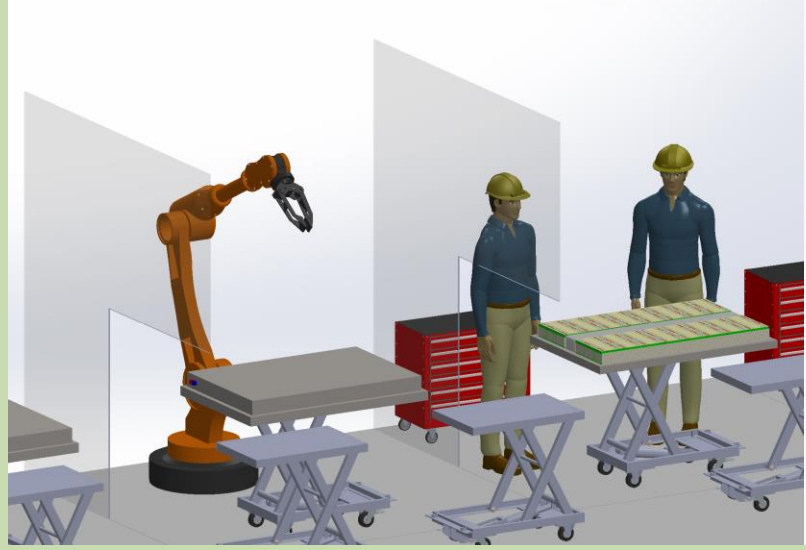


Disassembly at cell level

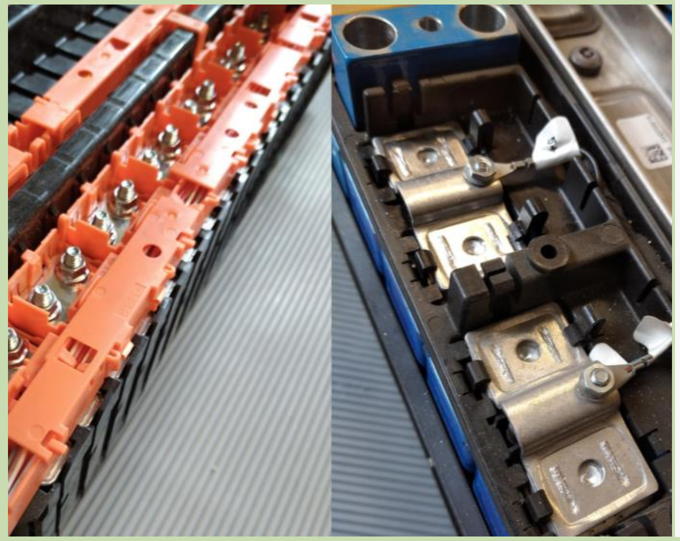
- The **disassembly of the cells from the modules** is an optional step in the disassembly strategy, and ensures the removal of structural and electronic components that would impair downstream recycling performance
- The **joints** between the modules are diversified:
  - The cells are almost always **welded**, often using laser or ultrasonic technology
  - **Glue** is used to improve the stability of the module
  - The external metal case can be **riveted**



Examples and applications



- Disassembly is often **done manually**
- **Process automation** and the realisation of semi-/automated solutions are developed by various research institutes and industrial operators:
  - **Robotic units** for repeatable tasks
  - **Collaborative support units**
  - Entire **semi-automated lines**



- **Process automation** depends on the geometry of the cell[1] and the welding:
  - **Cylindrical:** connected by lamellar busbars through resistance welding
  - **Prismatic:** connected by laser welding metal plates
  - **Pouch:** ultrasonic welding to connect terminals without additional components

Notes: 1) Car makers use three different types of cells: cylindrical, prismatic and pouch
Source: Politecnico di Milano

Pre-treatment

Pre-treatment solutions can be combined to improve efficiency

	Mechanic	Thermal	Chemical	Mechanical-chemical
	• Mechanical pre-treatment **cracks and screens** the cells or modules, exploiting the **fine size** of the cathode and anode material to segregate them from the remaining components • Mechanical pre-treatment processes lithium-ion cells or modules using only **mechanical processes**	• Heat pre-treatment **thermally stimulates** batteries in conventional or microwave ovens (600 – 800°C), at times exploiting the inert atmosphere • The internal thermal drift leads to the**explosion of the cells** and the high temperature **decomposes the binder** (PVDF) releasing the black mass	• Chemical pre-treatment involves **dissolution of the binder** through chemical agents, typically organic solvents, at controlled temperatures (~100°C) • Chemical pre-treatment is always **preceded by mechanical processing** to release the active material	• Mechanical-chemical pre-treatment combines the mechanical and chemical processes in a **single stage** • The most exploited mechanical-chemical process is **wet grinding**, which uses grinding chambers immersed in aqueous solutions. *More efficient solution*
Pros	• **Economic and environmental sustainability** for low energy consumption and absence of reagents • **Low investment cost** and consequent scalability	• Possibility of **using the residual energy** of batteries that are not fully discharged to power overheating • Excellent **release of the binder**	• Pre-treatment **not very aggressive** for the other components present • Low temperature**binder release**	• More **robust and industrially attractive** pre-treatment than purely chemical ones • **Lithium dissolution**
Cons	• **Inability to decompose the binder**, and consequent difficulty in segregating the black mass from the other components • **Risk of contamination** of the black mass	• Highly **energy-intensive** process • **Dissolution or thermal degradation** of various organic and non-organic materials	• **The effectiveness** of the pre-treatment influenced by **factors that are difficult to control**: the quality of the incoming material, the solvent concentration and the type of binder.	• **High rate of water recirculation** during grinding, due to the need to keep the lithium concentration low

Source: Politecnico di Milano

Treatment for metal extraction

There are two treatment processes for metal extraction, with different outputs

Metal extraction process

Pyrometallurgical

- **Mature technological option** involving the stimulation of chemical and physical reactions through **high operating temperatures**
- The final stage is the **casting of an alloy rich in cobalt, copper and nickel**, which is then destined for subsequent chemical purification
- **Preliminary roasting and/or calcination phases** may be included, to isolate cathode metals by reducing oxygen and introducing carbon to create CO2, obtaining a pre-concentrate to be purified by hydrometallurgy and recovering lithium in the form of carbonate

Hydrometallurgical

- **Three main phases**

① **Smoothing**: solubilisation of black mass metal oxides, for which the most industrially used method is aggression through inorganic acids1;alternatively it is possible to use organic^{acids2}, ammonia or microorganisms (bio-leaching)

② **Purification** of the resulting solutions and metal compounds

③ **Chemical precipitation** (by oxalates), solvent extraction and electrolytic deposition

	Pyrometallurgical	Hydrometallurgical
Pros	• **Reliability** in handling variable and poorly controlled inputs • High **production rates** • **Low emissions** of volatile organic residues and harmful gases	• More suitable solution for metal **recovery** , in particular **lithium and cobalt** • **Higher recovery rates** than in pyrometallurgy • Wider portfolio of **upgradeable materials**
Cons	• High operating **temperatures** and high **energy consumption** • **Lower recovery rate** of target materials compared to hydrometallurgical processes	• **Processes that are difficult to control**, as they are very sensitive to input black mass, especially when contaminated with aluminium and copper
Output	• The cast alloy produced downstream of pyrometallurgical processes enables the recovery of **cobalt, nickel and copper** with efficiencies of Co > 80 %; Ni ~ 95 %; Cu ~ 95 %. • All other materials are considered **waste** • **By roasting,** almost **all cathode metals can be obtained**: – For NMCs, the recovery efficiency reaches Ni 98%, Mn 98%, Co 93% – Lithium carbonate with efficiency above 90% can also be obtained	• The type of chemical compounds that can be obtained and their recovery efficiency strongly depends on the type of reagents and chemical reactions used • **Inorganic acids** allow **efficiencies of over 90%** even on an industrial scale and have been demonstrated in the laboratory to recover up to 100% Li, 99% Mn, 98% Co, 96% Ni

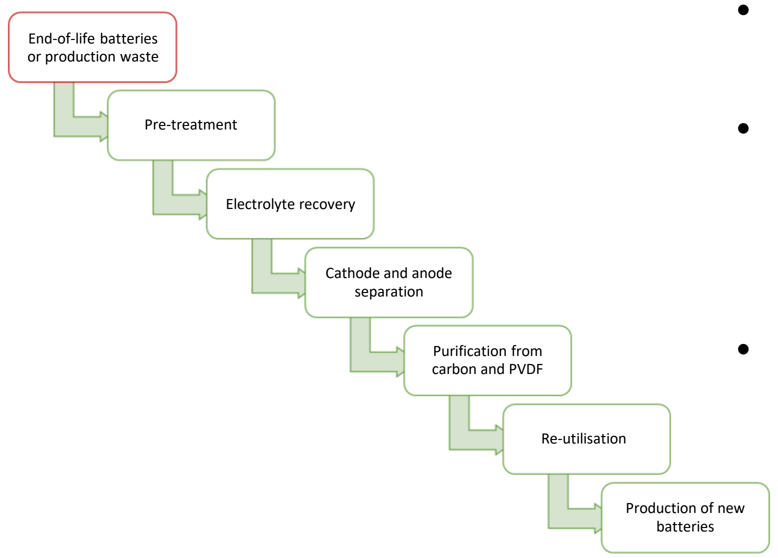
Notes: 1) HCI, H2SO4, HNO3; 2) Typically citric acid
Source: Politecnico di Milano

Treatment for regeneration

Direct recycling is an innovative process for anode and cathode regeneration

Anode and cathode regeneration process

Direct recycling



- Direct recycling is a **new technological frontier.** The batteries are processed **recover active anodic and cathodic material** and reusable in the production of new batteries by closing the loop without going through individual precursor chemicals
- The two components of anode and cathode can be segregated from the black mass composed of both with good efficiency by **foam flotation processes**, exploiting the different degree of hydrophilicity of cathode and anode. Finally, chemical and heat treatments reactivate the lithium at the cathode and complete direct recycling. These so-called **"division"** processes constitute the innovative, often patented focus of the actors studying these processes
- Direct recycling requires the treatment of **uniform batteries**, both in terms of cathode chemistry and constituent materials, **perfectly known and uncontaminated** and requires pre-treatment technologies that guarantee the production of **black mass with very little contamination of metal and polymeric fractions**

Direct recycling processes are so far demonstrated in **laboratory scale and highly controlled pilot plants** . The strong constraints mentioned above suggest their applicability to recovering **scrap and waste from "circular" gig-factories**

Pros

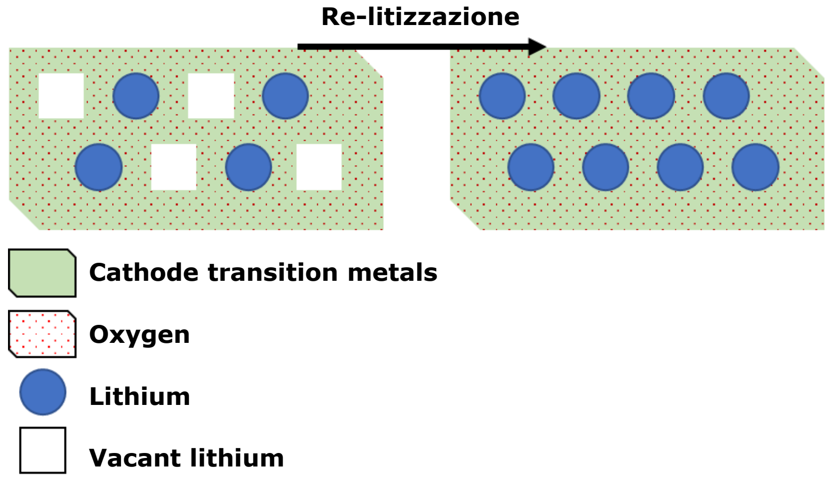
- **High added value** obtained from the output of the process
- The process is also desirable for **batteries low in precious metals** such as Cobalt (e.g. LFP)

Cons

- Need to process **very uniform input material**
- Need to use **specific pre-treatments to obtain the black mass**

Output

- **The anode**, typically graphite, retains traces of PVDF (binder) with which it shares the hydrophobic character
- The composition of the **cathode** reflects the chemistry in input



Source: Politecnico di Milano

Technical difficulties and potential solutions

Technical difficulties along the value chain require targeted solutions

	Technical difficulties	Value chain issue	Potential solutions
1	**High variability of circulating batteries** in terms of constituent materials and assembly strategies	Difficulty in **diversifying** treatment	Development of **technologies flexible and adaptive**
2	Inherent risks in handling batteries such as **electric shock, thermal drift, harmful gases**	**Danger** to operators at different stages of the operational chain	Identification of **risks** and the development **of support devices**
3	**Trade-off** between opportunities related to the **recycling and the second life** of batteries for stationary applications	Risk of **not optimising** the recovery of the residual value of the battery	Development **of decision support systems for** end-of-life battery management
4	**Lack of nominal** and usage phase data of the battery	Independent and redundant **search** for data useful for processing	**Digital product passport** that shares the minimum quantity of useful information

Source: Politecnico di Milano

Agenda

Estimation of the recycling market and necessary investments

Considerations on business models

Technological view

Recycling processes and technologies

Technological trends with impact on recycling processes

Industry drivers and technology trends

5 major industry drivers generate 4 new trends for battery technologies

Industrial drivers

1. **Need to automate production processes**
2. **Reduction in production costs / cost of raw materials**
3. **Requirement for more mileage**
4. **Increased battery life cycles**
5. **Increased battery safety**

Focus on the next slides

Technological trends		Reason
1 Battery design	Distribution of **prismatic cells**	Thanks to the greater size and rigidity, **prismatic cells** can **be handled more easily** than other cells by transport systems and automatic lines, facilitating the automation of battery production processes
	More **modular** and structured product design	The greater need to automate and speed up assembly combined with less dependence on structural retrofitting logic lead to the design of **more orderly and rational battery packs**
2 Cathode	Reduction of critical and hard-to-find materials within the **cathode**	The macro-trends of Europeanisation of the battery production chain for the coming years require a **drastic reduction in the use of critical metals** for cathode materials, penalised by a highly unstable and uncertain supply chain
3 Anode	Increased energy density through innovative **anode**	**The increase in energy density allows the increase in range**; the bulkiest component at present is the graphite anode, the replacement of which could benefit substantially on the overall energy density of the cells
4 Electrolyte	Use of **solid state electrolyte**	One of the main electrochemical degradation mechanisms is the reduction of the electrolyte to form what is known as SEI[1], which is most evident at high temperatures and voltages and can be **overcome through the use of solid electrolytes**
		The use of solid electrolyte would bring **two joint advantages relating to battery** safety: it would avert the risk of combustion of the liquid electrolyte and allow the use of metal anodes without the formation and propagation of dendrites

Notes: 1) SEI = Solid Electolyte Interphase
Source: Politecnico di Milano, internal processing

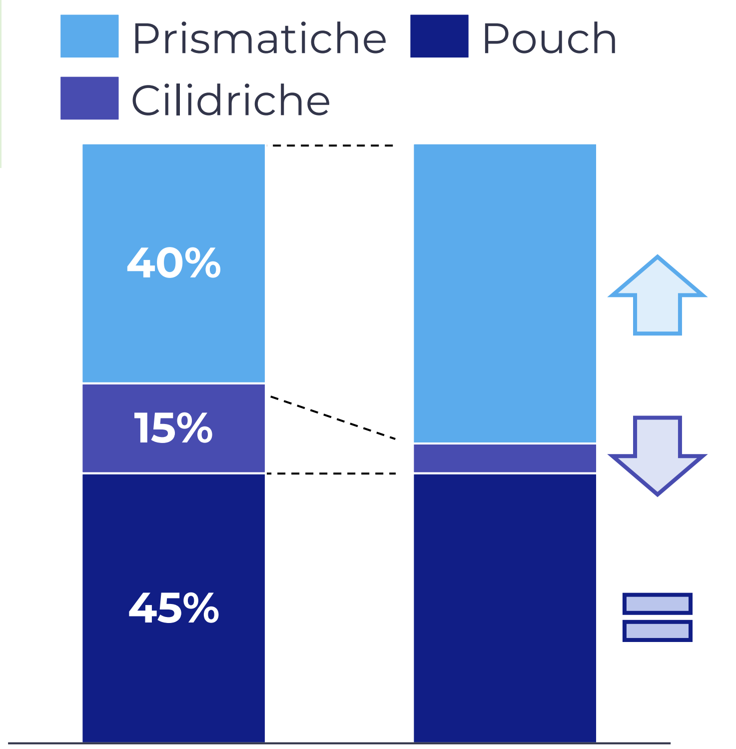
New designs for batteries

Design innovations affect cell geometry and battery layout

Cell geometry

Type	Configuration	Mechanical resistance	Thermal exchange	Specific energy (mass)	Energy density (volume)
Prismatic	Spiral, with tolerances	◕ Aluminium casing	◕	◕	●
Cylindrical	Spiral, optimal use of space	◕ Casing steel	◑	◕	◕
Pouch	Zig-zag, good use of space	◔ No rigid parts	●	●	◕

AS IS **Trends**



Impact on the process

The more extensive use of **prismatic cells** (larger in size and capacity, as well as more easily manipulated) is to be seen from the perspective of **automation** and greater production rate of battery assembly systems

Battery layout

Type	Configuration	Joints
First generation	Retrofit, to fit into old chassis	Diversified and manually grafted
Second generation	Rational, compact, modular	Standardised and grafted in-line

AS IS: Increasing adoption of **second-generation batteries**

Trends: Adoption of the **cell-to-pack method,** which provides for the insertion of battery cells without the use of modules

Impact on the process: **Rational and standardised** assembly solutions aimed at automation will simplify the disassembly process

● High
○ Low

Source: Politecnico di Milano

Evolution of cathode chemistry

The cathode will evolve towards a progressive reduction of Cobalt

	AS IS			Trends			
Main chemicals	**Cobalt-rich[1]**	**LFP**	**NCA**	**Nickel-rich[2]**		**Li-S**	**Lithium - oxygen**
	NMC 111			**NMC 622**	**NMC 811**		
Properties	**Good capacity**, power, service life and reliability	**Excellent reliability**, service life and power, decent capacity	**Excellent capacity**, good power and service life, decent reliability	Compared to traditional NMCs: greater **capacity**, **shorter service life** and greater sensitivity to thermal stress		The cathode is distorted from a mixture of **metal oxides** to poor materials such as **sulphur and oxygen**.	
TRL	9	9	9	6-8	4-5	3-5	2-3
Pros	Most common chemistry Widely tested and reliable	No risk of thermal drift	Performance comparable to NMCs	Low cobalt content, higher capacity		Excellent energy density Low cost of materials	Good energy density
Cons	High percentage of cobalt	Poorer performance than NMCs	High percentage of cobalt	Shorter service life and greater sensitivity to thermal stress		Low service life	Instability Interface resistance

Impact on the process

- Irrespective of the mix of cathode types used in the future, the trend of **decreasing cobalt use** in future battery generations is clear
- This will have strong **implications for the economic viability** of pyrometallurgical processes, which rely mainly on cobalt recovery
- Alternative strategies such as **hydrometallurgy or direct recycling** will be able to leverage more materials and battery functionality

Notes: 1) Cathode with higher Cobalt concentration; 2) Cathode with higher Nickel concentration
Source: Politecnico di Milano

Evolution of anode chemistry

The anode will evolve towards greater stability, performance and energy density

	AS IS		Trends		
Main chemicals	**Graphite**	**Lithium titanium oxide**	**Graphite-silicon composite**	**Silicon**	**Lithium metal**
Properties	This material is **easy to find** and is the commercial choice for almost all lithium-ion batteries to date	An alternative to graphite, with special properties such as **high thermal stability**; rarely used in the automotive sector	The integration of silicon in the graphite anode, up to the borderline case of its complete replacement, **increases energy density** while maintaining the use of easily available materials and excellent environmental sustainability		This anodic configuration **excludes any lithium housing structure**, forming a metal layer between the copper collector and the solid electrolyte separator
TRL	9	9	6-8	3-5	2-4
Pros	• Low cost • Low volumetric excursion between charge and discharge	• Ability to handle high C-rates • Good useful life • Low volumetric excursion	• High capacity • High stability • Non-toxic materials		• Excellent energy density and consequent capacity
Cons	• Low energy density	• High cost • Low capacity • Low rated voltage	• High volumetric excursion • Reduced electrical performance		• High instability and high risks due to dendrites and possible accidents

Impact on the process

- The possible **introduction of titanium** in commercial batteries would merit a dedicated review of recovery processes, but there are no particular market signals in this regard
- The gradual **replacement of graphite with silicon** would not affect recycling processes; both materials can be considered as "non-metallic contaminants" of the black mass
- The recycling of **lithium metal batteries** requires an **inertisation of the active material** during the pre-treatment phases. Typically, cryogenic crushing is carried out in an inert environment. The subsequent stages of the recycling chain are not altered in any particular way

Source: Politecnico di Milano

Evolution of electrolyte chemistry

A transition of electrolyte chemistry from liquid to solid state is expected

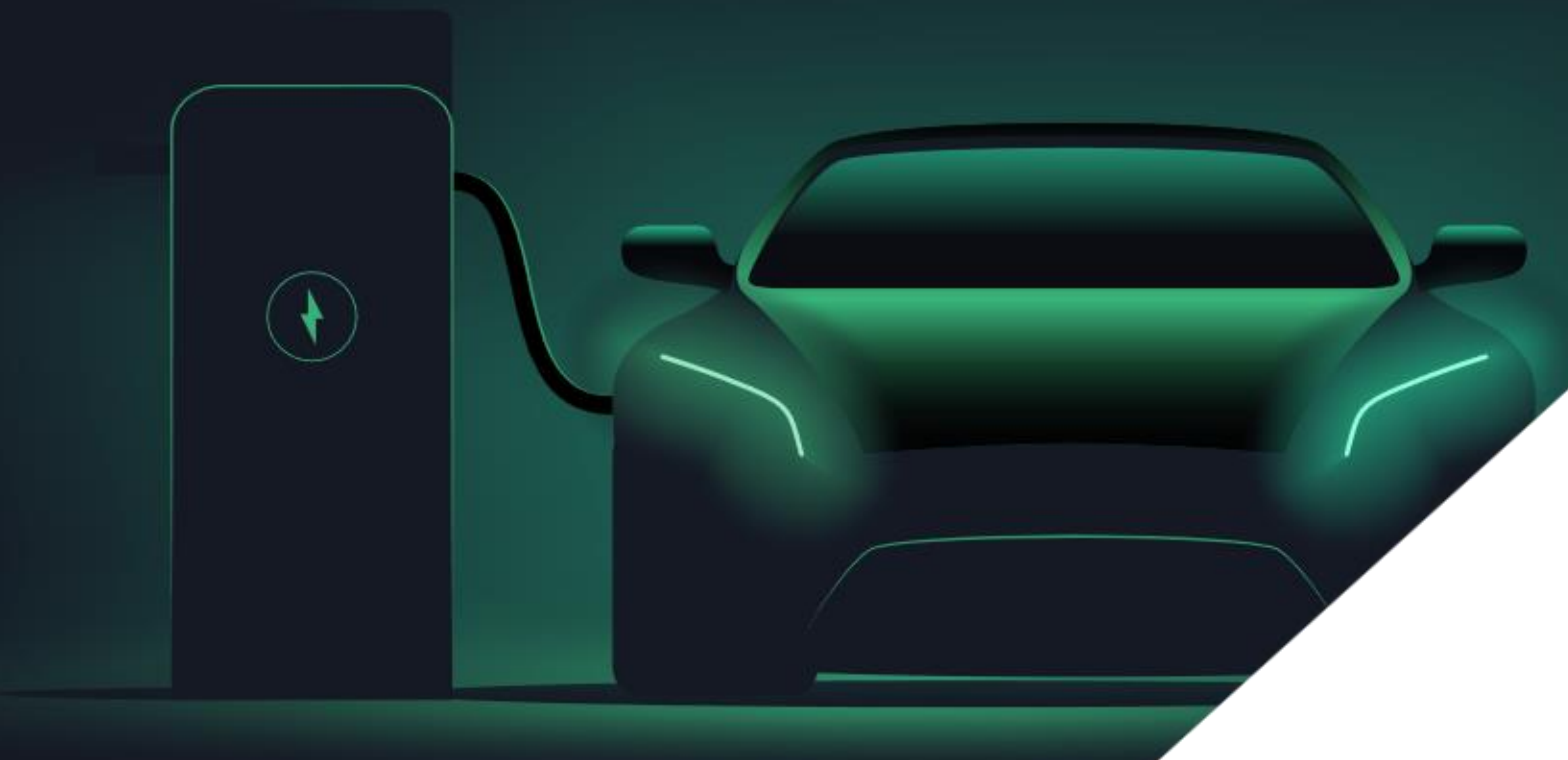
	AS IS	Trends	
Main chemicals	**Liquid electrolyte**	**Solid ceramic electrolyte**	**Polymeric solid electrolyte**
Properties	**Liquid electrolyte** is, by its very nature, the alternative available today that most facilitates the passage of lithium ions between cathode and anode. This key feature provides it with a particularly attractive proposition for automotive applications, which need responsive and dynamic batteries	Mainly **sulphites, oxides or phosphates**, whose crystalline configuration provides them with the ability to create thin films. They are particularly suitable for use at high temperatures	They may have **solid or gel consistency**; in particular, the gel electrolyte incorporates liquid particles in a polymer matrix (typically PVDF, also used as an electrode binder)
TRL	9	3-4	3-4
Pros	• High conductivity of lithium ions	• Good performance at high temperatures and demanding operating conditions	• Maintains greater flexibility, easily manageable in large-scale production
Cons	• Electrochemical instability and uncontrolled formation of SEI[1] • Flammability • Creation of overpressure during short circuits • Need for evacuation through valves	• Low ionic conductivity severely limits the use of solid electrolyte in the automotive sector	

Impact on the process

- The ceramic or organic nature of **solid electrolytes** does not particularly interfere with metallurgical processes
- The presence of **ceramic material** could contaminate the **black mass**, lowering the concentration of target metals
- **The gel electrolyte** could affect the **crushing and screening**processes, if the release of these materials does not favour the evaporation of the liquid fraction

Notes: 1) Solid electrolyte interphase
Source: Politecnico di Milano

Thank you



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Appendix

Glossary abbreviations

Abbreviation	Language	Extended term	Extended term translation
BEV	English	Battery electric vehicle	Battery electric vehicle
BMS	English	Battery management system	Battery management system
PPE	Italian	Personal protective equipment	Personal protective equipment
EPR	English	Extended producer responsibility	Extended producer responsibility
EV	English	Electric vehicle	Electric vehicle
HDV	English	Heavy-duty vehicle	Heavy-duty vehicle
LCV	English	Light commercial vehicle	Light commercial vehicle
LFP	English	Lithium Iron Phosphate	Lithium iron phosphate
LNMO	English	Lithium Nickel Manganese Oxide	Lithium nickel manganese oxide
LNO	English	Lithium Nickel Oxide	Lithium nickel oxide
NCA	English	Lithium Nickel Cobalt Aluminium Oxide	Lithium, nickel, cobalt and aluminium oxide
NMC	English	Lithium Nickel Manganese Cobalt Oxide	Lithium, nickel, manganese and cobalt
PC	English	Passenger Car	Passenger Car
PHEV	English	Plug-in hybrid electric vehicle	Plug-in hybrid electric vehicle
RAEE	Italian	Waste from electrical and electronic equipment	Waste from electrical and electronic equipment
SEI	English	Solid electrolyte interphase	Solid electrolyte interface
SOC	English	State of charge	State of charge
SoH	English	State of health	State of health
TRL	English	Technology readiness level	Technology readiness level

Notes: 1) The scenario considered includes only HDV and Bus with BEV technologies; 2) SoH = State of Health
Source: PwC Strategy&

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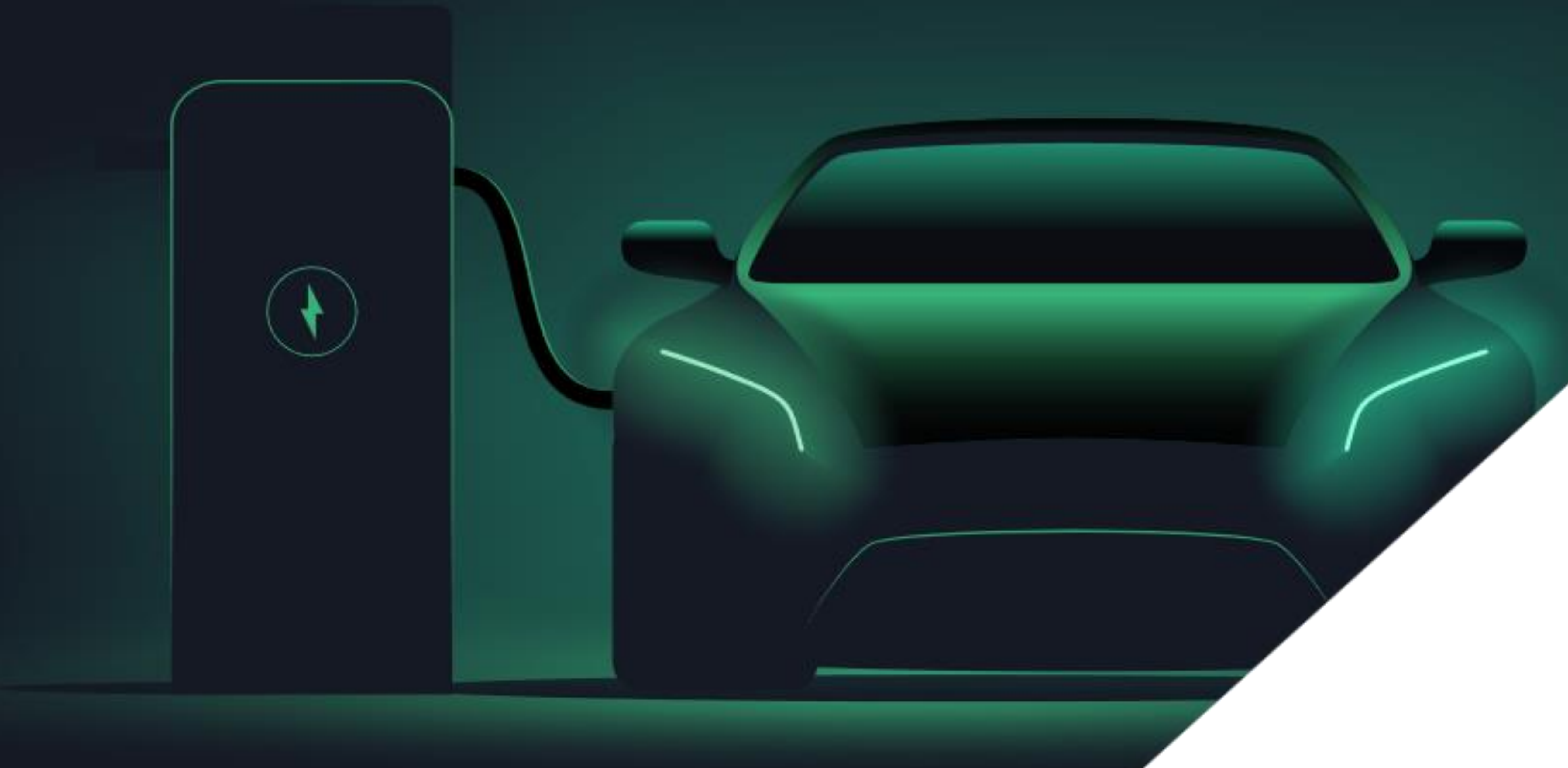

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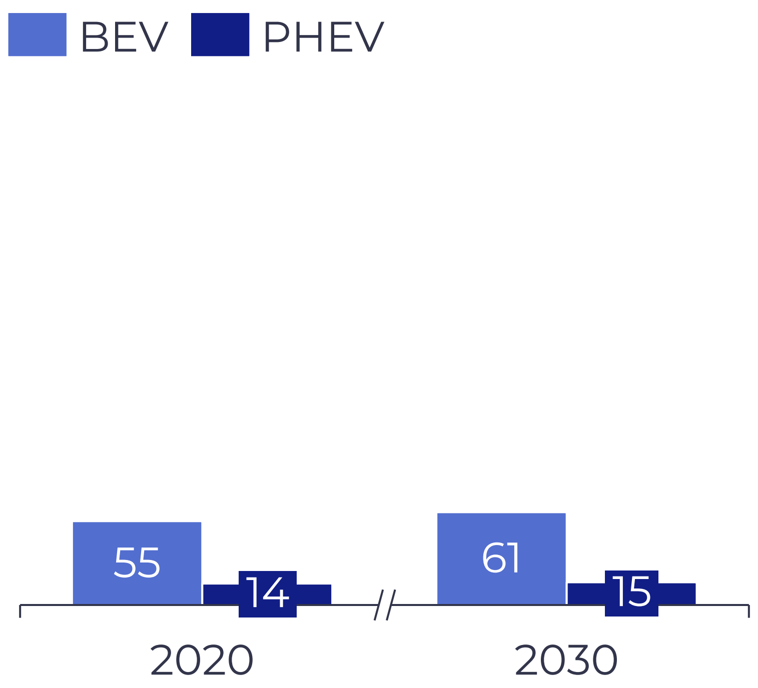
Appendix – for internal use

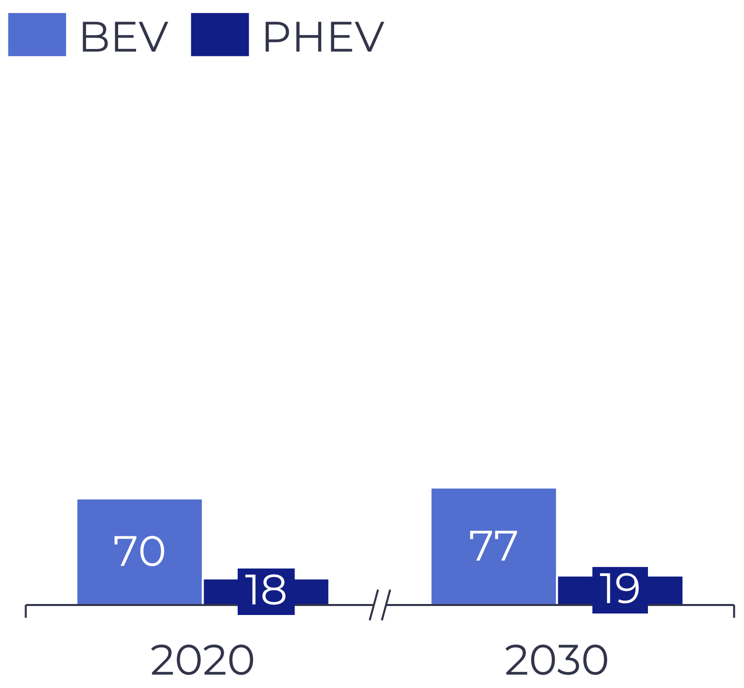
Battery capacity

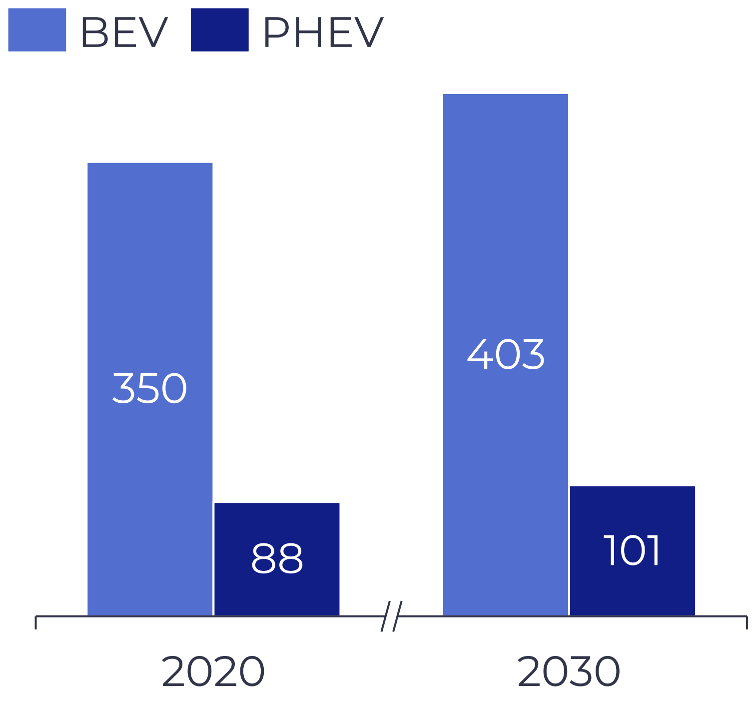
Improved capacity is estimated for all vehicle categories and models

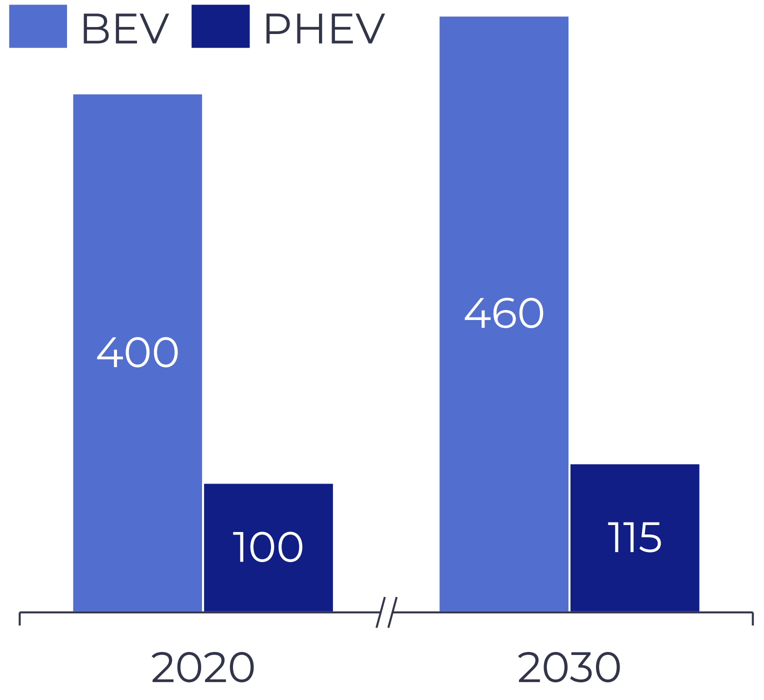
	Passenger car	Light Commercial Vehicle	Heavy Duty Vehicle[1]	Bus[2]
Hypothesis	• **10% improvement** in battery performance from **2020 to 2030** for both BEV and PHEV models • **No improvement** anticipated **after 2030**	• **Improved** battery performance **in line** with the expected evolution for the **PC category** (10% from 2020 to 2030 for both BEV and PHEV models and no improvement after 2030) • **PHEV** battery capacity is predicted to be **25% of BEV CAPACITY**	• Improvement of **battery performance by 15% from 2020 to 2030** for both BEV and PHEV models (higher improvement margins compared to PC/LCV categories given the early stage of technology development) • **No improvement** anticipated **after 2030**	• **Improved** battery performance **in line** with the expected evolution for the **PC category** (15% from 2020 to 2030 for both BEV and PHEV models and no improvement after 2030) • **PHEV** battery capacity is predicted to be **25% of BEV CAPACITY**

Capacity development (kWh)







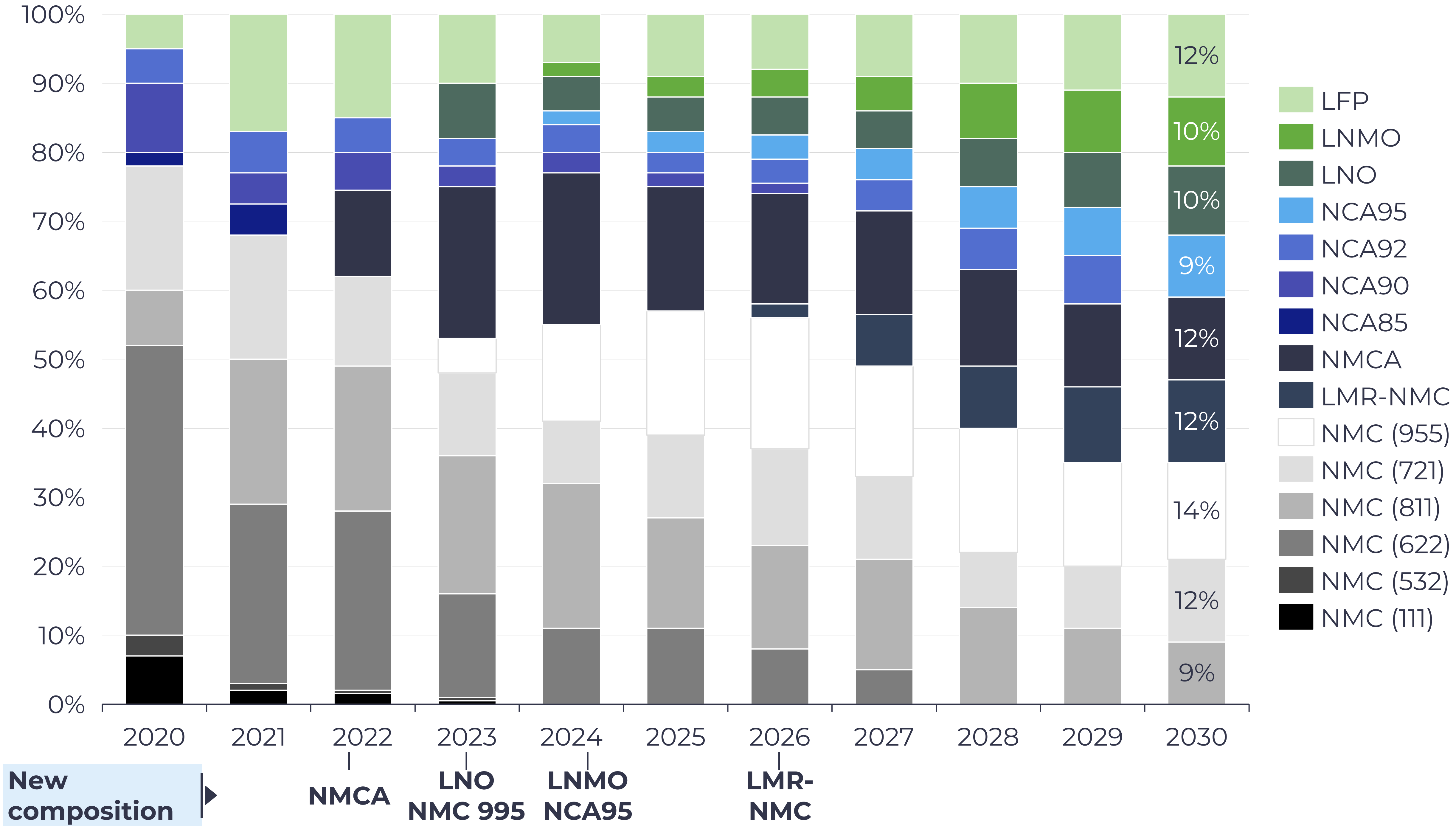


Notes: 1) Average value for different types of heavy vehicles; 2) Average value for different types of buses
Source: IEA, Motus-e, PwC Strategy&

Cathode chemistry for PC and LCV

The trend in chemical composition shows a progressive reduction of cobalt

Evolution of the chemical composition of the cathode of EV batteries sold (% of total)



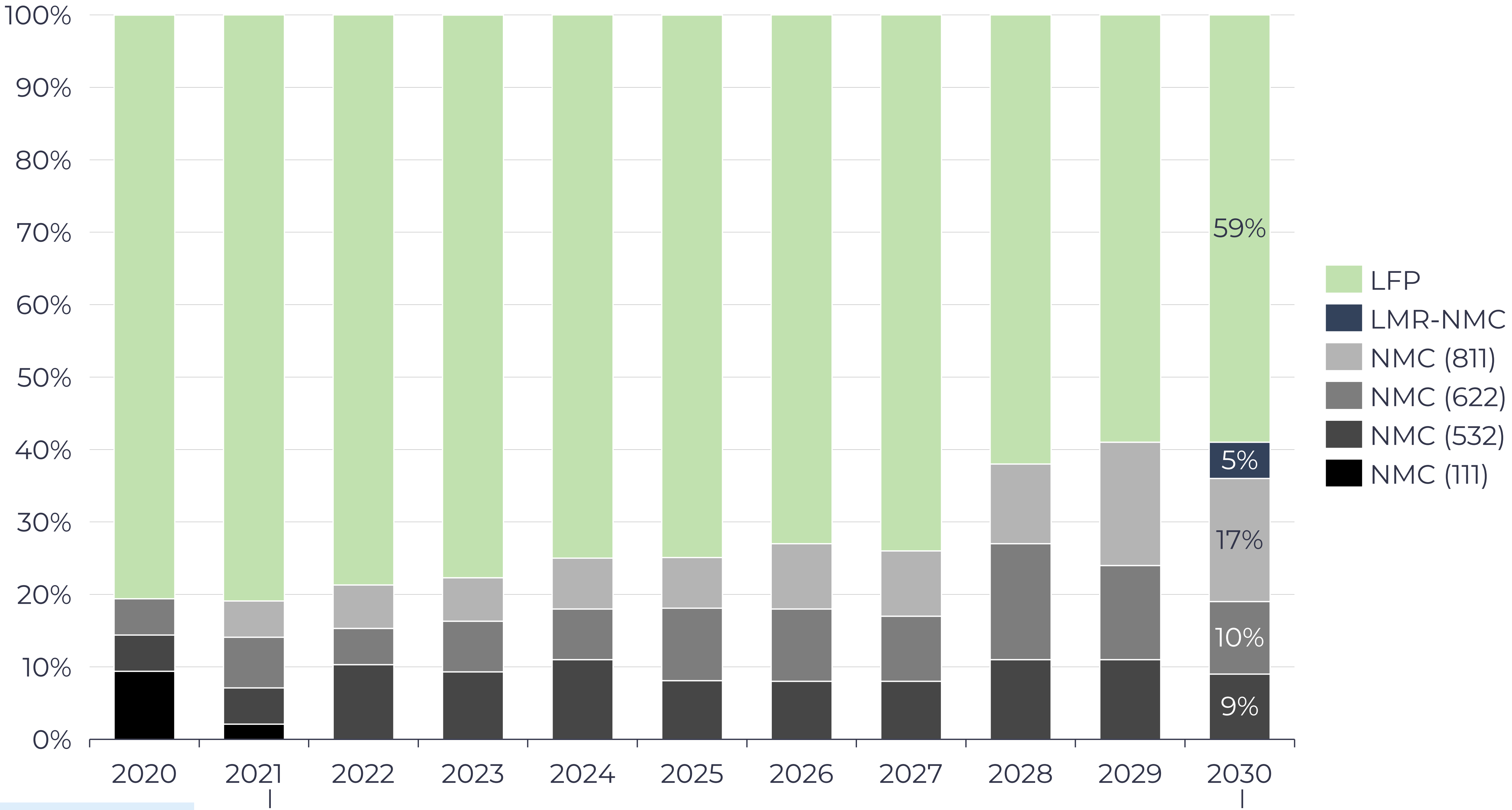
Source: Bloomberg, PwC Strategy&

Main materials in the cathode	CAGR year intro - 2030
Lithium, Iron, Phosphorus	+9%
Lithium, Nickel, Manganese, Oxygen	+31%
Lithium, Nickel, Oxygen	+3%
Nickel, Cobalt, Aluminium	+28%
Nickel, Cobalt, Aluminium	-100%
Nickel, Cobalt, Aluminium	-100%
Nickel, Cobalt, Aluminium	-100%
Nickel, Manganese, Cobalt, Aluminium	-1%
Lithium, Manganese, Nickel, Cobalt	+57%
Nickel, Manganese, Cobalt	+16%
Nickel, Manganese, Cobalt	-4%
Nickel, Manganese, Cobalt	+1%
Nickel, Manganese, Cobalt	-100%
Nickel, Manganese, Cobalt	-100%
Nickel, Manganese, Cobalt	-100%

Cathode chemistry for HDV and Bus

The chemical composition is dominated by LFP and NMC for the period 2020 - 2030

Evolution of the chemical composition of the cathode of EV batteries sold (% of total)



New composition ▶ 2021 **NMC811**; 2030 **LMR-NMC**

Main materials in the cathode	CAGR year intro - 2030
Lithium, Iron, Phosphorus	-3%
Lithium, Manganese, Nickel, Cobalt	*n.a.*
Nickel, Manganese, Cobalt	+15%
Nickel, Manganese, Cobalt	+7%
Nickel, Manganese, Cobalt	+6%
Nickel, Manganese, Cobalt	-100%

Source: Bloomberg, PwC Strategy&

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Energy density of the cells

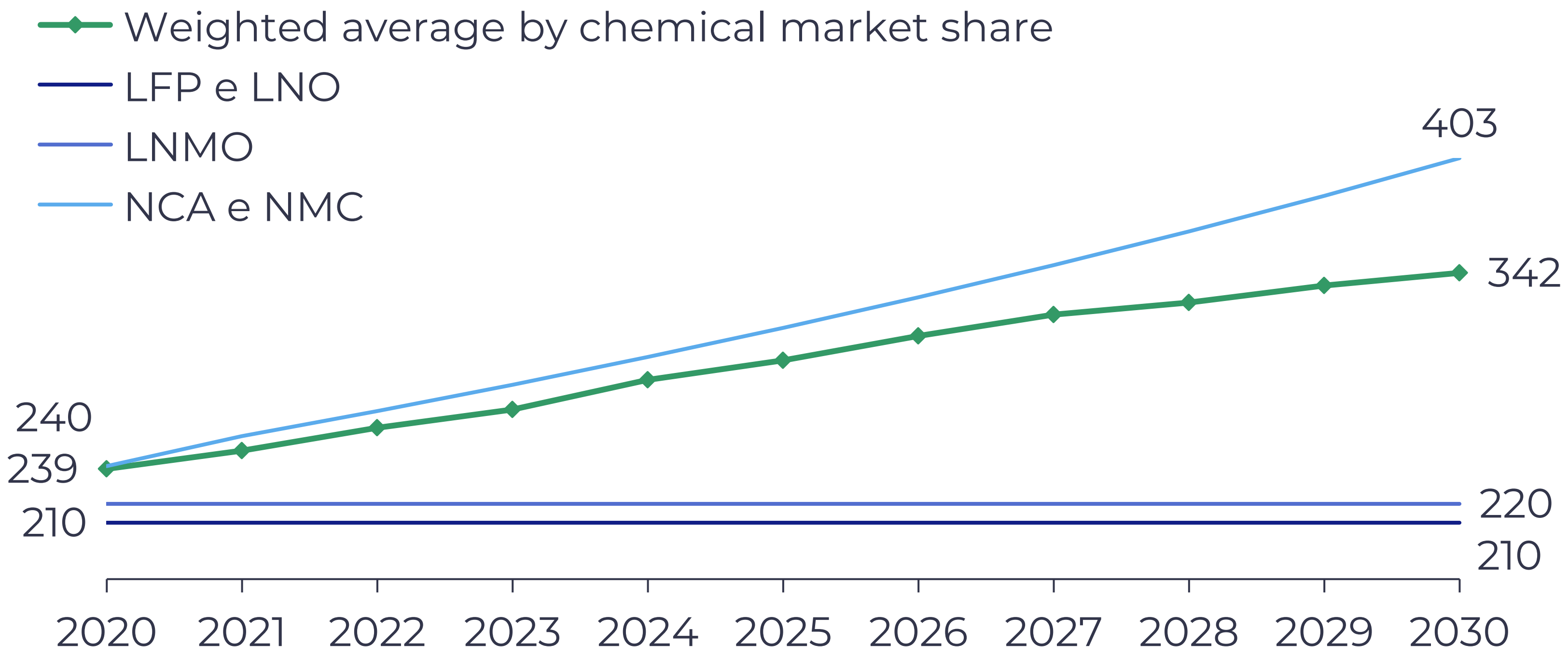
The model uses the weighted average energy density per chemical composition

Passenger Car and Light Commercial Vehicle

Hypothesis

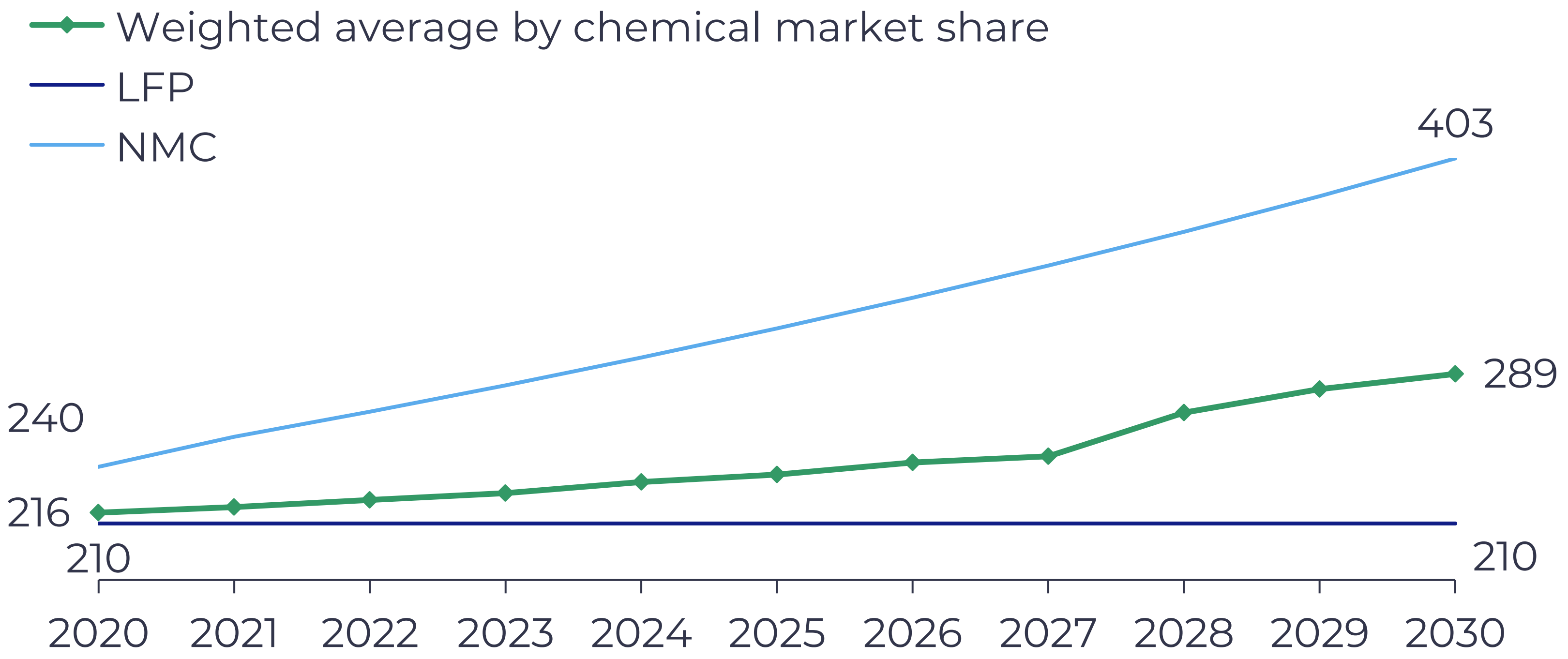
- The chemicals used for batteries in the PC and LCV categories are **NMC, NCA, LFP, LNO** and **LMNO** (detail in previous slide)
- **The average value** of energy density is weighted by values of **chemical composition** (detail in previous slide)
- The energy density of **NMC and NCA** chemicals is expected to increase by **+5% per year** in the period 2020-2030, thanks to the increase in the **amount of Nickel** used in the cathode; the average values grow from **240 Wh/kg** in 2020 to **403 Wh/kg** in 2030
- **No expected improvement** on the energy density of the chemicals **LFP, LNO and LMNO**, which are fixed stable at **210 Wh/kg**

Evolution of average energy density (Wh/kg)



Heavy Duty Vehicle and Bus

- The chemicals used for batteries in the HDV and Bus categories are **NMC** and **LFP** (detail in previous slide)
- **The average value** of energy density is weighted by values of **chemical composition** (detail in previous slide)
- The energy density of the **NMC** chemistry is expected to grow by **+5% yearly** in the period 2020-2030, thanks to the increase in the **quantity of Nickel** used in the cathode; values increase from **240 Wh/kg** in 2020 to **403 Wh/kg** in 2030
- **No expected improvement** on the energy density of the **LFP**chemistry, which are fixed stable at the value of **210 Wh/kg**



Source: Argonne, Politecnico di Milano, Cobat, Motus-e, PwC Strategy&

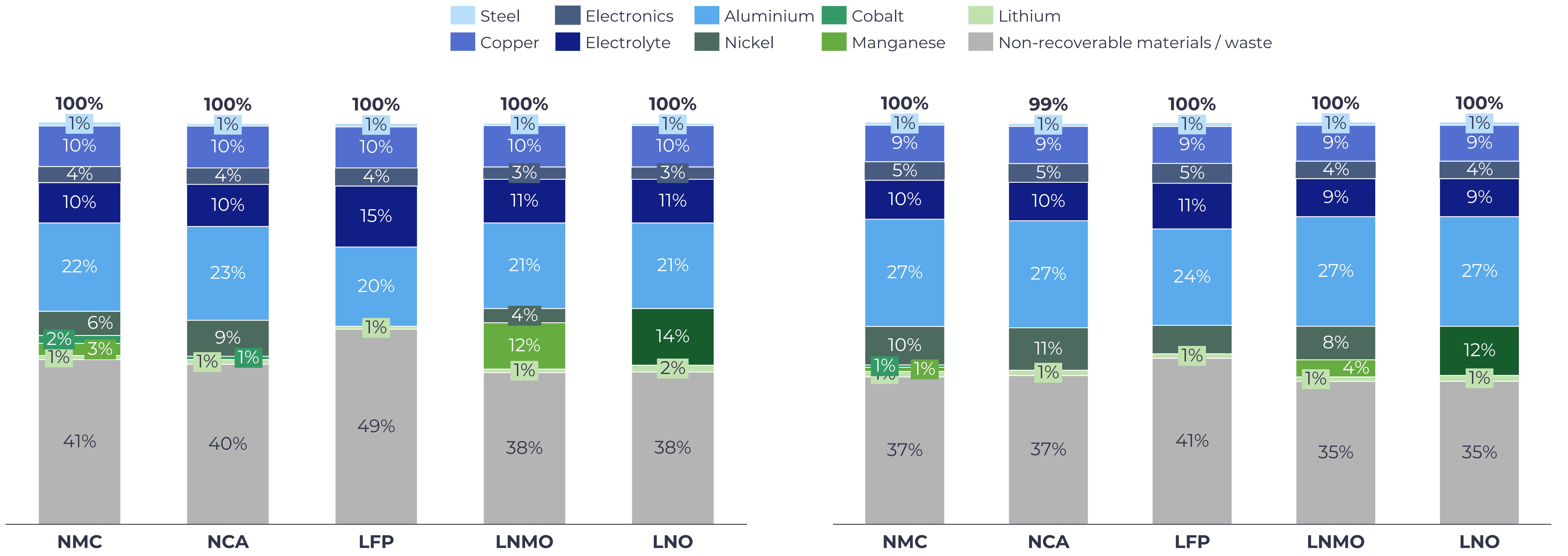
Recovered materials and recycling waste

The model makes it possible to calculate the material recovered depending on the chemistry

Hydrometallurgical treatment

Passenger Car and Light Commercial Vehicle

Heavy Duty Vehicle and Bus



Source: Argonne, Politecnico di Milano, Cobat, Motus-e, PwC Strategy&

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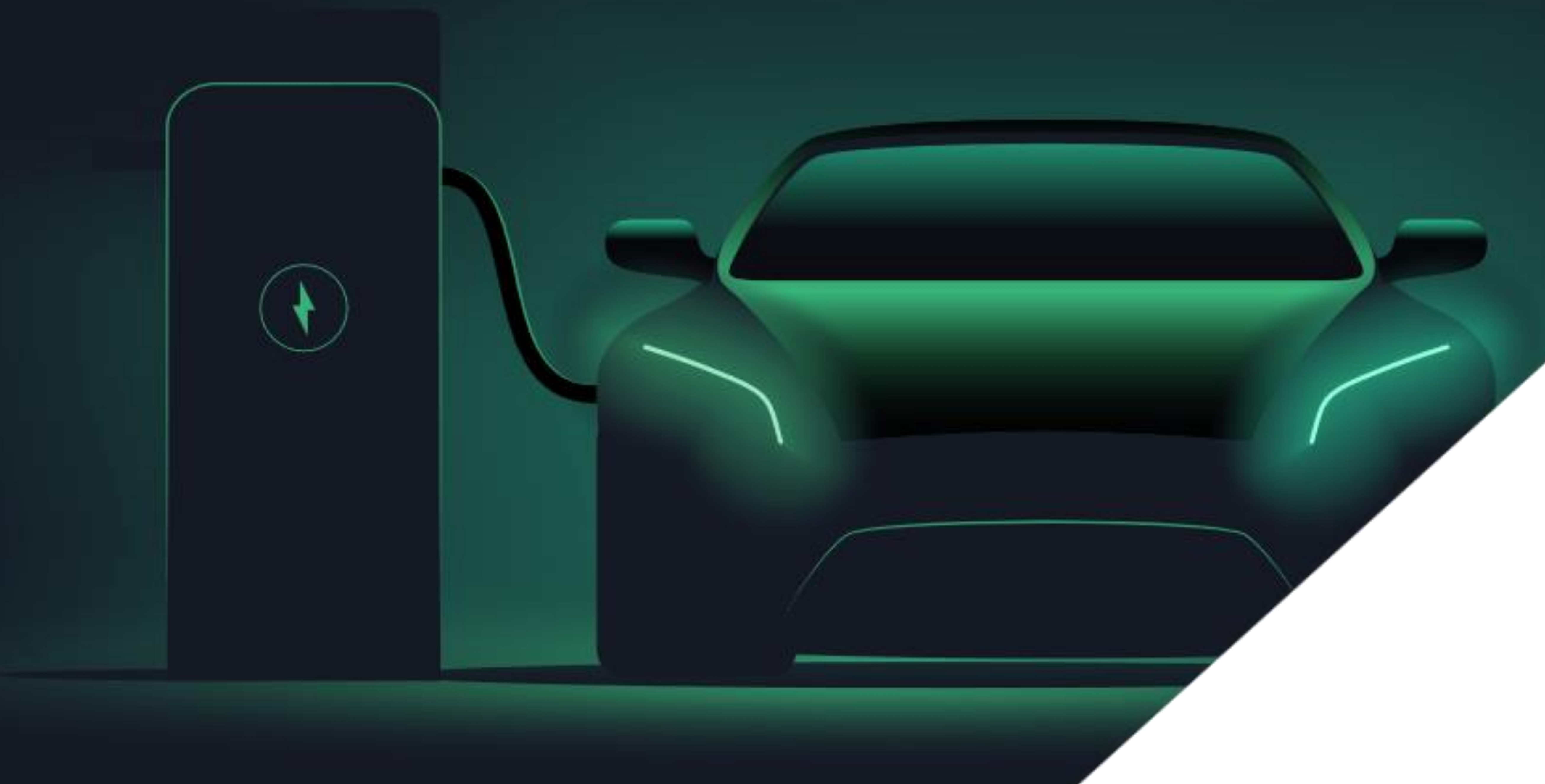

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