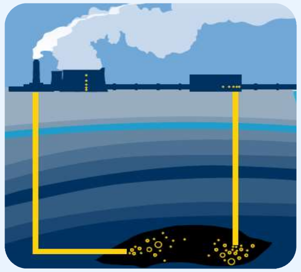


Batteries on wheels: the role of battery electric cars in the EU power system and beyond

Technical Appendix

June 2019

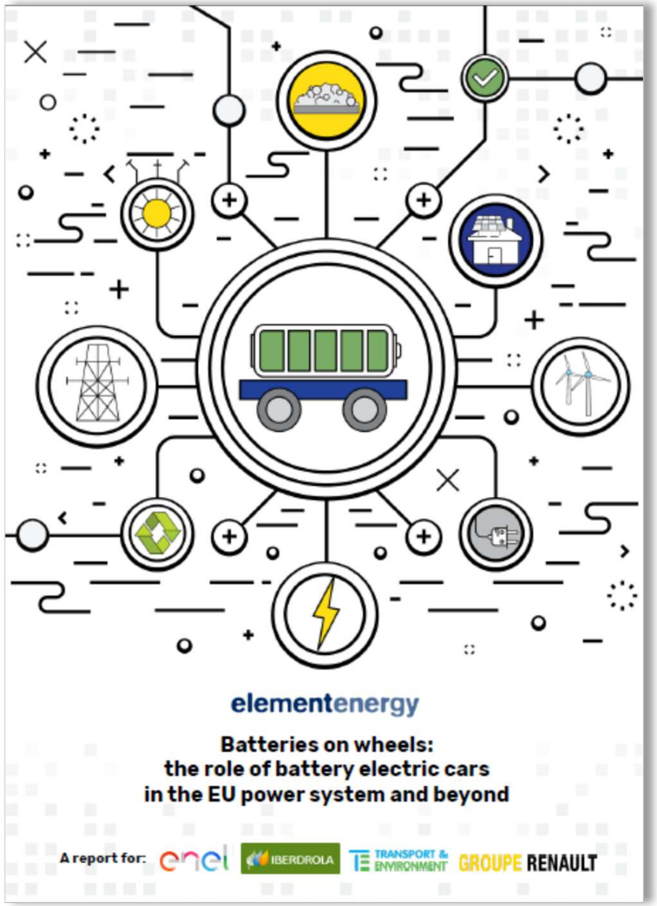
Element Energy Ltd

http://www.element-energy.co.uk/

About this document

About this document

- This slide pack accompanies the *Batteries on wheels: the role of battery electric cars in the EU power system and beyond* report issued by Element Energy and prepared for Transport & Environment, Iberdrola, Renault, and ENEL.
- It presents the modelling approach and the main assumptions used in this study.
- This appendix follows the work package structure on which the project was developed, and consists of four main sections:
  - Projections of available battery volumes
  - The role of EVs in the power system
  - Review of recycling processes and policies
  - Economics of end of life options
- A supplementary information section provides additional outputs and information on the modelling tools used.



elementenergy

Batteries on wheels:
the role of battery electric cars
in the EU power system and beyond

A report for: enel IBERDROLA TRANSPORT & ENVIRONMENT GROUPE RENAULT

Structure

- **Projections of available battery volumes**
  - Vehicle sales and stock
  - EV usage assumptions
  - Battery fates
  - Battery cost projections
- The role of EVs in the power system
- Review of recycling processes and policies
- Economics of battery end of life options
- Supplementary information
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General approach and key components used in estimating the volumes of available batteries

EV uptake scenarios

- Taken from existing literature – the outputs from one main scenario are shown in the report, with a second scenario being used as a sensitivity only. Battery size and capacity assumptions are attributed to each vehicle type in the uptake scenario.

EV usage profiles

- Proposed EV usage profiles (time they plug-in), charging windows and availability for V2G. This is relevant for evaluating the potential for providing grid services. Assumptions are provided in this document.

Available GWh for grid support

- Modelling of EV stock + assumptions above → annual volumes of batteries that may be available each year. The vehicle stock is calculated using the EE vehicle stock model and includes new assumptions differentiating between the life of ICE and electric vehicles. Assumptions on battery size and degradation are used to estimate the residual capacity of batteries recovered from EV.

Battery and of life fates

- Key assumptions about battery performance/operational conditions are shown on slide 19 showing the capabilities of batteries at the end of their 1st life, in terms of remaining kWh capacity.

Battery cost projections

- Cost projections based on Bloomberg and split between battery sizes.

Structure

Projections of available battery volumes

- **Vehicle sales and stock**
- EV usage assumptions
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The modelling uses EV uptake scenarios based on the 2018 Fuelling Europe's Future study

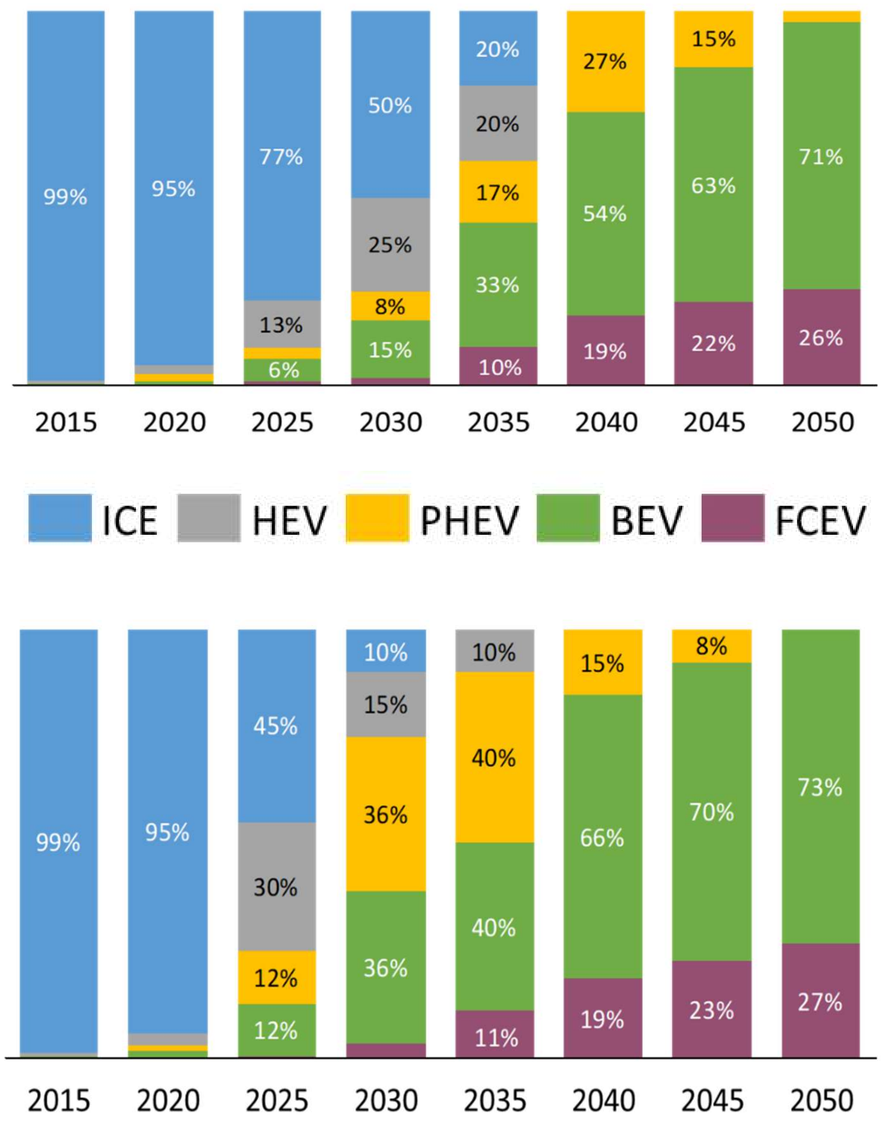
Baseline scenario

- This scenario is based on the TECH scenario of the FEF2 Study and assumes a gradual increase in the share of advanced powertrains up to 2030.
- Post 2030, BEV market share grows rapidly in response to policy pushes in 2040. PHEVs and HEVs are deployed initially but HEV sales stop in 2040 and sales of PHEVs decline sharply after 2040.
- This is the main scenario used in the modelling. All results presented in the report are based on this scenario.

Accelerated EV Uptake scenario

- This scenario models OEMs responding to policy actions by ceasing production of ICE vehicles from 2035, followed by HEVs in 2040.
- This results in a more rapid deployment of advanced powertrains with ZLEV share reaching 25% in 2025 (in line with recent announcements from some OEMs).
- This scenario was used as a sensitivity only and the results are not presented in the report.

Car sales in the EU

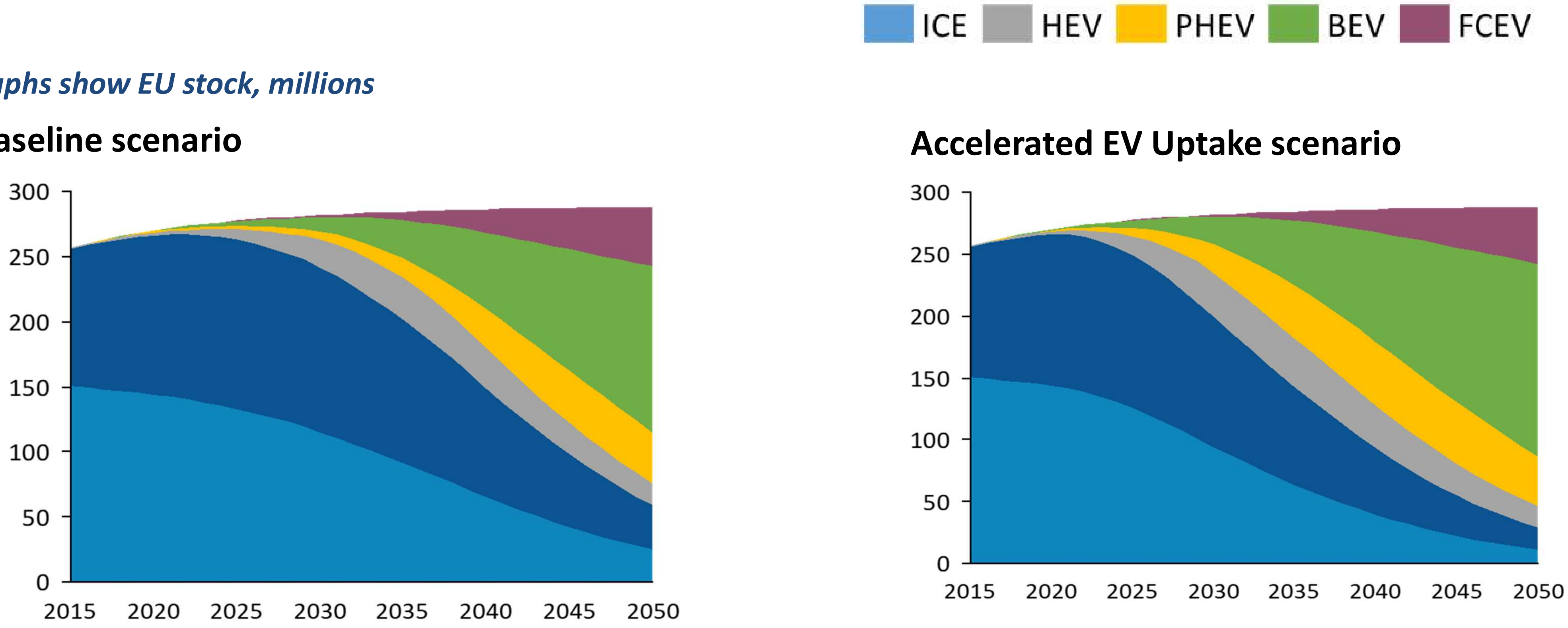


Source: Cambridge Econometrics and Element Energy for ECF, Fuelling Europe's Future study, February 2018.

The modelling uses EV uptake scenarios based on the 2018 Fuelling Europe's Future study

The European vehicle stock is modelled under each scenario and is shown in the diagram below:

Graphs show EU stock, millions



Baseline scenario

Accelerated EV Uptake scenario

A detailed description of Element Energy EU Vehicle stock model is provided in the Supplementary Information section of this slide pack

Source: Cambridge Econometrics and Element Energy for ECF, Fuelling Europe's Future study, February 2018. Scenarios with very little EV uptake not shown

Battery capacity of new vehicle sales

The following Lithium-ion battery sizes (total original pack capacity) are assumed for the vehicles sold and entering the stock model:

Powertrain	Market segment	Battery sizes (kWh)			
		2020	**2030**	**2040**	**2050**
PHEV	**Small**	7	6.3	5.6	4.9
PHEV	**Medium**	10	9	8	7
PHEV	**Large**	15	13.5	12	10.5
BEV	**Small**	45	45	45	45
BEV	**Medium**	60	60	60	60
BEV	**Large**	90	100	110	110

Small, medium and large refer to the car segments

- These values are based on work previously conducted by Element Energy[1], with an update to the large BEV case (to a greater capacity in 2030-50).
- In the case of PHEVs, the battery capacity decreases in line with technological improvements (lower kWh/km and greater usable State of Charge window) whilst the vehicle range increases from 60 km (in 2020) to 80 km (2030-2050) for medium and large PHEVs (and 40km to 50km for the small segment).
- In the case of batteries used in hybrid (HEV) and fuel cell EV (FCEV), a capacity of 1kWh is assumed, but this battery stock is tracked only from 2030, as the packs would be mostly based on Nickel-Metal Hydride technology before that date.

[1] - Cambridge Econometrics and Element Energy for ECF, FEF II study, February 2018.

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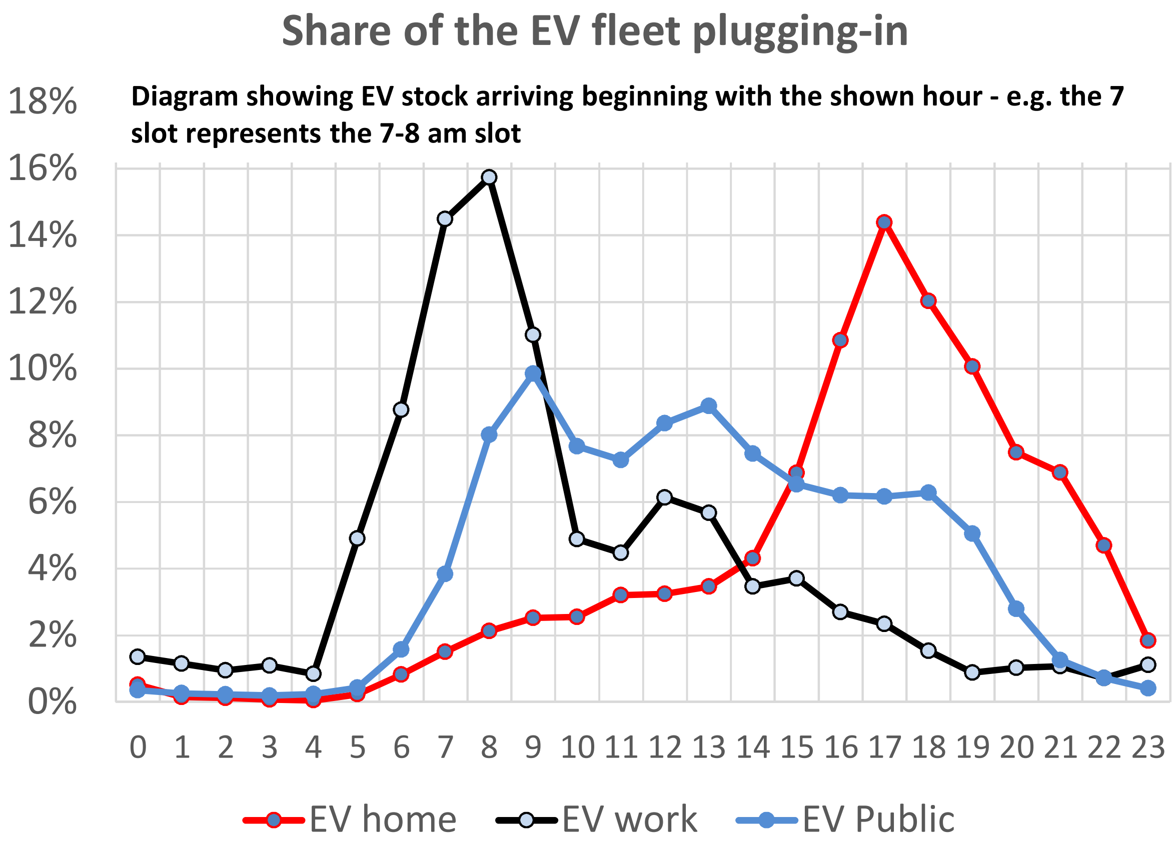
EV charging profiles – the time EVs are plugged-in is relevant to the provision of grid services



- These profiles are based on the latest evidence from an exhaustive literature review on EV usage profiles conducted for UKPN – Charger Use Study (2018).
- This is relevant when evaluating the potential for providing grid service.

In addition, the following must be noted:

- We consider rapid public charging to be fast and inflexible – no grid services can be provided from a rapid public charge point.
- Trials have shown that slow public charging at destination (plug in window length 1-2h) is negligible.
- Slow on-street public charging in residential areas is equivalent for our modelling purposes to home charging (mostly overnight) and thus already captured in the 'home charging' category.

Source: [Charger Use Study, EE for UKPN, 2018]

EV charging – key assumptions regarding charging locations

In 2030 we assume an average overall kWh split of charging locations [1]:

Charging location	Base behaviour [1]	Changed behaviour (sensitivity)
Home (including private home charging and on-street residential charging)	50%	20%
Work	20%	20%
Slow public charging (7-22 kW)	10%	10%
Rapid public charging (50+ kW)	20%	50%

A sensitivity regarding different behaviour in certain countries (e.g. Spain) where access to home charging is restricted (due to population living in flats) has also be considered – values shown in the last column.

The 2040 assumed charging capacity available at each charging point are:

	Charging capacity (kW)			
	Home charging	Work charging	Slow public charging	Rapid public charging
Base case	3	7	7	50
Sensitivity	3	7	7	50

Among public charging, the rapid to ultra rapid charging (50-350kW) is included in the model as an energy demand, but it is not flexible.

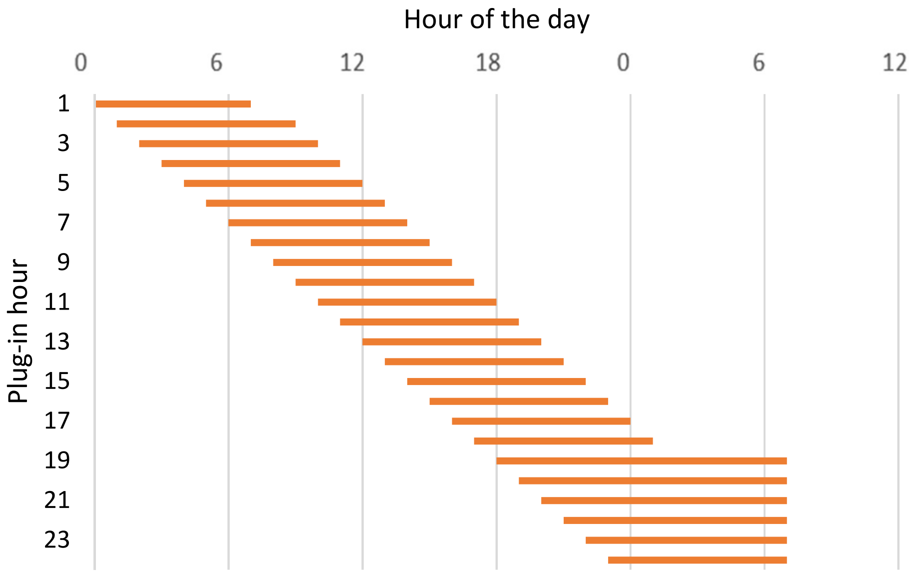
[1] Electric vehicles in Europe: gearing up for a new phase?, McKinsey, 2014

EV charging – plug-in time window at each location

Our model uses different time lengths for charging at both home and work, depending on driver's behaviour (e.g. time of the day the EV is plugged in).

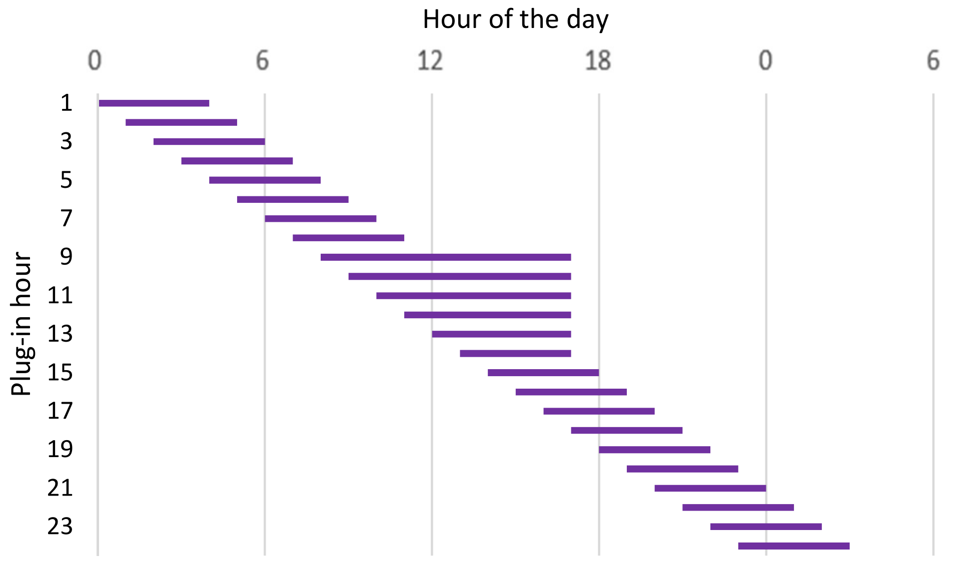
Home EV plug-in time

It is assumed that at home EVs stay plugged in until 7:00 if plugged in between 18:00 and 00:00, otherwise for 8 hours.



Work EV plug-in time

Our modelling assumes that at work EVs stay plugged in until 17:00 if plugged in between 8:00 and 13:00, otherwise for 4 hours.



Within the shown time range, the vehicle would be charging (passive / smart mode).

Assumptions based on Assimon et al, Une évaluation prospective des véhicules électriques, 2011

EV charging – key assumptions regarding battery specs and service provision

The following assumptions regarding electric vehicles are used in understanding the provision of grid services:

Parameter	Unit	Value	Source
% of battery available for V2G	%	50%	Element Energy analysis
% of fleet stationary at any point	%	80%	[1]

For V2G services, it is assumed that since vehicles are stationary 80% of the time, they can participate in providing grid services using vehicle storage (up to 50% of available battery capacity).

V2G as well as smart charging is assumed to be provided by BEVs and PHEVs. Due to the small share of PHEVs in the overall EV fleet, the contribution from PHEVs is low.

[1] Quelle contribution du vehicle electrique a la transition ecologique en France?, Foundation pour la Nature et L'homme, 2017

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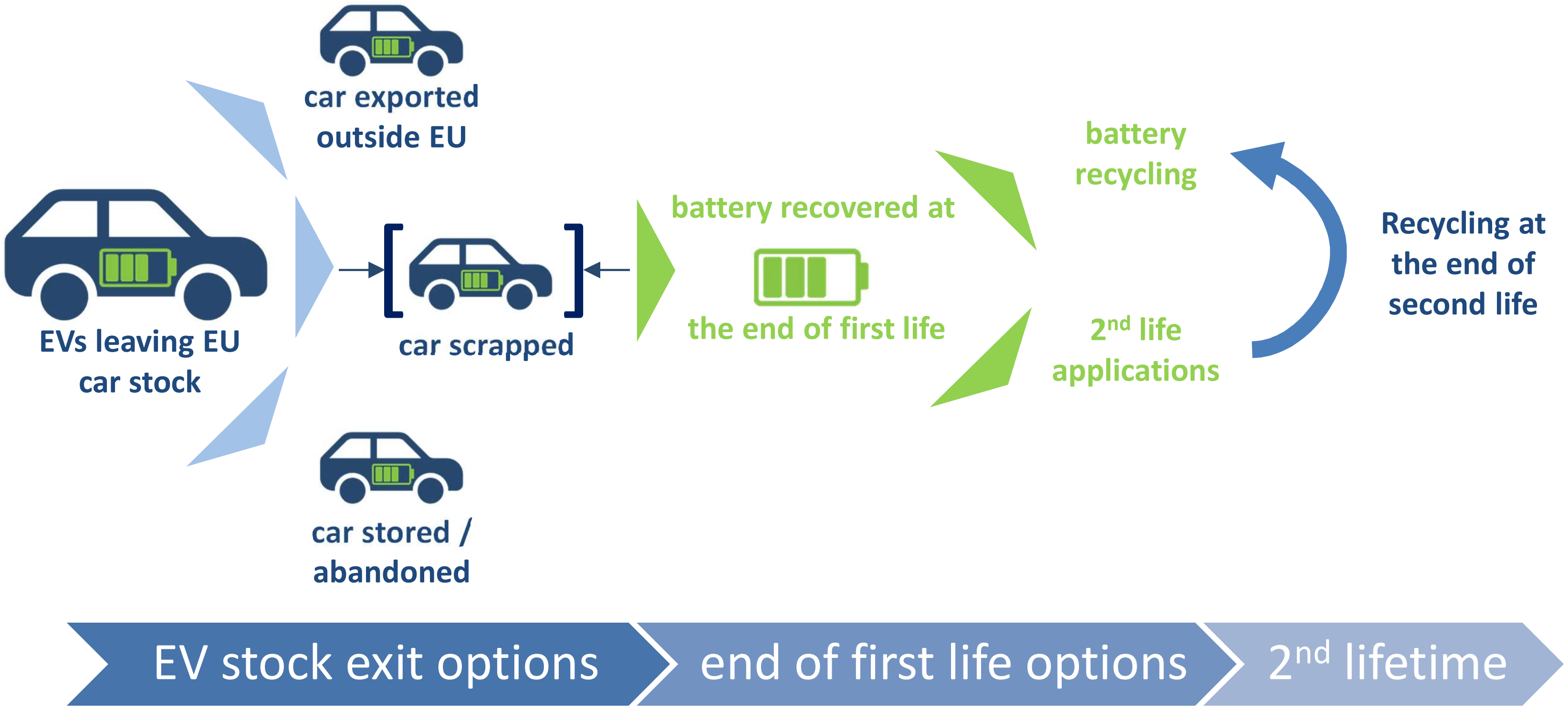
Understanding batteries' end of life options

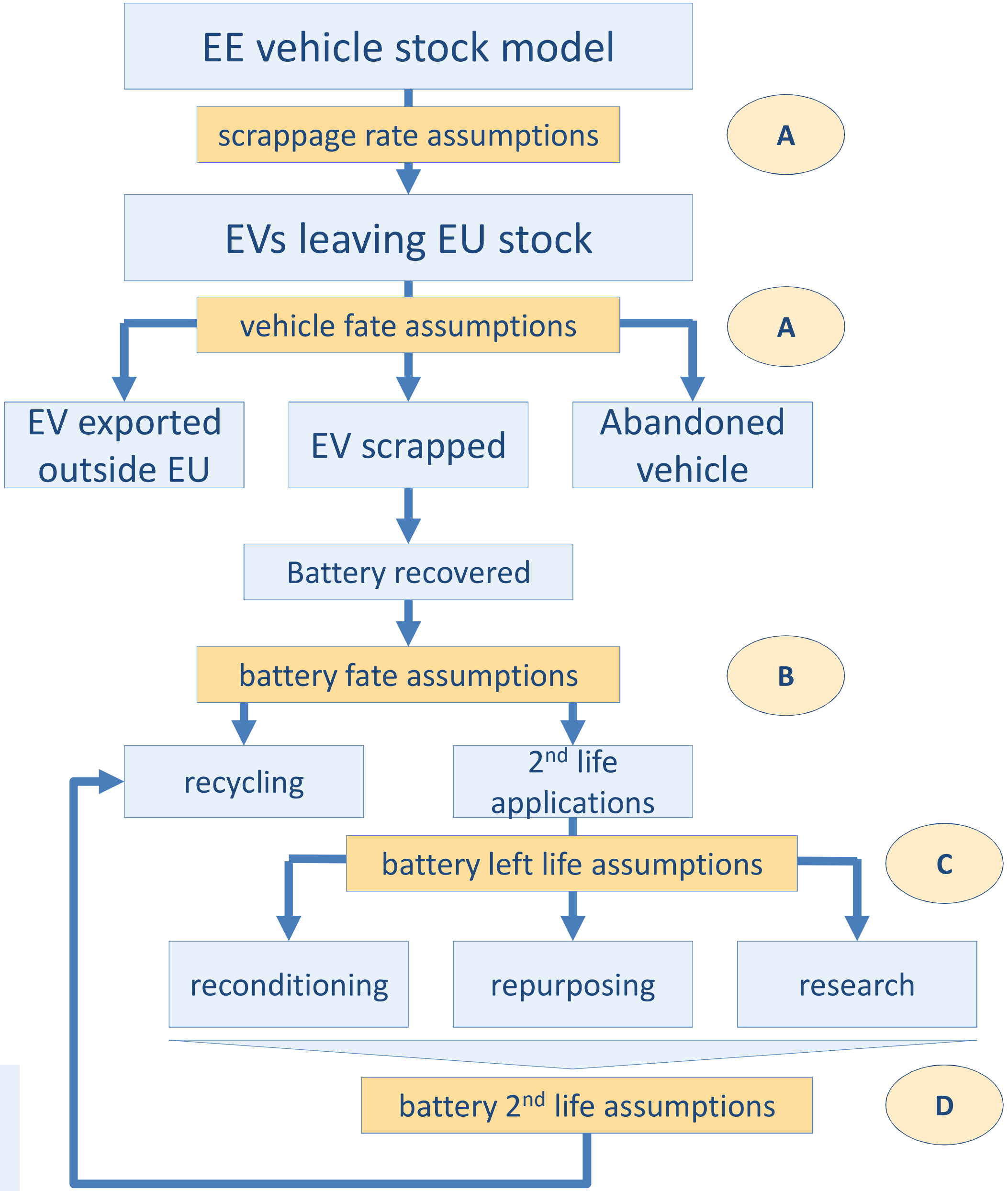
EE's vehicle stock modelling predicts the number of vehicle that leave EU's roads every year. In the case of electric vehicles, depending on the age, batteries can follow several pathways, including recycling or utilisation in 2nd life applications (see below). For batteries involved in 2nd life applications, recycling at the end of the 2nd life is also modelled.



The assumptions for end life options are outlined on the following slides.

Understanding batteries' end of life options: Assumptions roadmap

- Our modelling examines the EU vehicle stock and employs several assumptions to determine vehicle's and battery's fate and to calculate the amount of batteries used in 2nd life applications and/or recycled.
- The battery volumes thus determined are further used for scaling the European recycling facilities and assessing the economics of select 2nd life applications.
- All assumptions are based on the vehicle and battery age and are detailed in the diagrams and tables shown on the following slides.
- A worked example using the assumptions detailed on the next slides is also shown on slide 21.



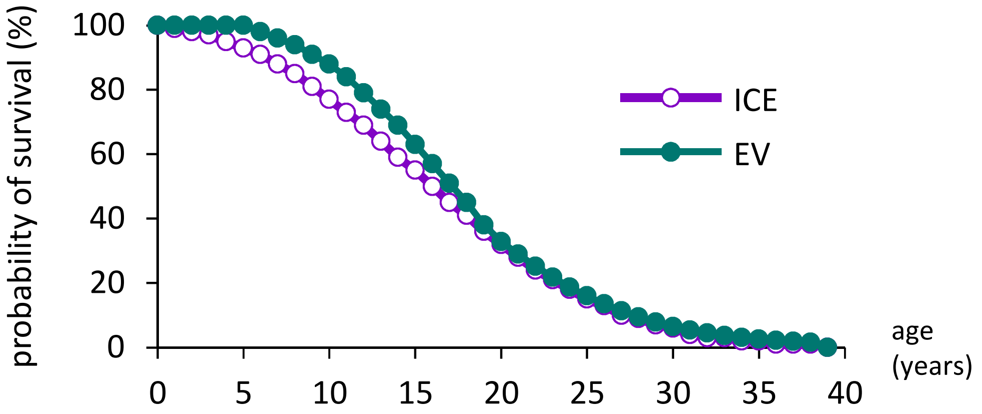
Bubble refers to slide where assumptions are detailed

Understanding batteries' end of life options: EV stock scrappage and vehicle fate assumptions

A

- The diagram below shows the scrappage rate used in EE's vehicle stock model. In the case of ICE vehicles, this is based on observed data.
- In the case of EVs, it is assumed that
  - they will exhibit longer lifetimes relative to ICE-powered vehicles, based on OEMs and customers experience to date.
  - the scrappage curve assumes EVs younger than 6 years are all kept in the stock.
  - they are retained in the EU stock for longer, with no EU exports as neighbouring non-EU importing countries (e.g. Turkey, Russia, North Africa) will lack charging infrastructure (and admin burden to cross borders with EV). As a result, only one pathway is modelled: vehicle scrappage (with the battery recovered) and no vehicle exports outside EU.

Scrappage curves for ICE and electric vehicles leaving the EU stock



ICE: Internal combustion engine

Understanding batteries’ end of life options: battery fate upon vehicle leaving the EU stock

B

- In line with the assumptions on the previous slide, once the vehicles leave the EU stock, several options are possible for the battery packs.
- For vehicle exported outside EU, the battery is assumed to have left the EU alongside with the vehicle and thus are not considered any further in the modelling., however no exports are assumed in our modelling.
- Regarding batteries recovered from vehicles scrapped within EU, these would either be considered for 2nd life applications or recycled.
- Newer batteries would be more likely to be considered for 2nd life applications as they would have a higher residual capacity. Conversely, old batteries would be more likely to be technologically exhausted and thus recycled, with exclusively all 20+ years old batteries being sent to recycling.
- A detailed breakdown of 2nd life applications is provided on the following slide.

Assumptions for battery fate upon vehicle leaving stock (% of retired EV stock)

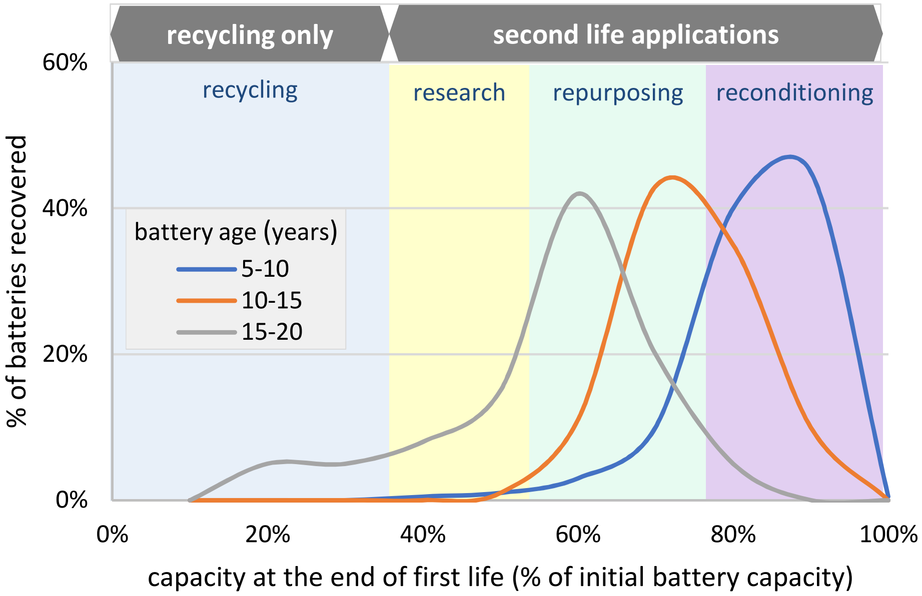
		Battery age (years)			
Battery fate		6-10	11-15	16-20	21+
Battery recovered within EU	Batteries considered for 2nd life application	100%	70%	40%	0%
	Batteries recycled	0%	30%	60%	100%
Exported outside EU as part of the car		0%	0%	0%	0%

Understanding batteries' end of life options: fate of recovered batteries

C

- The batteries recovered from vehicles at the end of first life would have different residual capacities depending on the battery age and the number of cycles the battery had been subjected to, and operating conditions (in particular temperature and (dis)charging rates). The distribution of different residual capacities as a function of battery age is presented in the diagram on the left (illustrative)
- The fate of the battery at the end of its first life would depend on the residual capacity and state of health and may include recycling (if the battery is considered exhausted) or 2nd life applications.
- The table below shows the pathways that the recovered batteries may face. For example, all batteries between 6-10 years old will be considered for second life applications. Of these, 10% will be reconditioned (with an average capacity left of 90%), 88% repurposed (e.g. for storage), whilst 2% will be used in research applications.

Illustrative diagram



	Battery age (years)			
Battery fate	**6-10**	**11-15**	**16-20**	**21+**
Batteries considered for 2nd life application (% of retired stock)	100%	70%	40%	0%
Reconditioning (for use in EV) Avg. capacity left	10% 90%	5% 85%	0% 82%	-
Re purpose (e.g. storage) Avg. capacity left	88% 70%	90% 73%	90% 65%	-
Research applications Avg. capacity left	2% 58%	5% 56%	10% 48%	-
Batteries recycled (% of retired stock)	0%	30%	60%	100%

Understanding batteries' end of life options: second lifetime assumptions

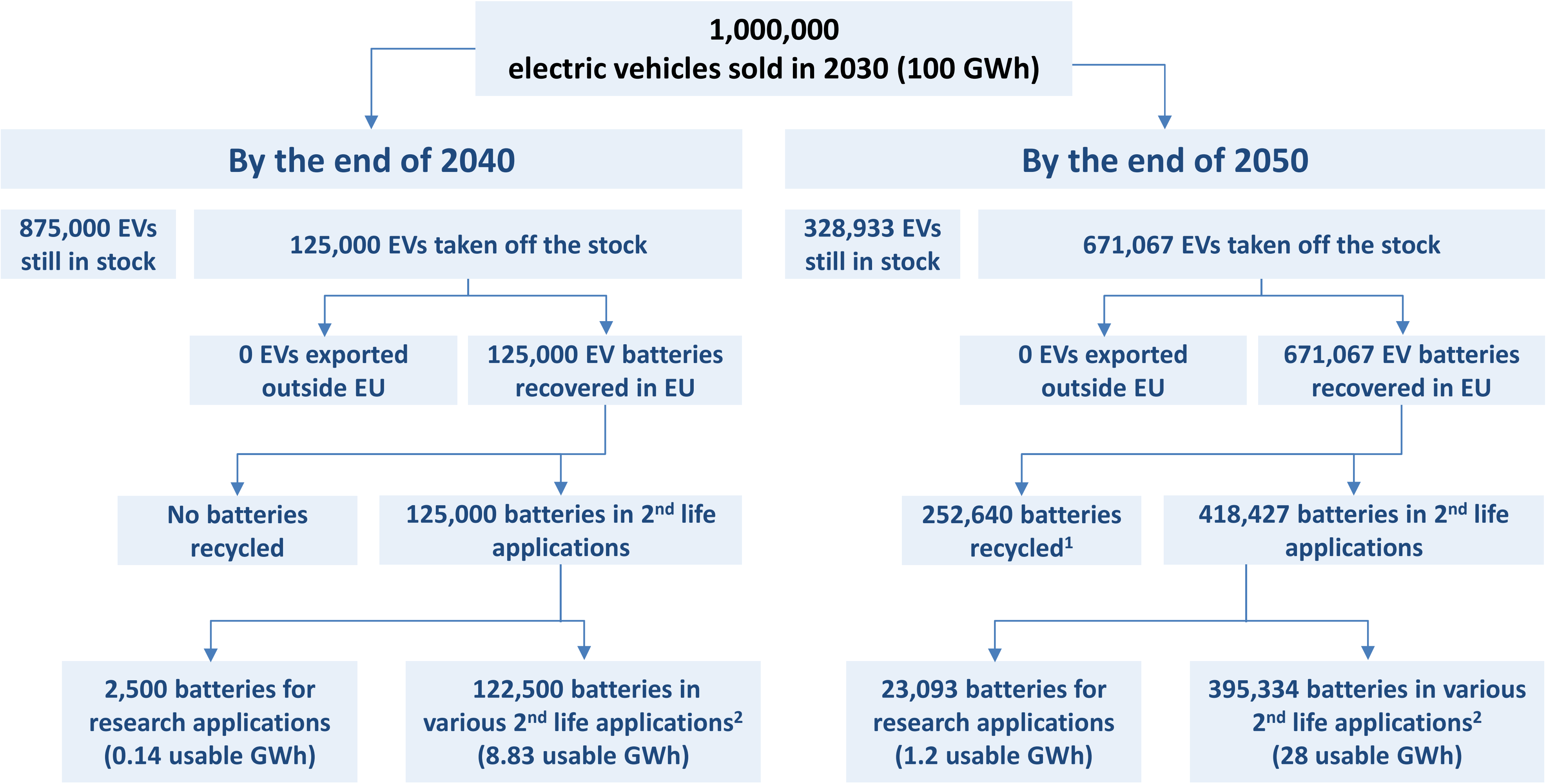
D

- The batteries recovered and involved in second life applications will have a 2nd lifetime proportional to the capacity left at the end of the first life and dependant on the type of application they serve in the second life. Intensive second life applications would reduce the 2nd lifetime considerably.
- The 2nd lifetime is important for scaling the recycling capacity, as batteries would leave their 2nd life applications and will be recycled at different times as shown in the table below.
- The assumed 2nd lifetime varies between 3 and 10 years. For example a battery recovered from an EV within 6-10 years of manufacturing and used in energy storage would have an expected 2nd lifetime of 10 years. Similarly, an older battery (16-20 years old at the end of 1st life) used in similar storage applications would only last 5 years in service.

Assumptions for second life service (years)

Battery age (at the end of 1st life)	6-10	11-15	16-20
Batteries considered for 2nd life application (% of retired stock)	100%	70%	40%
Reconditioning	10	8	5
Re purpose (e.g. storage)	8	8	5
Research applications	3	3	3

Understanding batteries' end of life options:
Worked example using assumptions on previous slides



1,000,000
electric vehicles sold in 2030 (100 GWh)

By the end of 2040

875,000 EVs still in stock

125,000 EVs taken off the stock

0 EVs exported outside EU

125,000 EV batteries recovered in EU

No batteries recycled

125,000 batteries in 2nd life applications

2,500 batteries for research applications (0.14 usable GWh)

122,500 batteries in various 2nd life applications[2] (8.83 usable GWh)

By the end of 2050

328,933 EVs still in stock

671,067 EVs taken off the stock

0 EVs exported outside EU

671,067 EV batteries recovered in EU

252,640 batteries recycled[1]

418,427 batteries in 2nd life applications

23,093 batteries for research applications (1.2 usable GWh)

395,334 batteries in various 2nd life applications[2] (28 usable GWh)

In this example an initial battery capacity of 100 kWh is assumed for all EVs entering the stock in 2030

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[1] – If 2030 pack energy density was 150 Wh/kg, that would be 168,427 tonnes

[2] - Including reconditioning and repurposing for grid-services and mobility applications

Additional assumptions

- **Battery chemistry:**
  - Vehicles manufactured up to 2030:
    - all batteries considered will be Li-ion, with graphite-anode in PHEVs and BEVs
    - HEVs and FCEVs are assumed non-lithium. Li-ion used in these vehicles post 2030.
  - Vehicles manufactured post 2030 could contain ‘post lithium-ion’ batteries:
    - there is uncertainty around electrolyte (liquid vs solid), electrodes chemistry. In the model vehicles are still assumed to use Li-ion batteries post-2030.
    - However, analysis shows that if new chemistries were to be introduced in 2030, this will affect recyclers in the long-run, with up to 40% of residual battery stream consisting of the new chemistry in 2050. Comment on the impacts on recycling facilities are included in the report.

- **Currently no battery replacement whilst vehicle remaining in stock assumed:**
  - Battery replacement in private cars are considered unrealistic by industry (including Renault) due to increased reliability of EV batteries and high costs of replacements.
  - In the case of vehicle fleets, it is expected that some EVs will be highly utilised, especially with new mobility patterns (e.g. shared mobility), therefore battery replacement may be economically feasible.

- **Geography and intra-European trade:**
  - Vehicle trade between EU countries is not considered. Predictions regarding vehicle leaving stock are conducted at an EU-level only.
  - Batteries recovered from vehicles may be repurposed for 2nd life applications or recycled in any of the member states, regardless of vehicle’s country registration.

Structure

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- Vehicle sales and stock
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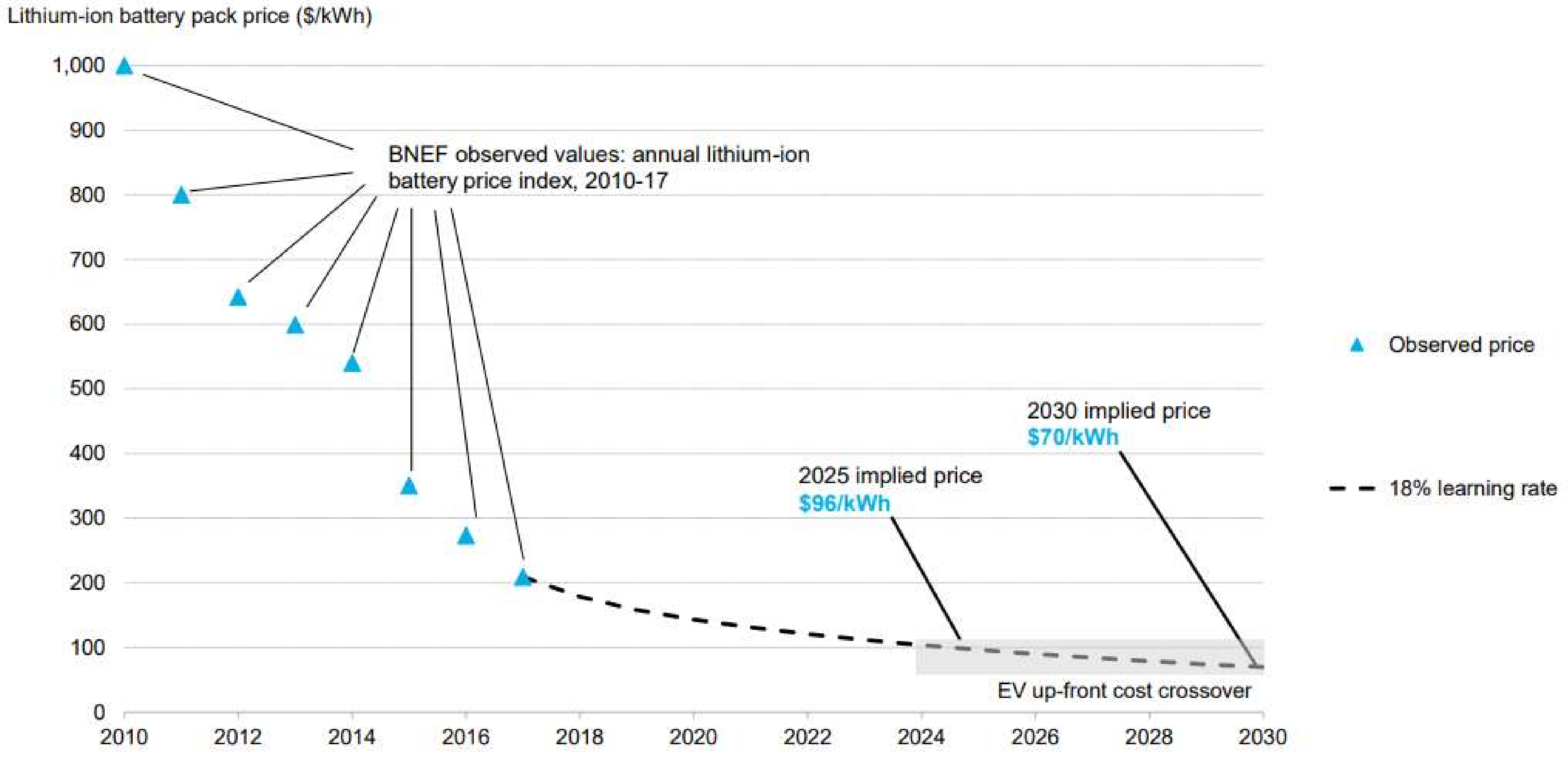
Battery cost projections – to be based on existing projections

The following battery cost projections (Bloomberg June 2018) were used as a basis for building our battery cost projections (next slide) that are used in our modelling:

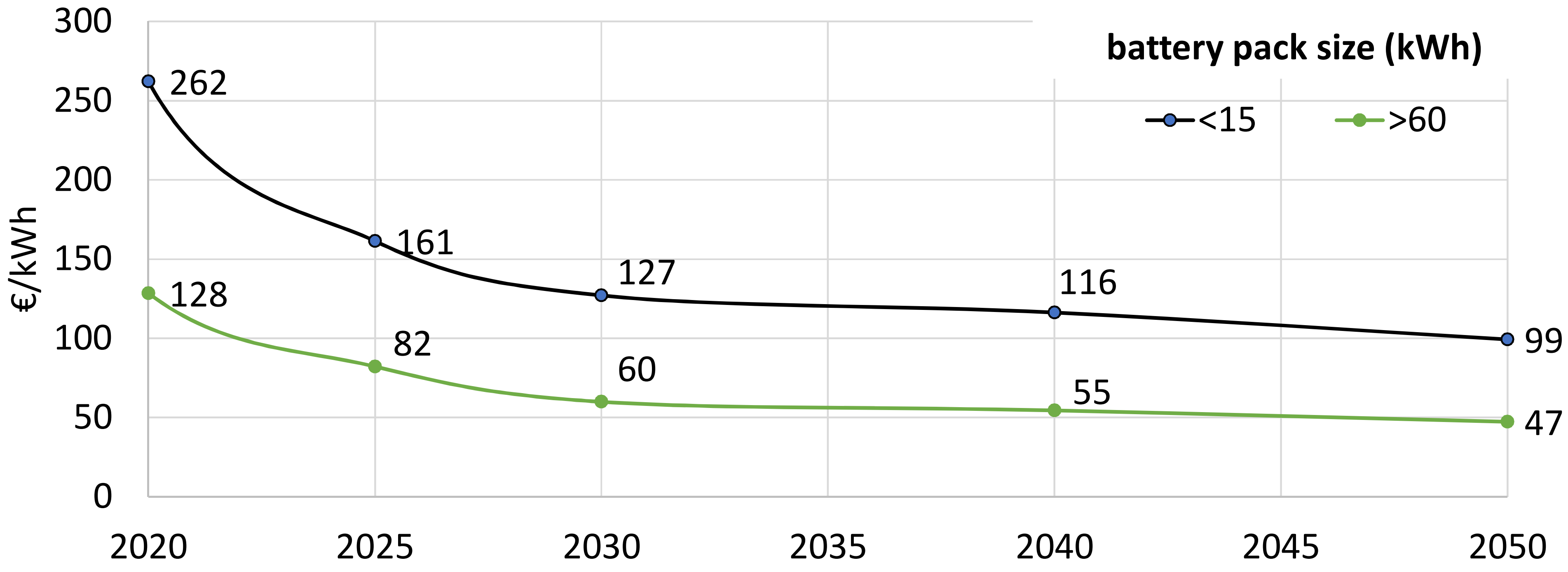


Source: Bloomberg New Energy Finance

Battery cost projections for different battery packs

The data shown on the previous slide (Bloomberg 2018) was adjusted for a series of relevant battery pack capacities (based on the battery capacity assumptions shown earlier) and extended up to 2050 using in-house EE assumptions.

For capacities, in the 35-60kWh range, the cost is 9% higher than for the >60kWh range.



Values shown in 2018 EUR. Conversion rate (June 2018): 1 EUR = 1.1674 USD

Source: Battery Cost and Performance and Battery Management System Capability Report and Battery Database, Element Energy, 2016

Projections of available battery volumes

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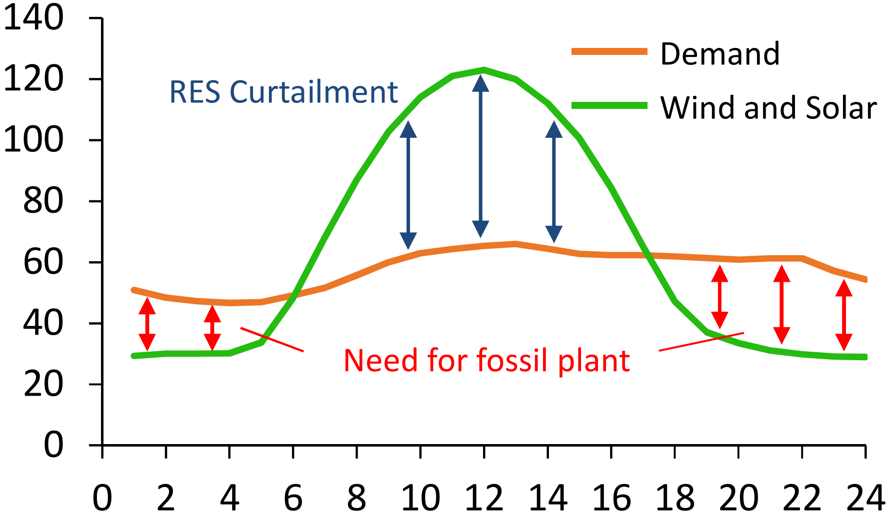
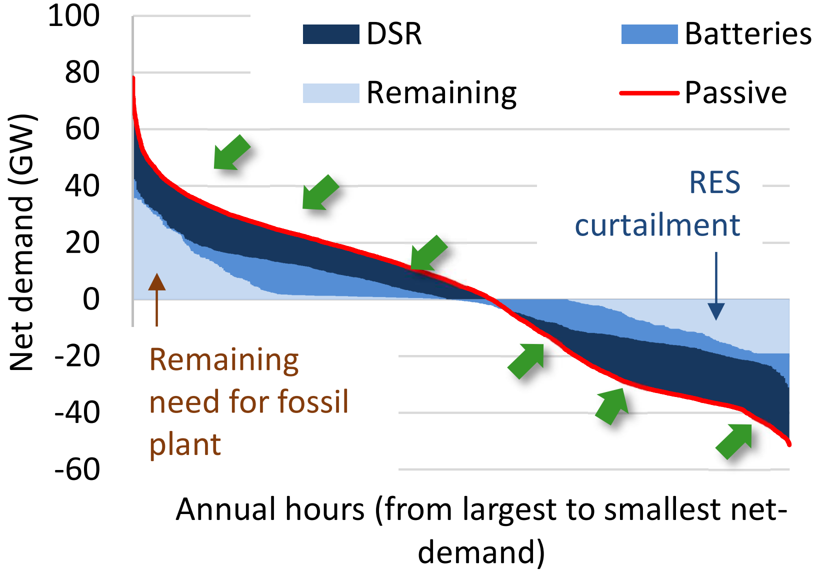
Context: to integrate variable renewable energy sources, flexibility provided by storage and demand side response is key

Intermittent renewable supply



- Decarbonisation of electricity requires wind and solar to become the dominant sources of electricity generation
- Wind and solar are inflexible: their generation cannot be adjusted according to demand
- Instead, demand side response (DSR) and storage are required to reduce net demand, the mismatch between demand and renewable generation

Net demand: critical for system operation



- DSR and storage shift demand from hours of excess demand (positive net load) to hours of excess generation (negative net load)
- This reduces
  - Fossil backup capacity requirement
  - Fossil fuel and carbon costs
  - RES Curtailment

Developments to be captured in the modelling: interactions of batteries with the power system and with each other

Development	Description
The need for batteries	**Batteries** can play a significant role in the future electricity system as a **provider of flexibility** storing electricity at times of high renewable generation and providing it to consumers at times of demand
Roll out of EVs	The roll out of battery storage technology will coincide with **mass deployment of EVs**
Smart vs uncontrolled charging	EVs can either provide flexibility to the system or increase the demand for it depending on how their charging is managed
Stationary batteries vs batteries in EVs	Various ways in which **stationary batteries and EVs will interact and compete** with each other are possible which we represent in 4 scenarios

Modelled scenarios: capturing impacts of passive and smart EV charging as well as V2G and stationary batteries

Scenario	Description
Baseline	Reference scenario corresponding to ENTSO-E model EV demand is modelled flat and no stationary batteries are deployed
Passive	EV charging is uncontrolled No stationary batteries are deployed
Passive + storage	EV charging is uncontrolled Stationary battery storage is deployed up to an economic level
Smart	EV charging is managed providing flexibility to the system Stationary battery storage is deployed up to an economic level
V2G	EV charging is managed and in addition, electricity is discharged back from vehicles to the grid (V2G) V2G infrastructure is deployed at the economically optimal level Stationary battery storage is deployed up to an economic level

Recap: methodology and data inputs

Electricity dispatch model and comparison of scenarios

- Electricity dispatch model modelling electricity production and consumption on national level and **hourly basis** for 1 year; outputs include **fuel and carbon costs**, **RES curtailment**, peaking generation and network **capacity requirements**
- Stationary battery storage is sized by the model based on **economic viability**
- A **Baseline** scenario is run in addition corresponding to the ENTSO-E modelling, which does not take into account the profile of EV charging. In this scenario EV demand is added as flat profile throughout the year no batteries are deployed. The 4 scenarios are compared against the Baseline scenario in terms of costs and emissions.

Main data inputs and sources

Quantity	Source
Generation capacities per technology and country; annual electricity demand	ENTSO-E TYNDP 2018, scenario Global Climate Action (GCA) 2040
Hourly load profile of baseline demand	ENTSO-E TYNDP 2018, scenario GCA 2040
Hourly wind and solar generation profiles	Renewables.ninja
EV stock, elect. consumption, battery capacity	WP 1, TECH scenario
EV departure and arrival times (home/work)	UKPN Charger Use Study
Fuel and CO2 prices	ENTSO-E TYNDP 2018 and IEA WEO

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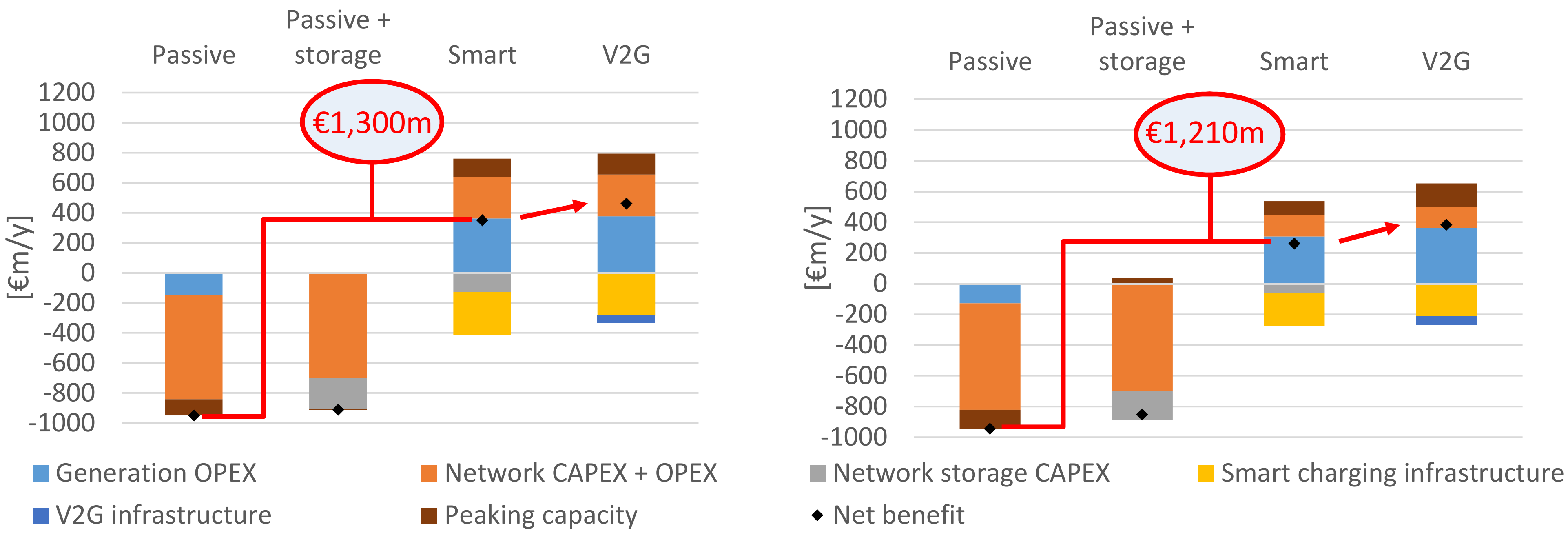
High cost of passive charging largely avoided through smart charging, V2G provides benefits additional to smart charging

Costs & benefits UK rel. to ENTSO-E baseline

Costs & benefits FR rel. to ENTSO-E baseline



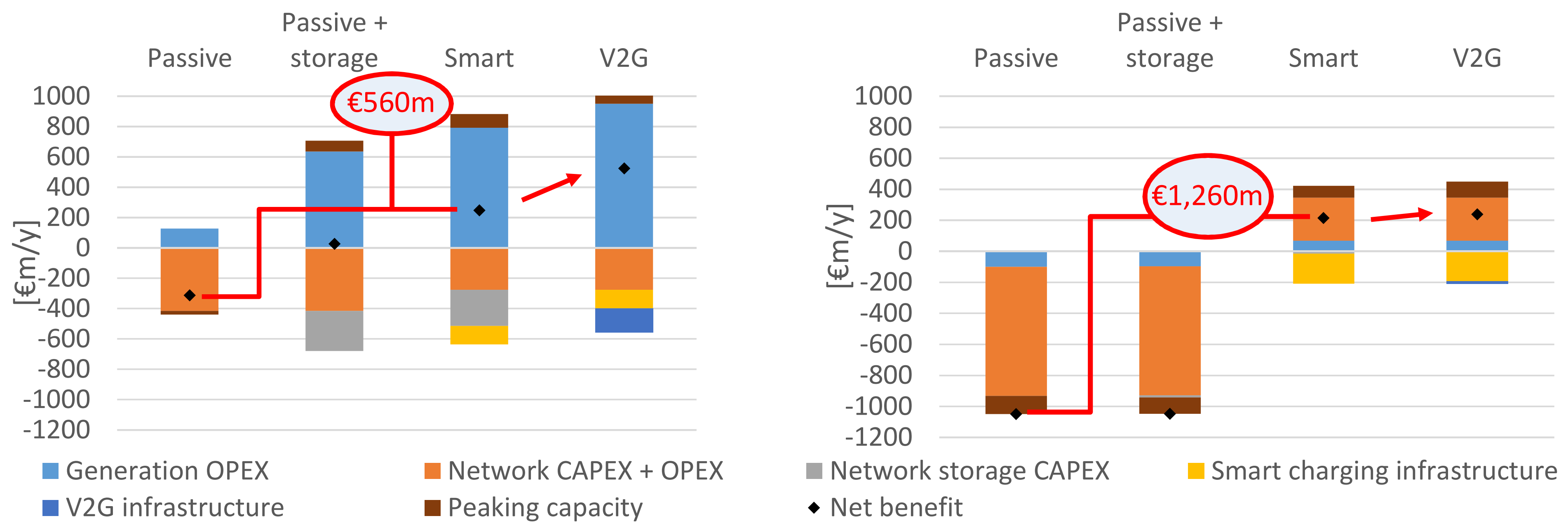
- Smart offers a net benefit of €1,300m per year compared to Passive
- V2G offers a net benefit of €1,410m compared to Passive
- Only 10% of the potential V2G storage capacity is used, due to low curtailment;
- V2G enables generation savings at a lower costs than stationary batteries

- Smart offers a system net benefit of €1,210m per year compared to Passive
- V2G offers a net benefit of €1,330m per year compared to Passive
- 15% of potential V2G capacity is used
- Wind (about 30%) and solar (about 10%) shares of electricity generation are similar in the UK and FR

High cost of passive charging largely avoided through smart charging, V2G provides benefits additional to smart charging

Costs & benefits ES rel. to ENTSO-E baseline

Costs & benefits IT rel. to ENTSO-E baseline

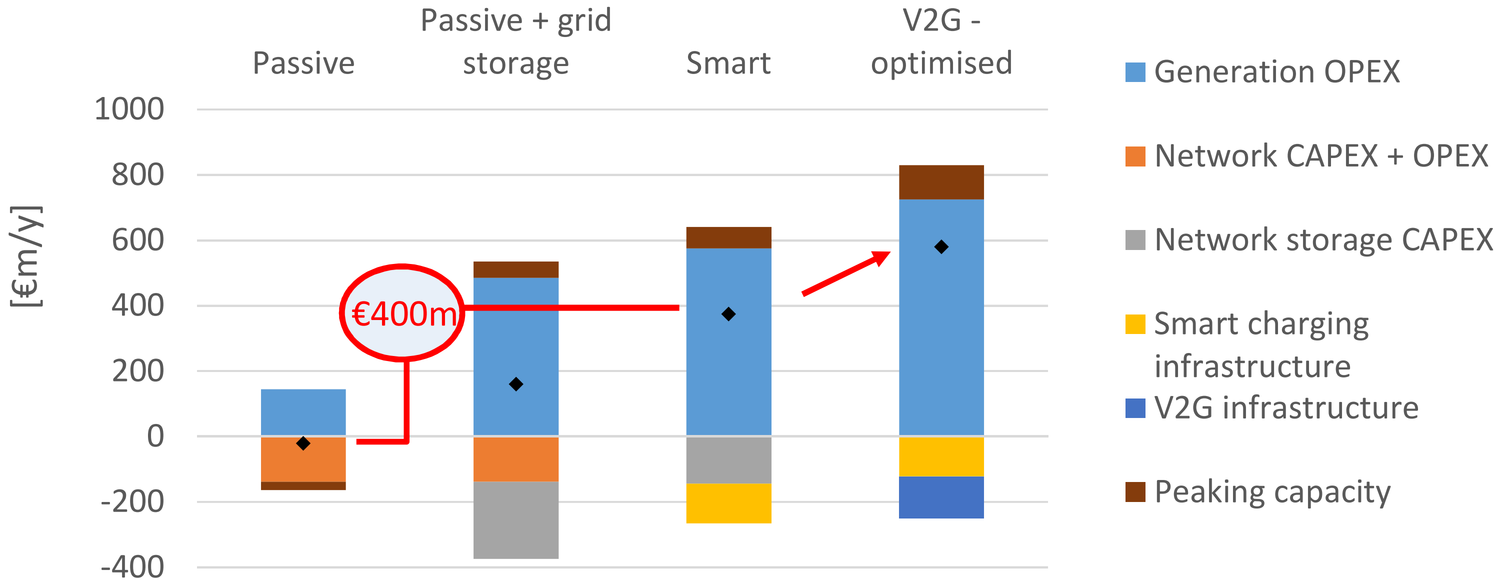


- Scenario Smart offers a net benefit of €560m per year benefit over Passive
- V2G offers a net benefit of €840m per year over Passive (74% of potential used)
- High wind and solar penetration (70% of total generation) enables significant additional savings in V2G

- Smart shows a net benefit of €1,260m per year cp. to Passive
- Low additional generation savings in V2G cp. to Smart due to low RES penetration and curtailment
- Only 5% of potential V2G capacity is used

Sensitivity Spain: Higher proportion of EV charging at work, and public charge points

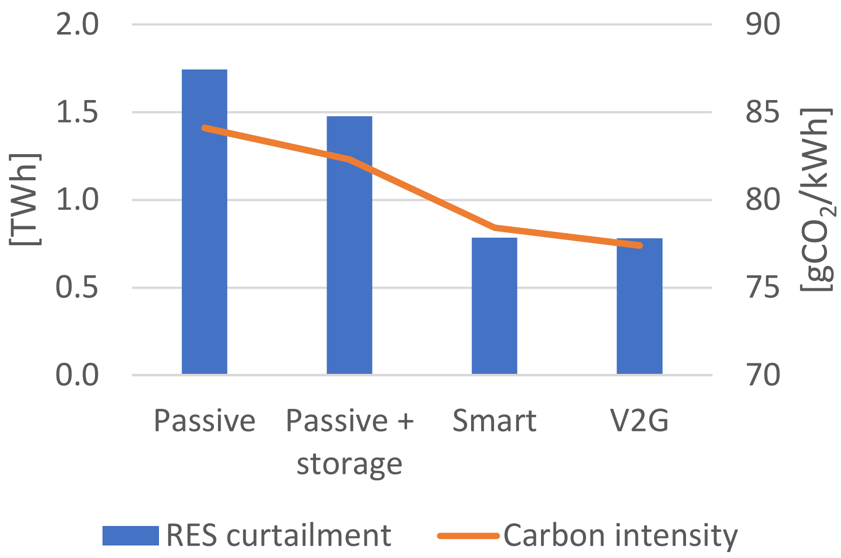
Costs & benefits ES rel. to ENTSO-E baseline, ENTSO-E scenario “Distributed Generation”



- Lower grid penalty of passive charging, as more passive charging is done primarily during the day as opposed to the evening, as there is more work and public charging
- Generation savings are reduced in smart and V2G scenarios by about €200m cp. to original distribution of charging; however net benefit of both smart and V2G scenario is increased
- Grid capacity is 50GW in the passive case, reduced to 49 in smart and V2G scenario, the same as in the counterfactual
- In the run with higher home charging, the grid capacity was reduced from 52GW in the passive case to 51 in the smart and V2G scenarios, vs 49GW in the counterfactual

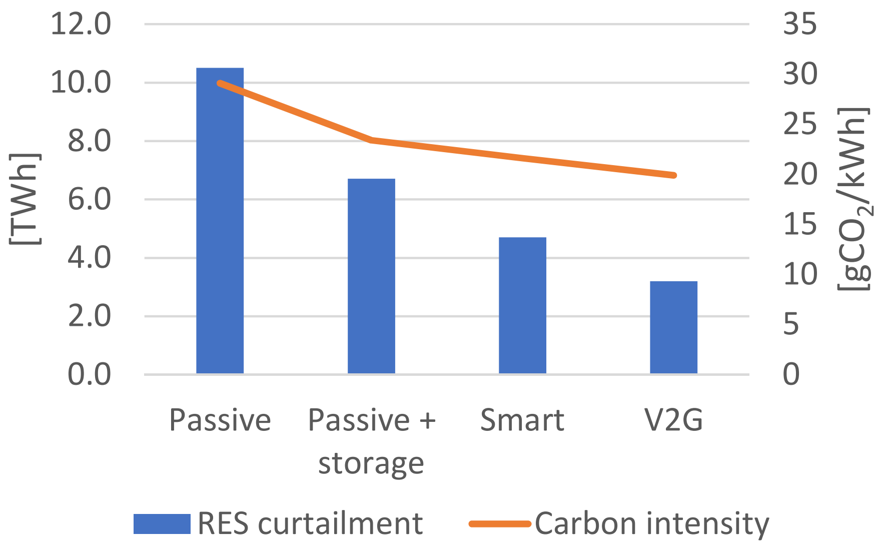
Generation savings: batteries and EVs increase the use of renewable energy sources and reduce carbon emissions -

Curtailment and carbon intensity UK



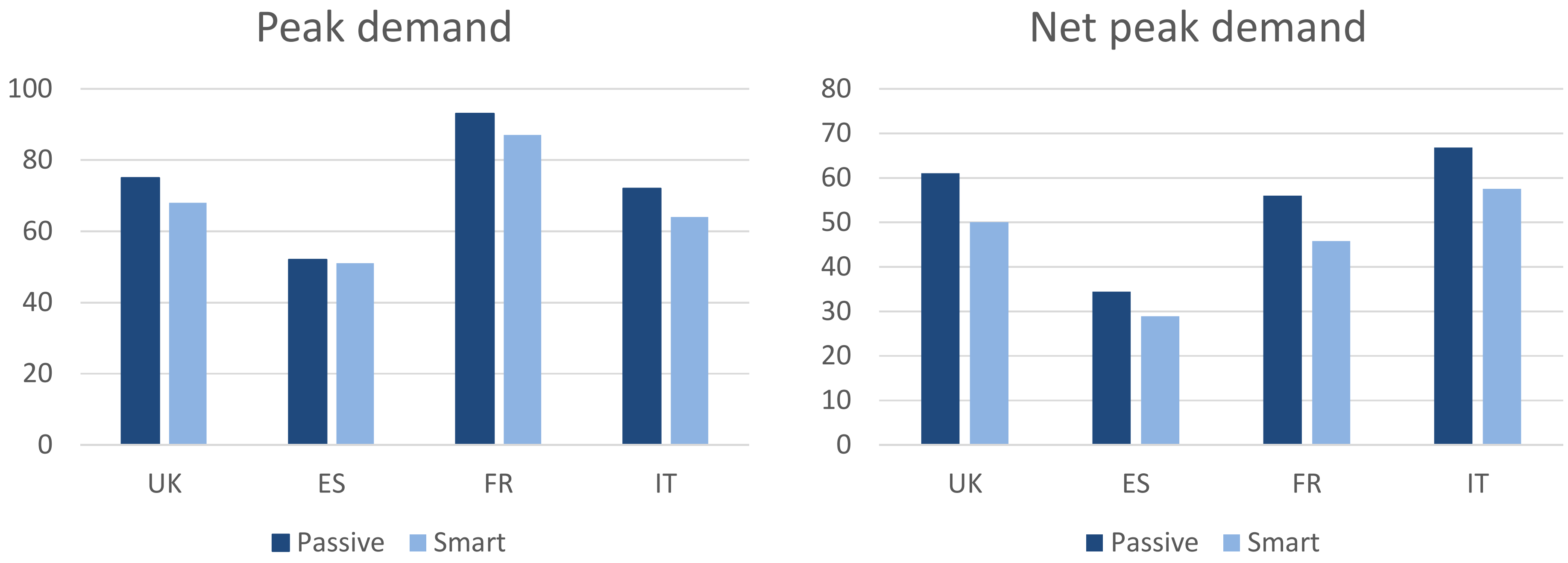
- Low impact on RES utilisation as curtailment rate of wind, solar and hydro is less than 1% in the baseline
- EVs and batteries help to increase run hours of more efficient thermal plant
- Smart charging and V2G also avoids need for network capacity upgrade
- CO_2 intensity of electricity is reduced by 8% in V2G relative to passive scenario

Curtailment and carbon intensity Spain



- Grid storage leads to 37% reduction in curtailment
- Smart charging can achieve 66% curtailment reduction with a storage capacity 6% smaller than that used in Passive with storage
- Graph shows curtailment due to demand not being coincident with VRE generation
- Curtailment due to network constraints is increased in Smart and V2G compared to Passive due to lower grid capacity

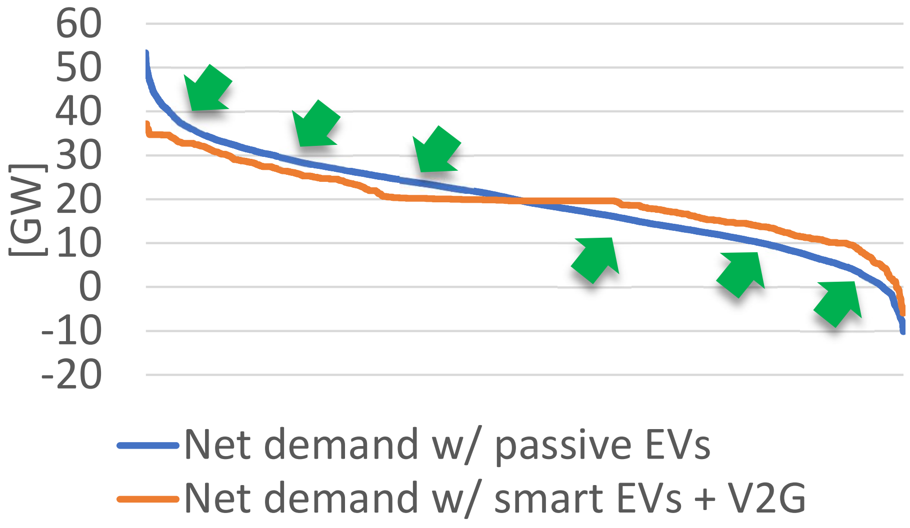
Capacity savings through EVs: Smart charging reduces demand in times of high system stress



- Across all modelled countries net peak demand is reduced by 9-18% by smart charging compared to uncontrolled charging
- System peak demand is reduced by 2-11% by smart charging compared to uncontrolled charging
- In Spain, peak demand is reduced by only 2%, but net peak demand is reduced by 16%, as allowing a higher peak demand on the transmission grid increased VRE utilisation

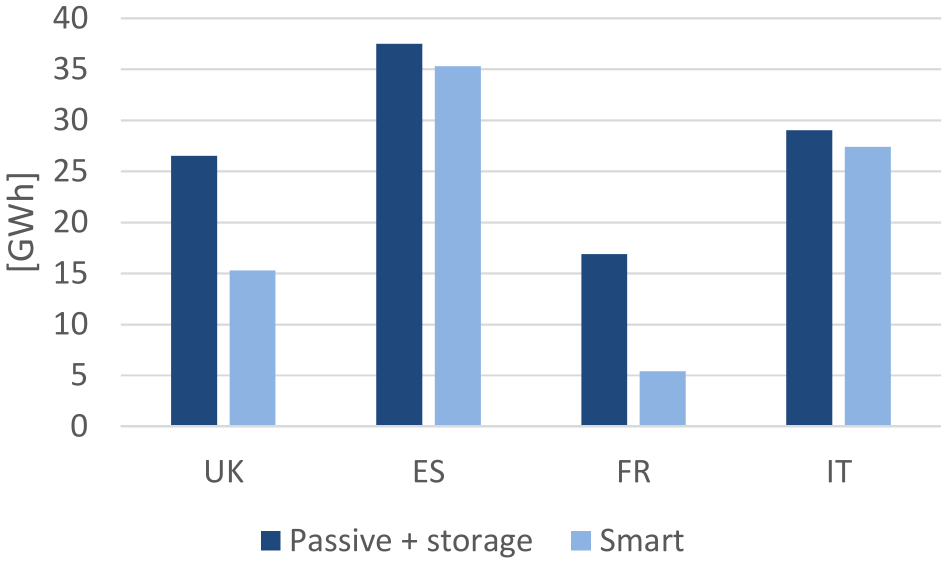
Batteries compete with vehicles to provide flexibility but high demand for flexibility will require utilizing the potential of both

Smart EVs reduce batteries' opportunities



- In the case of passive charging, the economic opportunity for batteries is bigger and a larger battery capacity is deployed
- This is displayed in the graph above showing how net demand is significantly flattened after applying smart charging and V2G

Opportunity for storage remains significant



- The cycling opportunity for stationary battery capacity is reduced by smart charging
- However a significant potential for economic storage deployment remains
- E.g. the economic capacity in the UK (15.3GWh) is 34 times as high as the battery storage capacity deployed today

Structure

Projections of available battery volumes

The role of EVs in the power system

  Context and methodology recap

  Country results

  Threats to EV batteries

Review of recycling processes and policies

Economics of battery end of life options

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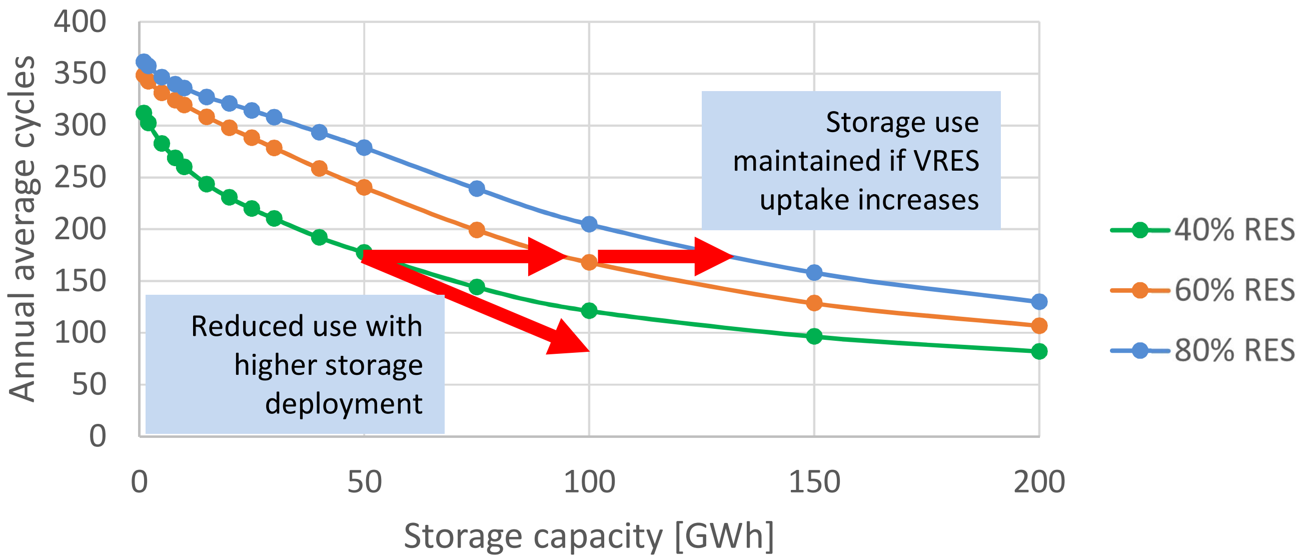
The marginal benefit of batteries decreases with installed capacity – but there is synergy with high renewable energy targets

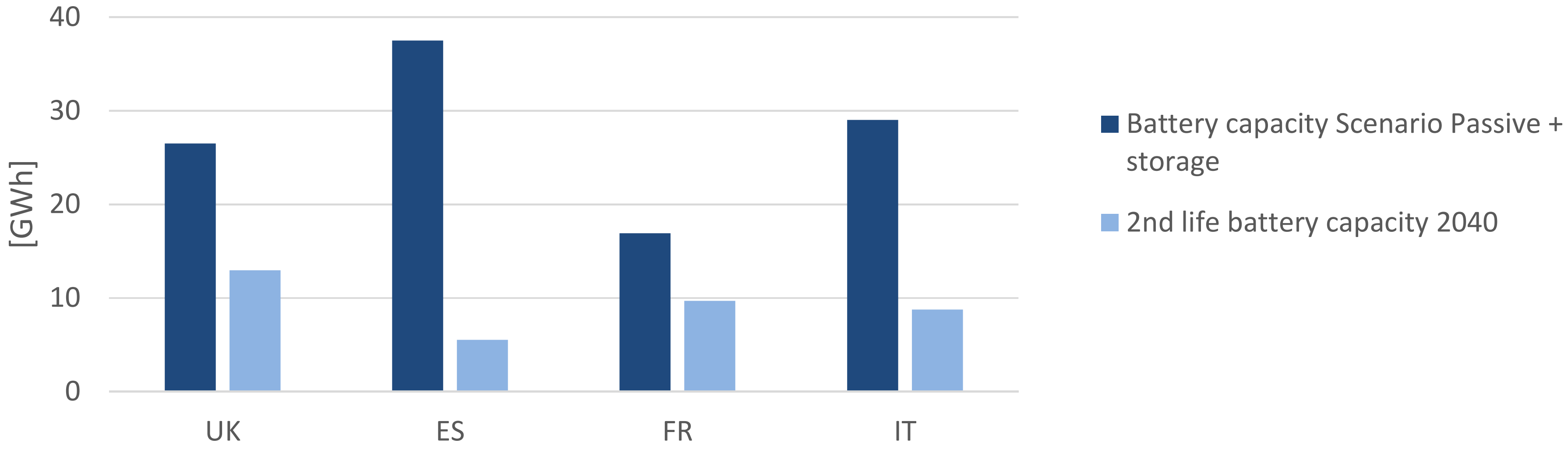
Positive synergy between storage utilisation (revenues) and VRES deployment



- The more storage is already deployed in the system, the lower additional storage capacity is utilised
- For example for 40% RES only 75GWh of storage have 150 average cycles per year, whereas for 80% RES this capacity is doubled to 150GWh
- With higher RES penetration, a larger storage capacity is used frequently and can be deployed economically
- Policy support or appropriate market mechanisms might be necessary to deliver the deployment of battery storage necessary to reach carbon targets

2nd life batteries could supply a significant share of demand for stationary battery storage in 2040

Cumulative repurposed 2nd life battery could play significant role in or outside the EU

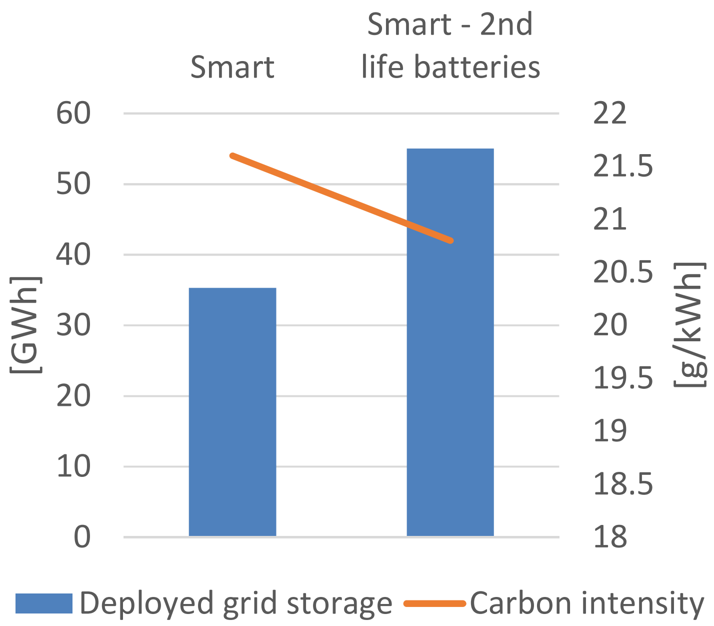


- The cumulative capacity of the repurposed 2nd life battery stock could provide a significant share of the amount of battery storage which is able to be deployed economically in most modelled countries (in scenario Passive + storage)
- With cheaply available repurposed 2nd life batteries the cost of storage could decrease which in turn would increase the level of storage that is economic
- 2nd life batteries could find also application in markets outside the EU, in particular in countries with immature electricity grids and high demand for off grid solutions
- The total retaining capacity of 2nd life battery stock across the EU is estimated to be 70.4 GWh in 2040 (from work package 1 modelling, TECH scenario)

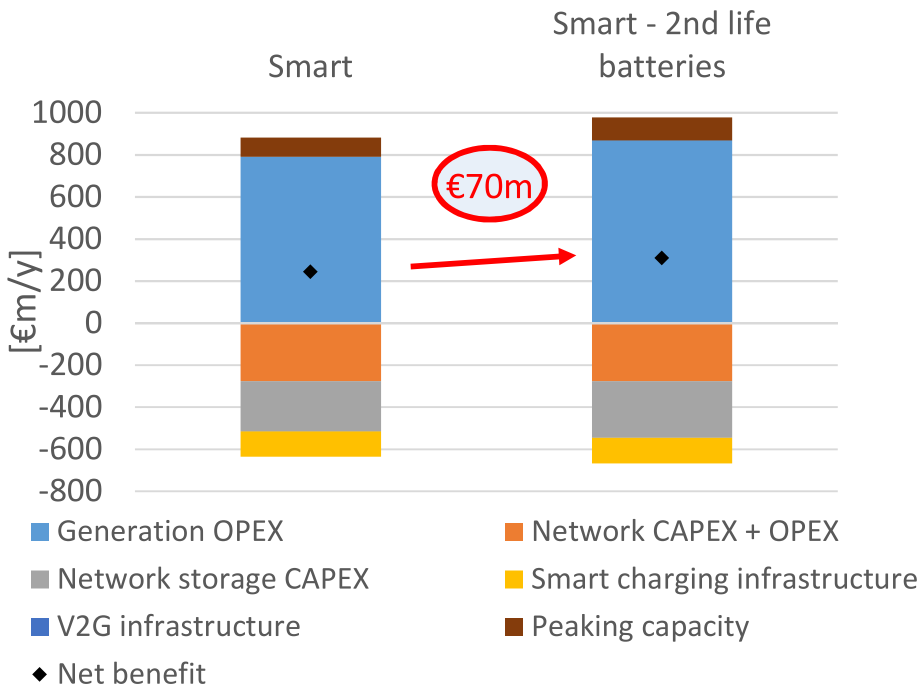
Results for Italy are for scenario runs with increased solar capacity (sensitivity)

Cheap 2nd life batteries could lead to increased storage deployment and lower grid emissions

Storage capacity and carbon intensity



Costs & benefits ES rel. to ENTSO-E baseline



- Availability of cheap repurposed 2nd life batteries could lead to increased storage deployment
- Even after accounting for a shorter lifetime the economically deployable storage capacity is increased by more than 50% in the Smart scenario
- The additional storage capacity helps to achieve an additional net benefit of €70m per year and to reduce the carbon intensity by 4% in the Smart scenario

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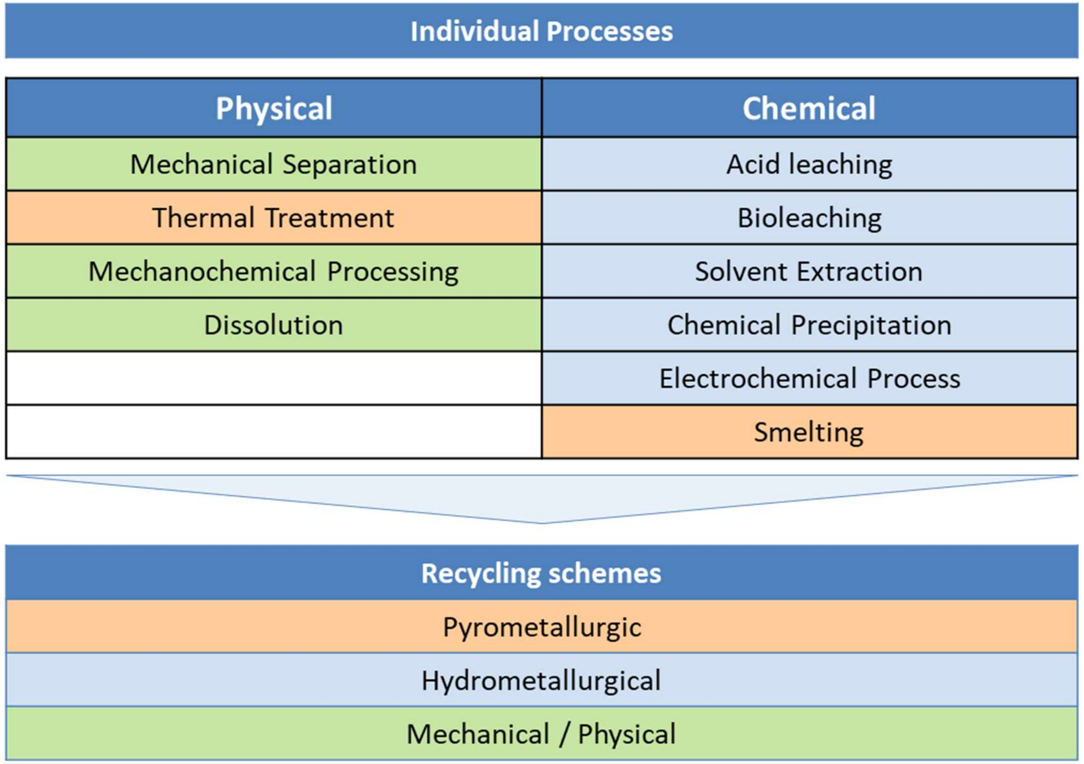
Battery Recycling Review: Our Approach

- The following section provides a summary of the pertinent technical information regarding battery recycling techniques and for each technique covers the pros and cons of the technology.
- Battery recycling involves a series of individual physical and/or chemical processes combined under a recycling scheme.
- Depending on the energy intensity of the processes involved, the recovered materials can be in the form of battery components (for mechanical / physical recovery), inorganic salts (hydrometallurgical schemes), or metallic residues (pyrometallurgic)
- The following slides have benefitted from the review of RECHARGE and EBRA.



Individual Processes

Physical	Chemical
Mechanical Separation	Acid leaching
Thermal Treatment	Bioleaching
Mechanochemical Processing	Solvent Extraction
Dissolution	Chemical Precipitation
	Electrochemical Process
	Smelting

Recycling schemes
Pyrometallurgic
Hydrometallurgical
Mechanical / Physical

Recycling technologies were assessed on the following Key Performance Indicators (KPIs):

- Technology readiness
- Range of recovered materials
- Battery pre treatment / input criteria
- Future economic viability
- Emissions
- Efficiency

Different recycling schemes and recycled components may by-pass several steps during the manufacturing of new batteries

- Recycling schemes can be broadly categorized as:
  - Pyrometallurgical
  - Hydrometallurgical
  - Physical
  - A mixture of the three

- Different schemes may eliminate battery production steps, hence increasing the value of recycling. A battery recycling scheme may:
  - Return some raw materials recovered from batteries **(pyro and hydro-metallurgical)**
  - Return raw materials in a form that removes some processing steps in the battery supply chain – **intermediate recycling** **(physical, hydro-metallurgical or a pyro/hydro combination)**
  - Return materials in a form so that they can immediately be reused to form electrodes and electrolytes – **direct recycling** **(physical)**

- Reconditioning is an extreme physical recycling under which a new battery pack is made out of used cells. Note: Reconditioning and repurposing are here defined differently – repurposing is used if a used pack undertakes a different responsibility.

Overview of main recycling schemes

Recycling schemes can be broadly categorized as:

- **Pyrometallurgical:**
  - Involves placing the battery pack in a high-temperature furnace, after some preliminary dismantling of the pack might have also be performed
  - Some components are burnt to generate heat (e.g. graphite anode, aluminium wires, plastic casing) whilst other chemical compounds are reduced to metals.
  - The solids recovered consists of an alloy of Cu, Co, Ni, and Fe and a slag containing Li, Al, Si, Ca, and some Fe compounds. The solid alloy is usually recycled whilst it is considered uneconomical to recover individual components of the slag.

- **Hydrometallurgical:**
  - It usually involves the dismantling of the battery pack into individual cells, which may be further subjected to further physical and mechanical processes (e.g. shredding, milling)
  - The resulting battery fragments/powder are leached with acids and/or alkali, which dissolve most of the components. Bioleaching, using microorganisms to conduct chemical dissolution, has been demonstrated in the laboratory, however it is not industrially used. The dissolved components are then extracted using solvents, precipitation, and/or electrochemical techniques.
  - The process has a high recovery rate. All recovered materials are under the form of inorganic salts.

- **Physical:**
  - Consists of manual and/or automated dismantling of the battery pack, with key components being recovered in their original state (e.g. electrodes, wiring, casing)
  - Some recovered components (e.g. electrodes) may be used directly in the manufacturing of new batteries whilst other components (e.g. wiring) can be recycled using usual schemes (as metals).
  - Other physical processes may include thermal or vacuum treatments in which the electrolyte is evaporated

Recycling Process Scheme Comparison (2019)

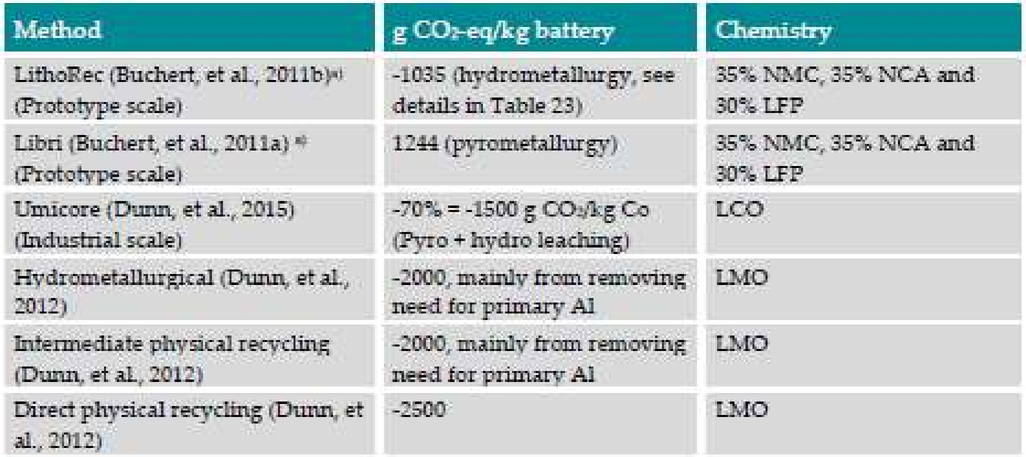
high concern level low

KPI	Pyrometallurgical processes	Hydrometallurgical processes	Physical processes (direct recovery focus)
Technology Readiness	Heavy commercial use	Used commercially currently, high volume use is challenging (R&D phase)	Limited commercial use, ongoing research. If business case works, could be years, not decades.
Range of recovered materials	Typically recover Ni, Co, Cu, Fe. Lithium is wasted in slag (but could be recovered if economical).	Complete electrode recovery (including Lithium) is usually possible	Enables recovery of most of the battery pack, direct recovery reduces future production stages needed
Input criteria / pre-treatment	No pre-treatment required, all battery types (and a mix of types) can be smelted. Larger (EV) battery packs may need to be dismantled or facilities designed differently	Battery packs must be dismantled and the cells typically are treated in a mechanical process	Individual treatment needed of each battery cathode type for direct recovery to be possible. There is EC funding for automatic recognition of electrodes which would help enable this
Future economic viability	Unlikely to be economically viable without batteries with high Cobalt content. High energy input and high running costs	Economic viability will decrease for low Co batteries. Schemes that recover a wider range of materials may still be viable	Direct recovery produces valuable outputs regardless of cathode type as usable electrode powder is produced not just the raw material.
Emissions	Have to undergo gas treatment to remove toxic emissions e.g. HF	Traditional acid leaching produces toxic emissions – Cl_2, NO_x, SO_3. Active research into alternatives – bioleaching and leaching with other acids	Physical processes, like all recycling processes, inevitably result in the need to handle waste. Dust and gases generated.
Efficiency	Low – best schemes (e.g. Umicore) just meet EU target of 50%wt material recovered. Ni and Co recovered at 90% efficiency, most other materials lost. Efficiency statistics could improve if burning of graphite to produce energy for the smelter counted.	Higher than pyrometallurgical. Experimental 90-100% efficiency for most steps.	Use of supercritical CO_2 to extract electrolytes has been seen to be ~90% efficient (although the performance of such electrolytes is unproven). Overall efficiencies similar to hydrometallurgical, with a mixture of directly reused and recovered materials

KPI: Key Performance Indicator. Source: Element Energy literature review, with input from RECHARGE and EBRA

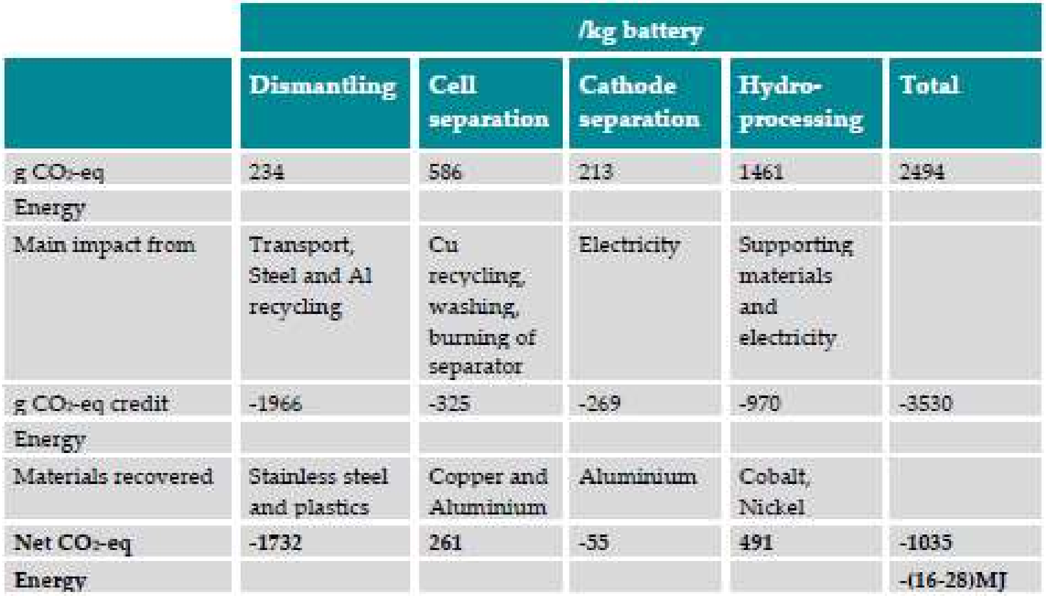
Review of battery recycling emissions

- A study conducted by the IVL Swedish Environmental Research Institute reviewed the estimated emissions published in several publications.
- The upper table shows an overview of Life Cycle Assessment (LCA) results for the recycling stage. The way that recycling is included, chemistry, scale and technology vary so that the results are not always comparable.



Method	g CO_2-eq/kg battery	Chemistry
LithoRec (Buchert, et al., 2011b)[a] (Prototype scale)	-1035 (hydrometallurgy, see details in Table 23)	35% NMC, 35% NCA and 30% LFP
Libri (Buchert, et al., 2011a) [a] (Prototype scale)	1244 (pyrometallurgy)	35% NMC, 35% NCA and 30% LFP
Umicore (Dunn, et al., 2015) (Industrial scale)	-70% = -1500 g CO_2/kg Co (Pyro + hydro leaching)	LCO
Hydrometallurgical (Dunn, et al., 2012)	-2000, mainly from removing need for primary Al	LMO
Intermediate physical recycling (Dunn, et al., 2012)	-2000, mainly from removing need for primary Al	LMO
Direct physical recycling (Dunn, et al., 2012)	-2500	LMO

- In addition, for the first process in the upper table (LithioRec hydrometallurgical prototype recycling plant), a breakdown of emission is provided in the same study.



	/kg battery				
	Dismantling	**Cell separation**	**Cathode separation**	**Hydro-processing**	**Total**
g CO_2-eq	234	586	213	1461	2494
Energy					
Main impact from	Transport, Steel and Al recycling	Cu recycling, washing, burning of separator	Electricity	Supporting materials and electricity	
g CO_2-eq credit	-1966	-325	-269	-970	-3530
Energy					
Materials recovered	Stainless steel and plastics	Copper and Aluminium	Aluminium	Cobalt, Nickel	
Net CO_2-eq	**-1732**	**261**	**-55**	**491**	**-1035**
Energy					**-(16-28)MJ**

The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries, IVL Swedish Environmental Research Institute, 2017

Structure

Projections of available battery volumes

The role of EVs in the power system

Review of recycling processes and policies

Economics of battery end of life options

- Economics of Recycling
- Economics of Repurposing
- Economics of Second life

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Economics of battery fate: Our approach and scope

The slides in this section describe the modelling approach and the assumptions used in exploring the following topics regarding the economics of battery fates at the end of first life:

1 **Economics of recycling**: understanding recyclers' business model and how volumes of used EV batteries will affect the industry.

- Will OEMs have to pay a recycling fee or be paid to recycle batteries in the future?

2 **Economics of repurposing**: investigating future workshops buying, repurposing, and selling used batteries.

- How much does it cost to repurpose a battery?
- How does the resulting price compare to a new battery?

3 **Economics of second life**: the value of used batteries in service

- What are the savings associated with using an used battery?
- How does that compared with using a new battery instead?

Structure

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Economics of battery end of life options

- **Economics of Recycling**
- Economics of Repurposing
- Economics of Second life

Supplementary information

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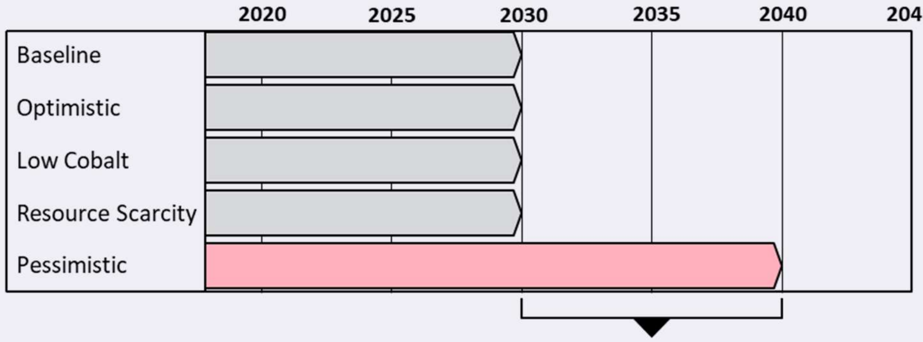
Economics of battery recycling: key assumptions and sample outputs

Five recycling economics scenarios each dependent on four parameters

Scenario name	Battery chemistry	Metal prices	Recycling efficiency implementation year	Recycling variable costs
Baseline	Baseline	Baseline	2030	2018 levels
Optimistic	Baseline	Increased Co and Ni prices, others baseline	2030	0.9 x 2018 levels
Pessimistic	Baseline	Increased Co and Ni prices, others baseline	2040	1.5 x 2018 levels
Low Cobalt	Increased LFP uptake	Baseline	2030	2018 levels
Resource scarcity	Baseline	Increased Co and Ni prices, others baseline	2030	1.5 x 2018 levels

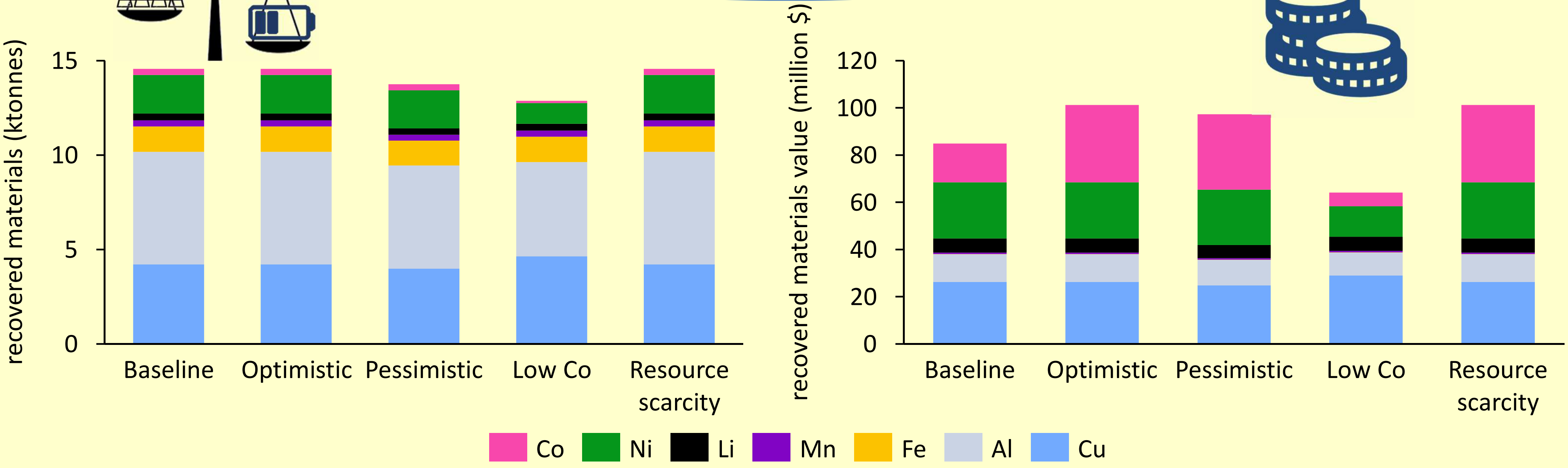
Recovery efficiency improvements are modelled dynamically



delay in implementing higher recovery targets under the pessimistic scenario

Several parameters assess the content of six key metals in the exhausted batteries, the metal recovery efficiency and market value (exemplified for the recovery efficiency on the right).

The 27,595 tonnes of batteries will be recycled in 2035 could translate in…

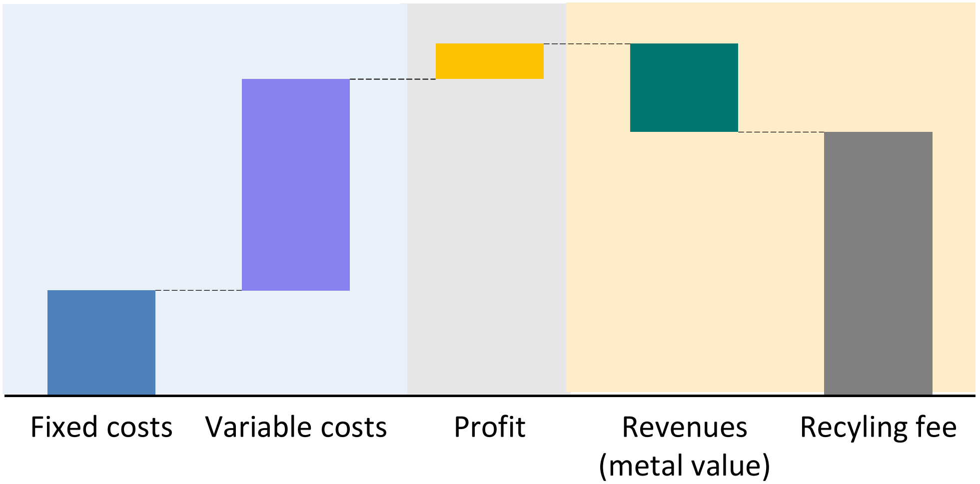


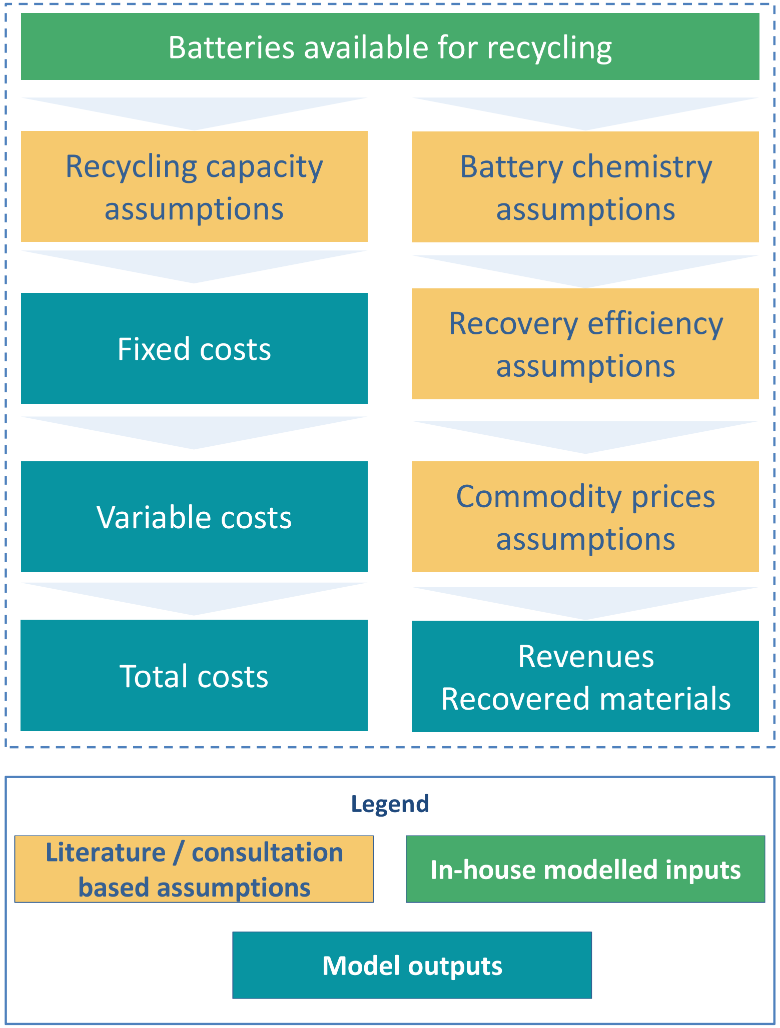
Economics of recycling: Recycling fees modelling approach

1

- Since the recycling fees determine the feasibility of each end-of-life option, this task was started by modelling the economics of future recycling facilities in Europe.
- The recycling fees are the difference between recycler's revenues, profit, and the costs incurred:
  - Costs (based on literature review and industry consultation)
    - Fixed costs (investment in new facilities / upgrades, maintenance, overhead)
    - Variable costs (Labour, electricity, gas, chemicals, etc)
  - Revenues (mainly based on the amount of metals recovered) – modelling detailed on next slide
  - Profit (assumed at 10%).

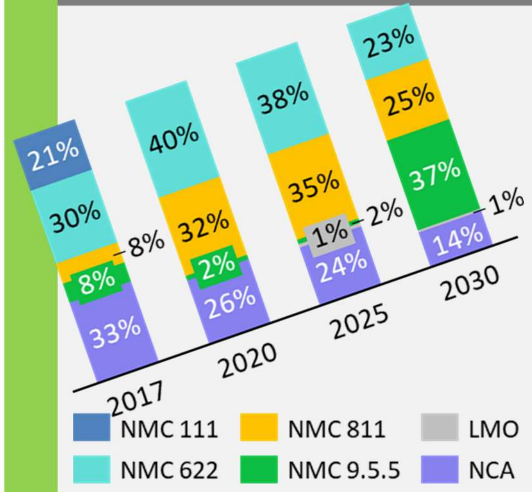
Illustrative diagram





Economics of recycling: Key factors captured in our scenarios

Battery chemistry and energy density



Source: McKinsey Energy Insights

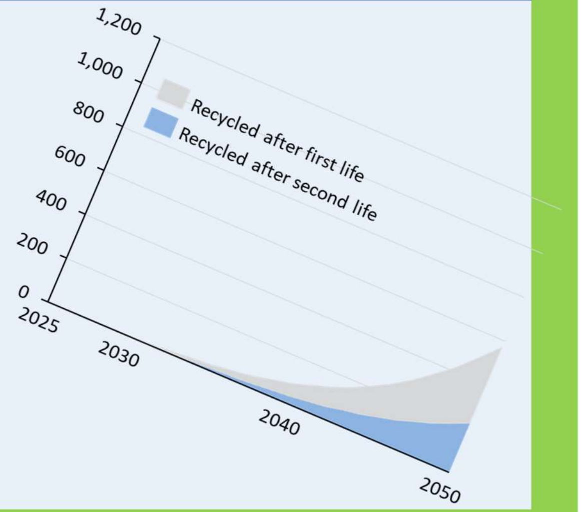
Future batteries will have a significantly lower cobalt content due to economics and ethics.

Batteries are becoming more compact and efficient than ever. Same performance but at a lower weight means fewer metals to recover

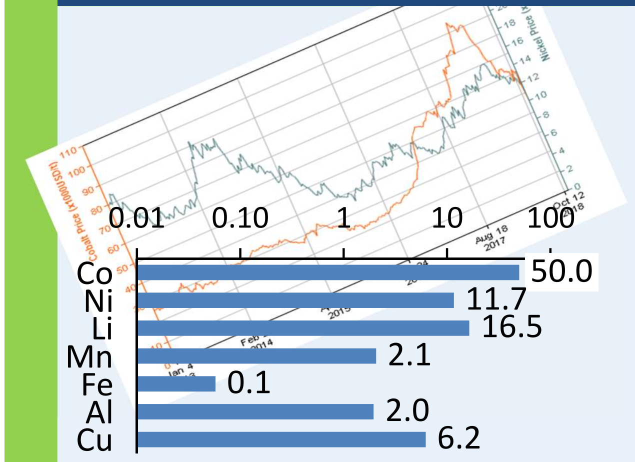
Battery volumes

Uncertainty around the volumes of recycled batteries can make capacity planning difficult.

Misplanned investments and spare capacity may become problematic until market maturity.



Commodity prices



Volatility of valuable metals (Co and Ni) puts under uncertainly recyclers' long term financial returns.

Difficult to predict recycling fees to charge battery manufacturers and OEMs.

Source: London Metal Exchange, Metalary (Spot prices 07/11/2018)
Lithium as Lithium Carbonate; Commodity prices ($/kg metal)

Policy and recovery efficiency

R&D advances, technology readiness, and regulatory targets regarding recovery efficiency and emissions can make or break recyclers' business model.

Increased recycling costs could ultimately mean higher battery and EV costs.

Comparison of future economic and policy scenarios

1

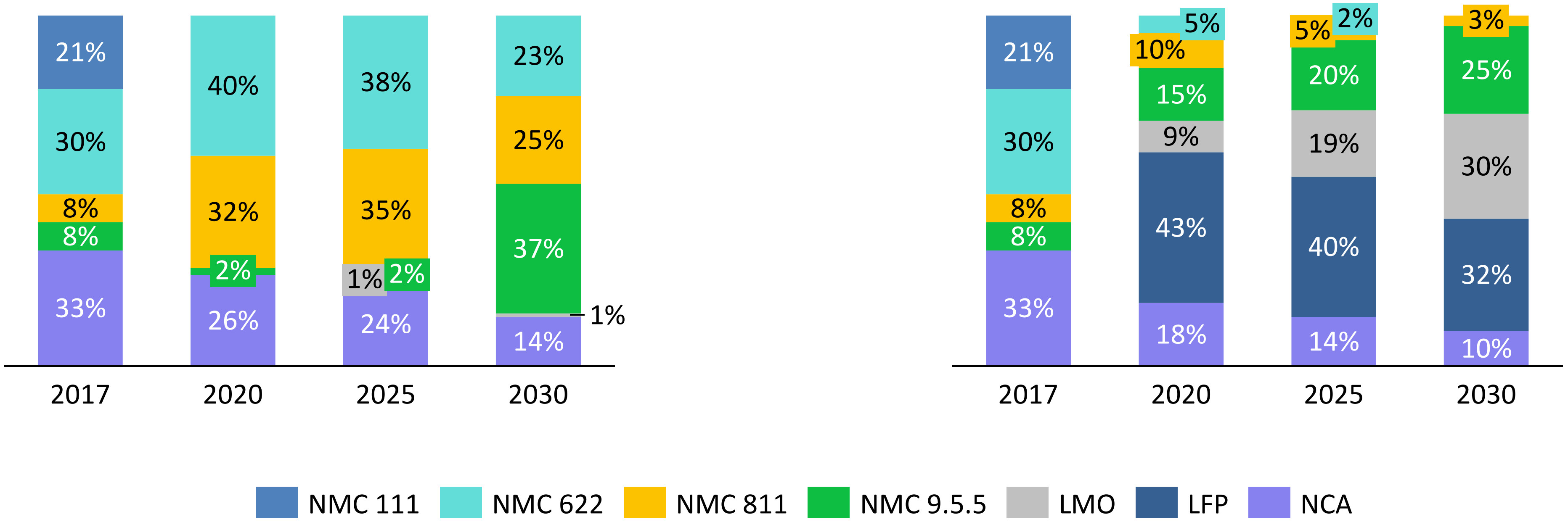
Scenario name	Scenario description	Battery chemistry*	Recycling efficiency	Metal prices	Logistics costs**	Recycling costs
Baseline	Scenario characterised by steady metal prices, recycling efficiency reaching targets by 2030, unchanged recycling costs, battery chemistry following current European trends., and standard but efficient logistics	World mix (McKinsey)	Achieve targets by 2030	Current (2018)	Baseline	current (2018)
Optimistic	Industry change with increased metal prices, recycling improvements implemented by 2030, reduced recycling costs due to automation, and standard battery chemistries, improved recycling efficiency, and standard but efficient logistics	World mix (McKinsey)	Achieve targets by 2030	Increases Co (2X) and Ni (1.5X) prices	Baseline	current (2018)
Pessimistic	Scenario characterised by decreased recycling value for recyclers determined by steady metal prices, delayed improved recycling efficiency, increased recycling costs, and delayed logistics	World mix (McKinsey)	Delayed process, achieve targets by 2040	Current (2018)	Slow ramp-up	1.5 times current variable costs
Resource scarcity	Simulates a world with lower available resources, both human (determining increased recycling labour costs) but also material, increasing the cost of metals. Due to the lack of resources and increased need for recycled metals, technology improvements follow the baseline trend, reaching targets by 2030. Slow ramp-up of logistic is assumed	World mix (McKinsey)	Achieve targets by 2030	Increases Co (2X) and Ni (1.5X) prices metals	Slow ramp-up	1.5 times current variable costs
Low Cobalt	Variation of the baseline scenario, keeping almost all assumptions but assuming a transition of battery chemistry towards low cobalt technologies (LFP, NCM 9.5.5, and LMO).	Large proportion of low-Co batteries	Achieve targets by 2030	Current (2018)	Baseline	current (2018)

* Chemistry based on Lithium and Cobalt – a tale of two commodities, McKinsey Energy Insights, June 2018

** Logistic costs are used for calculating the cost of repurposing and are not used in estimating the future recycling fees.

Economics of recycling: Battery chemistry transition

- The observed transition towards battery chemistries with lower Cobalt costs (expensive and volatile) is likely to impact the revenues of battery recyclers.
- Our model assumes the following chemistry mix of batteries recovered in the future.
- A Low Cobalt scenarios assume a higher uptake of LFP batteries – this is used as a sensitivity only, to show the impacts of OEMs adopting battery chemistries well established in China and aggressively moving away from Cobalt.



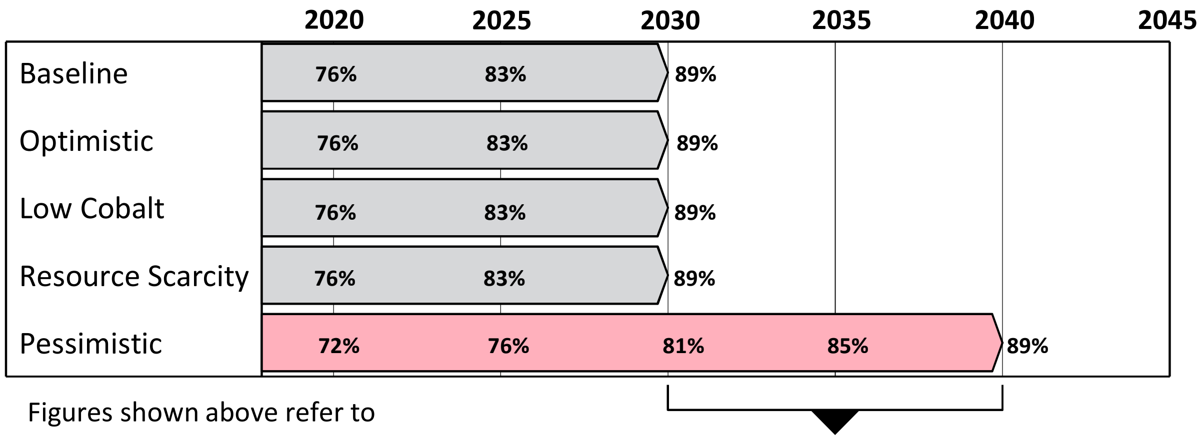
Demand of EV batteries (Baseline case)

Demand of EV batteries (Low Cobalt case)

Lithium and Cobalt – a tale of two commodities, McKinsey Energy Insights, June 2018

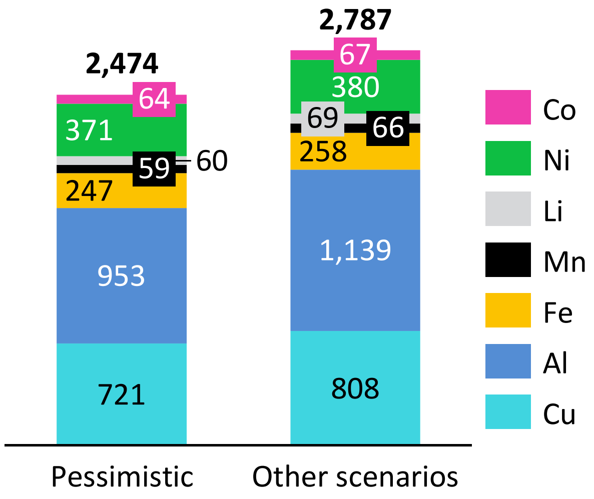
Economics of recycling: Recovery efficiency

- Recovery efficiency is likely to vary depending on the type of battery recycled, recycling processed used (pyro-, hydro-metallurgical, or direct/physical), and technological improvements in the technology.
- Apart from the variation across each type of recycling process, accurate industry figures are kept confidential by recyclers and thus difficult to obtain. For the same reason, literature is very scarce in terms of industry estimates.
- Most academic journals cite demonstrated lab-scale yields for very specific recycling processes (e.g. hydrometallurgical with bio-leaching, physical direct recycling etc), which vary widely from publication to publication and which may be difficult to replicate at an industrial scale. In order to account for this variation, several sources were reviewed, and recovery targets were modelled for seven different metals.
- Technological advances and regulatory pushes are simulated by modelling the recovery efficiency is modelled dynamically, as follows:
  - High value achieved by 2030 in the Baseline, Optimistic, Resource scarcity and Low-Co scenario.
  - Late target achievement (by 2040) in the Pessimistic scenario
- The difference in the total weight of metals recovered is exemplified for batteries recycled in 2030 (left). Under the pessimistic scenario, 11% fewer metals are recovered relative to the other scenarios.



Figures shown above refer to average recovery efficiency across seven metal types.

delay in implementing higher recovery targets under the pessimistic scenario



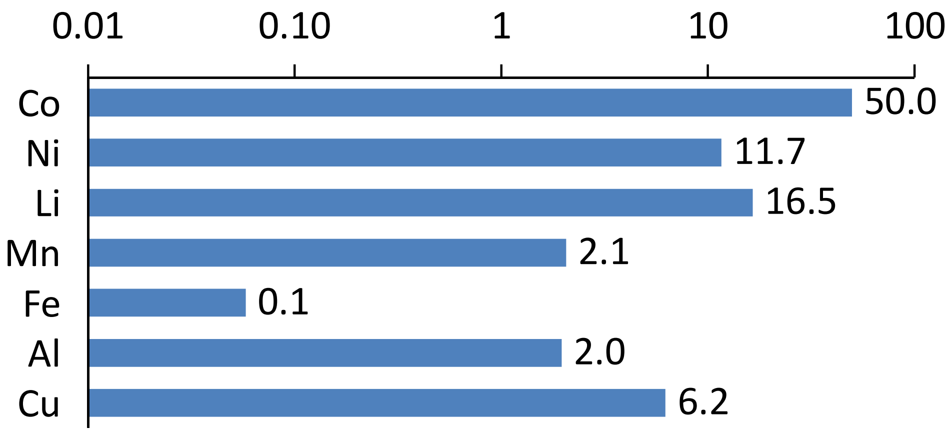
Mass of recovered metals (tonnes) from the same battery input (3,615 tonnes) under different scenarios in 2030

Sources: 1.. X. Wang et al. / Journal of Environmental Management 135 (2014) 126 – 134   2. X. Wang et al. / Resources, Conservation and Recycling, 83 (2014) 53-62   3. M.K. Jha et al. / Waste Management 33 (2013) 1890–189   4. X. Zheng et al. / Engineering 4 (2018) 361–370

Economics of recycling: The cathode chemistry has a large influence on recycler’s profitability

- To assess the economics of recycled batteries, the value of the recovered metals was calculated using commodity prices.
- Due to the market volatility, only current commodity prices are used in the modelling, as projects beyond the next couple of years are unavailable. In reality, recyclers deal with daily fluctuations by price hedging with metal collectors once battery stream composition is clear. The hedging period is usually less than a year.
- A transition towards batteries with a low Cobalt content would reduce the value of recycled batteries and thus the profitability of recyclers. For this reason, it is expected that recyclers will tweak their processes focusing on a higher recovery of Co or other valuable metals. It is also likely that some plants would specialise in a given chemistry.
- In the modelling, it is assumed that the batteries are processed by a recycling facility with a capacity of 22,000 tonnes/year, a CAPEX of $16.8m depreciated over 10 years, and a variable cost of $2,968/tonne batteries under the baseline case[2].

Commodity prices ($/kg metal)



Source: London Metal Exchange, Metalary (Spot prices 07/11/2018)
Lithium as Lithium Carbonate

Comparison of historical Cobalt and Nickel prices[1]

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1. www.infomine.com
2. X. Wang et al. / Resources, Conservation and Recycling 83 (2014) 53– 62

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Economics of battery end of life options

- Economics of Recycling
- **Economics of Repurposing**
- Economics of Second life

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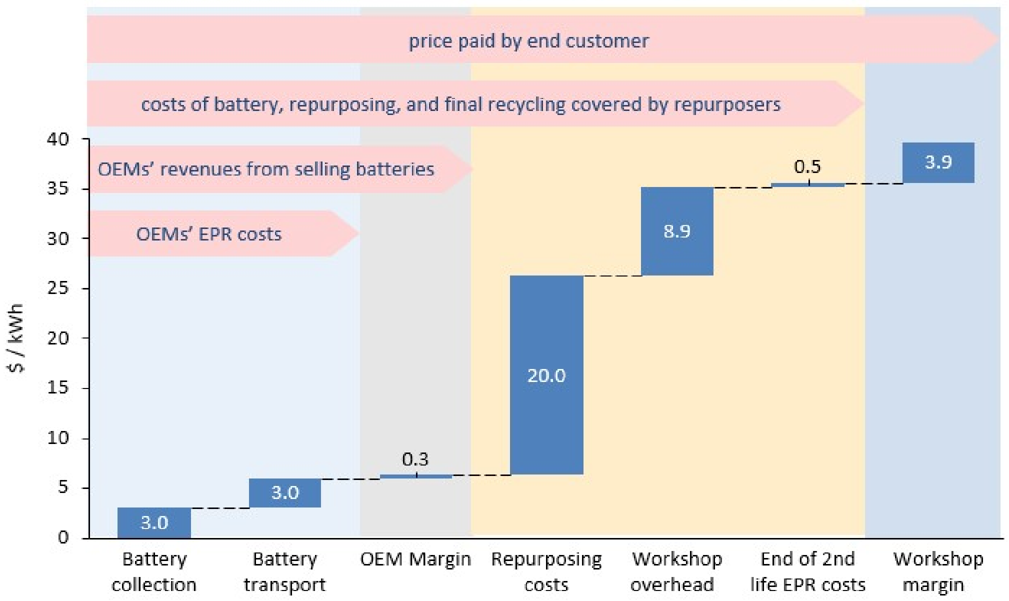
Economics of repurposing: Overview

In the case of battery repurposing a bottom-up approach is used:

- It is assumed car OEMs would collect and sort batteries as usual.
- Exhausted batteries requiring recycling would be delivered to the appropriate facilities, whilst those deemed viable for second life applications would be sold to repurposing workshops.
- The sale would represent the EPR transfer from the OEM to the repurposing workshop.
- Once repurposed, batteries would be placed on the market for second life applications.


Price breakdowns of a repurposed battery placed on the market in 2030

Illustrative bottom-up approach used

Key assumptions on battery collection and logistics, repurposing and placement on the 2nd life market are shown in the table below:

Cost component	2018	2030	Source
Battery collection	$1,000/tonne	$333/tonne	Industry consultation
Battery transport	$1,000/tonne	$333/tonne	Industry consultation
Repurposing cost	$100/kWh	$20/kWh	IDTechEX, Webinar "Second-life Electric Vehicle Batteries“, Oct 2018, reviewed by Steering Group
OEM margin for selling batteries	5%	5%	EE's assumptions
Repurposers' margin	10%	10%	EE's assumptions

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- Economics of Repurposing
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Economics of second life: our approach

This task explored the economics of using 2nd life batteries in different applications.

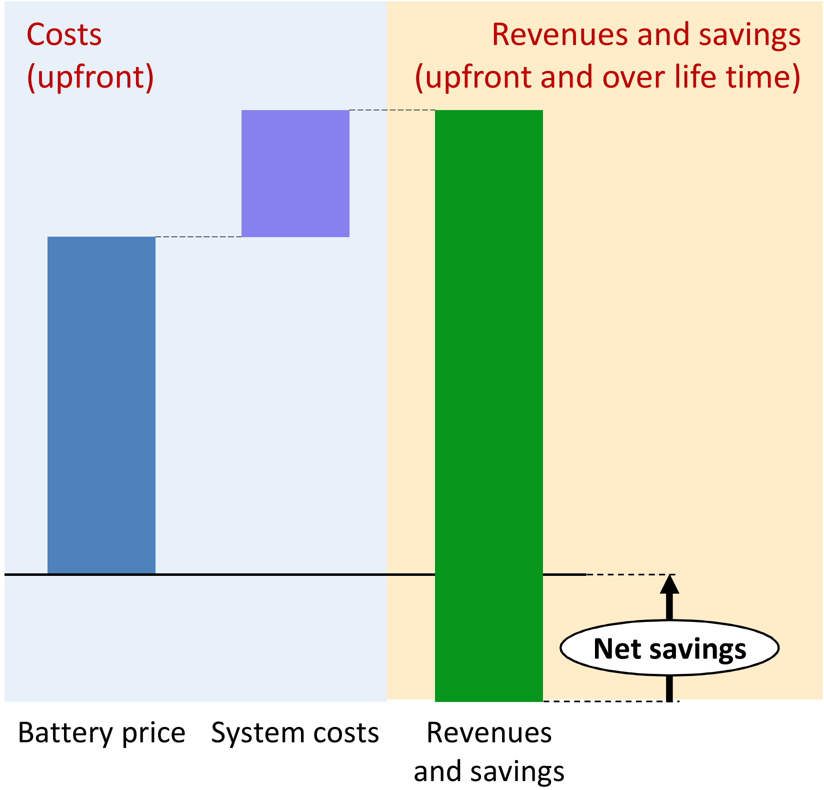
Investigated aspects include:

- Costs associated with buying the battery units and building the system
- Revenues and savings achieved directly and over the batteries lifetime.
- The net savings calculated for two case studies (presented in the report)

For each case study, the performance of 2nd life batteries are assessed against:

- New batteries – with a higher upfront cost but potential for larger revenues due to the longer lifetime
- Counterfactual technology (e.g. network upgrades or peaker replacement)

Illustrative diagram



Savings may include avoided reinforcement costs, ancillary services, and avoided high tariff

Fleet vehicles seeking to move to 100% electric operations are likely to require overnight charging, creating high levels of local power demand

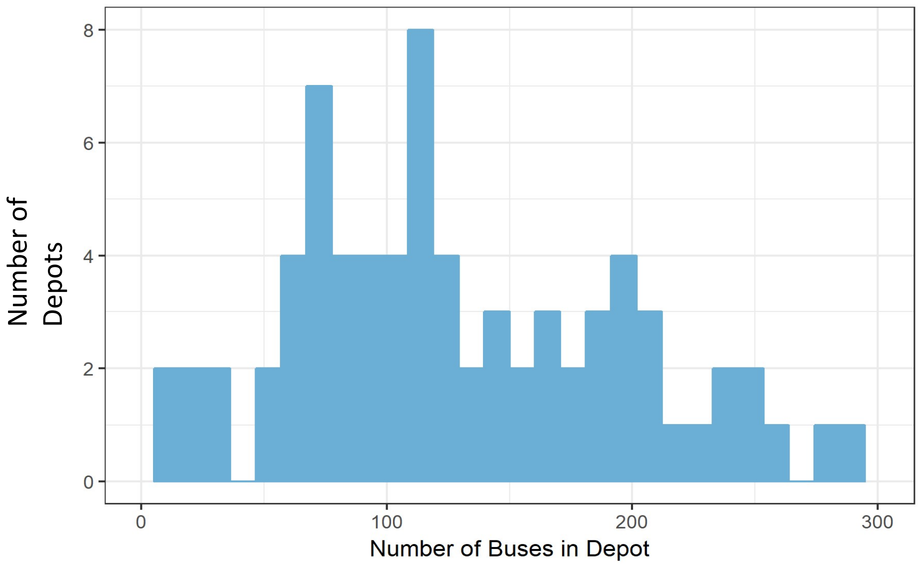
Vehicle charging requirements: using electric buses as an example

Vehicle fleets (including buses) tend to refuel overnight in depots. A move towards 100% electrification would require the majority of the vehicles in the depot to recharge during the same period, creating a large localised electricity demand, with the average electricity demand for a depot during the charging period being equal to the **total daily electricity demand in kWh / the hours available for charging.**

Case study example

- A typical London depot has 100 buses
- Each bus travels 150-200km/day
- Load is 160kWh/100km.bus
- 6 hour charging window

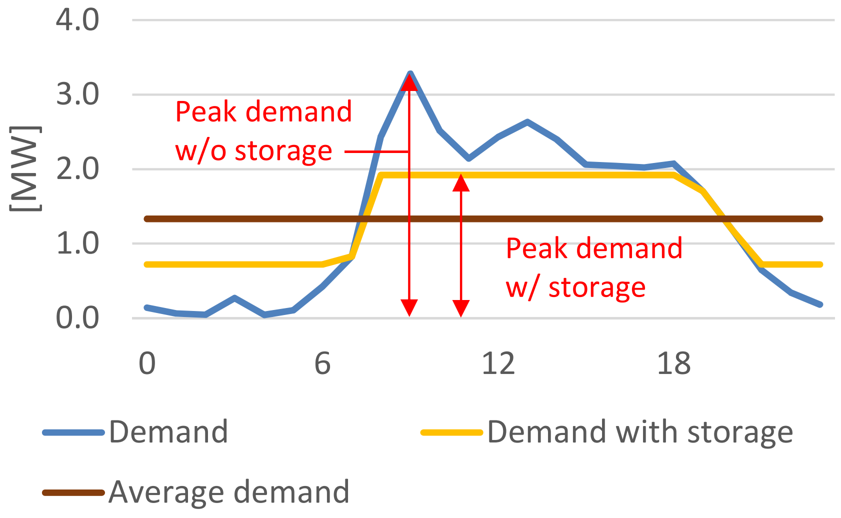
Number of buses in London depots



London bus statistics: https://tfl.gov.uk/corporate/publications-and-reports/bus-fleet-data-and-audits

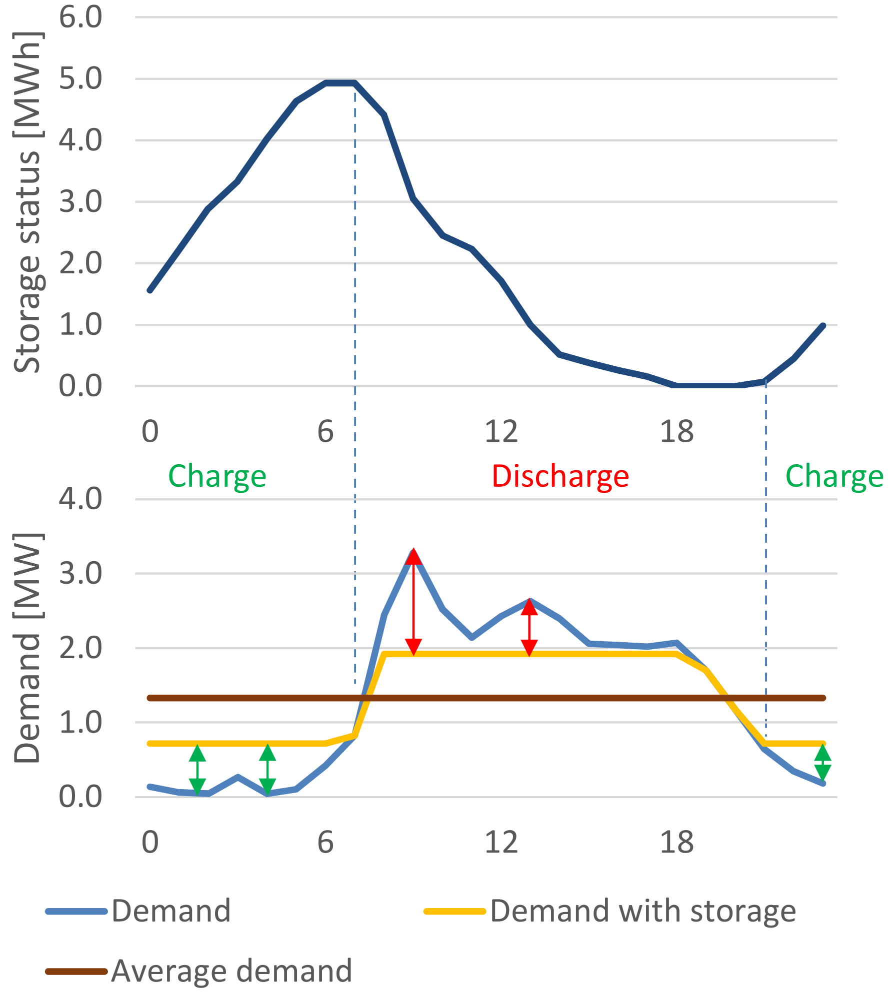
Storage operation to reduce peak demand consumption

Daily demand profile



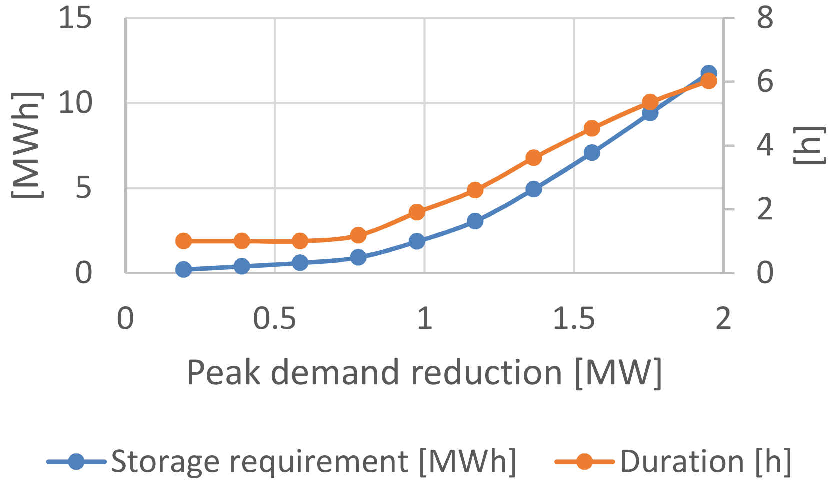
- Storage is charged and discharged in such a way that overall peak demand is reduced (above)
- Above graph is for a bus depot with mileage of 20,000km/day
- Storage is charged at times of low demand and discharged at times of high demand (right)
- The minimum peak demand that can be achieved in this way is the average consumption of the bus depot (flat consumption profile)

Storage status



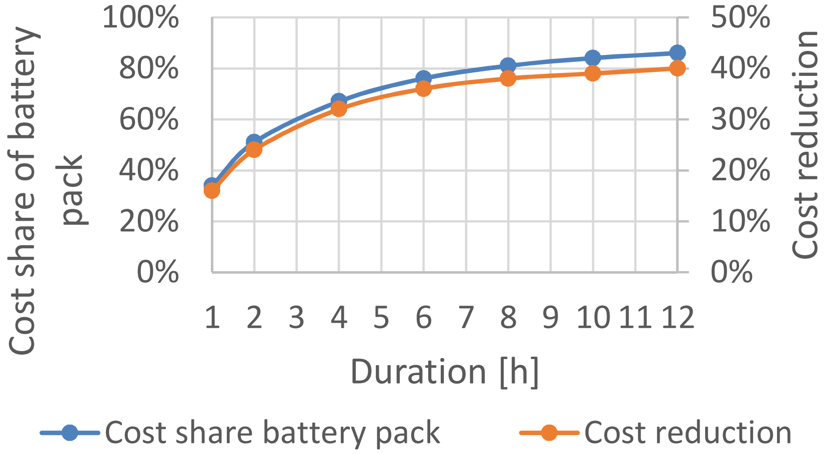
2nd life batteries are most attractive for long duration applications

Storage capacity needed for peak reduction



- Higher peak reduction requires larger storage capacity (in MWh) and longer duration storage
- A peak reduction by 1MW requires a 2MWh storage system, whereas a peak reduction by 2MW requires a 6MWh system
- 1MW grid reinforcement would incur capital expenditure of £1M (London)

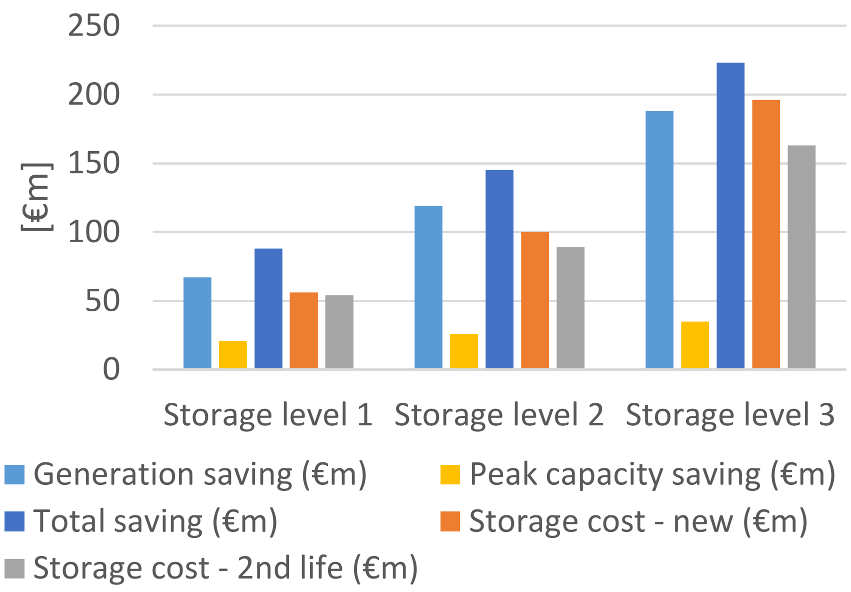
Cost reduction by using 2nd life batteries



- The share of the battery pack in the total system cost (in €/kWh) increases with the storage duration (blue line above)
- We assume new battery pack costs of €59/kWh and repurposed pack costs of €33/kWh
- This allows a capital cost reduction of about 25% for 2h duration and about 35% for 6h duration storage

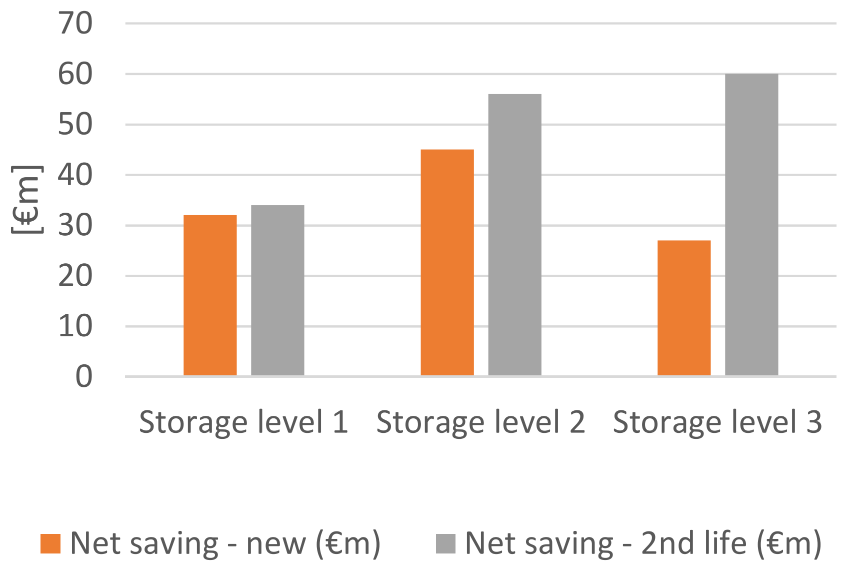
Peaker replacement: higher deployment rate allows larger cost saving when using 2nd life batteries

Savings for different deployment levels



- The above graph shows the costs and benefits of storage for 3 different deployment levels
- Level 1: 2.1GW/5.2GWh
- Level 2: 2.6GW/11.9GWh
- Level 3: 3.5GW/27.3GWh
- The average duration in level 3 is 7.8h vs 2.5h in level 1

Net savings for different deployment levels



- The above graph shows the net savings for the 3 storage deployment levels both in case of using new and using 2nd life battery packs
- At deployment level 3, 2nd life batteries offer a significantly higher saving than new batteries due to the long storage duration available through cheaper of 2nd life batteries

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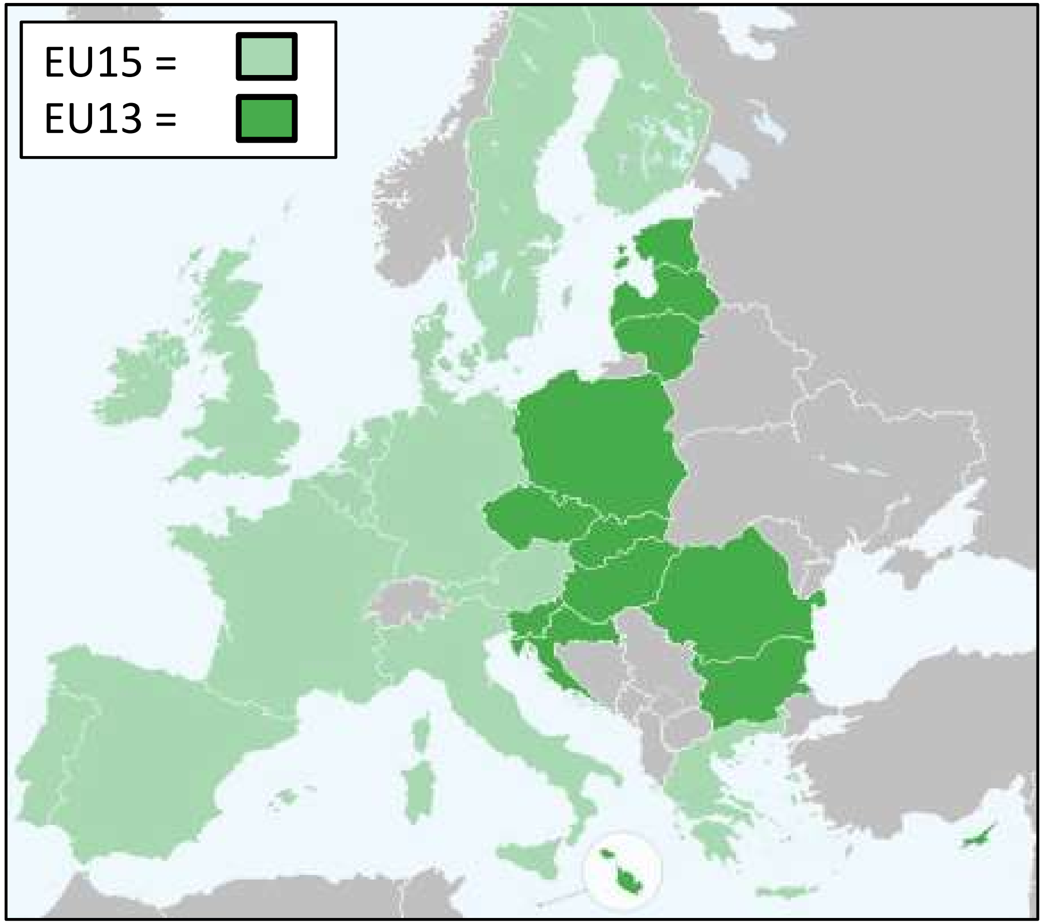
Summary assumptions for stock model

EE vehicle stock model uses the following assumptions:

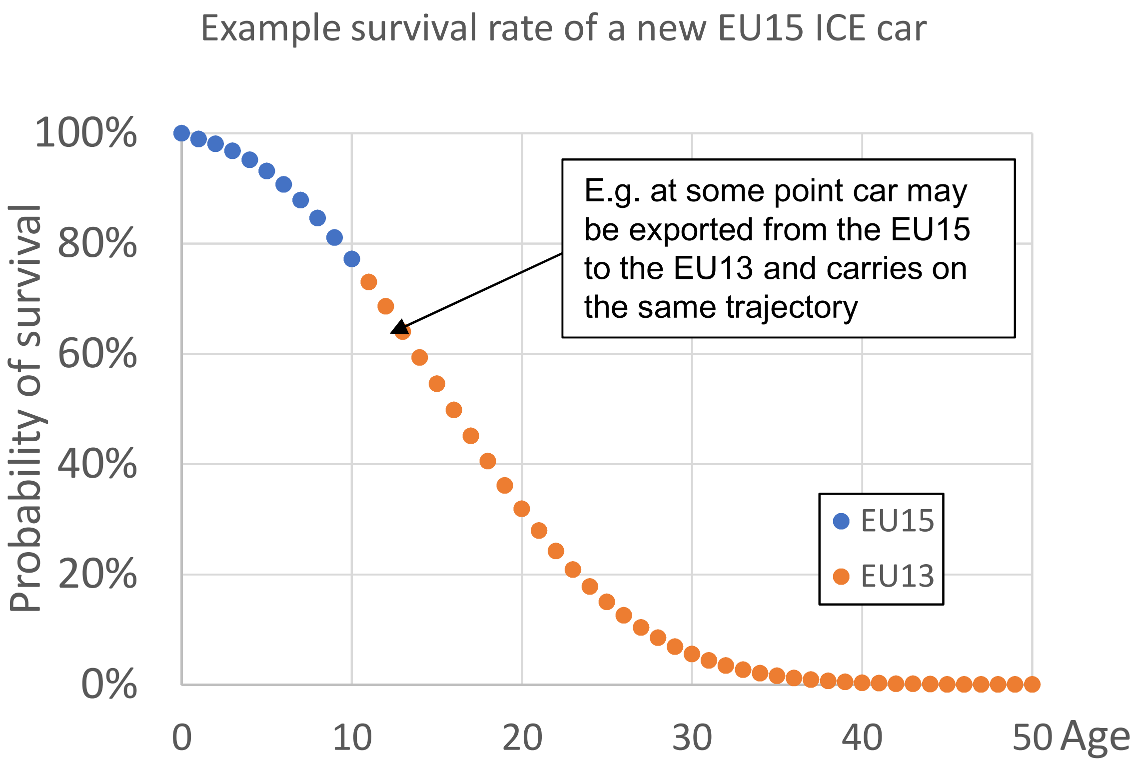
- EU15 and EU13 stocks
- 2nd hand sales from EU15 to EU13 accounted for – 67% of first time registrations in EU13 are imports
- Total new sales kept constant at 14.6m per year.
- Annual mileage is a function of age
- Car stock scenarios translated to small/medium/large car sales



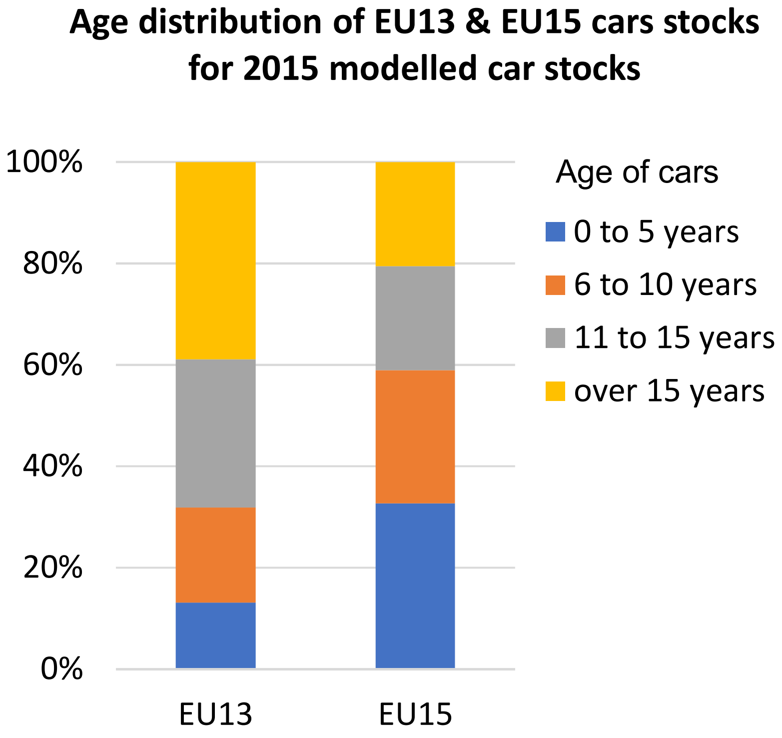
This is the model that was developed and used for the European Climate Foundation study, Fuelling Europe's Future study, published in January 2018

Source: Cambridge Econometrics and Element Energy for ECF, Fuelling Europe's Future study, February 2018.

The stock model accounts for the scrappage rates and EU15-EU13 trade flows



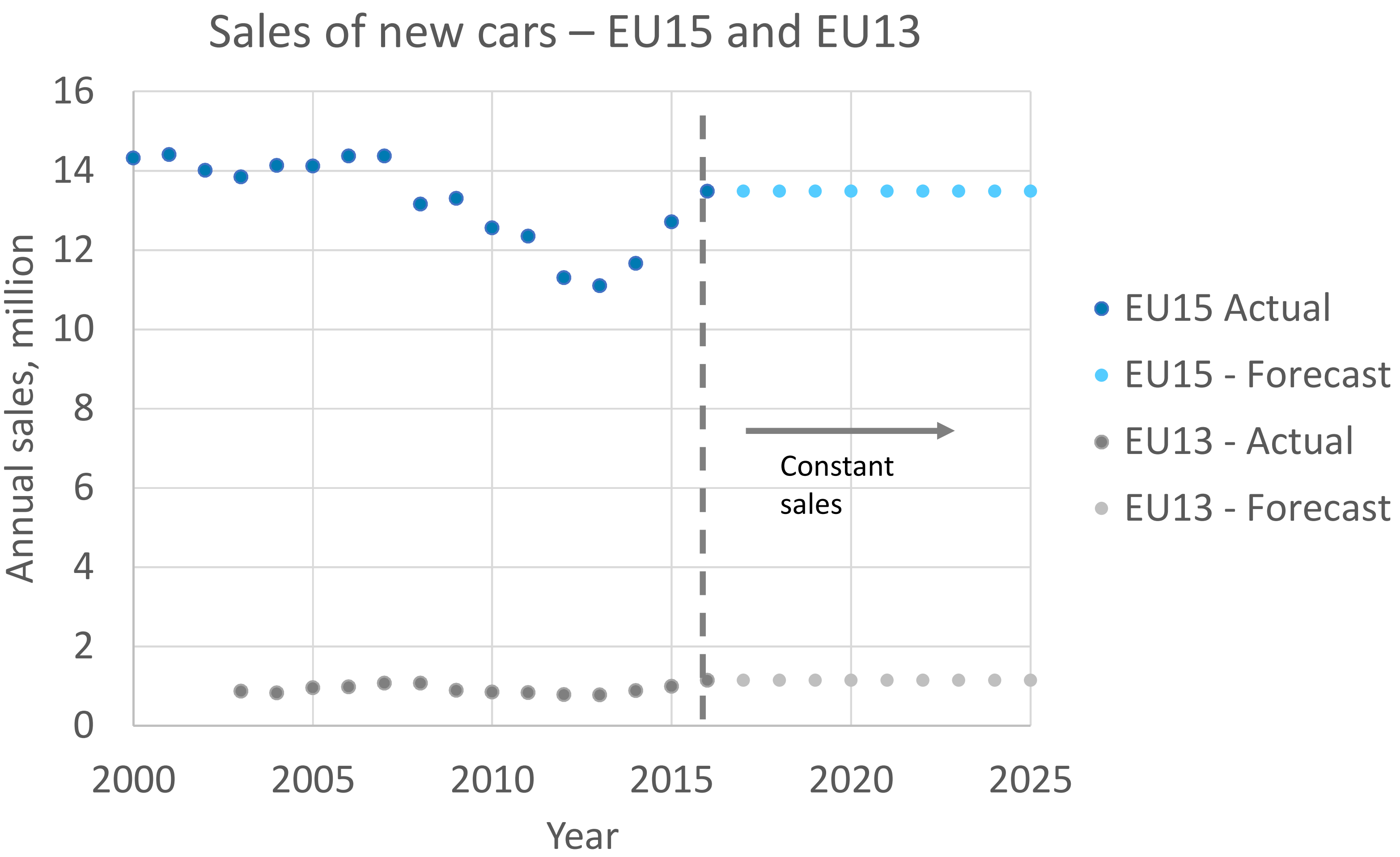
E.g. at some point car may be exported from the EU15 to the EU13 and carries on the same trajectory



- EU15: all new registrations are assumed to be new car sales
- EU13: 67% of new registrations are assumed to be imports from the EU15, 33% new car sales
- The age of car exported from EU15 to EU13 based on CE trade flow analysis for the ICCT (2016)

Source: EE stock modelling using import from CE analysis for T&E; EE analysis of TRACCS model (mainly based on Eurostat)

Total annual sales of new cars are kept constant from 2016



- The stock model assumes annual sales remain constant post-2016
- Note new car sales **exclude** used cars exported from EU15 to EU13

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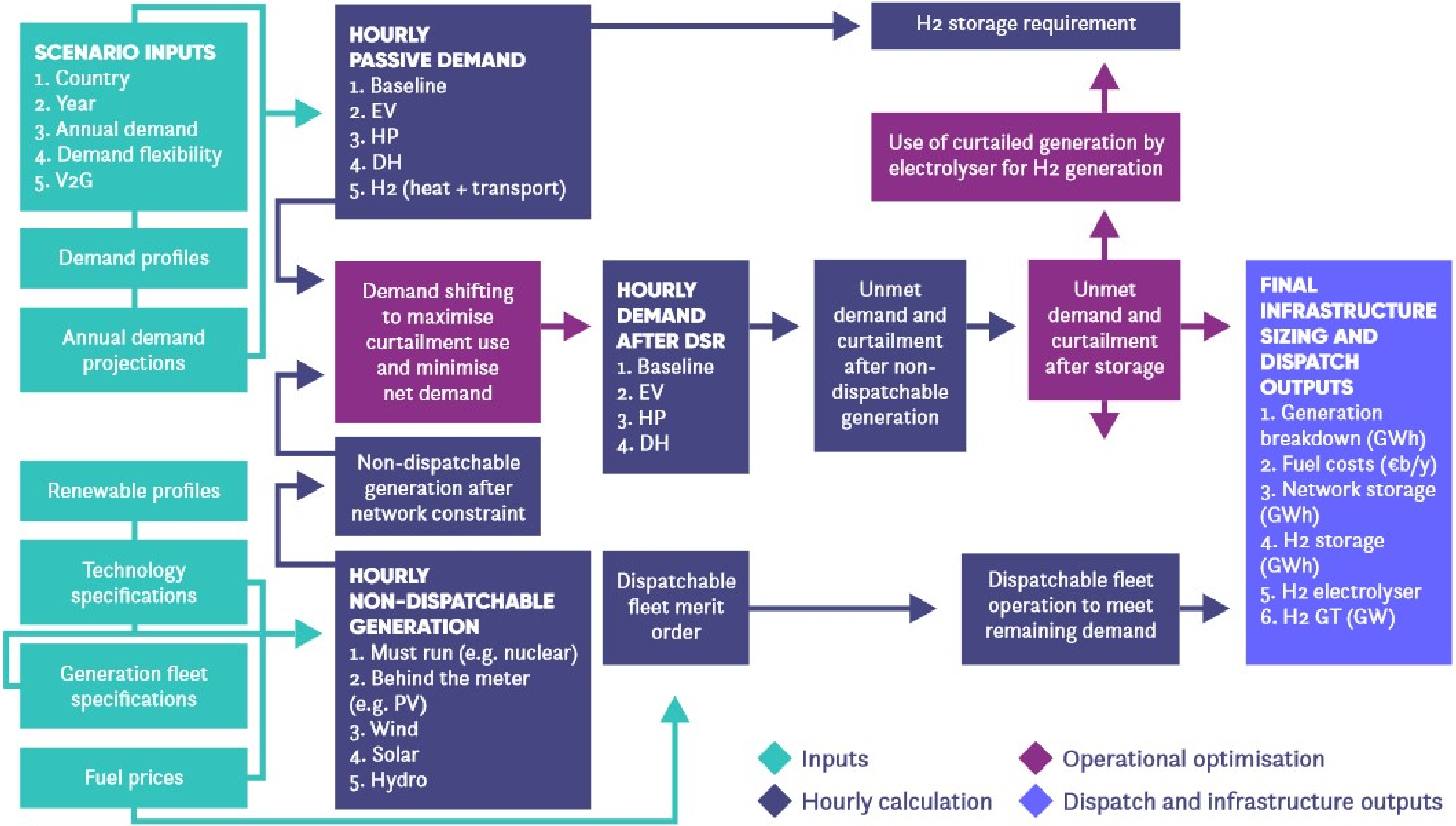
Element Energy Whole System Power Dispatch model



SCENARIO INPUTS
1. Country
2. Year
3. Annual demand
4. Demand flexibility
5. V2G

Demand profiles

Annual demand projections

Renewable profiles

Technology specifications

Generation fleet specifications

Fuel prices

HOURLY PASSIVE DEMAND
1. Baseline
2. EV
3. HP
4. DH
5. H2 (heat + transport)

Demand shifting to maximise curtailment use and minimise net demand

Non-dispatchable generation after network constraint

HOURLY NON-DISPATCHABLE GENERATION
1. Must run (e.g. nuclear)
2. Behind the meter (e.g. PV)
3. Wind
4. Solar
5. Hydro

HOURLY DEMAND AFTER DSR
1. Baseline
2. EV
3. HP
4. DH

Dispatchable fleet merit order

H2 storage requirement

Use of curtailed generation by electrolyser for H2 generation

Unmet demand and curtailment after non-dispatchable generation

Unmet demand and curtailment after storage

Dispatchable fleet operation to meet remaining demand

FINAL INFRASTRUCTURE SIZING AND DISPATCH OUTPUTS
1. Generation breakdown (GWh)
2. Fuel costs (€b/y)
3. Network storage (GWh)
4. H2 storage (GWh)
5. H2 electrolyser
6. H2 GT (GW)

◆ Inputs
◆ Hourly calculation
◆ Operational optimisation
◆ Dispatch and infrastructure outputs

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- **Additional model outputs**

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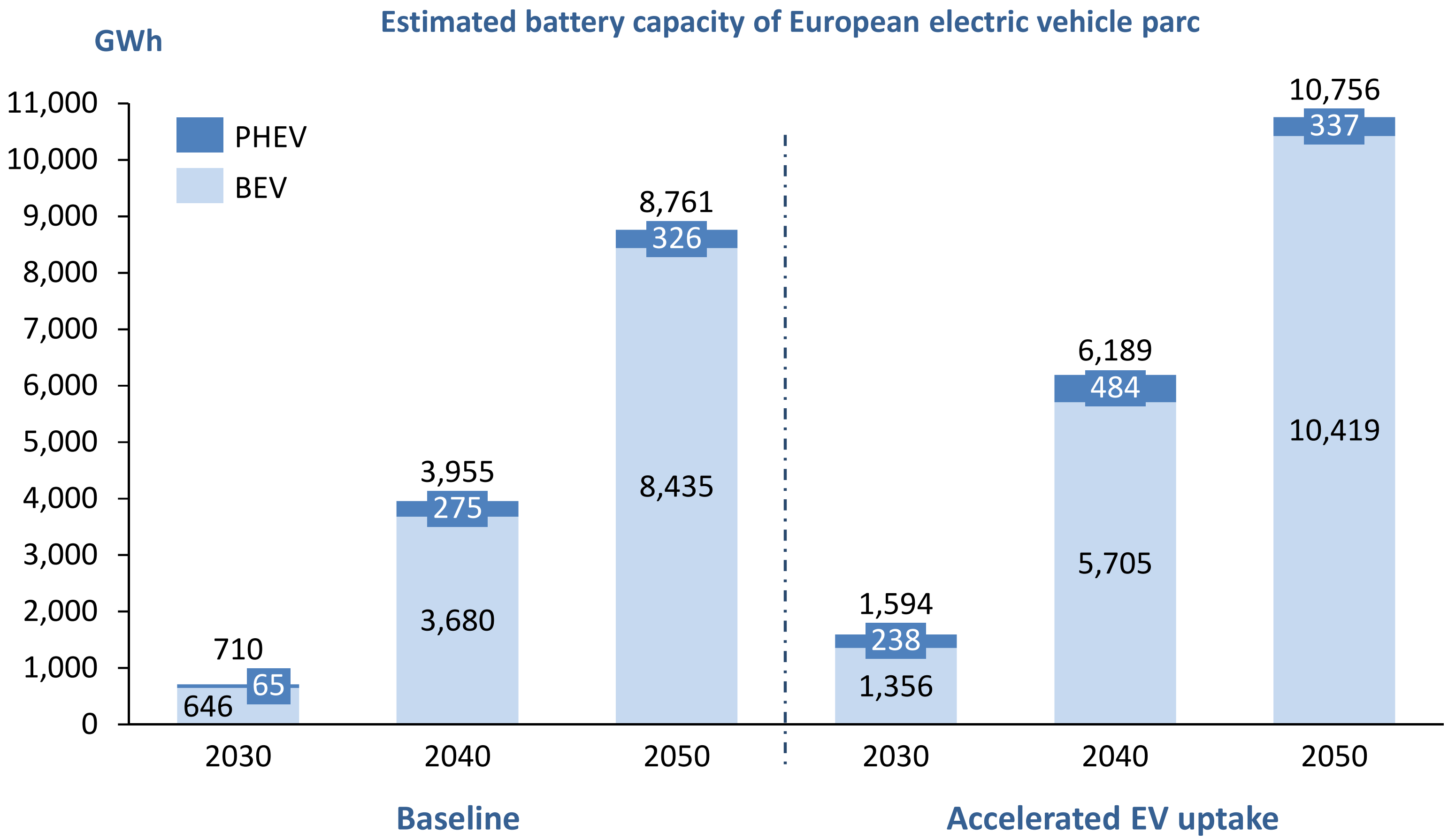
By 2050, up to 10.7 TWh of battery capacity would be available on the roads

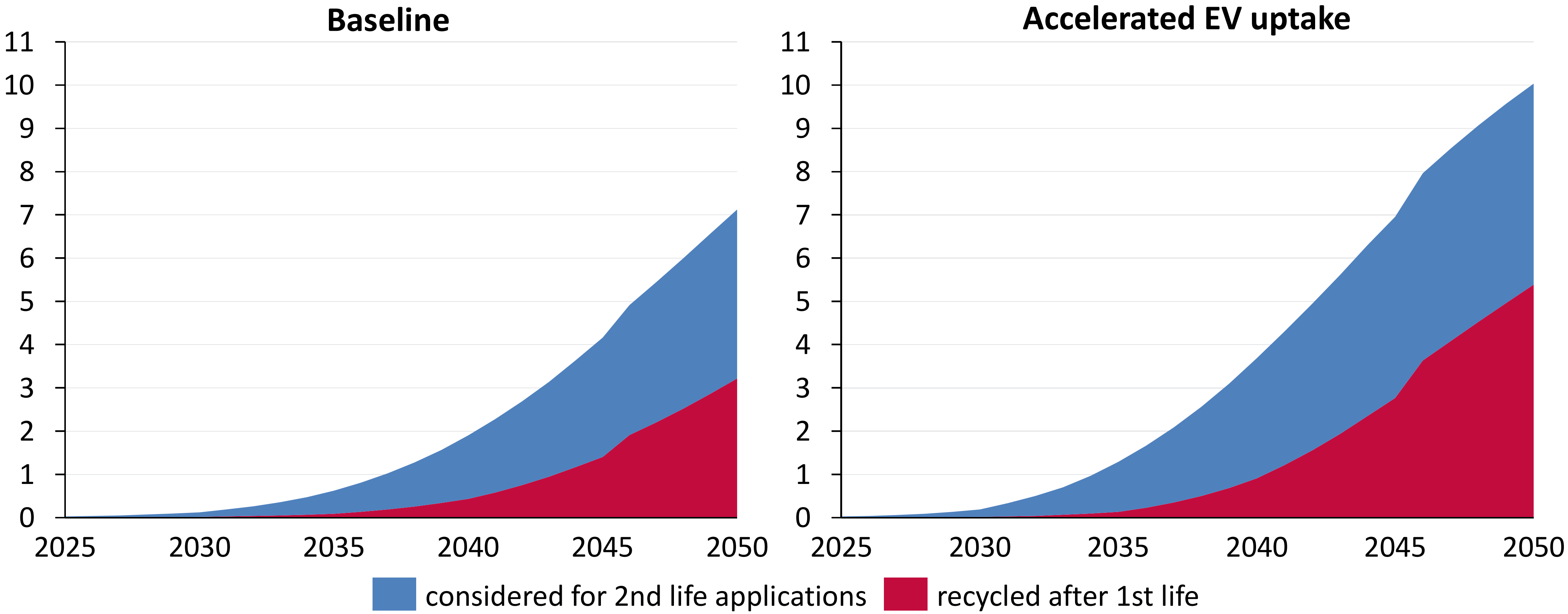


- This estimation considers the number of vehicles in the European vehicle parc and the battery capacity when entering the parc as a new sale.
- The values above do not account for battery degradation, usable depth of discharge window, and the availability for providing grid services.

Vehicles leaving EU stock – In 2040, 1.5 to 2.8 million EV batteries will be suitable for 2nd life applications

- The vehicles leaving the stock (shown on the previous slide) will have their batteries recovered.
- Depending on the residual capacity, batteries would be considered either for second life applications or recycling.
- At all times, most recovered batteries could be reused in second life applications. Volumes of such suitable batteries could reach up to 4.6 million units in 2050 under the Accelerated EV uptake scenario.

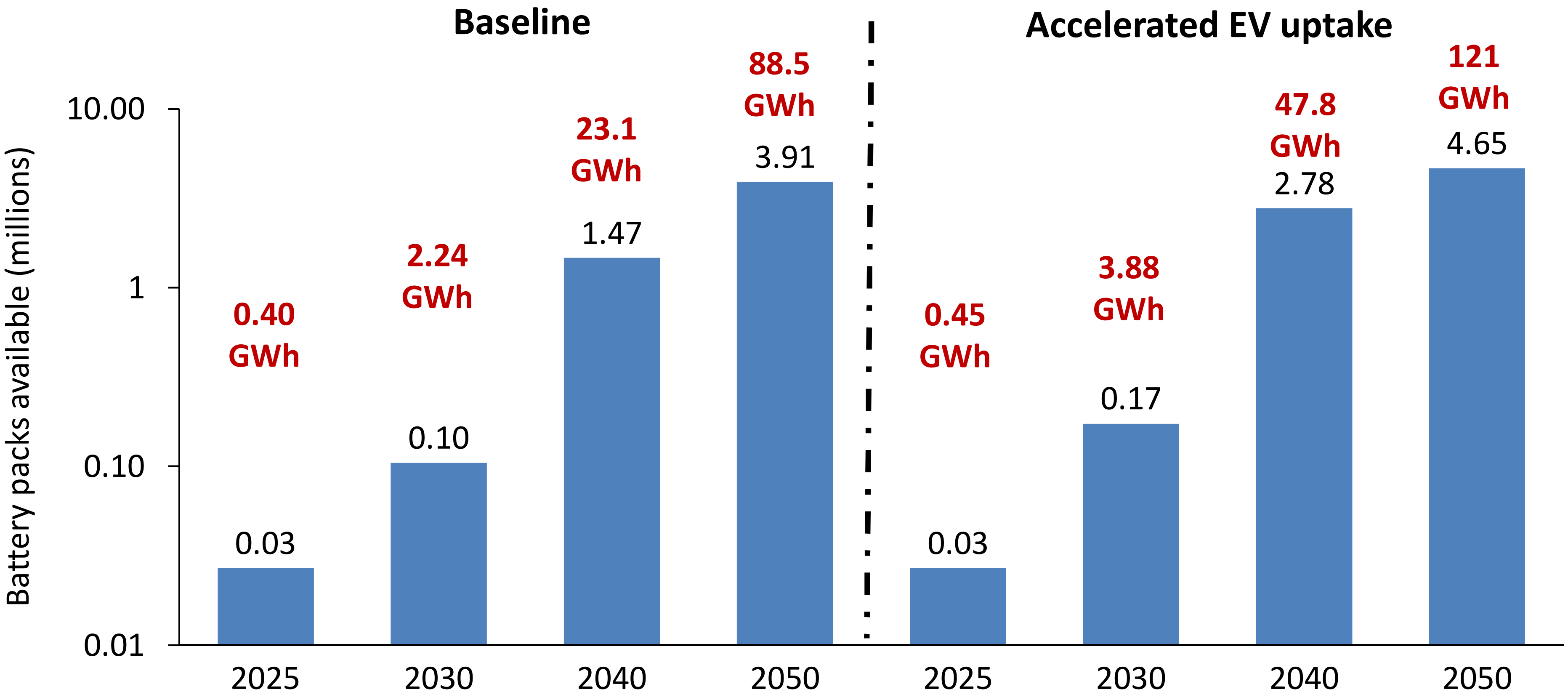
Fate of recovered batteries (millions)



Observed steep increase around 2045 due to increased uptake of EVs after 2030

Available volumes for 2nd life applications – by 2040, 23 to 48 GWh of second hand battery capacity will be available

- All retired vehicles will be scrapped with the battery recovered.
- Out of the recovered batteries, the following units will be considered viable for 2nd life applications. Total available residual capacity shown In red.
- These batteries will enter the 2nd life applications stock each year, building the stock shown on the next slide.

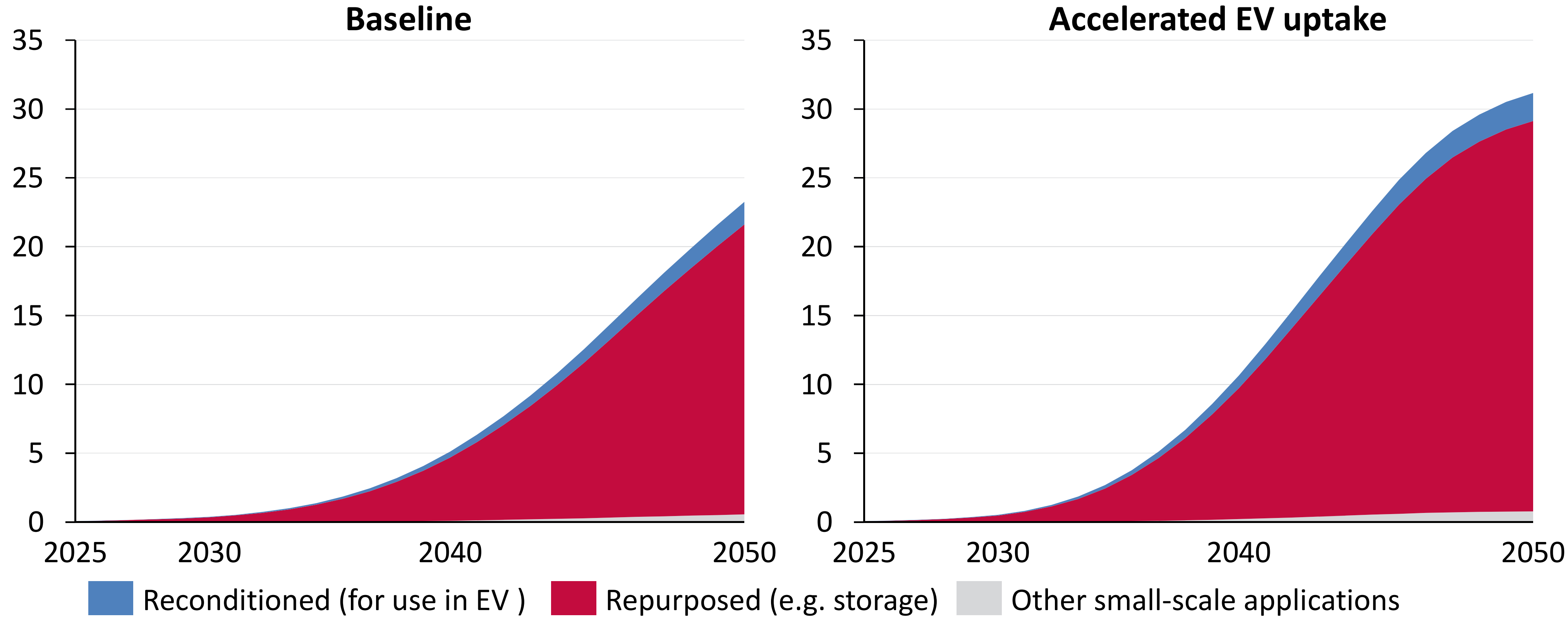


1. Total EU generation capacity is 996 GW. European Network of Transmission System Operators for Electricity, Statistical Factsheet, 2017. Total consumption in 2017 was 3,090 TWh

4 to 10 million batteries could be in 2nd life applications in 2040, and up to 35 million in 2050

- The battery units considered viable for 2nd life applications will enter the 2nd life applications and will remain in this stock depending on their remaining life (see slide 19 of the assumptions book)
- In terms of weight, in 2050 the 2nd life stock will contain 3,103 kilotonnes in the Baseline Scenario and 4,785 kilotonnes in the case of Accelerated EV uptake Scenario respectively.

Battery units in second life stock (millions)

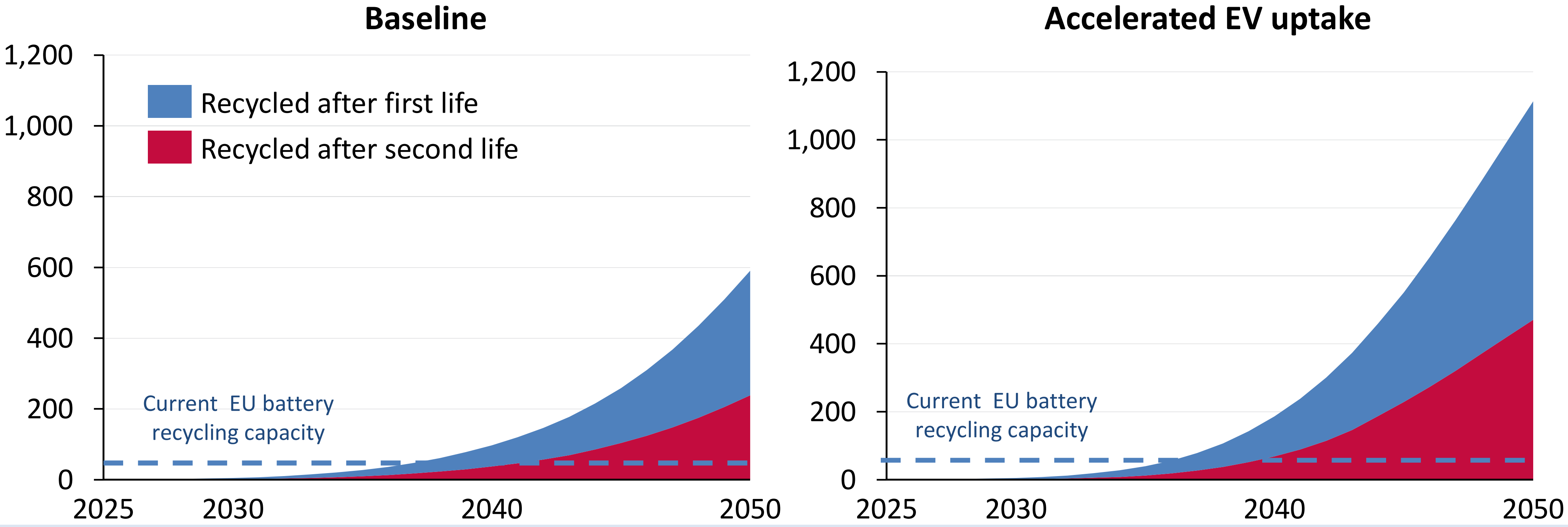


The forecasted volume of batteries to recycle will far exceed the current recycling capacity before 2035

- The Accelerated EV uptake Scenario will almost double the weight of batteries recycled in 2050 in comparison to the Baseline Scenario (slower uptake) – 1,100 vs 574 ktonnes
- Batteries are recycled either at the end of their first or second life, however most of the recycled volumes will still consist of batteries recovered after the first life

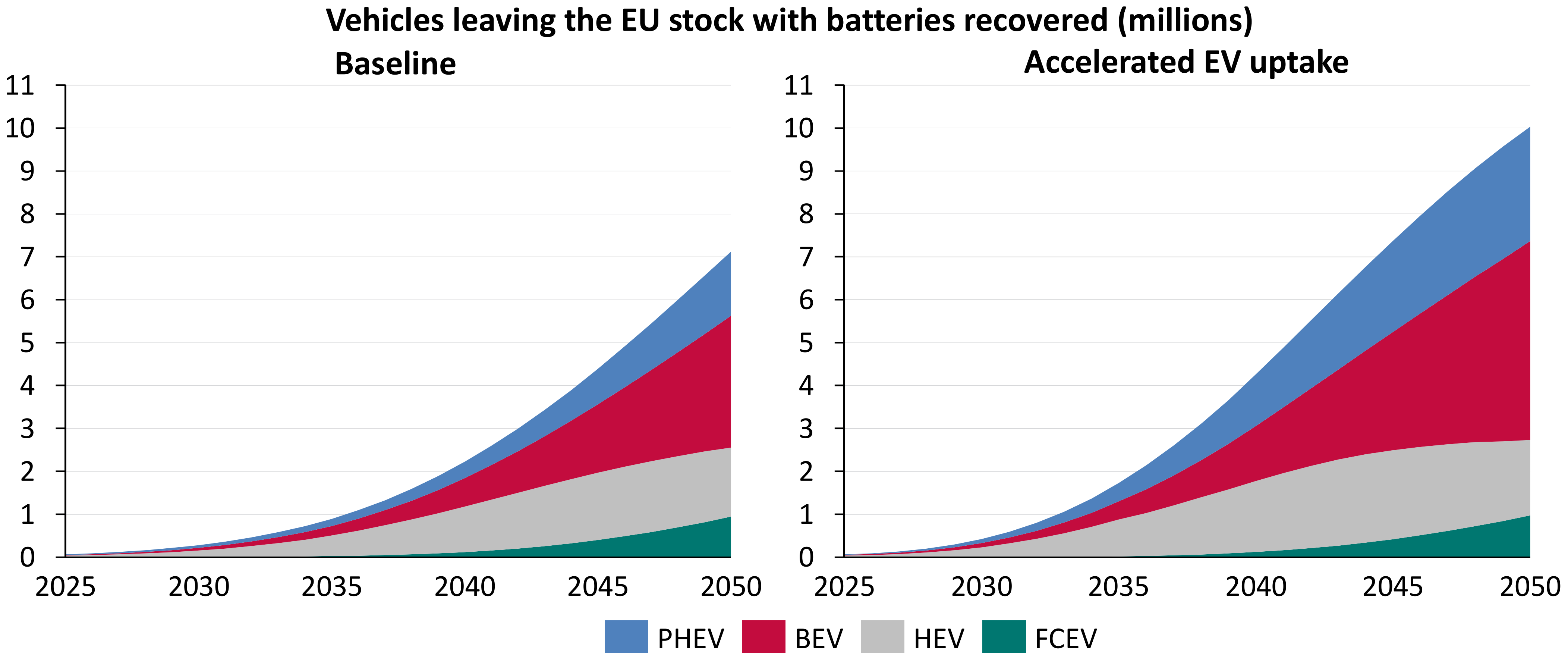
- The total estimated recycling capacity is 33 ktonnes/year (all battery chemistries, presented in later section). Even if all current capacity was used for recycling EV batteries exclusively, EU would face capacity issues as early as 2035.
- It will be much earlier in practice as the current capacity is not designed to deal with large automotive packs.

Batteries recycled each year in EU (kilotonnes)



Vehicles leaving EU stock – In 2040, 2 to 4 million EVs will be leaving the stock, 47% - 58% being plug-in vehicles.

- Element Energy's fleet stock model estimated the number of vehicles leaving the EU stock using the exit curve shown on slide 17.
- Under the more intensive Accelerated EV uptake Scenario, more EVs are expected to be placed on the market and be scrapped by 2050 -> more available batteries for 2nd life applications
- The results in the next slides focus on the batteries from BEVs and PHEVs, and considering only HEV and FCEV batteries produced after 2025[1].



1. It is assumed that batteries used by HEV and FCEV produced before 2025 will not be of Li-ion chemistry

Key model outputs table

		BASELINE SCENARIO					ACCELERATED EV UPTAKE SCENARIO				
Item	unit	2020	2025	2030	2040	2050	2020	2025	2030	2040	2050
Vehicles scrapped and batteries recovered											
Number of vehicles scrapped	vehicles	11,425	69,030	282,805	2,228,708	7,124,875	11,425	69,038	425,855	4,262,493	10,035,267
Number of recovered batteries	recovered batteries in EU	11,425	69,030	282,805	2,228,708	7,124,875	11,425	69,038	425,855	4,262,493	10,035,267
Original capacity of vehicle batteries	original capacity (kWh)	57,625	603,677	3,644,187	43,214,237	201,813,161	57,625	677,123	6,063,275	88,565,397	311,636,785
Weight of vehicle batteries*	tonnes batteries*	550	5,142	25,035	220,057	892,922	550	5,664	39,636	449,419	1,391,291
* includes HEV and FCEV batteries as well, however in early years those are not Li-ion and thus not fed into this model											
Battery fate at the end of EV life											
Li-ion recycled batteries	battery units	-	1,967	20,512	437,388	3,217,697	-	1,967	20,517	909,059	5,388,777
	original capacity (kWh)	-	38,832	422,496	10,499,188	76,545,063	-	38,832	471,795	21,075,312	138,584,674
	tonnes Li-ion batteries	-	371	3,614	59,938	351,856	-	371	3,965	117,370	642,867
EV batteries considered for 2nd life	battery units	2,916	26,960	104,810	1,466,325	3,907,179	2,916	26,968	173,275	2,776,099	4,646,491
	original capacity (kWh)	57,625	556,275	3,119,131	32,402,160	125,268,098	57,625	629,721	5,414,340	66,924,856	173,052,111
	tonnes Li-ion batteries	550	4,686	20,556	157,542	541,066	550	5,208	34,219	327,494	748,424
	residual capacity (kWh)	41,352	400,080	2,238,725	23,110,331	88,517,203	41,352	452,785	3,886,906	47,778,887	121,326,703
Batteries in second life applications (totals all possible applications)											
Batteries entering second life applications	battery units	2,916	26,960	104,810	1,466,325	3,907,179	2,916	26,968	173,275	2,776,099	4,646,491
Batteries in second life applications	battery units	5,687	78,916	391,271	6,343,275	23,261,191	5,687	78,930	524,646	12,932,698	31,155,734
Batteries retired from second life applications	battery units	6	433	9,492	252,832	2,246,038	6	433	9,623	494,189	4,010,180
Batteries entering second life applications	tonnes	550	4,686	20,556	157,542	541,066	550	5,208	34,219	327,494	748,424
Batteries in second life applications	tonnes	1,062	13,822	73,177	703,510	2,999,114	1,062	14,773	104,737	1,501,371	4,612,396
Batteries retired from second life applications	tonnes	1	77	1,669	37,603	238,716	1	78	1,750	68,964	470,689
Total batteries recycled											
Recycled after first life	tonnes Li-ion batteries	-	371	3,614	59,938	351,856	-	371	3,965	117,370	642,867
Recycled after second life	tonnes Li-ion batteries	1	77	1,669	37,603	238,716	1	78	1,750	68,964	470,689
Total	**tonnes Li-ion batteries**	**1**	**448**	**5,283**	**97,541**	**590,572**	**1**	**449**	**5,715**	**186,335**	**1,113,556**

All figures shown for the industry situation in the relevant year.

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List of Acronyms

Ah	Ampere hours
BAT	Best Available Technology
BD	Battery Directive (2006/66/EC)
BEV	Battery Electric Vehicle
BMS	Battery Management System
Co	Cobalt
DG	Distributed Generation
DH	District Heat
DNO	Distribution Network Operator
DOD	Depth of Discharge
DSR	Demand Side Response
EC	European Commission
ELV	End-of-Life Vehicle
EPR	Extended Producer Responsibility
ES	Spain
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FFR	Firm Frequency Response
FR	France
GB	Great Britain
HEV	Hybrid Electric Vehicle
HF	Hydrofluoric acid
HP	Heat pump
ICE	Internal Combustion Engine
INL	Idaho National Laboratory
IT	Italy
KPI	Key Performance Indicator
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
Li	Lithium
LIB	Lithium Ion Battery
Li-S	Lithium Sulphur (battery)
LMO	Lithium Manganese Oxide
LTO	Lithium Titanium Oxide
Mn	Manganese
NCA	Lithium Nickel Cobalt Aluminium Oxide
NGO	Non-Governmental Organisation
Ni	Nickel
NMC	Lithium Nickel Manganese Cobalt Oxide
OEM	Original Equipment Manufacturer
Opex	Operating Expenditure
PCR	Primary Control Reserve
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
QR	Quick Response (code)
R&D	Research and Development
SOC	State of Charge
SOH	State of Health
STOR	Short Term Operating Reserve
TCO	Total Cost of Ownership
ToU	Time of Use
TSO	Transmission System Operator
V2G	Vehicle to Grid
VRES	Variable Renewable Energy Sources
ZLEV	Zero and Low Emission Vehicle

Note on terminology

Throughout the report and this appendix, ‘EV’ refers to a plug-in vehicle, which can be either a PHEV or BEV. Zero and Low Emission Vehicles (‘ZLEVs’) refer to PHEVs, BEVs, and FCEVs.