OVERCOMING CHALLENGES FOR SECOND-LIFE APPLICATIONS FOR BATTERY PACKS

Lessons from pilot cases

Marika Moreschi and Vasileios Rizos

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Summary

In the battery ecosystem emerging from the growing diffusion of battery-powered electric vehicles, second-life applications for batteries can contribute to more sustainable management. They can be deployed in residential, commercial and industrial settings, helping to extend battery service life and postpone their entry into the waste stream.

Across the EU, various pilots and private initiatives as well as a limited number of commercialised second-life solutions have begun to shape the landscape for second-life battery applications. Drawing on insights from pilot initiatives, this report identifies several challenges in the policy, economic, supply chain and technical domains that need to be addressed to create fertile ground for scaling up second-life battery applications. It also identifies a number of opportunities.

Some of the key challenges include regulatory uncertainties surrounding responsibilities after end-of-life, high repurposing costs complicating the economic case for second-life applications, underdeveloped supply chains for second-life electric vehicle batteries (EVBs) and battery pack designs that do not support efficient disassembly.

Opportunities, on the other hand, can be found in the economic benefits of using second-life EVBs in relatively low performance requirements applications (such as residential storage and microgrids), revenue opportunities from repurposing EVBs and the growing demand for affordable battery storage systems.

The report recommends that more clarity should be provided regarding the liability framework governing responsibilities for batteries entering repurposing pathways. Further efforts will be needed to adequately standardise the second-life EVBs' framework and provide harmonised approaches in areas such as State of Health (SoH) and State of Charge (SoC). In addition, more is required to boost demand for second-life applications and help create a market for them. Funding schemes and EU-funded projects can also continue supporting innovation, particularly in the automation of repurposing processes to enable further cost reductions.

Marika Moreschi is a former Associate Research Assistant in the Energy, Resources and Climate Change (ERCC) unit at CEPS. Vasileios Rizos is a Senior Research Fellow and Head of the ERCC unit at CEPS.

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CEPS ▪ Place du Congrès 1 ▪ B-1000 Brussels ▪ Tel: (32.2) 229.39.11

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1. INTRODUCTION

As battery-powered electric vehicles (EVs) become more widespread, circular applications of batteries are emerging as a key strategy for promoting more sustainable battery management. After their initial operational life in electric vehicles, battery packs or modules can be repurposed for second-life applications, depending on their state of health (SoH) and estimated remaining useful life (RUL). This approach extends their overall service life (Akram and Abdul-Kader, 2024). Potential applications include repurposing battery packs or modules for battery energy storage systems (BESSs) in residential, commercial, and industrial settings, as well as the possible refurbishment of batteries for automotive use (Toorajipour et al., 2024; Huster et al., 2022).

Extending the batteries' service life through second-life applications and postponing their entry into the waste stream can reduce demand for new and material-intensive battery packs. This can in turn deliver environmental and carbon-saving benefits depending on the specific second-life application and the carbon intensity of the electricity used for charging (Dong et al., 2023). Second-life applications can also unlock businesses opportunities and new revenue streams by utilising assets that would otherwise become waste. While tensions may arise with recycling, particularly due to the increasing demand for battery materials, battery packs and modules will ultimately enter the recycling stream recycling route since second-life applications can only postpone this route (Ellen MacArthur Foundation, 2026).

In the EU, the landscape for second-life battery applications is at a nascent stage, although several pilots and demonstrations are emerging as shown later in this report. Scaling up such applications in the EU is unlikely to be easy in practice and would require overcoming policy, economic, supply chain and technical challenges (Toorajipour et al., 2024; Ellen MacArthur Foundation, 2026). This report examines these challenges as well as the opportunities arising from battery second-life application drawing on insights collected from partners in the BATRAW EU-funded project and other actors operating across the second-life value chain.

The following sections of the report first examine the current EU policy framework relevant to second-life applications (Section 1), and then provide an overview of pilot cases in the EU, including BATRAW (Section 2). The report discusses challenges and opportunities for second-life circularity applications of battery packs, based on interview data collected from actors in the battery value chain (Section 3). We conclude with several policy messages based on this research.

2. CURRENT EU POLICY FRAMEWORK FOR SECOND-LIFE APPLICATIONS

EU policy has increasingly focused on promoting circular battery value chains to minimise environmental impacts, enhance supply security and strengthen industrial competitiveness. Within this circularity agenda, second-life batteries are receiving increasing attention.

The term 'second-life batteries' is commonly used to broadly refer to batteries that are reintegrated into the market after their first use. Such second use can involve a range of circular practices. Box 1 outlines the definitions used in the EU regulatory framework to clarify key differences among such processes. This paper primarily focuses on battery repurposing, as most common second-life applications for electric vehicle batteries (EVBs) serve a different purpose than their original one.

Box 1. Processes and practices related to second-life batteries.

1. Reuse' means any operation by which a product (e.g. a battery) or its components that are not waste are used again for the same purpose for which they were designed (Directive 2008/98/EC).
2. 'Repurposing' means any operation resulting in a battery which is used for an application other than the one for which it was originally designed (Regulation 2023/1542).
3. 'Remanufacturing' means any technical operation on a used battery that includes: the disassembly and evaluation of all used cells and modules, and the use of battery components – new, used or recovered from waste – to restore the battery capacity to at least 90 % of the original level. In remanufactured batteries, the State of Health (SoH) of all individual battery cells must not differ by more than 3 %. Remanufactured batteries are used for the same application for which the battery was originally designed. (Regulation 2023/1542).
4. 'Recycling' means reprocessing waste materials (e.g. battery-related waste) into products, materials or substances whether for the original or other purposes (Directive 2008798/EC).
5. The term 'treatment' is used to refer to all the following operations undertaken on a waste battery: sorting, preparation for re-use, preparation for repurposing, preparation for recycling. (Regulation 2023/1542).

While earlier EU legislation on batteries laid the foundation for circularity, it paid little attention to second-life uses. The Batteries Directive (2006/66/EC) focused on improving environmental impact and safety of collecting, treating and recycling waste batteries, but it lacked provisions on reuse, repurposing and remanufacturing. As a result, key questions around second-life batteries, such as the limits of original producers' responsibility and issues related to safety and performance, have remained unaddressed (Strupeit & Tojo, 2023). In this context, the adoption of the EU Battery Regulation marks a step towards a more comprehensive approach to battery circularity by laying out a set of measure to extend the battery lifetime and foster second uses.

2.1. PROVISIONS FOR SECOND-LIFE USE IN THE BATTERY REGULATION

Introduced in 2023, the EU Batteries Regulation 2023/1542 is the EU's primary tool for managing batteries. The Regulation not only introduces ambitious requirements covering all types of batteries placed on the European market[1], but also aims to extend the lifespan of industrial batteries, light means of transport (LMT) batteries, and EVBs. In particular, it sets requirements for electrochemical performance and durability alongside a set of measures to foster reuse, repurposing, and remanufacturing before recycling. Some of the key provisions concerning the second life of EVBs are described below and an overview of relevant articles is shown in Table 1.

To ensure second-life batteries are not regarded as lower-tier alternatives, the Batteries Regulation subjects them to the same safety, environmental and quality standards as new batteries. Operators involved in preparation for repurposing, preparation for reuse, repurposing or remanufacturing are assimilated to original manufacturers and must fulfil corresponding due diligence obligations. Similarly, those placing a second-life battery on the market for the first time are treated as original producers and assume responsibility for complying with all relevant EU laws and standards, including extended producer responsibility (EPR). To avoid overlapping obligations, the Regulation allows voluntary cost-sharing mechanisms between producers and second-life actors, reached by mutual agreement and based on their different roles across the life cycle. For instance, the first producer might cover recycling costs due to hazardous materials in the original design of the pack, while transportation needed to reintroduce the battery in the market may be attributed to the second-life actor.

Furthermore, the Regulation aims to strengthen data transparency and traceability across the battery supply chain to support reuse and recycling. A central measure is the introduction of a battery passport carrying information on performance, durability, State of Health (SoH), State of Charge (SoC), and other operational data (Rizos &Urban, 2024b). Second-life batteries must also be equipped with a digital passport linked to the original

[1] See Rizos et al. (2026) for an overview of key requirements on sustainability, labelling, EoL management and due diligence that apply to Electric Vehicle Batteries.

one and indicating the change of status (e.g. from 'original' to 'remanufactured'). To support second-life operators, producers are obliged to share the information necessary for safely collecting, storing and transporting end-of-life batteries, including details on the location of hazardous substances. Crucially, the Regulation also requires key parameters – such as the SoH and expected lifetime of the pack – to be stored in the Battery Management System (BMS). Non-discriminatory access to these data must be granted to those purchasing the battery to assess the pack's remaining lifetime or preparing it for second use[2]. Additionally, the original BMS must include a reset function, enabling the installation of a new software tailored to the second-life application. Indeed, clearing previous data and configurations allows for recording new operational parameters (e.g. voltage, temperature, SoC, etc.) without interfering with the original settings.

At the same time, the Regulation aims to reduce administrative hurdles resulting from the legal classification of used batteries. It explains how to prove that a battery has been prepared for reuse or repurposing and, as a result, is no longer considered waste. Relevant documents must demonstrate the precautionary measures taken during transport, the transfer of ownership from the first-life user, and confirm that a SoH evaluation was conducted within an EU Member State. The latter must be accessible to both the competent authorities and the end users. The technical criteria for used LMT, EV, and industrial batteries to no longer be classified as waste will be detailed in an upcoming implementing act by the Commission.

Table 1: Relevant provisions for second-life applications in the EU Battery Regulation

Performance and Safety Requirements	Article 10	Performance and durability requirements for EVBs, rechargeable industrial batteries and LMT batteries
	Article 12	Safety of stationary battery energy storage systems
Labelling and Information Requirements	Article 13(9)	New labels for batteries subject to preparation for reuse, repurposing or remanufacturing
	Article 14	SOH and lifetime data must be accessible to enable second-life operations; the BMS software shall include a reset function

[2] The BMS is an electronic system used to monitor the overall state of the battery pack, including SoH, charging cycles, voltage and capacity. Repurposed batteries require their new BMS to comply with the specific requirements of their new application while simultaneously adapting to the characteristics of the used modules. For this reason, access to the original BMS and fast diagnostic techniques are key to ensuring the safety and performance of second-life batteries.

Obligations of Relevant Economic Operators	Article 38 (11)	Obligation of manufacturers, comprehending second-life operators
	Article 45	Quality control, safety, and compliance obligations for placing second-life batteries on market
	Article 56 (2)	Extended Producer Responsibility for second-life operators
	Article 73	Proof and conditions for waste batteries to cease being waste after preparation for reuse or repurposing
Transparency and Data Accessibility	Article 74 (2–3)	Battery producers must share dismantling, safety, and handling information with second-life operators
	Article 77 (7)	Battery passport for second-life batteries

2.2. OTHER REGULATIONS AND STANDARDS ON SECOND-LIFE BATTERIES

Moving beyond the Battery Regulation, other EU legislative instruments include provisions relevant to second-life batteries. For instance, the upcoming Regulation on End-of-Life Vehicles[3] aims to update the existing framework to promote greater circularity in the European automotive sector[4]. While the proposed Regulation broadly applies to all types of vehicles, some provisions are particularly significant for used EVBs (e.g. Art 7, 11 and 24). Indeed, the proposal obliges EV manufacturers to improve battery removability and replaceability at the design stage, to support both recycling and second uses. It also requires providing waste management operators with all the relevant information for safe and non-destructive removal of EVBs. Specific technical requirements for batteries removability will be further detailed in a delegated act. Moreover, the proposal aims at scaling up collection of used batteries by exempting end users from charges when returning their electric vehicle.

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[3] A provisional agreement between the European Parliament and the European Council on the European Commission's proposal for a regulation was reached in December 2025. The agreed text is available here.

[4] The proposal replaces the End-of-Life Vehicles Directive (2000/53/EC) and the 3R (e.g. reusability, recyclability and recoverability) type-approval of motor vehicle Directive (2005/64/EC) by combining them in one single instrument. The goal is to align the existing framework on EoL Vehicles with the Circular Economy Action Plan. For this reason, the proposed text includes targets for reuse, recycling and recover of vehicles' components. However, these provisions exclude EVBs as those are already covered by the EU Batteries Regulation.

Additionally, the newly revised Waste Shipment Regulation (2024/1157) and European List of Waste shape market opportunities for second life. Indeed, as black mass and most chemistries used in EVBs are classified as hazardous waste[5], operators moving end-of-life (EoL) batteries across borders are subject to strict requirements and additional procedural obligations. While crucial for improving environmental protection and human health across battery value chain, these rules can impact costs and generate administrative hurdles for second-life operators. Section 4 of this paper explores the challenges for second-life applications linked to the regulatory landscape on battery transport.

There have also been efforts to develop technical standards for second-life practices. A notable example is the work of the International Electrotechnical Commission (IEC), Technical Committee (TC) 21 which recently published two key standards addressing battery repurposing: IEC 63338 and IEC 63330. The latter sets the general requirements for repurposing of cells, modules and packs, targeting lithium-ion batteries. In particular, it provides a protocol to evaluate safety and performance of used batteries intended for repurposing. An upcoming second part will further complement this document by specifying classification criteria for batteries eligible for repurposing. IEC 63338, on the other hand, covers both lithium-ion and nickel-metal hydride cells and batteries. It also addresses environmental aspects of reuse and repurposing and emphasises the importance of lifetime traceability for such operations. International standardisation efforts are mirrored at the EU level by CENELEC, where the committee CLC/TC 21X is working on adopting IEC's standards (Strupeit & Tojo, 2023). In addition, noteworthy initiatives are emerging at the national level. For instance, the Spanish standardisation organisation UNE has developed a standard (i.e. PNE 0075) focusing on second-life applications in stationary energy storage.

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[5] The European List of Waste (Commission Decision of 3 May 2000) is undergoing an update. It classifies black mass, lithium-based, nickel-based, and zinc-based batteries as hazardous. Such classification triggers the prior notification and consent of all involved authorities when shipping battery-related waste across borders.

3. SECOND-LIFE APPLICATIONS PILOT CASES IN THE EU

In recent years, numerous initiatives have emerged across the EU to develop pilot cases for second-life applications of EVBs. These efforts focus on repurposing used batteries for energy storage systems, testing a variety of use cases. Notable examples include energy storage solutions integrated in wind and solar plants, backup power supply for residential or commercial purposes, and EV charging stations. This section presents a non-exhaustive overview of pilot applications for second-life EV batteries.

3.1. EXAMPLES OF PILOT CASES

Alongside a growing landscape of private initiatives and few commercialised second-life solutions, several pilot projects have been developed with the support of the European Commission. Horizon Europe funds numerous initiatives to advance circular value chains in the EU battery ecosystem, including the BATRAW project (see Section 3.2). Table 2 presents an overview of such efforts.

A notable example of an EU-funded project focusing on maximising the useful life of EVBs is RECIRCULATE. Its objective is to develop cost-effective and AI-based characterisation techniques for used batteries with a SoH above 80 %, making them suitable for repurposing. Similarly, the REBORN project explores pack design optimisation for second-life use, leveraging AI to construct ageing indicators of used batteries. Additional Horizon-funded projects such as RHINOCEROS and REINFORCE are directly demonstrating repurposing pathways for EV lithium-ion batteries. Early findings suggest that there are environmental benefits when comparing repurpose to direct recycling, though challenges persist due to the lack of efficient and standardised processes for dismantling and battery characterisation (see Hossain et al., 2019; Pinto et al., 2023) . Under Horizon 2020, the CIRCUSOL Innovation Action project successfully demonstrated the feasibility of using retired EVBs for solar power storage. Researchers concluded that in addition to demonstrating technical feasibility, a second-life business model requires close cooperation between manufacturers and repurposes to reduce dismantling costs and improve market competitiveness (Strupeit & Tojo, 2023).

Table 2: Examples of Horizon-funded projects relevant to EVBs second life

Project	Description	Dates	Coordinator	EU Budget
BatteReverse	Develops advanced reverse logistics for Li-ion batteries, including safe transport, automated dismantling, battery diagnostics, digital twin simulations, and data sharing to boost	2023–2026	CEA	€ 4 910 972,00

	recycling, repurposing, and reduce critical raw material use.			
BATRAW	Develops and demonstrates pilot systems for dismantling and recycling EV and domestic batteries, enabling high recovery of critical materials, battery reuse, eco-design, and traceability through a battery passport platform.	2022-2026	LEITAT	€ 9 786 739,20
CIRCUSOL	Enables second-life use of PV panels and batteries for solar energy generation and storage through circular product-service models.	2018–2022	VITO	€ 7 014 892,76
RECIRCULATE	Advances battery circularity through fast sorting, safe transport, health diagnostics, automated dismantling, reuse strategies, and a blockchain-enabled battery passport and marketplace to extend lifespan and improve resource efficiency.	2023–2026	Centria	€ 4 901 817,50
REBORN	Promotes second life by focusing on enhancing assembly/disassembly processes and using AI for assessing battery ageing and performance.	2025–2028	VRIJE University	€ 7 477 609,93
REINFORCE	Creates a circular value chain for end-of-life batteries with optimised logistics, smart diagnostics, robotic dismantling, and a battery passport to improve safety, automation, and cost-effectiveness in recycling and recovery.	2023–2027	INEGI	€ 4 999 993,75
REUSE	Focuses on sustainable recycling of low-value LFP battery waste by developing automated sorting, disassembly, and reuse processes, combined with life cycle assessments to improve Europe's battery ecosystem competitiveness.	2024–2026	Fraunhofer-Gesellschaft	€ 4 927 664,93
RESTORE	Develops a scalable, holistic recycling process to safely pre-process end-of-life EV and domestic batteries, recovering valuable materials like electrolyte salts, graphite, and cathode components to meet EU targets.	2024–2028	LEITAT	€ 7 999 189,50
RHINOCEROS	Focuses on economical and environmentally friendly routes for reuse, repurposing, reconditioning, and recycling of end-of-life batteries by developing smart systems for automated classification of battery materials and repurposing.	2022–2026	Tecnalia	€ 8 943 025,75

Some OEMs have taken part as battery providers in publicly funded second-life pilots. For instance, Ford OTOSAN participates in BATRAW, RHINOCEROS and RECIRCULATE projects

(Ford Otosan, 2023). In parallel, car manufacturers have been exploring repurposing as a business opportunity. Indeed, second-life applications might offer additional revenue streams while simultaneously contributing to companies' sustainability goals. Mecedes-Benz, for instance, launched a subsidiary company offering sustainable energy storage solutions built with retired EVBs. Nissan provided batteries from their LEAF model for a variety of pilot projects, including community-focused efforts to improve energy resilience in underserved areas. Similarly, the Renault Group runs several partnerships with second life operators and supplies end-of-life batteries for a UK government-led initiative implementing second-life battery storage in residential settings.

In addition to public and OEM-driven initiatives, a growing number of start-ups and SMEs have emerged to commercialise second-life applications in Europe. BeePlanet Factory is a Spanish enterprise that repurposes EVBs into stationary storage systems. In northern Europe, ECO STOR offer similar second-life energy storage products and the UK-based Connected Energy has been exclusively using repurposed EVBs for their products since 2013. Libattion, a Swiss company, is also engaged in circular solutions for battery energy storage. Although circular business models are most often still reliant on subsidies and R&I fundings, these companies are aiming to shift from experimental pilots to marketed second-life solutions.

3.2. THE BATRAW CASE

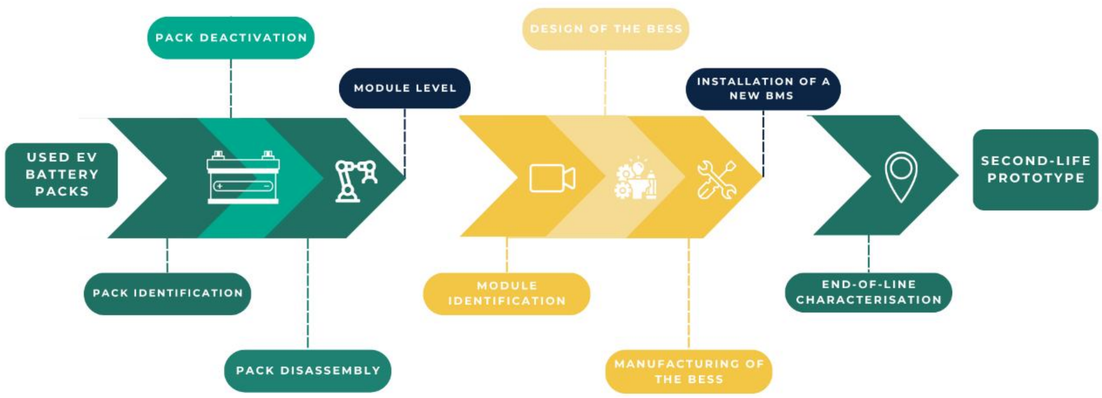
The Horizon-funded BATRAW project is a notable example of an EU-supported initiative that aims to contribute to the advancement of closed-loop practices in the battery sector. It demonstrates two pilot systems for the sustainable end-of-life management of EVBs, domestic batteries and battery scraps. The project aims to enhance circularity in the battery sector through multiple approaches, by including work on CRM recovery, supply chain traceability, eco-design frameworks, and innovative solutions for recycling and repurposing. BATRAW partners are strategically placed across different segments of the value chain. The consortium includes EV manufacturers, battery recyclers, companies responsible for dismantling, providers of traceability software, and enterprises specialised in repair and/or second-life applications.

The first BATRAW pilot involves a semi-automatic disassembly procedure for EVBs (Figure 1)[6]. Before dismantling, the state of the battery packs is evaluated by means of an

[6] The second BATRAW pilot focuses on mechanical pre-treatment and continuous hydrometallurgical recycling technology. It aims to recover battery raw materials (e.g. Cobalt, Nickel, Manganese, Lithium, C-Graphite, Aluminum and Copper) with high accuracy to ensure reuse possibilities. The demonstrator has a recycling capacity of 1 ton lithium-ion packs dismantled each 8 hours and can treat up to 300kg of black mass per day (Aucher & Marín, 2023; Zapico et al., 2024).

innovative identification and characterisation tool developed by BeePlanet Factory. This tool aims to reduce the time needed to identify the type, chemistry and state of health of the pack from several hours to about 30 minutes (Aucher & Marín, 2023). Given the high variability of EVBs depending on their original design and first usage, such a fast diagnostic holds potential to unlock opportunities for second-life business models. BATRAW will deliver the design of a dismantling line from the pack to cell level, both for recycling (cell level) and second-life (modules level) purposes. Within the pilot, partners are developing workstations for pack identification , SoH evaluation and discharge. EVBs are then disassembled through a semi-automatic process based on human-robot collaboration. Extracted modules are further evaluated to select those suitable for second-life applications. Based on lessons learned in this exercise, a set of guidelines for reuse and dismantling will be drafted. Additionally, BATRAW partners assessed opportunities for repairing packs by replacing damaged modules and reusing them in EVs (Zapico et al., 2024).

Figure 1: BATRAW dismantling pilot line and second-life BESS prototype. Author's own elaboration.



One of BATRAW's key achievements is the development a prototype second-life battery for stationary energy storage. This demonstrator serves as a proof-of-concept for EVB repurposing. The first phase includes a rigorous inspection of the battery modules and the design of a Battery Energy Storage System (BESS) tailored to their electrical, thermal and mechanical features. The next step is to manufacture the BESS, starting with the replacement of unusable modules and ending with the installation of a new BMS. The BATRAW BESS prototype consist of a battery cabinet with capacity of 80 kWh, which can be expanded up to six times (i.e. to 480 kWh) using the same control cabinet.

4. CHALLENGES AND OPPORTUNITIES TO SECOND-LIFE CIRCULARITY APPLICATIONS FOR BATTERY PACKS

4.1. METHODOLOGY

This study uses qualitative data from relevant stakeholders to investigate challenges associated with second-life applications of EVBs in Europe. With the recent revision of the EU regulatory framework on battery circularity, there is still a need for empirical evidence on the challenges and opportunities associated with circular business models based on repurposing EV batteries. Therefore, this paper employs an exploratory research approach using semi-structured interviews. This inductive methodology has been widely used in social sciences to identify patterns and trends for under-researched phenomena by drawing on interviews and/or case studies (Stebbins, 2001).

Table 3: Overview of the sample

No.	Activities	Position of the Interviewees	1st/2nd Round
1	Automobile manufacturer	Head of Sustainability	1st
2	Automobile manufacturer	Innovation Analyst	1st
3	Developer of circular solutions for energy storage systems	Chief Technological Officer	2nd
4	Developer of second-life applications	CEO	1st
5	Developer of second-life applications	Engineer	1st
6	Developer of second-life applications	Innovation Manager	2nd
7	Developer of second-life applications	Head of Environmental Management	1st
8	Developer of standards	Head of Public Affairs	1st
9	Dismantler & provider of automotive parts	Head of Innovation	1st
10	Dismantler & provider of automotive parts	Head of Innovation	2nd
11	Provider of traceability services	Manager	1st
12	Recycler	CEO	1st
13	Recycler	Heah of Public Affairs	1st

14	Semi-automated disassembly of EVBs	Project Manager	2nd
15	Supplier of automotive parts	Head of Battery Development	1st
16	Supplier of battery materials	Manager	1st
17	University	Researcher	2nd
18	Logistics Operator	Manager	2nd

We conducted a total of 18 interviews across two rounds. The first round took place in 2023 and included 12 interviews, while the remaining 6 were conducted in 2025. Two companies from the first round were re-interviewed to explore potential changes in their perspectives. The final sample includes a mix of large companies and SMEs, alongside one university. Participants include both organisations involved in the BATRAW project and external actors. Companies in the sample are active across different segments of the second-life value chain, such as car and battery manufacturing, battery disassembly, repurposing, traceability tool implementation, and designing of second-life battery products. Furthermore, interviewees hold diverse roles spanning among engineering, business development, and regulatory affair (see Table 3). The following section outlines the main challenges for second-life applications of EVBs, identified through the interviews and supported with evidence from the literature.

4.2. CHALLENGES FOR SECOND-LIFE APPLICATIONS OF EVBS

Cost barriers and market uncertainties for second-life applications

The economic viability of business models focusing on second-life applications of EVBs emerged as a central issue in many interviews[7]. A key barrier lies in high repurposing costs, which include expenses for collecting, evaluating, disassembling and repackaging used modules, building a new BMS and conducting safety and performance testing (Shahjalal et al., 2022; Zhao et al., 2021). Developers of second-life solutions identified the purchase of used modules as the largest cost, with one interviewee even claiming their price to be close to the market value of new components. This aligns with findings of other studies (see Shahjalal et al., 2022; Zhao et al., 2021). The lack of automation in sorting, testing and disassembly further exacerbates these costs, as processing used batteries is typically labour-intensive (Ahmed et al., 2025; Meyer et al., 2024; Prenner et al., 2024). Interviewed companies exploring robotic and AI-based disassembly applications added equipment costs to the list of financial hurdles.

[7] An analysis of economic competitiveness aspects of second-life applications including scenarios about the price margin between new and repurposed batteries is provided by Rizos et al. (2026).

Many companies flagged that transboundary movement of batteries can be costly due to stringent safety requirements (see Gu et al., 2024; Zhao et al., 2021). For instance, one participant explained that complying with these rules often entails consultancy fees to understand how to correctly interpret regulations. Additional transport-related costs identified by companies involve investments to establish permitted storage locations for used EVBs and to adapt vehicles with enhanced safety features. These adjustments may involve special containers to transport used modules, modifications to fire safety systems, and the installation of temperature monitoring tools (see Slattery et al., 2021). One interviewee further highlighted staffing costs as a major component of reverse logistics operations, noting the need for ongoing training of human resources to ensure regulatory compliance.

Second-life applications of EVBs in energy storage are also increasingly challenged by the declining cost of new batteries (Albertsen et al., 2021; Gu et al., 2024). Although Zhao et al. (2021) argues that the trend might reduce purchasing costs for repurposing companies, others argue it might reduce the key price advantage of second-life solutions (Albertsen et al., 2021; Strupeit and Tojo, 2023). Indeed, interviewed companies involved in second-life BESS observed that customer demand for their products is primarily driven by their relatively lower market prices compared to new solutions. Prenner et al. (2024) quantified the cost ratio of second-life to first life and found that secondary applications must be at least 30 % cheaper than new products.

Participants also emphasised the role of market uncertainties in delaying investments. Indeed, interviewees argued that high upfront costs for testing and disassembly must be weighed against the unpredictability of the volume of retired EVBs (see Ahmed et al., 2025; Prenner et al., 2024). Hellström and Wrålsen (2024) further argued that uncertainties extend also to the quality of batteries and their suitability for second-life applications, which depends on future technical developments (Toorajipour et al., 2024). Additionally, variables such as energy, transportation and labour costs can vary across countries depending on the policy framework in place. Overall, unpredictability makes it difficult to estimate profitability of second-life EVBs in a real-word scenario and convince major players in the automotive industry to invest (Prenner et al., 2024; Toorajipour et al., 2024).

Regulatory ambiguity and lack of standards on second-life batteries

Interviewees pointed to several areas where regulatory uncertainties pose challenges for repurposing EVBs. One car manufacturer, for instance, stressed that the absence of a clear liability system slows down the development of business models. This view is echoed in the analyses by Hellström and Wrålsen (2024) and Toorajipour et al. (2024), which find that ambiguity around the allocation of responsibilities for second-life batteries discourages companies from entering the market. Interviewees emphasised this issue also in the context of the EU battery passport, arguing that responsibilities for data gathering and updating after the batteries' end-of-life remain remain unclear (Rizos and Urban, 2024b).

Some participants also pointed out that the current EU policy framework places greater emphasis on waste management and recycling rather than supporting second-life applications of batteries (see Júnior et al., 2023). One interviewee also noted that the current regulations do not clearly distinguish between reuse, repair, repurposing and remanufacturing. Although the Batteries Regulation defines them separately (see Box 1), such practices are often grouped under one-size-fits-all provision. As a result, the same rules and requirements apply to different technical processes involved in second uses of EVBs, with the risk of neglecting the support needs of each.

Regarding the EU Batteries Regulation, some participants felt that its impact on second-life applications may remain limited in the near future. This is due to the time lag between the implementation of regulatory requirements and the point at which compliant batteries will reach their end of life. The issue was particularly stressed when discussing mandatory BMS accessibility, as second-life operators explained benefits will materialise only when batteries placed on the market after 2027 begin to enter the second-life phase (see Strupeit and Tojo, 2023). An additional issue relates to the documentation requirements set by the Regulation to prove that a battery is no longer waste and is intended for second-life (see Section 2.1). One interviewee explained that obtaining evidence on the SoH evaluation from OEMs can be difficult due to technical complexities. This can pose a challenge for logistics operators, as they must implement different transport solutions depending on whether a battery is classified as waste or intended for second-life uses.

Regulations affecting the transportation of batteries are frequently identified by studies as a barrier to developing circular battery value chains (see Strupeit and Tojo, 2023; Prenner et al., 2024). Several interviewed stakeholders corroborated this barrier pointing to the principle of prior and informed consent under the EU Waste Shipment Regulation (see Section 2.2), arguing that it imposes significant compliance costs. Additionally, participants explained that the lack of harmonisation in regulations governing battery storage across countries complicates logistics operations, as requirements and permitting processes can vary significantly even within the same Member State. Some interviewees also mentioned that they anticipate stricter regulations on storage in the near future in response to the increasing volume of used EVBs, and they expressed concerns about potential additional obstacles. While acknowledging the health, safety, and environmental hazards associated with moving and storing used batteries, most participants agreed on the need to simplify procedures to boost circularity.

Interviewees also highlighted the absence of technical standards tailored to second-life EVBs. Examples of areas lacking harmonisation include ageing indicators, testing procedures, SoH and SoC assessments, and the reassembly of used modules (see Salek et al., 2024). Inconsistencies on key parameters might challenge certifications and warranty systems for second-life applications (Salek et al., 2024; Strupeit and Tojo, 2023). One interviewed company noted that OEMs are particularly interested in clear threshold values to determine when used batteries can be shipped as products intended for secondary uses rather than waste. Additionally, some participants attributed the lack of standardisation in battery pack designs to weak policy frameworks, calling for stricter eco-design requirements to support disassembly.

Underdeveloped ecosystem for second-life EVBs

The underdeveloped supply chains for second-life batteries is a recurring theme across both the literature and interviews. For instance, one participant reported a scarcity of laboratories performing key testing procedures for second-life applications. Similarly, Strupeit and Tojo (2023) and Toorajipour et al. (2024) identified a lack of collection facilities for used EVBs. During the interviews, challenges in the collection stage were frequently attributed to the wide variety of EVB chemistries and configurations, even when sourcing from the same manufacturers (see Júnior et al., 2023; Strupeit and Tojo, 2023).

Transport-related issues further contribute to supply chain fragmentation, as already discussed in previous sections of this paper, since current regulatory requirements might hamper the establishment of reverse logistic systems (see Ahmed et al., 2025). One interviewee noted that the assessment on the state of used batteries is difficult to perform at the dealer level. As a result, used EVBs often need to be shipped to central facilities with engineering capacity for testing before they can be further transported for repurposing, repair or recycling, adding an additional step for the logistics chain. Some participants added that transport companies might lack familiarity with second-life batteries, which makes cooperation more challenging. For instance, one company mentioned that logistical partners had at times refused to handle their products due to inaccurate safety concerns.

Cooperation across the battery ecosystem was also described as challenging. Second-life operators explained that, unlike first-life producers, they must purchase used EVBs from multiple suppliers, which requires a considerable effort to build and maintain strong partnerships (see Strupeit and Tojo, 2023; Meyer et al., 2024). Collaboration with OEMs regarding data access was reported to be very difficult in the absence of strict non-disclosure agreements (NDAs). According to interviewees, such reluctance is due to the fear of losing intellectual property by disclosing sensitive information (see Gu et al., 2024; Prenner et al., 2024; Song et al., 2024). One participant argued that OEMs simply lack interest in second-life solutions, as they see few economic opportunities beyond the battery's first life. Meyer et al. (2024) further suggest that OEMs might avoid cooperating with repurposing companies because they fear reputational damages should the battery fail or cause hazards during its secondary use.

Overall, limited data transparency across the battery supply chain remains a major challenge for circularity (see Rizos & Urban, 2024a). Restricted access to BMS data were frequently cited as a key barrier to second-life development, aligning with findings from the literature (see Strupeit & Tojo, 2023; Toorajipour et al., 2024). For instance, operators involved in disassembly reported difficulties in retrieving essential battery information due to manufacturers often withholding decoding protocols. Therefore, they need to use expensive equipment to safely deactivate EVB packs and costly diagnostic tools to assess SoH, SoC and degradation patterns (see Gu et al., 2024). While most participants agree that upcoming regulatory measures – such as mandatory BMS accessibility under the Batteries Regulation and the implementation of the battery passport – might have positive impacts on such challenges, they also stressed again that the regulatory impact on second-life batteries in the short-term is very limited.

Technical complexities in disassembly and characterisation of used EVBs

Technical challenges in repurposing EVBs for secondary applications were highlighted during the interviews. Most difficulties originate from inadequate pack design, as original manufacturers typically focus on optimising performance for the first use with little consideration for end-of-life disassembly (Ahmed et al., 2025; Hellström & Wrålsen, 2024). For example, participants reported that glues and adhesive used to seal covers and cooling systems make it difficult to open the battery pack. More broadly, the heterogeneity of battery designs discussed in previous sections limits the possibility to develop automate disassembly processes (see Shahjalal et al., 2022).

Disassembly issues are also exacerbated by the lack of data transparency mentioned earlier. For instance, one interviewee explained that the inability to retrieve BMS data complicates the discharging process. Indeed, end-of-life-batteries need to be brought back to a safe voltage level and this can be done electrically through controlled discharged processes (see Salek et al., 2024). However, if operators cannot access key parameters stored in the BMS, such as the SoC and the cell voltage, they must physically open the pack and perform deactivation manually.

Furthermore, EVBs reach the end of their first life in varying conditions depending on their initial use , 2023; Toorajipour et al., 2024), which adds another layer of complexity. This means that battery ageing and performance profiles may vary greatly among collected packs, making the characterisation of used modules more challenging (see Toorajipour et al., 2024). Indeed, interviewees explained that SoH evaluation for second-life purposes remains time-consuming and costly (see Ahmed et al., 2025). One participant also added that although machine learning models have been applied to battery characterisation within academia, their commercial application is still rare.

Adoption barriers for second-life EVBs

Interviewees identified challenges hindering the uptake of second-life battery applications on both demand and supply side. Firstly, low customer acceptance was frequently mentioned. Despite growing environmental awareness, companies selling second-life BESS flagged that clients still prioritise price over sustainability. One interviewee explained that marketing their products by focusing on engineering know-how is often more effective than emphasising their environmental value. This is echoed by Albertsen et al. (2021), who reviewed current examples of CBMs in the battery sector and concluded that most consumers are not satisfied with their environmental appeal, as their decision-making remains centred around technical and economic features of the product.

Misconception around safety and reliability of second-life batteries also play a role (see Ahmed et al., 2025; Schulz-Mönninghoff & Evans, 2023). Participants explained that even if second-life batteries must meet the same standards as new ones when used for energy storage, clients often perceive them as more prone to failure, performance issues and reduced lifespan. Case studies such as by Schulz-Mönninghoff and Evans (2023) confirm that users' perception of second-life batteries may be distorted.

On the supply side, some interviewees observed that the rapid expansion of the battery market is putting pressure on organisational structures. For instance, one participant argued that it is difficult to remain flexible and adapt to evolving regulations and technical features around EVBs. Further, as many players on the second-life markets are SMEs, they can have limited resources to respond to new market and policy demands. For instance, one participant noted that smaller companies lack the financial and human capacities to implement requirements such as the battery passport. Nevertheless, larger companies interviewed also reported difficulties in keeping pace with the evolving regulatory landscape, emphasising the need to continuously invest to keep in-house personnel trained to navigate complex requirements. Toorajipour et al. (2024) also reports gaps in supply-side readiness to second-life applications, noting that companies within the EVB ecosystem often show reluctance to change. This lack of adaptive capacity limits the widespread adoption of CBMs.

4.3. OPPORTUNITIES FOR SECOND-LIFE APPLICATIONS OF EVBS

Price advantage and market value streams for second-life batteries

In most interviews, the price competitiveness of second-life EVBs emerged as a key economic driver. Participants flagged that the cost gap between repurposed EVBs and new batteries determines their attractiveness for secondary uses characterised by relatively low performance requirements, such as residential storage and microgrids (see Akram & Abdul-Kader, 2024; Gu et al., 2024). Júnior et al. (2023) adds that the price advantage of repurposed EVBs reinforces the economic benefits for households using domestic BESS. Indeed, residential battery storage systems allow households to avoid purchasing energy from the grid at high rates during peak hours, thus lowering the overall electricity cost for the household (see Akram & Abdul-Kader, 2024).

The rapid growth of the EV market further enhances economic opportunities for the second-life business model. As EV adoption accelerates, the rising supply of retired batteries creates incentives to invest in their reuse (see Júnior et al., 2023). One participant noted that regional synergies can reinforce this trend, explaining how the company's proximity to automotive productions sites and battery manufacturing plants motivated them to explore the second-life battery market.

Overall, second-life applications of EVBs can generate multiple value streams for different actors (see Bai et al., 2019; Schulz-Mönninghoff & Evans, 2023), including grid-service operators, companies involved in EoL treatment and OEMs (see Ahmed et al., 2025). For instance, one participant pointed out that selling used batteries to second-life actors can maximise OEMs' returns on the expensive raw materials used in EVBs production (see Zhao et al., 2021). According to available studies, second-life applications can help meet the growing demand for electrification without putting additional pressure on scarce and price-volatile resources such as nickel and cobalt (see Gu et al., 2024; Júnior et al., 2023).

The EU battery framework and funded pilots for second-life applications

The EU Battery Regulation was regarded by most interviewees as a positive step towards fostering second-life business models. Provisions such as BMS accessibility and EPR rules were notably stressed as promising due to their focus on supporting more sustainable end-of-life solutions for EVBs (see Albertsen et al., 2021; Prenner et al., 2024). Participants further cited the battery passport as a valuable tool providing crucial information on the pack's first use (see Meyer et al., 2024; Rizos & Urban, 2024b). Zhao et al. (2021) further explains that a battery passport can reduce repurposing costs by enabling automated disassembly and streamlining performance testing thanks to enhanced transparency along the supply chain.

Beyond the battery regulatory framework, renewable energy policies provide additional incentives for second-life EVBs applications. Indeed, EU-level targets on renewable generation determine the need for stationary storage to balance intermittent energy supplies. Participants noted that such measures indirectly increase interest towards repurposing EVBs, as second-life batteries can help meet such novel demand (see Albertsen et al., 2021; Strupeit & Tojo, 2023). Additional incentives stem from publicly funded pilot projects, which offer opportunities to showcase the feasibility of CBMs and attract investments (see Toorajipour et al., 2024). Interviewees emphasised that EU-funded initiatives such as Horizon Europe (e.g. Table 2) can offer valuable financial support for SMEs. One participant highlighted how such public funds unlocked opportunities to upskill workers and expand the company's technical capabilities.

Collaboration with OEMs and localised supply chains for repurposed EVBs

Strong partnerships were consistently mentioned by participants as crucial for the scalability of second-life business models. Collaboration with OEMs was emphasised as particularly valuable for improving the efficiency of repurposing operations (see Meyer et al., 2024). These partnerships typically provide access to BMS data and enable volumes and characteristics of incoming EVBs to be partially predicted (Meyer et al., 2024; Toorajipour et al., 2024). Long-term collaboration can also foster shared learning around CBMs (Toorajipour et al., 2024). For instance, one interviewee described how partnering with a more experienced company helped navigate complex regulatory requirements, while another participant emphasised how partnering with a recycling firm provided them with a deeper understanding of reverse logistics operations.

Interviewees also discussed the advantages of localised supply chains for repurposed batteries. One participant stressed that, while new batteries are largely imported from Asia and remain highligh vulnerable to supply chain disruptions, second-life EVBs might offer a more secure alternative. Indeed, as repurposing is often carried out near end users, transportation costs are reduced and traceability is improved.

Safety benefits and resource savings of repurposed EVBs for energy storage

Repurposed EVBs may offer safety benefits over newly manufactured storage batteries. As EV applications typically require batteries to meet higher performance and safety standards than other uses, some participants argued that repurposed EVBs can be more reliable than their new counterparts in storage applications (see Strupeit & Tojo, 2023). One interviewee further noted that, having already completed a charge/discharge cycle, used batteries are less prone to overheating and unexpected chemical reactions compared to new ones.

Finally, repurposing EVBs is also linked to opportunities in terms of resource savings (see Akram & Abdul-Kader, 2024). One participant observed that, while both repurposing and recycling reduce the need for CRMs mining, their combination can further minimise resource extraction (see Seika & Kubli, 2024). Indeed, despite the many methodological challenges involved in conducting a life-cycle assessment of EVB repurposing (see Kotak et al., 2021), existing estimates suggest that recycling LIBs only after their second-life application can reduce the carbon footprint by 8-17 % (Tao et al., 2021).

Factors driving the adoption drivers of second-life applications for EVBs

Interviewees also pointed to a number of opportunities for the adoption of second-life applications of EVBs, fuelled both by rising societal awareness and by companies' strategic interests in CBMs. On the consumer side, participants emphasised the growing demand for residential battery storage systems as a promising market trend (see Al-Alawi et al., 2022). One interviewee further explained that current geopolitical uncertainties, with blackouts and grid interruptions becoming more likely, are further motivating households to seek affordable solution for backup power generation such as those based on repurposed EVBs.

From a company perspective, second-life batteries provide a strong sustainability value (see Toorajipour et al., 2024). For instance, one car manufacturer noted that using refurbished or remanufactured EVBs could help them reduce their overall carbon footprint, while another interviewee emphasised how second-life practices align with the firm's broader environmental commitments. More often, investments in circularity are framed as strategic and forward-looking bets that outweigh short-term costs. Drawing from these ideas, one participant presented the company's intention of setting up a second-life solutions as a way of securing a long-term position in the battery industrial sector. This perspective aligns with findings from Toorajipour et al. (2024), where innovative and forward-looking company behaviour is founded to be a driver of CBMs adoption.

Table 4: Overview of challenges and opportunities for second-life applications of EVBs identified through interviews

Challenges	Opportunities
High repurposing costs include the purchase of used modules, SoH evaluation, disassembly, cross-border transport, safety and performance testing	**Price competitiveness** of used EVBs makes them attractive for lower-performance applications, such as residential storage and microgrids
Market uncertainties regarding the volume of retired EVBs and their technical features challenge investment flows	Repurposing EVBs can generate **revenue opportunities** for OEMs, grid-service operators, and EoL treatment companies
Regulatory uncertainties surrounding responsibilities after the end-of-life of the battery slow down the emergence of a second-life business model	BMS accessibility and EPR rules in the **EU Battery Regulation** support second-life uses of EVBs
Strict requirements stemming from **transport regulations** raise compliance costs for operators exploring second-life markets	**Localised supply chains** for second-life applications can reduce transport costs and improve resilience
Limited availability of technical standards tailored to second-life batteries	Second-life EVBs benefit from the **high performance and safety standards used in EV applications** when competing with newly manufactured storage batteries
Lack of access to BMS data complicates safe discharging, hinders automated disassembly, and complicates SoH evaluation	**Battery passport** can improve data transparency, reducing repurposing costs by streamlining testing and disassembly
Misconceptions around safety and reliability of second-life batteries combined with low environmental awareness hinder customer acceptance	**Growing demand for affordable battery storage systems** due to renewable energy expansion and geopolitical uncertainties

Limited company resources to invest in exploring business models centred around second-life batteries	Second-life EVB business models support **corporate sustainability goals** and environmental commitments
Limited development of the supply chain for second-life applications, with missing facilities for collection and storage of used batteries as well as cooperation challenges among different actors	
Inadequate pack design as OEMs focus on first-life performance rather than end-of-life disassembly	

5. POLICY MESSAGES

Several policy messages can be drawn from the analysis in this paper. A first key message is that that even though the Battery Regulation is a milestone – introducing concepts such as repurposing and remanufacturing and including several provisions for second-life applications (e.g. on BMS accessibility, EPR rules and the battery passport) – several regulatory ambiguities remain. These are particularly evident regarding the allocation of responsibilities for the batteries after their first use. Companies developing second-life applications have emphasised the need for a clear liability framework that clarifies responsibilities (e.g. on data handling) for batteries entering repurposing pathways. Establishing a clear liability framework would also support investments in second-life applications. The standardisation framework for second-life EVBs is still underdeveloped and needs to be improved to provide harmonised approaches in areas such as SoH and SoC assessments. Greater standardisation of battery pack designs would further support disassembly processes and ultimately repurposing applications.

The economic attractiveness of second-life applications for EVBs remains challenging in practice and depends on various factors including collection and disassembly costs, transport-related costs for used batteries, building a new BMS and performing the necessary safety and performance tests. The declining price of new batteries may further undermine the economic attractiveness of second-life batteries, as repurposed batteries will typically need to offer a clear price advantage compared to new batteries in order to remain competitive. This highlights the importance of funding schemes and EU-funded projects such as BATRAW in supporting innovation particularly in the automation of repurposing processes to support cost reductions as well as in providing financial support for second-life applications until the market matures and larger volumes of retired batteries from first-life applications become available.

Further action will be needed to boost demand for second-life applications and help create a market for them. Targeted measures could include incentives for deploying stationary storage systems that use repurposed EVBs in residential, commercial and grid-support applications. Public procurement schemes, State aid support or dedicated funding under the Innovation Fund can help create lead markets for second-life solutions.

As shown by our analysis, access to reliable and standardised data will be key for second-life applications. While mandatory BMS accessibility under the Batteries Regulation is expected to have a significant positive effect, additional action will be needed to further close this data gap. For example, supply chain initiatives and industry-led collaborations can play a complementary role by building trust among value chain actors and by piloting practical use cases where data are effectively shared, thereby supporting decision-making on second-life suitability and facilitating disassembly and repurposing processes.

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ABOUT THE BATRAW PROJECT

BATRAW's main objective is to develop and demonstrate two innovative pilot processes for electric vehicle batteries: i) a semi-automated processes for the handling of the batteries to separate their components, including cells and modules suitable for reuse and ii) a mechanical pre-treatment and hydrometallurgical recycling process to improve the separation of the materials contained in the so-called black mass (a substance composed of non-ferrous metals resulting from the shredding of the batteries). The project will also create a prototype battery from the recovered raw materials and a digital battery passport to capture and communicate key information throughout the battery life-cycle, including the sourcing, processing, (re-)use and recycling of components. As part of the project, eco-design guidelines for the repair and dismantling of batteries, as well as best practices for the safe handling and transport of batteries will be developed. For more information about the project, see: https://batraw.eu

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PARTNERS

CEPS
PLACE DU CONGRES 1
B-1000 BRUSSELS