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Report on joint circular strategy development for better use of waste energy and renewable energy sources in public transport operations

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1. Executive Summary

The CE4CE project empowers circular economy system thinking for actors in public transport from Central European countries to reduce waste and create value along new life cycles of infrastructure and rolling stock. To do so, CE4CE jointly develops solutions that increase knowledge and capacities for the sector, help reduce barriers and costs and initiate the development of new services and skilled jobs, as well as strategies and action plans that improve policy development, learning and exchange on the regional and transnational level. CE4CE aims at bringing circular economy principles into the public transport sector and, thus, reduce waste, increase efficiency in the sector and improve the ecological footprint of public transport.

Furthermore, stakeholders from the public transport community will cooperate in CE4CE to jointly develop and adapt processes and solutions as key enablers for the integration of circular economy principles, like data sharing concepts, new (innovation) procurement guidance, product and business model designs, extended life-cycle assessment, and cost-benefit analysis methodologies.

CE4CE will jointly develop outputs based on co-creation and peer reviews for take up by the public transport sector, e.g. pilot actions and solutions such as the CE4CE Circularity Compass for public transport, the CE4CE Circularity Knowledge platform, a web-based second-hand marketplace, strategies and pilot actions to increase resource-efficiency and pilots demonstrating use more, reuse and recycle approaches for the public transport sector.

CE4CE's partnership reflects the whole value chain and transport sector system perspective including 11 project partners from 6 Central European countries, ranging from public transport authorities/operators, industry and research to interest groups. To enlarge this cooperation, associated partners like the international active networks ICLEI, UITP and EIT Urban Mobility/Raw Materials are strategically involved to maximise communication outreach and knowledge transfer of project results.

This document is a report on pilot action LVB that aims to give an overview of the pilot project implemented under the CE4CE initiative, explaining how they are conducted.

This document is organized as follows*:*

Chapter 2 presents the introduction to the strategies to circular economy principles

Chapter 3 addresses relevant strength, weaknesses, opportunities and threads of public transport with reference to energy.

Chapter 4 is collection of measures, followed by examples of implementation possible to be adopted.

Chapter 5 focuses on the framework of indicators at the intersection of transport and the circular economy

Chapter 6 contains conclusions and further recommendations.

2. Introduction to the strategy to capture and optimize use of waste energy and RES along new life cycle value chains

2.1. Why circularity and the need for the CE4CE strategies?

The transport sector accounts for roughly one-fifth of the total EU emissions. While sectors like energy have reduced emissions since the 1990s, emissions from road transport continue to rise, reaching nearly 700 $MtCO_2$ as of 2023. [1] The challenge, however, extends beyond tailpipe emissions: the transport sector consumes vast resources, creating significant embedded emissions from activities like steel production for vehicles, gasoline refinement, lithium mining for batteries, and cement manufacturing for infrastructure. For instance, embedded GHG emissions can account for 50-60% of total lifecycle emissions in electric vehicle manufacturing, compared to just 10% for combustion engine cars.[2].

Emissions are symptomatic of a deeper issue—a linear economy built on a "take-use-throw" model that depletes finite resources and disregards ecological restoration, leading to critical ecosystem exhaustion. Addressing this requires a fundamental shift in how resources are designed, used, and consumed. A circular economy offers a cradle-to-cradle solution, tackling direct ecological impacts of transport activities while addressing the influence and effect in areas like construction, energy, and waste. By rethinking resource use, the circular economy seeks to address the systemic ecological and social impacts of the transport sector and beyond.

The CE4CE project pioneers this shift by transitioning from a linear model to a circular "Avoid-Extend-Transform-Enable" (AETE) approach, positioning public transport as a catalyst for transformation. Its initial phase developed the Circularity Compass[3], establishing the AETE framework for understanding public transport activities within a life-cycle perspective, spanning three public transport pillars: Energy, Infrastructure, and Rolling Stock, with Governance as a cross-cutting pillar.

Building on this foundation, CE4CE is advancing **three strategies focused on Energy, Infrastructure, and Rolling Stock.** These strategies leverage the life-cycle approach of the Circularity Compass and adopt a common document structure to uncover the full ecological impacts of each area, exploring in detail their conditions, direct and embedded emissions, and sector-specific recommendations to advance a more circular approach. These strategies form the basis for localized action plans, offering concrete, time-bound measures and clearly defined responsibilities to make circularity a reality and drive the transition to net-zero public transport systems.

[1] European Environment Agency. (2024). *Transport and mobility*. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport

[2] Transport & Environment. (2024). *Cleaning up steel in cars: why and how*. https://www.transportenvironment.org/articles/cleaning-up-steel-in-cars-why-and-how

[3] Circular Economy for Public Transport. (n.d.). *Circularity Compass*. https://circularity4publictransport.eu/circularity-compass/

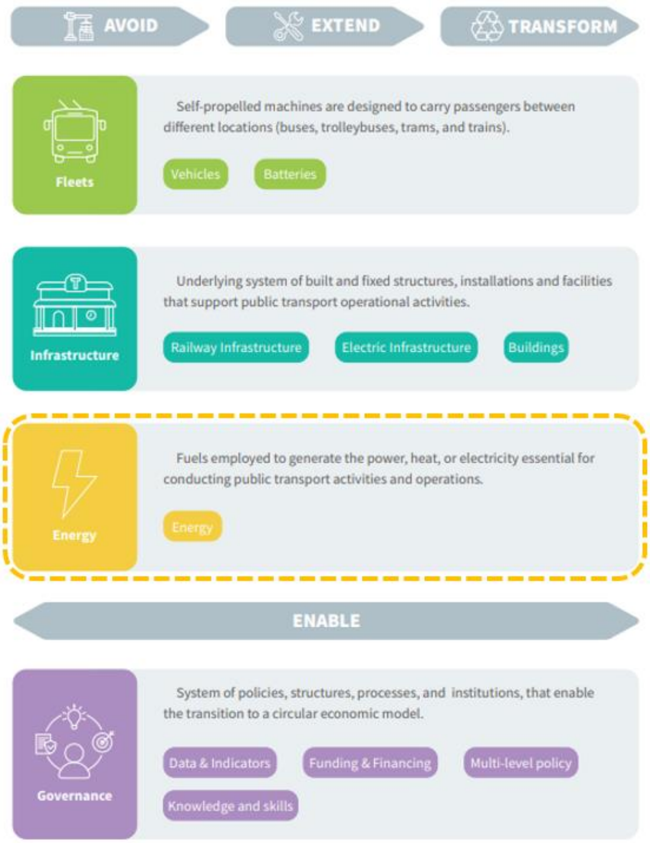

Figure 1. Visual summary of circularity compass life-cycle approach and public transport pillars. The frame highlights the focus of this strategy is on public transport infrastructure elements. Source: CE4CE

2.2. Greening Public Transportation Through Circular Economy Principles: Field of Energy

Public Transport Energy Use (hereafter, PTE) is fundamental to the functioning of modern society. They enable the movement of people and goods, drive economic activity, and provide essential access to services. However, these assets are often underappreciated in the broader push for sustainable transport solutions, with a focus placed more on vehicles and operations than on the physical infrastructure itself. This oversight can undermine system resilience, reduce long-term efficiency, and compromise sustainability goals.

Public transport systems worldwide are undergoing a transformative shift towards sustainability. This shift is driven by the need to reduce greenhouse gas emissions, mitigate air pollution, and enhance energy efficiency. Electric buses (e-buses) are at the forefront of this transition, offering a cleaner alternative to traditional diesel-powered vehicles. However, while e-buses significantly reduce tailpipe emissions, the overall environmental benefits are contingent upon how the energy required for charging and the lifecycle of the buses and their batteries are managed.

Recent developments in PT operations emphasize the integration of renewable energy sources (RES) and advanced energy management systems when powering e-buses. This approach not only supports the decarbonization of the transport sector but also promotes the resilience and reliability of the energy supply. Despite known advancements, challenges related to energy source and consumption and waste management remain. Addressing these challenges necessitates a strategic incorporation of circular economy principles into PT operations.

The circular economy model offers a holistic framework for optimizing resource use, reducing waste, and promoting sustainability. In the context of PT, this involves designing systems that maximize the use of renewable energy, recover and repurpose waste energy, and ensure efficient recycling of materials, particularly batteries. By integrating circularity into planning and decision-making, stakeholders can enhance environmental performance, reduce waste, and support long-term value creation—ensuring that transport infrastructure not only serves society effectively but also aligns with broader environmental and sustainability objectives.

3. Conceptual and Contextual Basis

3.1. Approximation to a definition of Public Transport Energy use (PTE)

Energy in public transport encompasses all the processes, systems, and resources required to power public transport vehicles and related operations. Broadly speaking, energy use primarily refers to energy management, which is directly linked to the areas of infrastructure and rolling stock, forming the core components of the public transport system. This includes the processes of generation, storage, distribution, and consumption of energy, as well as the associated technologies and fuels used to ensure efficient, reliable, and sustainable mobility.

Energy in public transport is not limited to powering vehicles but also addresses broader systemic goals, such as reducing environmental impacts, enhancing energy security, and supporting circular and sustainable energy systems. It plays a pivotal role in enabling the transition to cleaner and more efficient transport solutions that align with global climate and sustainability objectives.

The field of energy use in public transport aligns somewhat with economic and climate-related sector categories in the EU. Within this framework, the category of energy use can be divided into three main areas:

- **Energy Sources**: This refers to the different types of energy carriers used to power public transport systems, including the vehicles themselves. The choice and availability of energy sources directly influence vehicle technology, environmental impact, and operational efficiency.
- **Energy Infrastructure:** This encompasses the physical systems and facilities required for the production, distribution, and storage of energy used in public transport. Energy infrastructure is essential for enabling pro circular transport principles and technologies.

- **Energy management:** This involves the strategic planning, monitoring, and optimization of energy use within public transport operations. Effective energy management contributes to reducing operational costs, improving energy efficiency, and minimizing environmental impacts across the transport system.

In this broader context, energy use in public transport is a fundamental enabler of sustainable mobility, yet it is typically classified outside the conventional transport sector and the manufacturing subcategory of vehicles. Its classification and scope require purpose-built definitions and a nuanced, flexible approach to reflect its cross-sectoral nature, the diversity of energy sources and technologies involved, and its pivotal role in decarbonizing transport systems.

3.2. Defining public transport energy use for the CE4CE strategy

In the framework of the Circularity Compass, the provisional definition of energy within the context of the public transport systems pillar is: **The set of systems, carriers, technologies, and processes that enable the generation, distribution, storage, and efficient use of energy for the operation of public transport modes. Energy is a critical enabler of low- and zero-emission mobility and directly affects the environmental performance, cost-efficiency, and sustainability of public transport systems.** The Circularity Compass further breaks down the energy pillar into three interrelated subpillars:

- **Energy Sources and fuels** refers to the range of energy carriers and technologies used to power public transport vehicles. This includes conventional fossil fuels such as diesel and natural gas, transitional fuels like biodiesel and biogas, and renewable or alternative energy sources including electricity generated from solar, wind, or hydropower and waste(d) energy. This strategy focuses primarily on electricity as the main energy source for public transport, emphasizing the transition to electric mobility and the supporting infrastructure.
- **Network and Grid Supply, Charging Infrastructure, and Energy Storage Systems** encompasses the infrastructure and networks responsible for delivering, transmitting, distributing, charging, and storing energy for public transport operations. It includes charging stations for electric vehicles, hydrogen refueling stations, and fuel supply chains for liquid or gaseous fuels. The strategy places particular emphasis on charging infrastructure for electric buses—such as overnight chargers at depots, opportunity chargers at selected stops, and pantograph systems—which form the core focus of the strategy. Regarding energy storage technologies, the focus is on stationary batteries installed at depots and onboard vehicle batteries. The design and lifecycle performance of this infrastructure must consider local grid capacity, system resilience, spatial limitations, and energy efficiency to enable circular, low-impact energy use.
- **Energy Management and Efficiency** refers technologies and practices used to monitor, optimize, and reduce energy consumption across the public transport network. This includes smart energy management systems that facilitate load balancing and dynamic charging, as well as energy-

efficient operational processes as vehicle scheduling and eco-driving practices. It also encompasses integrated approaches to demand-side energy management, which aim to align energy consumption with availability, minimize peak loads, and support system-wide efficiency. Effective energy management is crucial not only for reducing emissions and operational costs but also for maximizing the use of renewable energy within the constraints of existing infrastructure and service needs.

It is important to mention that while various energy systems are integral to public transport, certain elements were not included within the scope of this strategy. Specifically, overhead catenary systems and third rail infrastructure used for trams, metros, and trains fall outside the direct focus, as the strategy deliberately concentrates on electric energy use in bus systems. This focus was chosen to ensure depth and applicability within a clearly defined operational context. However, many of the solutions, principles, and approaches outlined in the strategy—particularly those related to energy efficiency, charging infrastructure, and storage—can be transferred to other public transport modes, especially those that are also powered by electricity.

3.3. Introducing a life cycle approach in public transport energy use

A first and crucial step in advancing circularity in public transport energy use is adopting a life cycle perspective. This is essential for understanding the full range of energy flows, resource dependencies, and environmental impacts, as well as for identifying where priorities should be set.

To achieve this, the strategy builds upon existing frameworks. On one hand, it is grounded in the **Circularity Compass Avoid-Extend-Transform-Enable framework**[4], which, as part of the CE4CE project, has been tested, widely shared, and positively received by a large community of public transport stakeholders. On the other hand, the life-cycle stages align with the **EN 15978 standard**[5]—a non-compulsory, Europe-wide reference providing clarity on life cycle perspectives in buildings, specifically as a framework for conducting life cycle assessments (LCAs). LCAs help measure resource use (such as energy carriers) and associated carbon emissions and have become the standard approach in the energy and construction sectors. Since its release, the standard has been adapted to suit specific cases while maintaining its core principles.

For this strategy, **a tailored version was developed by combining these two frameworks, aiming to strengthen the circularity aspects and adapt them to the specific conditions and elements of PTE**, thereby filling an important gap in guidance for advancing circularity within this sector.

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[4] Circular Economy for Public Transport. (2024). *The Circularity Compass* (Version 2024.12.09). https://circularity4publictransport.eu/wp-content/uploads/2025/02/The-Circularity-Compass-2024.12.09.pdf

[5] British Standards Institution. (2011). *BS EN 15978:2011 Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method.* https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/?msclkid=20388604c93b1a91b166ee28445f41f1

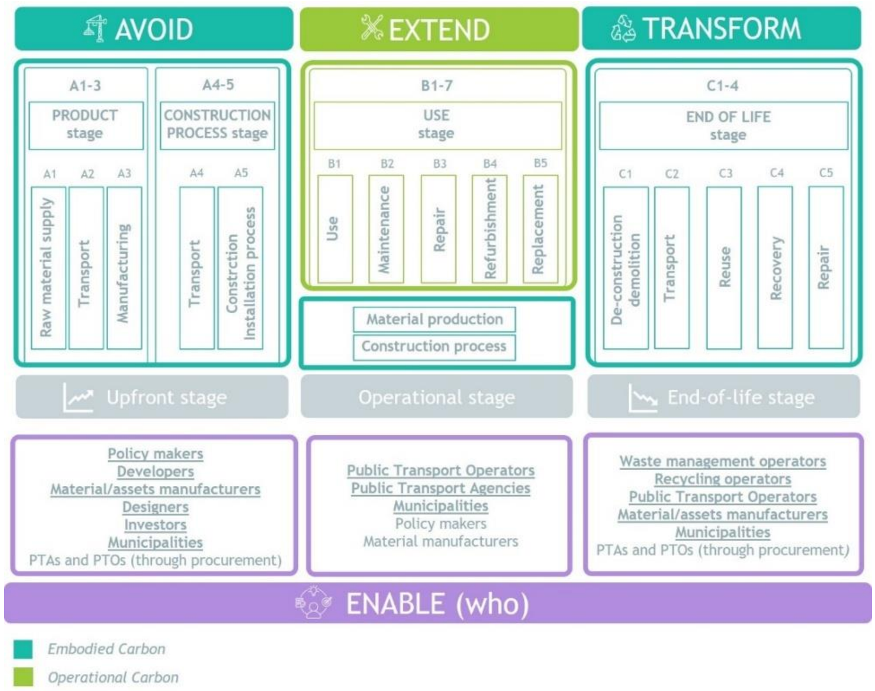


Figure 2. Adapted PTI Life-cycle-based on EN15978 version

3.3.1. General overview

The PTE life cycle diagram is divided into three main stages: AVOID–upfront (A), EXTEND–operation (B), and TRANSFORM–end of life (C). Each stage is further broken down into specific and essential sub-stages, covering key activities within each phase. Additionally, the ENABLE aspect acts as a cross-cutting element, highlighting the core and secondary actors involved at every stage.

The diagram also depicts two types of energy use and associated emissions: operational and embodied. **Operational energy and associated emissions** (also called direct emissions or Scope 1 emissions) refer to the energy directly generated by the actors or organizations involved in each stage. such as electricity used to power vehicles. Embodied energy and associated emissions **Embodied energy and associated emissions** (also referred to as indirect or Scope 2 and 3 emissions) occur outside the organization's direct scope but are still influenced by its activities and have indirect impacts.

As seen in the PTE life cycle diagram, Public Transport Operators (PTOs)—and, to a lesser extent, Public Transport Authorities (PTAs) and municipalities—are typically responsible for direct emissions and energy consumption generated during the operational stage. This primarily refers to energy used to **operate electric buses and associated network, grid charging and storaging infrastructure**.

Another important factor, not prominently highlighted in the diagram but crucial in the Life Cycle Assessment (LCA) approach, is the lifespan of the assets used in public transport—more specifically, in the field of PTE. While the average operational lifespan of a bus may be 10–15 years, supporting energy infrastructure components vary widely. For example, charging units may need upgrades every 8–10 years, whereas substations or grid connections could remain functional for several decades. Batteries, both onboard and stationary, also represent a key challenge, as their degradation rates and replacement cycles significantly influence total embodied energy and environmental impact.

3.3.1.1. AVOID (A-Upfront stage)

As previously mentioned, the upfront stage refers to the selection and sourcing of the energy source for powering the system—primarily the rolling stock—and is divided into two sub-stages

(»Tank« Stage) refers to the integration of energy systems into the operation of public transport. This stage addresses what is commonly referred to as the **"tank-to-wheel" (TTW)** part of the energy chain—that is, the emissions and efficiency of energy use during vehicle operation. The strategy prioritizes avoiding the use of fossil fuels, such as diesel and compressed natural gas, and supports the adoption of clean energy carriers such as electricity and, where feasible, green hydrogen. Selecting propulsion systems with low or zero tailpipe emissions—such as battery-electric drivetrains—is central to this phase. This also includes infrastructure choices (e.g., depot vs. opportunity charging), which influence operational efficiency and overall energy demand.

(»Well« Stage) complements this by addressing the **"well-to-tank" (WTW)** dimension—that is, the environmental impact of how energy is produced and supplied before it reaches the vehicle. While public transport operators have limited control over upstream production, the strategy recognizes that choosing electricity from renewable sources (e.g., wind, solar, hydropower) significantly reduces the overall carbon footprint. Therefore, energy procurement practices—such as sourcing certified green electricity or entering into renewable energy agreements—are essential actions to support systemic circularity.

By combining both the **tank-to-wheel** and **well-to-wheel** perspectives, the strategy ensures that energy decisions contribute to long-term sustainability and circular goals—not only by improving operational performance, but also by reducing hidden upstream impacts. This integrated life cycle view is key to avoiding lock-in to high-emission energy systems and supports a shift toward regenerative, low-carbon energy use. To achieve a comprehensive evaluation, **a Life Cycle Assessment (LCA)** approach should be considered. LCA goes beyond operational energy consumption, capturing the full environmental impact of public transport energy use, including:

- Raw Material Extraction & Processing: Assessing the environmental impacts associated with mining and processing materials required for batteries, charging infrastructure, and other energy-related components.
- Manufacturing: Evaluating emissions from the production of vehicles, energy storage units, power electronics, and related systems.
- End-of-Life Management: Addressing processes such as battery recycling, vehicle decommissioning, and material recovery to reduce waste and promote circularity.

LCA reveals that even clean energy sources like solar and wind carry environmental footprints due to material extraction and processing. This highlights the critical importance of embedding circular economy principles—such as material reuse, refurbishment, and recycling—across the entire energy and transport value chain to minimize impacts and foster sustainable public transport energy systems.

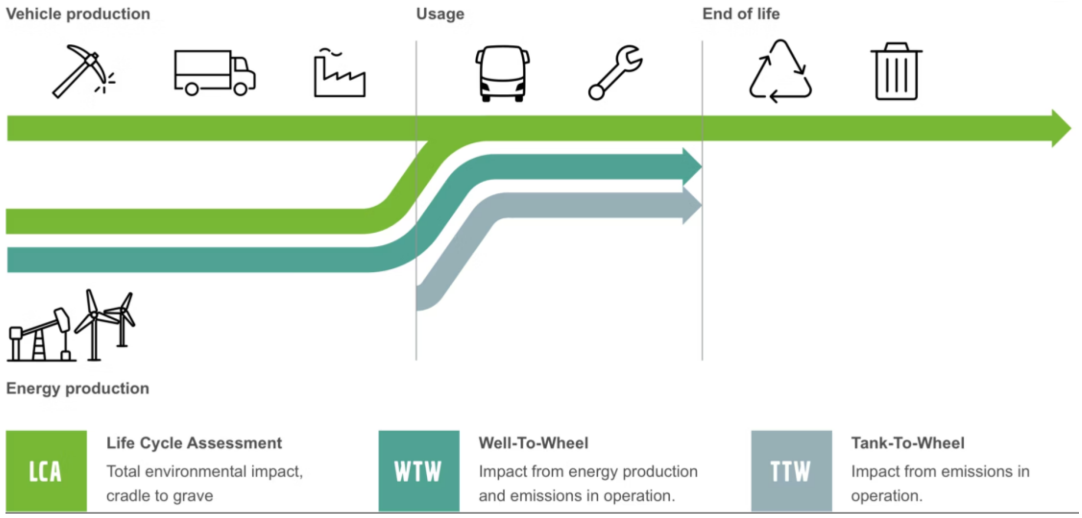


Figure 3. Scheme illustrating the principles of LCA, Well-to-Wheel (WTW), and Tank-to-Wheel (TTW) in the energy chain approach. Source: [Volvo Buses]

3.3.1.2. EXTEND (B- Operational stage)

Electrification of the vehicle fleet serves as the essential starting point for advancing energy performance and sustainability in public transport. Building on this foundation requires substantial investments in charging infrastructure to support the increasing number of electric vehicles and ensure reliable, efficient energy delivery. Beyond simply switching to electric power, optimizing energy use and carefully managing components—especially batteries—are crucial for extending their lifespan. This involves not only efficient energy management, but also proper usage and regular (predictive) maintenance, both of which are essential for ensuring the long-term reliability, safety, and sustainability of electric vehicles.

Extending the lifespan of electric vehicle components goes beyond batteries and involves a holistic approach to energy storage and management systems to maximize efficiency and sustainability. Effective energy storage systems play a key role in stabilizing the grid, mitigating fluctuations, and enabling greater integration of renewable energy sources. Thus, electrification is not an end in itself but a gateway to implementing a comprehensive energy strategy.

3.3.1.3. TRANSFORM (C-End-of-life stage)

After batteries reach the end of their operational or service life, their »after-life« management remains critical. The end-of-life (EoL) phase in public transport energy systems marks the point at which energy-related assets—primarily batteries—can no longer function as intended or be maintained cost-effectively. At this stage, it is essential to consider not only disposal but also solutions for extending the lifespan through repurposing or recycling into raw materials, aligned with circular economy principles.

Reuse and Repurposing Before Recycling

Before batteries are dismantled for raw material recovery, **second-life applications** offer significant environmental and economic value. Batteries that fall bellow performance grade can still be used in less demanding environments—such as stationary grid storage, depot-level energy buffers, or renewable energy smoothing systems. These applications can extend battery lifespans, delaying the need for resource-intensive recycling. However, scaling these practices depends on developing reliable state-of-health assessment technologies and standardized frameworks for second-life certification. Without these, market trust and safety concerns limit widespread adoption.

Recycling Challenges and Progress

When reuse is no longer viable, **recycling becomes the only sustainable route** to recover critical materials. Among assets, used batteries represent the most critical component due to their high environmental footprint, particularly during the disposal phase, as well as their material complexity. Batteries contain valuable raw materials like lithium, cobalt, nickel, and manganese, whose extraction is energy-intensive and often associated with significant environmental and social impacts. Current lithium-ion battery recycling technologies—hydrometallurgical and pyrometallurgical processes—can recover up to 95% of valuable metals. Yet, the global recycling rate for large-format EV batteries remains low, and practices vary significantly by region. In the EU, regulatory momentum is growing. The **EU Battery Regulation** (2023) mandates minimum recycling efficiencies and sets quotas for material recovery (e.g., 90% for cobalt and nickel by 2027).

Design for Disassembly and Circular Recovery

A significant barrier to high-quality recycling lies in the design of current battery systems. Most are **not designed for easy disassembly**, leading to complex and costly end-of-life processing. To change this, public transport authorities and Original Equipment Manufacturers (OEM) must adopt **"design-for-circularity"** principles, including modular designs, non-toxic chemistries, and standardized pack formats.

Additionally, **digital product passports**—which track the composition, use history, and condition of batteries—are emerging as tools to enable better material recovery and facilitate second-life applications. especially in light of stricter limits on **new procurements**.

3.4. EU regulatory framework relevant for circularity and sustainability

The regulatory landscape governing circular economy in public transport is characterised by a multi-tiered legal and policy framework, blending **binding legislations**, **strategic action plans**, and **supporting guidelines**. The enforceability of these instruments varies depending on their legal nature—whether they are **regulations**, **directives**, **decisions**, or **non-binding initiatives**—and on how they are implemented and monitored across Member States. This multilayered regulatory approach ensures that circular economy principles are embedded in EU legislation while allowing flexibility for Member States in implementation. At the core of this regulatory landscape is the European Green Deal[6]. It is EU's ambitious and overarching policy framework that aims to make Europe a climate-neutral continent by 2050 and to decouple growth from resource use and environmental degradation. It encompasses a broad spectrum of interconnected initiatives that address issues ranging from climate change to social fairness.

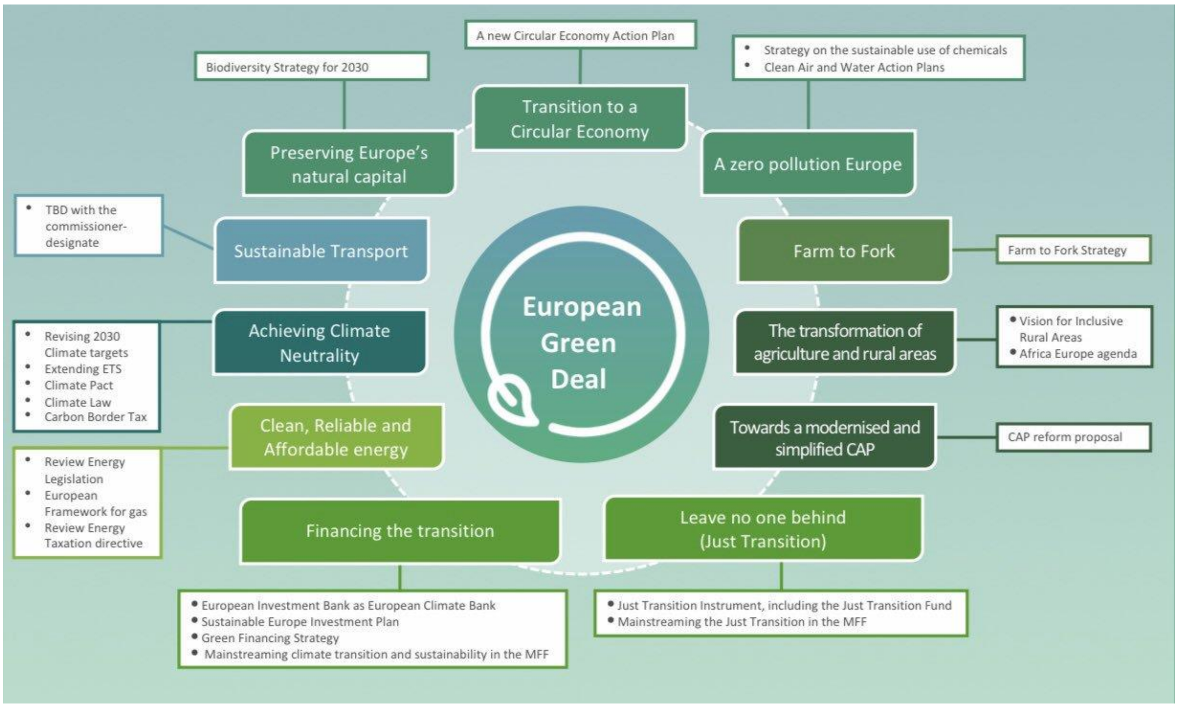


Figure 4. Framework of the European Green Deal. Source: The European Green Deal - European Commission

Supporting the Green Deal is the **Circular Economy Action Plan (CEAP),** which provides a framework of measures to implement circularity in the European economy. Updated in 2020, the CEAP prioritizes sectors with significant environmental impact, such as transportation, and promotes design and production practices that extend product lifespans and facilitate circular use.

[6] European Commission. (2020). *The European Green Deal*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

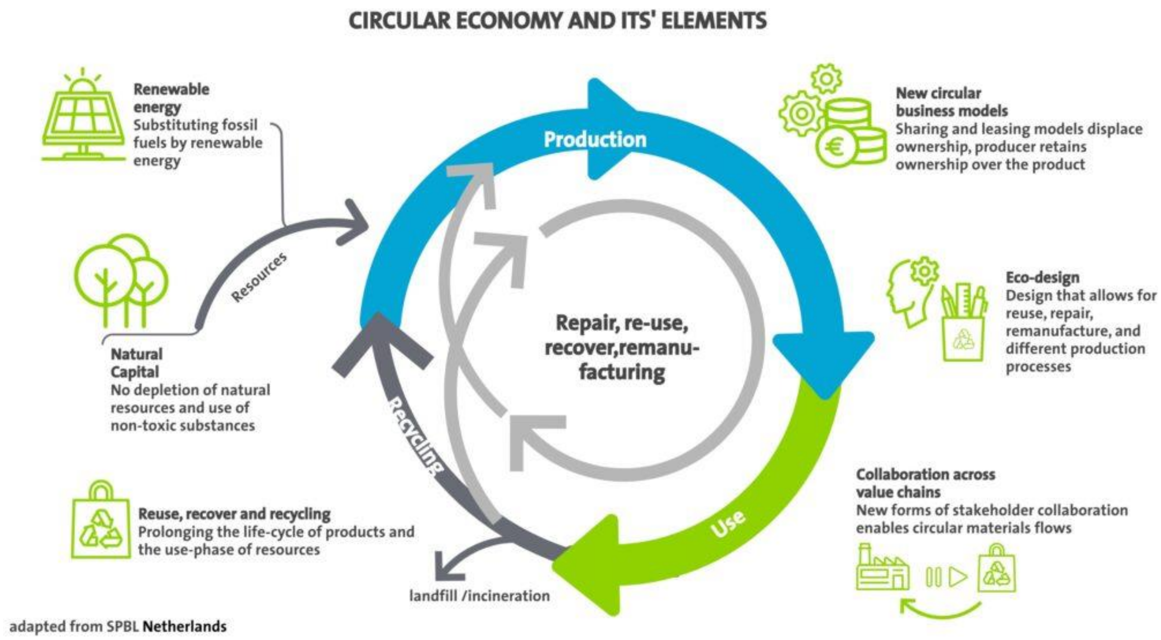


Figure 5. Circular Economy Action Plan and associated domains of influence Source: The Circular Economy Action Plan and its external Dimension.

The cornerstone of the action plan is to design and promote sustainable products that are durable, repairable, reusable, recyclable, and energy- and resource-efficient. The relevant product value chains which the action plan focusses on are: 'Batteries and vehicles' and 'Construction and Buildings' – both of which have direct implications on the public transport stakeholders. Public procurement, representing about 14% of the EU GDP (Special report 28/2023: Public procurement in the EU), will be leveraged to drive demand for sustainable products through mandatory green public procurement criteria and reporting. This would have a significant impact on the public transport stakeholders such as city authorities and PTAs who are heavily involved in procurement, especially of vehicles and associated components.

The above strategies are not legally binding. Rather, they serve as high-level frameworks that guide and shape legislative development. They also influence **funding allocations** (e.g., Horizon Europe, Cohesion Policy Funds, Just Transition Mechanism), by acting blueprints that steer EU financial resources toward sustainability and circularity. Hence, these strategic instruments translate high-level policy goals into concrete investments. For public transport stakeholders, this means that aligning projects with circular economy and climate objectives is increasingly essential to access EU funding, fostering innovation and infrastructure modernization that support Europe's green and just transition ambitions. The core enforceable elements of the EU's circular economy strategy are contained in **regulations** and **directives.** Key regulatory frameworks in the energy sector, particularly concerning battery management, play a central role in the EU's circular economy strategy. The Batteries Directive (2006/66/EC) and the newly adopted Battery Regulation (EU) 2023/1542 comprehensively govern the entire lifecycle of batteries—including their collection, recycling, and disposal—ensuring environmentally sound management practices. In line with the Waste Framework Directive (2008/98/EC), used batteries are classified as waste when no longer fit for their intended use and require proper handling under specific regulations. These energy-focused legislative measures are essential to support circular economy objectives by promoting reuse, second-life applications, and efficient recycling of batteries.

3.4.1. Analysis of key circular economy regulations and directives in the EU

The following table gives a list of the major circular economy related policies and regulatory frameworks that are relevant from the PTE perspective in Europe. It consists of a brief about the focus of the policy, its description and the main targets within it. Most importantly, it lists out the different public transport stakeholders who shall be affected by these policies/regulations and an analysis of how they would be affected.

Table 1 Analysis of key circular economy regulations and directives in the EU

Policy name (date first, include hyperlink)	Focus	Policy description	Policy targets	PT stakeholders affected/involved	Impact assessment on PT stakeholders
The European Green Deal (2019)7	Climate Neutrality	EU's strategic plan to transform its economy for a sustainable future, aiming for climate neutrality by 2050. The Green Deal encompasses various policies and initiatives that promote resource efficiency and reduce environmental impacts	Reducing GHG by at least 55% by 2030 and achieving net-zero GHG emissions by 2050 Increase the energy efficiency by 32.5% by 2030 and ensure that at least 32% of EU's energy consumption is from renewable sources by 2030	Governments, public transport operators, and infrastructure developers	Adoption of sustainable practices in planning and operations; Emphasis on reducing emissions an improving resource efficiency Public transport operators need to transition their fleets to zero emission vehicles. Governments should implement supportive policies like subsidies for green vehicles Infrastructure developers should use circular construction material for transport projects
REPower EU Plan (2022)[8]	Energy security and green transition	A strategy to diversify energy supplies and enhance efficiency and accelerate the green transition.	Reduce energy consumption by 13% by 2030 Renewable energy share at 45%	Energy suppliers, public transport authorities, and infrastructure investors	Public transport authorities should integrate renewable energy into operations, such as solar-powered depots, and collaborate with investors to expand electric vehicle (EV) charging and hydrogen fueling infrastructure.

[7] European Commission. (n.d.). *The European Green Deal*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640
[8] European Commission. (n.d.). *REPowerEU Plan*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0230

EU circular Economy Action Plan (2020)[9]	Accelerate the transition to a circular economy in Europe	Promotes sustainable product design, circular processes, and waste reduction. It targets stakeholders from six key value chains and sectors those are: Electronics and ICT, Batteries and Vehicles, Packaging, Plastics, Textiles, and construction and buildings	Double the circular material use rate in the next decade Reduce waste by 50% in major sectors such as construction and demolition by 2030 Achieve a recycling rate of 70% for municipal waste by 2030	PTOs, PTAs, public authorities and waste management sectors, battery and vehicle manufacturers	Promotion of Circular Infrastructure Design - the plan encourages the use of secondary raw materials and recycled content in infrastructure projects such as railway stations, metro lines, tram depots, bus terminals, and maintenance workshops. Encouraging digital tools (e.g., BIM—Building Information Modelling) to optimize resource use during infrastructure design, construction, and operation - greater compliance and cost factor on PTAs. Need to invest in training and capacity building to integrate circular economy principles in infrastructure planning, project management, and maintenance operations.
Batteries Directive (2006/66/EC) &	Lifecycle management of batteries	This regulation outlines the management of batteries and accumulators, including their disposal and recycling.	preventing and reducing the adverse impacts of batteries on the environment and to protect the environment and human health by	producers, distributors, end-users	Batteries with a power of more than 2 kWh must have clearly legible and indelible label indicating the carbon footprint. Batteries must have up-to-date data for the parameters for determining the state of health and expected lifetime of batteries.

[9] European Commission. (n.d.). *Circular economy action plan*. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en
European Commission. (2020, March 11). *A new Circular Economy Action Plan: For a cleaner and more competitive Europe* (COM(2020) 98 final). https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

Battery Regulation (EU) 2023/154210			preventing and reducing the adverse impacts of the generation and management of waste batteries.	operators directly involved in the treatment and recycling of waste batteries. Transport companies	Read-only access to the data for the parameters through the battery management system shall be provided to the person who has purchased the battery, including operators or waste management operators for the purpose of: (a) making the battery available to independent aggregators or market participants through energy storage. (b) evaluating the residual value or remaining lifetime of the battery and capability for further use, based on the estimation of the state of health of the battery. (c) facilitating the preparation for re-use, preparation for repurposing, repurposing or remanufacturing of the battery.
Waste Framework Directive11	Sustainable waste disposal	The policy sets a regulatory framework for the sustainable and non-harmful disposal of waste materials. It explains when waste ceases to be waste and becomes a secondary raw material, and how to distinguish between waste and by-products. The	Pushing for increased ambition in member states to meet or exceed the EU target of 70% recycling of non-hazardous Construction & Demolition (C&D) waste by 2020.	PTAs, PTOs, Local Governing bodies, Third-party contractors/sub-contractors.	It is a broad framework that includes a wide category of waste materials. The construction demolition waste category could be considered relevant to the public transport sector. Legal Definition of Energy-Related Waste - Public transport operators and authorities must identify energy-related waste streams, such as used batteries and electronic components, to ensure compliance with separate collection and recycling requirements.

[10] European Commission. (2006). *Batteries Directive*. https://eur-lex.europa.eu/eli/dir/2006/66/oj/eng
European Commission. (2023). *Battery Regulation*. https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng
[11] European Commission. (2023). *Waste Framework Directive*. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

		Directive also introduces the "polluter pays principle" and the "extended producer responsibility". It also introduces the 5-step "waste hierarchy", that establishes an order of preference for managing and disposing of waste.			Separate Collection - procedures must be implemented for on-site separation of energy-related waste, such as spent batteries and electric vehicle parts. This improves recycling rates and reduces contamination, though it requires adapted logistics and workforce training. Waste Hierarchy – PTAs and PTOs must integrate this to operational cycle of buildings - i.e. prevention of waste generation during construction, maximizing reuse of building materials, and prioritizing recycling. List of Recovery Operations – this must be complied with. For e.g. recycling of concrete and bricks or soil reuse in backfilling.
Clean and energy-efficient road transport Direcitve 2019/1161[12]	Sustainable road transport vehicles	This regulation promotes use of ecological vehicles With innovation in new technologies helps to lower vehicle CO_2 emissions and to reduce air and noise pollution, while supporting the decarbonisation of the transport sector.	reduce greenhouse gas emissions by at least 40 % by 2030 as compared to 1990 levels, to increase the proportion of renewable energy consumed to at least 32,5 %, to make energy savings of at least 27 %, and to improve the Union's energy security	Governments, car producers, transport companies.	With innovation in new technologies helps to lower vehicle CO2 emissions and to reduce air and noise pollution, while supporting the decarbonisation of the transport sector.

[12] European Commission. (2019) *Clean and Energy-Efficient Road Transport Directive*. https://eur-lex.europa.eu/eli/dir/2019/1161/oj/eng

Renewable energy sources Directive 2018/200113	Green economy, renewable enery	This Directive establishes a common framework for the promotion of energy from renewable sources. It also lays down rules on financial support for electricity from renewable sources, on self-consumption of such electricity, on the use of energy from renewable sources in the heating and cooling sector and in the transport sector.	reduce greenhouse gas emissions by at least 40 % by 2030 as compared to 1990 levels, share of energy from renewable sources in the Union's gross final consumption of energy in 2030 is at least 32 %.	Governments, municipalities, industry, transport companies.	
Ecodesign for Sustainable Products Regulation (ESPR)[14]	Sustainable and circular product design standards	To improve the sustainability of products placed on the EU market by improving their circularity, energy performance, recyclability and durability.	Varying targets to increase recycling and repairability in various sectors associated with public transport infrastructure such as iron & steel, aluminium etc.	PTOs, PTAs, Vehicle and component manufacturers, Vehicle repairs and maintenance garages.	The stakeholders need to undertake the following steps: Manufacturers - Design vehicles to meet ESPR guidelines – i.e. durable, modular, and repair-friendly. PTOs - Direct impacts in fleet management and procurement processes – i.e., prioritize EPSR compliant vehicles and equipment. Might incur higher upfront costs, but could achieve long-term savings through extended lifespan, re-use and recycling opportunities. PTAs - Revise tendering criteria to incorporate ESPR compliance, aligning purchasing decisions with sustainability and circularity goals

[13] European Commission. (2018) *Renewable energy sources Directive*. https://eur-lex.europa.eu/eli/dir/2018/2001/oj/eng
[14] European Commission. (2024). *Ecodesign for sustainable products regulation*. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en

					Digital Products Passport - provide comprehensive information about each product's origin, materials, environmental impact, and disposal recommendations. Provide transparency across supply-chain. PTAs and PTOs need to utilise DPP info in procurement, life-cycle management and end-of-life stages of vehicles and buildings.
Green Public Procurement[15]	Public procurement for better environment	A voluntary policy instrument whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle.	Varying targets on procurement in different sectors associated with public transport.	PTOs, PTAs, Vehicle and component manufacturers	PTAs – procure vehicles that comply with latest emission norms such as Euro VI or alternative fuel (electric, hybrid, biofuels etc.) – 100% compliance by 2025 PTOs – Monitoring of emissions + documentation and verification of the same – E.g. emission certificates, Independent 3rd party verification of retrofitted emission systems on vehicles. Mandatory technology requirements - Traffic information and route optimization systems must be embedded in vehicles, TPMS (Tyre Pressure Monitoring Systems) and low rolling resistance tyres must be included in all vehicles.
Innovative Public Procurement (IPP)[16]	Deployment of clean energy technologies via procurement	IPP supports the uptake of novel energy solutions through procurement practices, enabling public transport authorities to integrate innovative low-	No legally binding targets, but promoted under EU Green Deal and national innovation strategies.	PTAs, PTOs, municipalities, technology providers	Enables early adoption of clean energy tech in PT operations; access to innovation funds or pilot project financing; potential long-term energy savings and emissions reductions. However, higher upfront costs and risk of tech obsolescence may deter smaller operators.

[15] European Commission. (n.d.). *Green public procurement*. https://green-forum.ec.europa.eu/green-public-procurement_en

[16] European Commission. (2024). *Innovative Public Procurement*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX%3A52021XC0706%2803%29

		carbon technologies such as smart charging infrastructure, hydrogen refueling stations, and energy storage systems for fleets.			
EU Emissions Trading System (ETS)[17]	Carbon pricing for fossil fuel use	A market-based instrument that applies a cost to GHG emissions from fossil fuel consumption. In its revised form (ETS 2), it will include road transport fuels, indirectly affecting public transport operators still using diesel or natural gas.	Reduce GHG emissions by 62% in ETS sectors by 2030 (compared to 2005 levels).	PTOs using fossil fuel vehicles, PTAs overseeing fleet transition, national climate agencies	Imposes financial pressure on operators with fossil fuel fleets; drives investment in electric and hydrogen buses. May require operational adjustments, energy contracts renegotiation, and long-term planning to reduce exposure to carbon costs. Can make electric PT solutions more competitive.
Corporate Sustainability Reporting Directive (CSRD) [18]	Improve corporate transparency in sustainability	Requires large and publicly listed companies in the EU to disclose detailed, standardized information about their sustainability practices, including environmental impacts, social responsibilities, and governance structures (i.e. ESG practices)	Applies to all large companies (over 250 employees, €40 million turnover, or €20 million balance sheet total) and all companies listed on EU regulated markets (except micro-enterprises)	Public Transport Operators (PTOs), Subcontract suppliers, City/Municipal authorities	PTOs will be mandated to do the following: Double materiality assessment: Assess and disclose sustainability-related information from environmental + social perspective and financial perspective. Adherence to European Sustainability Reporting Standards (ESRS) regulation - report on resource inflows (e.g., fuel, materials) and outflows (e.g., emissions, waste)

[17] European Commission. (2023). *EU emissions trading system.* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Al28012

[18] European Commission. (n.d.). *Corporate sustainability reporting.* https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en

					Supply chain transparency – report on environmental impact across supply chain. Stakeholder Engagement - establish regular communication channels, such as surveys or community meetings, to gather feedback on sustainability initiatives. Digital Reporting Formats - Reports must be prepared in a digital, machine-readable format, adhering to the European Single Electronic Format (ESEF).

In summary, circular economy policies related to energy use in public transport emphasize increasing energy efficiency, extending the lifecycle of energy-related components (especially batteries), and enabling renewable integration. Regulations such as the Battery Regulation (EU) 2023/1542 directly affect how energy is managed across vehicles (e.g. depots, charging stations).

Public transport stakeholders are expected to adopt smart energy management systems, ensure the efficient use of electricity (especially from renewable sources), and plan for second-life uses of vehicle batteries, for example in stationary storage at depots. The reuse, repurposing, and recycling of these energy systems reduce overall consumption of primary resources and enhance system resilience.

Ultimately, these measures shift the focus from merely reducing emissions to optimizing the entire energy lifecycle—from procurement and use to reuse and recovery—making energy use in PT more sustainable, circular, and aligned with EU climate goals.

In addition to regulatory frameworks, initiatives such as the European Clean Bus Deployment Initiative and projects like ZeEUS, ASSURED, and eLobster demonstrate practical applications of these principles. These projects focus on the integration of RES, advanced energy management systems, and the potential benefits of energy recuperation technologies like regenerative braking.

4. Status Quo of public transport in respect to energy

This section provides an overview of the implementation of circularity approaches, principles, and solutions in public transport systems in Europe, along with the associated challenges and opportunities. For the development of this section, data collection was initially carried out from various European case studies, expert interviews, and stakeholder engagements.

As part of this research, a key local initiative was undertaken in Maribor. Slovenia in 2024. The event aimed to explore how circular economy principles could be effectively integrated into the city's public transport system. The workshop was organised as part of the CE4CE project and brought together relevant stakeholders from local government, academia, public transport operators (PTOs), energy providers, and waste management companies. The main goal was to establish a collaborative platform for identifying current barriers and potentials, as well as for co-developing circular solutions tailored to urban mobility infrastructure.

The workshop was structured around three core thematic areas: energy, vehicles, and infrastructure. Stakeholders were divided into three mixed groups and rotated between these thematic tables, ensuring that every group contributed to each area. Each table was facilitated by a dedicated moderator who guided the discussion using the AVOID – EXTEND – TRANSFORM framework. This structure allowed participants to reflect on how resources can be used more efficiently, how the lifespan of systems and components can be prolonged, and how systems can be transformed to enable circularity.

Participants engaged in open discussions and also contributed written inputs using sticky notes with their own statements or observations. This participatory and structured approach enabled a multi-perspective exploration of key issues across all three themes. Importantly, it also helped to capture the different roles and constraints that actors face in implementing CE in public transport systems.


4.1. Avoid stage

To facilitate the transition to circular public transport, it is essential to avoid practices that undermine sustainability. Most initiatives aimed at making PT more sustainable have so far focused on fleet modernization, with a strong emphasis on electrification. In the past decade, Maribor's municipal PT operator Marprom has modernized two-thirds of its fleet, with all new buses in recent years being electric—due in part, or even primarily, to available financial incentives.

In other areas, Maribor has participated in pioneering projects aimed at improving energy efficiency—such as opportunity charging for electric buses and the EfficienCE project—serving as a model for the development of innovative approaches. However, these solutions have not yet been broadly integrated into everyday operations. However, these practices have not yet been widely adopted in day-to-day operations. Additionally, there is minimal integration of RES. The city's circular economy strategy envisions further integration of alternative energy sources, primarily solar energy, and also explores the potential use of regenerative energy from trains. This is particularly relevant given that a major railway corridor—both passenger and freight—runs through the city.

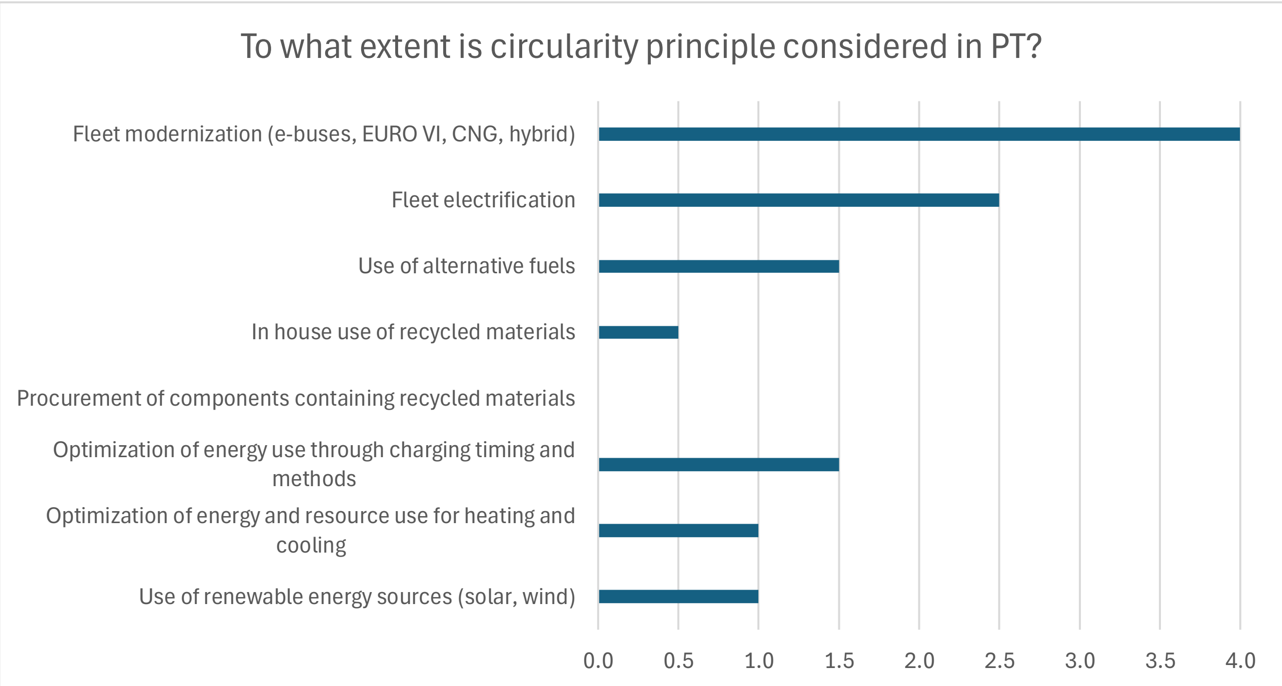


Figure 6. qOpinions on energy efficient measures in PT.

4.2. Extend stage

The main component for extending the lifespan of electric vehicles is the battery. Established best practices exist for prolonging battery life. Charging typically takes place overnight at the depot, while in Maribor, opportunity charging has also been implemented on one route. This serves as a basis for managing charging strategies. Currently, charging is done directly from the grid, so the impact is limited to the state of charge (SOC)—the battery's charging capacity.

In addition to batteries, the condition of the grid infrastructure must also be considered in the energy domain. Due to increasing electrification, the grid is under growing strain. The impact on the grid can be mitigated with energy storage systems. For example, within the CE4CE pilot project, Maribor plans to install an energy storage system at a fast-charging station. This system enables grid relief and support by utilizing energy during off-peak periods.

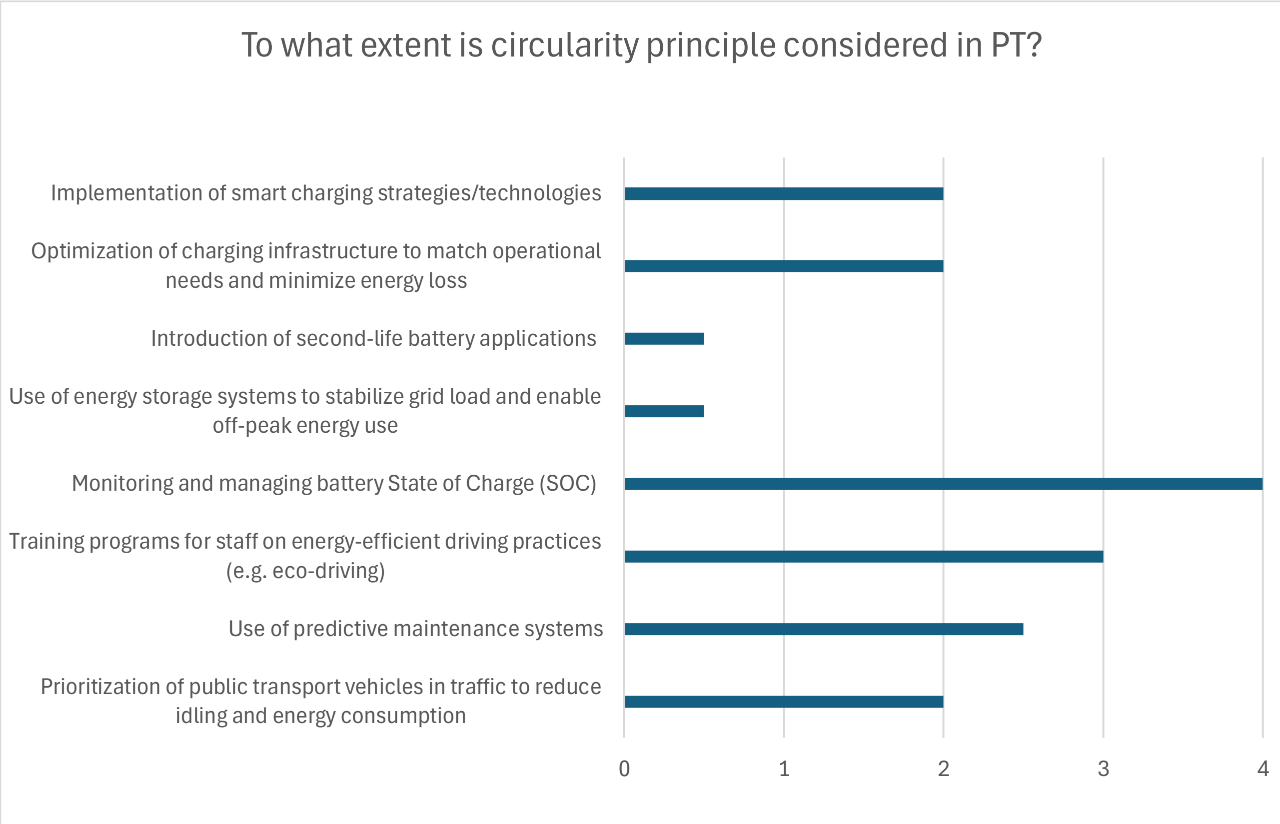
Additionally, energy efficiency can be improved through measures that optimize employee behavior. Eco-driving training for employees of the company operating public transport in Maribor is already in place, but it is not specifically tailored to driving electric vehicles. Further initiatives include technological solutions in the field, such as priority treatment for buses and predictive maintenance. These activities exist, but without a clearly defined goal, the overall impact is less than it could be.

4.3. Transform stage

The first generation of electric buses procured for Maribor's municipal public transport is approaching ten years of service. As these vehicles age, the issue of end-of-life batteries is becoming increasingly relevant for public transport as well. Current regulations require that public transport operators, such as Marprom, ensure decommissioned batteries are handed over to an authorized waste management company. However, formal procedures and systems for further battery recycling are not yet established. In practice, end-of-life batteries from electric buses are typically returned to the manufacturer or distributor, but there is limited transparency about their subsequent treatment. Although dedicated recycling systems are not yet in place, the upcoming EU Battery Regulation is expected to drive progress by assigning clearer producer responsibilities and setting ambitious targets, including 65 % recycling of lithium-ion batteries by 2025 and 80 % by 2031. Although battery take-back systems exist (e.g., through Interzero), standardized and transparent processes for recycling and repurposing batteries from public transport vehicles remain underdeveloped.

With the upcoming need to replace these batteries, the question of second-life applications is also gaining attention. Batteries that can no longer meet the performance requirements for regular vehicle operation may still be suitable for stationary energy storage, where capacity demands are lower. This is also the intention behind Maribor's involvement in the CE4CE pilot project, which envisions repurposing used batteries for such applications in the long term. However, due to the lack of standardized procedures for second-life battery use, the design and implementation of the storage systems must be customized on a case-by-case basis.

A key challenge in the absence of standardized end-of-life processes is the lack of a regulated or functional secondary market for used batteries. If such a market does emerge, it would need to comply with strict transport regulations under the ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road), as batteries are classified as hazardous goods. However, handling and trading of used (but not yet waste) batteries remain largely unregulated, creating legal and logistical uncertainties.



4.4. Enable stage

While governance aspects were not explicitly assessed in the Circularity Compass self-assessment, relevant insights were gathered through survey responses and in-depth interviews. These reveal key regulatory, organizational, and technological enablers—as well as constraints—affecting the energy use transition in PT systems.

4.4.1. Regulatory and Organizational Insights

Across interviews, it is evident that the circularity mindset is gradually taking hold in PT organizations, especially in relation to energy sourcing, storage, and consumption. Respondents attributed this shift to increasing regulatory pressure at the EU, national, and local levels. Policies promoting the integration of RES, energy storage systems, and optimized charging infrastructure were often cited as catalysts for change.

However, several interviewees pointed out that regulatory frameworks can be complex and unclear—particularly in areas such as battery reuse, grid interaction, energy monitoring protocols, and second-life energy systems. The lack of clear procedures often slows down or complicates the implementation of energy-related circular economy measures.

An additional organizational enabler—especially relevant in Central Europe—is the strong in-house technical know-how for maintaining and upgrading legacy infrastructure. This capacity is increasingly applied to energy systems as well, including local grid upgrades and the development of pilot battery storage solutions.

Rooted in decades of experience with constrained resources, this tradition of repair and optimization presents a solid foundation for integrating circular energy strategies, such as smart charging technologies or repurposing electric bus batteries for stationary storage. However, a major challenge remains in the form of generational change, which risks a gradual loss of expertise critical for managing both transport and energy infrastructure in a circular manner.

4.4.2. Digital Tools and Infrastructure Efficiency

Another enabler that was highly emphasized during is the potential of using technology—especially smart energy systems, digital monitoring tools, and predictive analytics—to advance circularity in infrastructure. PTOs expressed enthusiasm about the tangible impact these technologies can have, especially with increasing levels of automation. Digital twins and real-time diagnostics can help optimize electricity use, detect inefficiencies in charging operations, and reduce energy waste.

In particular, these tools support better management of grid demand, battery health, and localized RES integration, offering opportunities for reducing reliance on fossil-based grid electricity.

4.4.3. Key Barriers to Advancing Circular Energy Use in Public Transport

Despite promising opportunities, several systemic barriers still hinder the full implementation of circular energy practices in public transport. One of the most significant challenges is the limited and fragmented funding available for energy-related innovations and upgrades. While European and national incentives exist, long-term investments in renewable energy systems, battery storage, and smart energy management technologies often depend on unstable or short-term local budgets. This results in hesitation or delay in implementing measures such as:

- Deploying smart charging infrastructure and energy optimization tools;
- Developing second-life battery storage systems;
- Installing solar panels or other RES at depots and charging stations.

Moreover, the lack of consistent financial support discourages strategic planning for energy circularity, especially in medium-sized municipalities where public transport operators must balance basic service delivery with innovation. Without stable support mechanisms and clear regulatory frameworks, the transition to circular energy use remains slow and fragmented.

Table 2 Key Challenges

	Avoid (use less)	Extend (Use longer)	Transform (use again)	Enable
Electricity grid and electric infrastructure	**Challenges** Dependence on network grid High carbon emissions from traditional electricity sources **Opportunities** Reduce energy consumption by optimizing grid usage Promote off-peak charging for e-buses	**Challenges** Grid capacity limitations with increasing e-bus fleet High initial costs of upgrading charging infrastructure **Opportunities** Use smart grids for energy management and efficiency	**Challenges** Limited capacity for energy recovery in existing grid systems Energy losses during electricity transmission **Opportunities** Lower network load Supporting network during peak periods	**Challenges** Financial and regulatory constraints, that, may arise when upgrading grids Lack of alignment across charging technologies and e-bus fleets **Opportunities** Upgrade grid infrastructure to support different energy sources Develop policies for energy-efficient grid technologies
Battery Technologies	**Challenges** Overuse of (new) raw materials in battery production Environmental impact from battery disposal **Opportunities** Reduce reliance on rare materials in battery production Enforced recycled material quotas	**Challenges** Difficulty in recycling and reusing batteries at the end of life Limited lifecycle management for batteries **Opportunities** Design batteries with longer lifespans to postpone the need for replacement	**Challenges** Lack of used batteries in the market Insufficient infrastructure for second-life battery applications **Opportunities** Transform used batteries into stationary energy storage solutions Recycle materials used in batteries	**Challenges** Financial challenges to establish battery recycling systems Regulatory challenges for battery disposal and recycling **Opportunities** Incentivize second/after-life batteries applications Incentivize the digital passport for batteries (components)

		Create secondary battery applications (e.g., stationary storage) to extend their use		
Energy Storage & Management	**Challenges** High energy storage costs and (still) unavailability of used batteries Non-standardized and non-established storage technologies **Opportunities** Reduce reliance on the grid by improving battery storage solutions Lower energy costs and grid off-load	**Challenges** Limited availability of energy storage systems for e-bus fleets Space and safety constraints at charging stations for large-scale storage systems **Opportunities** Extend the capacity of energy storage systems at charging stations Improve integration with renewable energy sources	**Challenges** Underutilization of second-life storage solutions **Opportunities** Deployment of second-life batteries for energy storage Prolonging lifespan of used batteries	**Challenges** Investment constraints for energy storage technologies Regulatory and safety uncertainty on energy storage policies **Opportunities** Enable innovations in energy storage solutions Promote public-private partnerships to develop advanced energy storage infrastructure
Renewable Energy Integration	**Challenges** Limited and inconstancy availability of renewable energy sources in certain regions High “unnecessary” initial cost **Opportunities** Less dependence on the electricity grid	**Challenges** Grid instability when integrating large-scale renewables **Opportunities** Improve grid flexibility through better storage	**Challenges** Underutilization of renewable energy in public transport Lack of effective energy storage solutions to store renewable power **Opportunities**	**Challenges** Lack of infrastructure for direct integration of renewable energy at charging stations **Opportunities**

		Integrate renewables into charging hubs	Store excess renewable energy in batteries	Establish supportive policy frameworks for renewable integration in public transport
Repairing & Recycling	**Challenges** Limited information on end-of-life batteries Recycling is typically managed solely by manufacturers/ distributors, with little oversight or obligations **Opportunities** Reduce demand for virgin rare materials Lower generation of hazardous waste	**Challenges** Lack of established operational procedures for continuous (in-use) battery recycling **Opportunities** Enable partial replacement of battery components (e.g., cells) through regular maintenance to extend lifespan	**Challenges** No standardized processes for battery disposal and integration of recycled materials into new battery production **Opportunities** Promote modular battery design Mandate use of recycled content in new battery manufacturing	**Challenges** High costs for setting up battery recycling systems Recycled material use is not required in new battery production **Opportunities** Strengthen regulatory measures and support a network of specialized recycling facilities Introduce digital battery passports for improved traceability

5. Approaches to advancing circularity

After outlining the current state of circularity in public transport energy systems, this chapter explores proactive strategies to accelerate its adoption. It covers both tangible solutions to specific challenges and broader, holistic approaches such as innovative regulations, integrating circularity into operational processes—such as tender documents and procedures—and platform for fostering cross-sector collaboration. Each measure includes a brief description and, where possible, examples of direct implementation or potential adaptation to public transport infrastructure.

As with the status quo analysis, this chapter follows the AETE framework, using the circularity principles measures diagram as a foundation. In line with the Circularity Compass, the AVOID stage is prioritized as the most cost-effective, clean, and mindful resource use from the outset. In second place, the EXTEND stage focuses on maximizing resource lifespan, while TRANSFORM serves as a last resort when other strategies are exhausted. Additionally, this chapter highlights ENABLE as a cross-cutting stage essential for sustaining long-term change through cooperation, knowledge-sharing, and evidence-based decision-making. Some measures may apply to multiple stages; for clarity, they can be explicitly mentioned and assigned to a specific section.

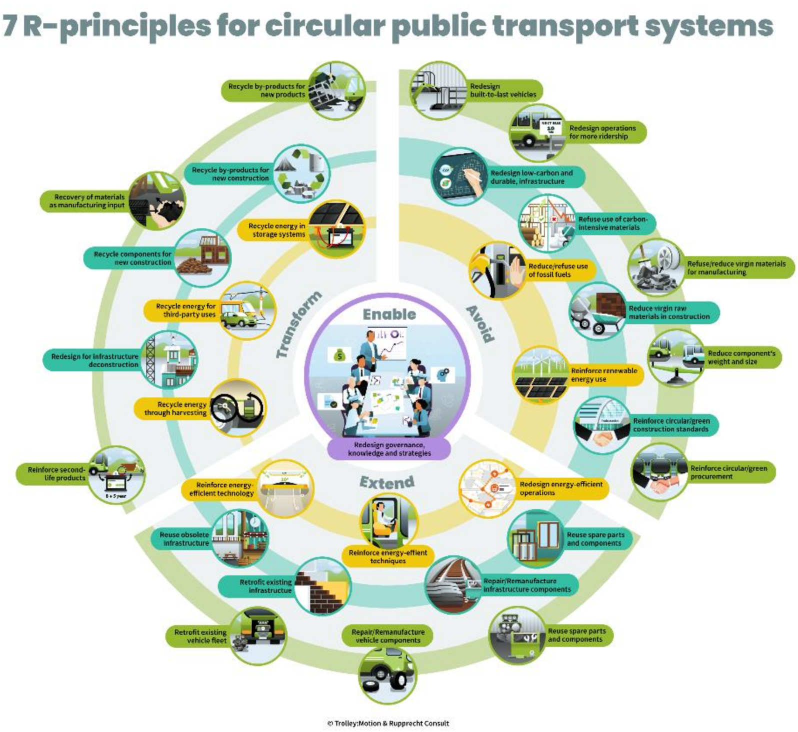


Figure 7. Circularity compass solutions diagram with a focus on PTI actions across the LCA

5.1. Reduce/Refuse Use of Fossil Fuels

Objective: Minimize reliance on fossil fuels by promoting electrification and renewable energy use in public transport.

The modernization of public transport fleets is a crucial step in the transition toward sustainable, energy-efficient urban mobility. At the core of this transformation lies the electrification of rolling stock—most notably, the replacement of diesel and compressed natural gas (CNG) buses with battery-electric buses (BEVs). Although technically a vehicle-oriented measure, fleet electrification serves as the critical foundation for broader strategies focused on improving energy use across the public transport system.

Driven by the dual imperatives of mitigating climate change and reducing local air pollution, cities around the world are embracing electrification as a central pillar of their decarbonization efforts. The shift away from fossil fuels is not only a response to environmental concerns but also a strategic move to future-proof transport systems against volatile energy markets and regulatory pressures. In Europe, this ambition has already led to significant investments in zero-emission technologies, including biofuels, fuel cells, and electric propulsion systems.

Among these, battery-electric buses have emerged as the dominant and fastest-growing technology, thanks to their operational simplicity, falling battery costs, and compatibility with renewable energy sources. According to the *2024 Electric Vehicle Outlook*[19], municipal e-buses are expected to surpass 60% of new bus sales by 2030 and reach 83% by 2040. This trajectory confirms the mainstreaming of e-bus technology in urban settings.

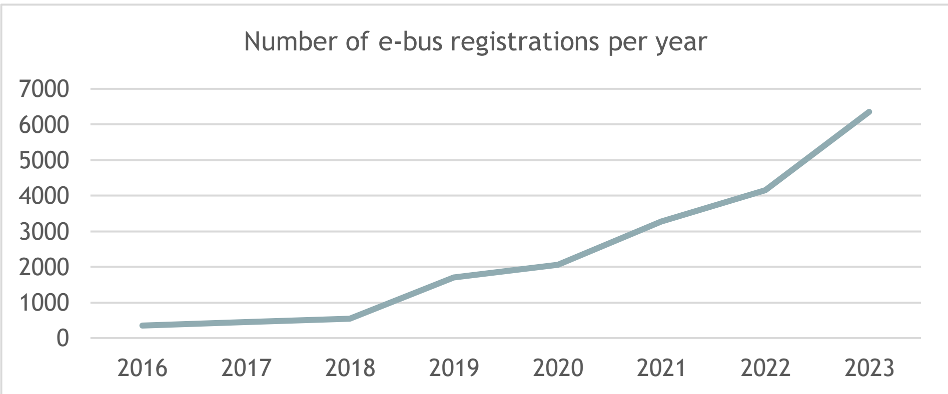


Figure 8. Number of e-bus registrations per year. Source: Sustainable-bus.

The electrification of fleets does more than eliminate tailpipe emissions—it enables a new generation of energy management practices. The use of electric buses opens pathways for optimizing energy consumption through smart charging strategies, integration with renewable sources, deployment of second-life battery

[19] Sustainable-bus.com. 2024. *2024 Electric Vehicle Outlook* https://www.sustainable-bus.com/news/bloomberg-nef-electric-vehicles-outlook-buses/

systems, and even vehicle-to-grid (V2G) interactions. These opportunities can only be fully realized once the core electrification of the fleet is in place.

Moreover, different types of electric vehicles offer flexibility for various operational contexts. Full Battery Electric Vehicles (BEVs) are ideal for urban routes with robust charging infrastructure, while Plug-in Hybrid Electric Vehicles (PHEVs) provide range assurance in mixed environments. Trolleybuses remain relevant in cities with existing overhead lines. Choosing the right mix ensures service continuity while maximizing environmental and energy benefits.

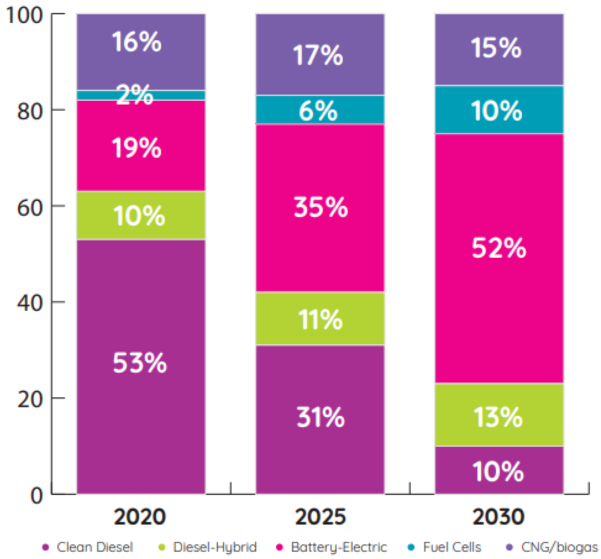


Figure 9. European urban bus market evolution. Source: ZeEUS and UITP.

5.1.1. Types of e-bus batteries

Electric buses rely on advanced battery technologies to provide the necessary power and range for efficient operation. Several types of batteries are commonly used in e-buses, each with distinct characteristics and performance factors. The choice of battery type and its management are critical to ensuring the longevity and efficiency of the electric bus fleet.

Table 3 Characteristics of bus batteries. Source: ZeEUS and UITP.

Type	Chemistry	Performance						Applicability	
		Energy	Power	Calendar Life	Cycle Life	Safety/ Stability	Cost	Buses	Grid
LFP	$LiFePO_4$	++	++	++	++	+++	+++	●	●
NCA	$LiNiCoAlO_2$	+++	+++	++	+	++	++		●
LMO	$LiMn_2O_4$	++	+++	+	++	+++	++		●
LTO	$Li_4Ti_5O_{12}$	+	++	+++	+++	++++	+++	●	●

NMC	$LiNi_xCo_xMn_xO_2$	+++	+++	++	++	++	++	●	●
HE-NMC	$LiNi_xCo_xMn_xO_2$	++++	++	++	+	++	++	●	●

In sum, fleet electrification is not just a technological upgrade—it is a strategic enabler for a holistic transition towards cleaner, more efficient, and future-ready public transport. It lays the groundwork upon which integrated energy management and circular practices can be built.

5.2. Charging Solutions for e-Buses

Objective: Optimize energy efficiency by integrating smart charging strategies, off-peak charging, and grid optimization.

With the growing adoption of electric buses, there has been substantial progress in charging technologies and infrastructure requirements. Urban energy planning for transport electrification now places significant emphasis on developing and optimizing charging infrastructure. As electric vehicles gain traction, the challenge of locating, securing, and ensuring the efficiency and effectiveness of charging stations becomes increasingly complex.

The infrastructure needed to support electric bus operations presents numerous challenges, as each bus route has distinct requirements. To minimize costs, charging solutions must be customized to meet the specific demands of individual routes. Key factors to consider include determining the appropriate battery size and deciding whether fast charging, slow charging, or a combination of both is best suited for the route.

The choice between slow and fast charging equipment involves trade-offs that can affect both costs and battery performance. Fast charging may not fully recharge the battery but can provide enough power for a single run, making it useful for high-frequency routes with short turnaround times. Conversely, if a bus is equipped with a large enough battery to complete a full day's route without recharging, slow overnight charging may be more cost-effective and gentler on the battery.

5.2.1. Charging infrastructure and network considerations

- A preliminary assessment of the required electrical energy supply system.

It includes evaluating the current capacity of the local electrical grid and determining whether it can meet the demands of the electric bus fleet. The assessment should consider peak load requirements, potential need for grid upgrades, and the overall availability of power from renewable sources. It also includes calculating the total energy required to charge the fleet based on the number of buses, their battery capacities, and daily operational needs.

- Identification of the various operational, technical and urban factors that may influence the location of the charger.

The location of charging stations is influenced by multiple factors such as proximity to bus routes, the availability of space, and urban planning regulations. Operational factors include the need for quick access during bus downtime and minimizing travel distance to chargers. Technical factors encompass grid accessibility and the potential for integrating renewable energy sources. Urban factors include land use restrictions, noise considerations, and integration with public infrastructure.

- Amount and dynamic of energy contribution needed (depends on timelines, routes and peak periods characteristics).

This refers to the quantity of energy required at different times of the day, based on bus schedules, routes, and peak usage periods. It includes the analysis of energy demand patterns to ensure that the charging infrastructure can handle high demand during peak periods without overloading the grid. This analysis helps in determining whether additional energy storage systems or demand response strategies are needed to manage the load dynamically.

- The type and performance characteristics of the electrical energy charging, storage and management systems.

This includes selecting appropriate charging systems (e.g., slow chargers, fast chargers, or ultra-fast chargers) and energy storage solutions (e.g., battery banks) based on the fleet's operational needs. It also covers the efficiency, charging speed, and reliability of these systems. The management systems should ensure optimal energy use, balance the load on the grid, and potentially integrate with renewable energy sources to reduce the carbon footprint.

- The performance characteristics of the e-chargers.

The e-chargers should be evaluated based on their power output, efficiency, and compatibility with the bus fleet's battery systems. This includes considering the charging time required for different chargers, the number of buses that can be charged simultaneously, and the overall reliability and durability of the chargers. Performance characteristics also cover safety features, such as overcurrent protection, and the ability to operate under various environmental conditions.

- The type of connection to the e-charger.

The connection type refers to how the bus interfaces with the charging station, such as through conductive (plug-in) or inductive (wireless) charging. This also involves considering the standards and protocols for communication between the bus and charger to ensure compatibility and interoperability. The connection type will affect the ease of use, maintenance requirements, and potential for future upgrades to the charging infrastructure.

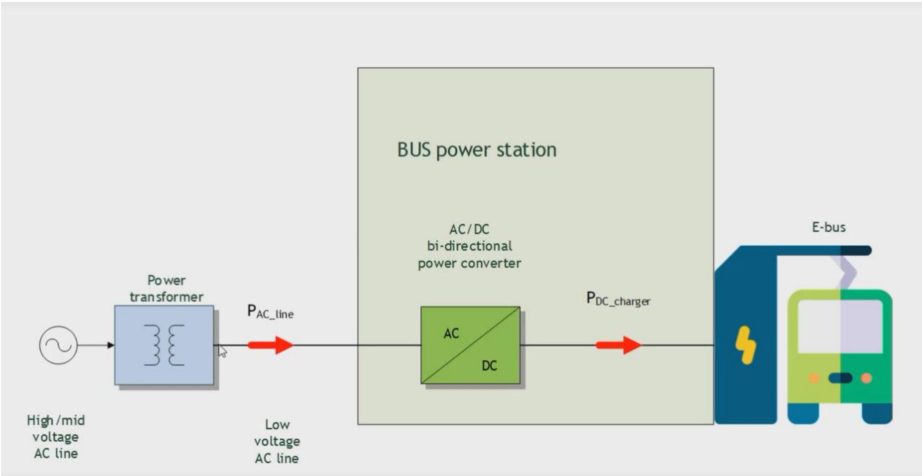


Figure 10. Technical diagram of charging infrastructure. Source: University of Maribor.

As electric buses become more prevalent, various charging technologies have been developed to meet the diverse needs of transit systems. Each method—ranging from plug-in charging to different pantograph configurations—offers unique advantages and challenges, making them suitable for specific operational scenarios and infrastructure setups.

5.2.2. Charging Approaches

Charging Approach	Characteristics	Purpose	Battery Requirements
Overnight Charging	Slow charging (typically 10-20 kW) at bus depots	Suitable for fleets with dedicated depots and low-to-moderate daily mileage	Larger battery packs; all battery types supported
Fast Charging	Charging speeds of 50-150 kW, typically at bus stops or terminals	Ideal for routes with frequent layovers or shorter operating periods	Moderate battery capacity
Super-Fast Charging	Charging speeds >300 kW, allowing rapid energy intake during short stops	Best for high-frequency routes with minimal layovers	Smaller battery packs; requires robust charging infrastructure
Opportunity Charging	Mix of fast and super-fast charging at strategic route points	Provides operational flexibility and minimizes downtime across various route configurations	Adaptable battery sizes; supports dynamic charging throughout the day

5.2.3. Technologies of charging

Charging Technology	Description	Typical Usage	Advantages	Challenges
Plug-in Charging	Manual connection via cable and plug (similar to EV car charging).	Overnight depot charging or during long breaks.	Cost-effective Simple and standardized Compatible with multiple charging speeds	Requires manual connection Time-consuming Needs dedicated parking and space
Overhead Pantograph	Pantograph mounted on charger; lowers to bus from above ("Pantograph Down").	Opportunity charging at terminals or stops during short layovers.	Fully automated Fast or ultra-fast charging Lower wear and tear	High infrastructure cost Requires overhead clearance
Roof-Mounted Pantograph	Pantograph mounted on bus roof; extends upward to connect with charger ("Pantograph Up").	Opportunity charging at various locations along route.	Automated and fast Good for high-frequency operations Flexible deployment along route	Requires bus modification Exposed to environmental wear Requires height clearance
In-ground Charging	Charging element installed under bus, connects with charging pad in the ground.	Used in bus lanes, depots, or where overhead installations are impractical.	Visually unobtrusive Protected equipment Can be integrated with road infrastructure	Complex and costly installation Harder to maintain underground components Less standardized and less widely deployed

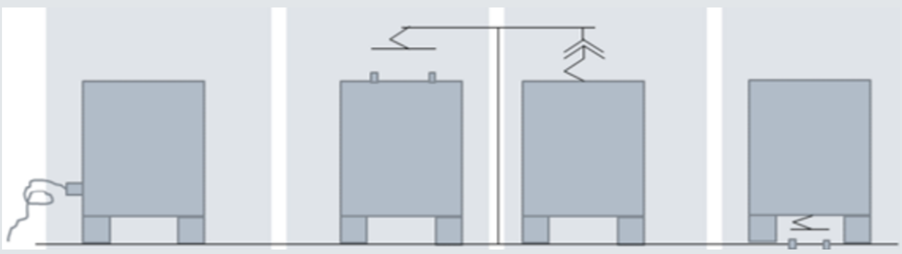
	Plug-in Charing	Overhead Pantograph	Roof-Mounted Pantograph	In-ground Charging
Charging technology				
	Manual plug-in	Automatic plug-in		

Figure 11. Types of charging technologies. Source: University of Maribor

Which batteries are suitable for which approach?

Overnight (slow) charging: Lithium-ion batteries (LFP, NMC, $LiFePO_4$) with suffiently big capacity for (daily) operation.

Opportunity (fast) charging: Lithium-ion batteries (LTO) with advanced chemistries (e.g., nickel-cobalt-manganese oxide, nickel-cobalt-aluminium oxide) to withstand high charging rates and can handle frequent charging and discharging cycles without significant degradation - lower capacities needed

Best practice: Standardized High-Power Charging for Fleet Interoperability

ASSURED Project - Multiple European Cities

Innovation:
The ASSURED project (Horizon 2020) focused on the development and deployment of high-power, interoperable charging systems (150–600 kW) for electric buses and other heavy-duty vehicles. Key innovations included the creation of **standardized interfaces** (like pantograph up/down and plug-in systems) and the **testing of multi-brand compatibility**, ensuring that vehicles from different manufacturers could use the same chargers without modification.

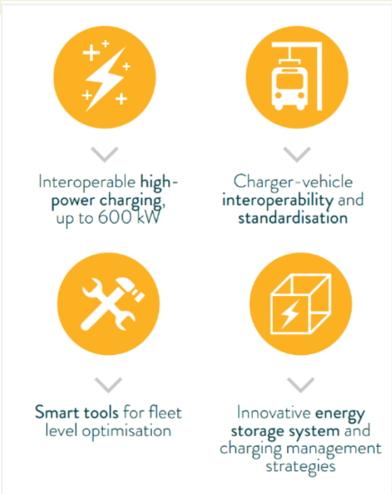


Figure 12. ASSURED project achivement badge. Source: https://assured-project.eu/

Impact:
The project enabled **efficient fleet operation across different cities and operators** by promoting hardware and software interoperability. Modular charging systems improved **energy efficiency** and reduced infrastructure redundancy. Cities participating in the project achieved **reduced total cost of ownership (TCO)**, enhanced **charging speed**, and smoother **integration with grid services** (including load balancing and smart energy use). ASSURED has significantly influenced EU policy and industry standards, contributing to the **adoption of the ISO 15118-20 and OCPP protocols**, supporting seamless vehicle-to-grid (V2G) communication and smart charging capabilities.

Challenges: The main challenges included the coordination of multiple stakeholders (OEMs, cities, utilities), aligning differing technical requirements, and **demonstrating large-scale compatibility under real operational conditions**. High initial infrastructure costs and evolving standards also required adaptive planning.

Transferable Lessons: Standardization is key to **future-proofing e-mobility infrastructure**. Cities planning to scale up their e-bus fleets should prioritize open protocols and modular charging systems that enable flexible operation and supplier independence. The success of ASSURED underscores the value of EU-level collaboration to **harmonize technical solutions** and accelerate urban transport decarbonization.

Sources: https://assured-project.eu/

https://ec.europa.eu/programmes/horizon2020/en/news/assured-new-solutions-electrification-urban-commercial-transport

https://cordis.europa.eu/project/id/769850

Best practice: Fast Charging to Maximize Operational Efficiency and Cost Savings

Barcelona, Spain – Transports Metropolitans de Barcelona (TMB) & H2020 Eliptic Project

Figure 13.

Innovation: As part of the Horizon 2020 Eliptic project, Barcelona implemented 400 kW fast charging infrastructure at key bus terminals to support its growing electric bus fleet. The chargers enabled quick top-up charging during scheduled layovers, significantly reducing the need for large onboard batteries and enabling efficient energy management throughout the operating day.

Impact: The use of high-capacity fast chargers led to energy cost savings of approximately 68%, while maintaining full schedule adherence and operational efficiency. Buses could be charged in as little as 5–10 minutes, allowing them to return to service quickly, thus minimizing downtime. This infrastructure allowed TMB to pilot a fully electric bus line, proving that high-frequency routes could be operated without diesel backup.

Challenges: Key challenges included ensuring electrical grid stability in areas with high peak loads, managing thermal constraints during rapid charging, and coordinating charger-bus compatibility with manufacturers. Initial investment in high-power infrastructure also posed budgetary and logistical hurdles.

Transferable Lessons: Barcelona's success demonstrates that fast charging can significantly reduce operational costs and enable high-demand electric bus service without major scheduling changes. Cities with dense urban routes and regular terminal stops can benefit from strategically located fast chargers, which reduce the need for oversized batteries and increase vehicle uptime.

Sources: TMB Barcelona Public Reports & Eliptic Deliverables

Best Practice: Multi-Purpose Charging for Optimized Urban Energy Use

Maribor, Slovenia - Marprom & Interreg EfficienCE Project

Figure 14. Opportunity "pantograph" charging station in Maribor. Source: https://programme2014-20.interreg-central.eu/

Innovation: As part of the Interreg EfficienCE project, Maribor implemented multi-purpose charging stations designed to serve electric buses, a cable car system, and electric car-sharing services. This integrated approach allows a single charging infrastructure to support diverse urban mobility modes, improving overall energy utilization and infrastructure efficiency.

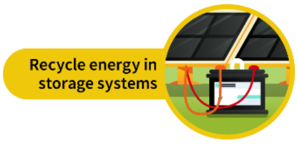
Impact: By enabling shared use of charging infrastructure, the project contributed to optimized grid usage, reduced infrastructure redundancy, and enhanced urban energy efficiency. This strategy also helped lower operational costs and supported the broader transition to clean, multimodal urban transport systems.

Challenges: Key challenges included technical harmonization across vehicle types, coordination of charging schedules, and developing smart management systems to allocate charging capacity based on priority and demand. Ensuring compatibility across different vehicles and user groups also required customized infrastructure planning.

Transferable Lessons: Maribor's model demonstrates the value of multi-functional charging hubs, particularly in medium-sized cities, where infrastructure resources may be limited. By sharing charging infrastructure across public and shared mobility services, cities can maximize return on investment, reduce environmental impact, and support a broader range of electric mobility options within the same footprint.

Sources: Interreg EfficienCE Project

5.3. Energy storage



Objective: Extend the lifespan of (e-bus) batteries by repurposing them for energy storage, reducing reliance on new batteries.

As electric fleets expand, the demand for electric power grows significantly, necessitating the development of effective energy management strategies to support sustainable fleet growth. A key approach in this context is "smart charging", which enables control over the timing and intensity of power drawn from the grid to charge vehicles. This approach not only optimizes energy consumption but also provides a substantial controllable power asset that can enhance grid stability and reliability.

Effective energy management is crucial in optimizing the operation of electric bus fleets, particularly when it comes to reducing network fees and leveraging cheaper energy sources. By smartly managing when and how buses are charged—such as charging during off-peak hours when electricity is less expensive – PTOs can significantly lower operational costs. This approach becomes even more critical as the scale of operations grows, with multiple buses and routes increasing overall energy demand. In addition, by storing energy as an extra source for peak periods, the system can help avoid the need for costly network upgrades or higher contracted power capacities.

5.3.1. General Objectives

Load Balancing: The primary objective of the battery bank is to balance electric power demands throughout the day. This involves storing energy during off-peak hours and supplying it during peak periods, thus reducing stress on the grid.

Network Stability: Enhance the stability of the power network by balancing demand fluctuations in energy supply, particularly in high demand spikes.

Cost Efficiency: Energy storage systems can significantly reduce operational costs by leveraging cheaper energy (cheaper tariff) and optimizing charging schedules. Additionally, these systems help lower the required network fees by maintaining a consistent charging demand, avoiding costly spikes in energy consumption.

5.3.2. Requirements for Integrating an Energy Storage System

When integrating an energy storage system into a charging infrastructure, it is essential to carefully evaluate both the technical requirements and the integration capabilities of the system.

Nominal Voltage Range: The system should be designed to operate within a specific voltage range suitable for the intended application, with the ability to handle both charging and discharging processes efficiently.

Overvoltage Resistance: Ensure the system can withstand occasional overvoltages in the power grid without compromising safety or functionality.

Charging/Discharging Mechanism: The battery bank should have a dynamic charge/discharge mechanism that activates based on real-time voltage levels in the power network, supporting rapid transitions between charging and discharging modes.

Current Specifications: The system should be capable of supplying and absorbing large currents to meet the high demands of electric bus operations.

High Safety Standards: The system must comply with stringent safety standards to prevent hazards such as fires, explosions, or electrical faults. This includes advanced monitoring and signalling systems for early detection of issues.

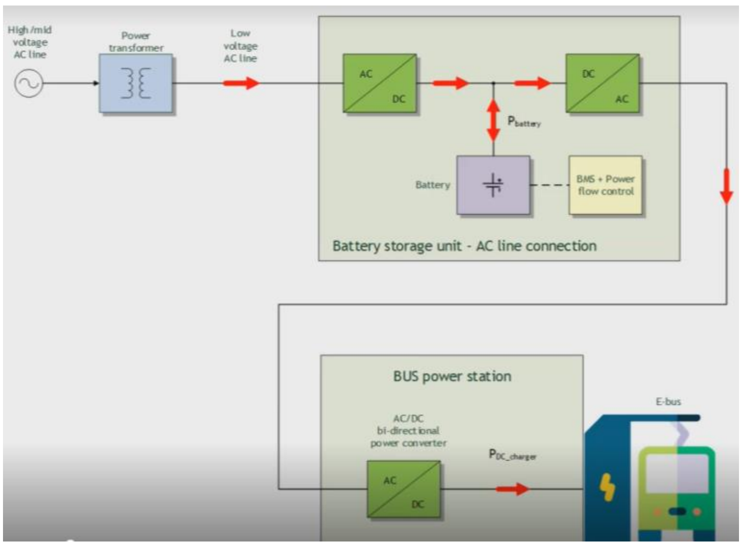
Standards Compliance: Ensure the battery bank meets all relevant electrical and safety standards applicable to public transport and energy storage systems.

5.3.3. Integration approaches

When integrating an energy storage system into an electric bus charging network, the configuration of the system is critical to ensure efficiency, reliability, and cost-effectiveness. In a typical battery system for charging an e-bus, the battery bank stores energy as DC. The bus's motor and other components might require AC, necessitating the conversion of DC to AC through an inverter. There are three primary configurations for integrating a battery bank as shown in Tabel…

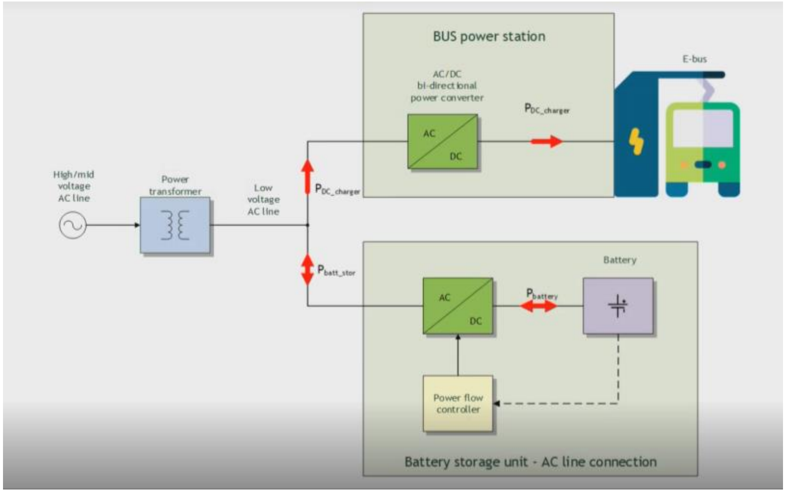
Serial Hybrid Configuration

In this configuration, the energy from the grid (usually AC) is first converted to DC to charge the battery (energy storage). When charging, the DC from the battery is converted back to AC to be used by the charger or the grid. All the energy used by the charger comes from the battery bank.



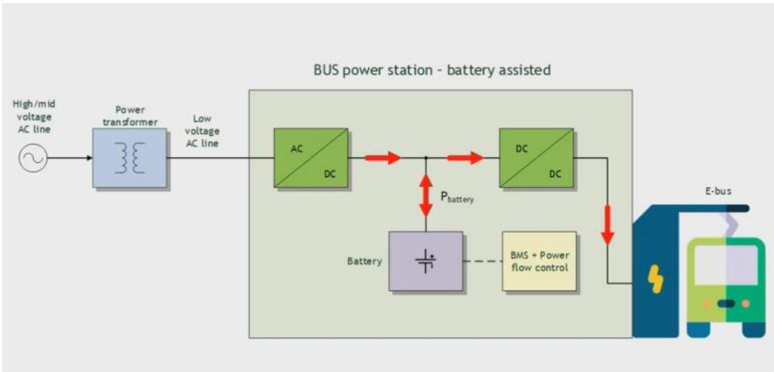
Parallel Hybrid Configuration

In a parallel hybrid system only a portion of the direct current (DC) from the battery bank is converted to alternating current (AC). This means that the battery and the grid supply power charger simultaneously but through separate paths.



Direct Hybrid Configuration (Direct DC Connection)

In a direct hybrid setup, the energy storage system is directly connected to the DC charger, with minimal conversion involved. The grid power is typically converted to DC before it interacts with the battery.



Category	Function	Description
Reduction of Network Fees	Peak Shaving	Stores energy during off-peak hours and uses it during peak demand, reducing electricity costs.
	Demand Charge Management	Lowers demand charges by minimizing the peak power drawn from the grid during billing cycles.
Offloading the Grid	Grid Stabilization	Provides power to e-buses directly, easing strain on the grid and enhancing stability during high demand periods.
	Defer Infrastructure Upgrades	Reduces the need for immediate grid upgrades by minimizing peak demand, lowering investment costs.
Additional Energy Sources	Integration with Renewable Energy	Stores solar or wind energy for use by e-buses, decreasing grid dependency and encouraging sustainable energy use.
	Energy Resilience	Acts as a backup power source during grid outages, ensuring uninterrupted public transit operations.

Each configuration has its own advantages and disadvantages in terms of energy conversion, efficiency, and complexity. Serial and Parallel Hybrid Configurations are more commonly used commercially because they offer greater flexibility and easier integration with different types of energy sources.

Serial Configuration: This configuration always requires the full energy power contribution from the battery bank to the charger. It is straightforward but can be less efficient in certain scenarios because the entire power output needs to be converted, often leading to higher energy losses.

Parallel Configuration: In contrast, the parallel configuration acts as an adjustable support for the network. It allows for more flexibility in energy management, as only the necessary portion of energy is converted. This configuration also offers resilience in case of network failures; the system can temporarily operate independently from the grid, ensuring continued operation even during outages.

On the other hand, the main advantage of the **Direct Hybrid Configuration** lies in its maximized efficiency. Here, the battery bank is connected directly to the DC link, which minimizes energy losses by reducing the number of conversions needed. This approach also simplifies the system by requiring fewer components, making it potentially more reliable and easier to maintain. However, the main drawback of Direct Hybrid Configuration is its compatibility with existing charging infrastructure. This approach has not yet become widespread commercially, making integration with current systems more challenging.

Components of energy storage

Component	Description
Battery	Battery type and purpose
Battery Management System (BMS)	Ensures safe and efficient operation by managing charge levels, temperature, and communication with bus systems.
Inverter	Converts DC to AC power and manages distribution; includes hybrid inverters and power distribution units.
Supportive Equipment & Infrastructure	Provides physical housing and connection points, including fire safety systems and charging interface.
Cooling & Heating Systems	Regulates battery temperature through liquid or air systems to optimize performance and safety.
Auxiliary Systems	Includes communication links, maintenance access, and additional sensors for performance monitoring.

Battery types and storaging

Battery Type	Best Use Case	Strengths	Limitations	Second-life Availability

LTO	Flexible	Extremely long lifespan, fast charging, wide temp. range	High cost, lower energy density, rare in second-hand market	Very low - not common on second-hand market
NMC	Flexible	Balanced energy and power, versatile use	Moderate availability second-hand, capacity may vary	Moderate - more common, but condition varies
LiFePO4	Overnight charging only	Stable, safe, long lifespan, good for large capacities	Limited rapid charging, moderate second-hand availability	Moderate - increasing availability, variable condition
Li-ion	Flexible	High energy density, efficient, fast charging capability	Shorter lifespan, higher cost for new units	High - widely available but varies in quality and lifespan

Battery Sourcing

New Batteries: Opting for new batteries ensures maximum capacity, efficiency, and safety, they certainly live up to expectations achieving optimal performance and longevity. However, the higher cost of new batteries can significantly increase the overall budget for electric bus projects.

Second-Life Batteries: Reused and repurposed second-life batteries support the circular economy by reducing waste and extending the useful life of resources. Second-life batteries, which are no longer suitable for their primary use in electric buses, can be repurposed for stationary energy storage. In these applications, where the performance requirements are lower, used batteries are still capable of effectively storing and managing surplus energy. This approach not only extends the lifecycle of the batteries but also supports sustainability efforts by reducing waste and promoting resource efficiency.

Availability

LTO: These are relatively new on the market and have a very long lifespan, meaning that there are currently very few, if any, second-hand LTO batteries available. Because of their durability, LTO batteries are less likely to enter the second-hand market in the near future, making them a less viable option for repurposing in stationary energy storage.

LiFePO4 and **NMC:** These are more common in electric vehicles and have a moderately long lifespan. As these batteries age, they are more likely to become available on the second-hand market. However, their availability is still limited compared to their new counterparts, and the condition and remaining lifespan of these batteries can vary widely.

Li-ion: These are more prevalent and have been in use longer, making them the most readily available type of second-hand battery. However, due to their high energy density and shorter overall lifespan compared to other types, the availability of second-hand Li-ion batteries is more robust but still constrained by the factors of demand and remaining battery life.

Transportation

In the EU, used batteries are considered hazardous goods and have to be handled by several regulations such as:

- **European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR)**: The ADR is a key regulatory document that defines and categorizes hazardous goods for road transport within and across EU member states. According to the ADR, **used batteries are classified as hazardous goods** due to their chemical composition and potential risks, such as leakage, fire, or explosion.
- **Waste Framework Directive (Directive 2008/98/EC)**: This directive covers the handling and transport of waste, including used batteries, and specifies that hazardous waste, such as used batteries containing dangerous substances, must be managed in a manner that protects human health and the environment.
- **Regulation (EC) No 1272/2008 (CLP Regulation)**: This regulation, which deals with the classification, labeling, and packaging of substances and mixtures, also classifies certain batteries as hazardous due to the chemicals they contain. The regulation covers the hazards associated with batteries and requires appropriate labeling and handling measures.

Additionally, for used or waste batteries classified as hazardous waste, companies must be licensed as hazardous waste transporters i.e., must hold an ADR certificate, which proves they have completed the required training to handle and transport dangerous goods safely.

Best Practice: Use of Buffer Storage for Grid Stabilization in In-Motion Charging

Pilsen, Czech Republic – Public Transport Operator PMDP (EfficienCE Project)

Figure 15. Buffer storage in Pilsen. Source: Interreg EfficienCE publication.

Innovation:A stationary energy storage system (buffer storage) was implemented at one of the in-motion charging (IMC) trolleybus substations. The system is designed to store electricity during off-peak hours and release it during peak consumption, thus stabilizing the power supply for the trolleybus network. This supports the operation of IMC trolleybuses without the need for expensive and time-consuming upgrades of the existing electrical grid.

Impact: The buffer storage system reduces voltage fluctuations in the overhead line network and minimizes the load on the grid. This enhances the efficiency and reliability of IMC operations. By covering short-term high power demands locally, the storage system enables a smoother power flow and reduces peak demand charges. Furthermore, it contributes to energy cost savings and enables the integration of renewable energy sources in the long term.

Challenges: Key challenges included ensuring the compatibility of the battery system with existing electrical infrastructure, optimizing the storage capacity and discharge strategy, and securing funding for such a pilot initiative. Operational testing was also crucial to assess system performance under real-life load conditions and fine-tune system settings for different traffic patterns.

Transferable Lessons: This case illustrates how stationary battery storage can enhance the operational flexibility of electric public transport systems, especially for trolleybuses with in-motion charging. It offers a replicable model for cities with similar infrastructure constraints, particularly where grid reinforcement is either impractical or cost-prohibitive. The project also highlights the importance of close collaboration between local utilities, transport operators, and city planners in implementing such energy innovations.

Source: https://programme2014-20.interreg-central.eu/Content.Node/EfficienCE.html

Best Practice: Integrating Second-Life Batteries with Renewables for Fast Charging

Maribor, Slovenia - Public Transport Operator Marprom (CE4CE Project)

Innovation: As part of the CE4CE project, Maribor is implementing a pioneering energy system combining second-life batteries and renewable energy sources (solar PV) to power a fast-charging station for electric buses. The system uses repurposed batteries from electric vehicles, giving them a second life as stationary storage, integrated with rooftop photovoltaic panels to supply clean energy.

Impact: The hybrid system reduces reliance on the grid for high-power charging events and supports the city's electrified public transport network. By combining second-life batteries with solar energy, the station can store excess PV energy and release it during peak demand. This not only enhances grid stability but also reduces operational costs and carbon emissions. Moreover, it demonstrates a circular economy approach by extending battery lifespans and minimizing waste.

Challenges: Implementing second-life batteries required careful assessment of their residual capacity, safety, and integration with the energy management system. Ensuring compatibility with fast-charging requirements and regulatory compliance for energy storage safety were also key challenges. Additionally, matching renewable generation with bus charging schedules necessitated intelligent energy control.

Transferable Lessons: This case highlights how second-life battery systems can be effectively used in public transport infrastructure when coupled with renewable energy sources. Cities seeking cost-effective, circular energy solutions can replicate this approach to reduce emissions, optimize infrastructure usage, and promote battery reuse. The project also underlines the value of cross-sector collaboration—between public transport operators, waste management companies, and energy providers—in delivering circular innovations.

Source: Maribor CE4CE Pilot Activity

5.4. Use Renewable Energy Integration (RES)

Objective: Reduce reliance on the centralized electricity grid and fossil fuel-based energy by promoting the use of renewable energy sources for charging infrastructure.

As cities transition to electric buses (e-buses) to decarbonize public transport, the focus increasingly shifts beyond the vehicles themselves to the sources and management of the energy they consume. While electrification reduces tailpipe emissions, true sustainability is only achieved when clean energy sources replace fossil fuels at the point of electricity generation. Integrating RES with electric bus charging infrastructure is thus a key strategic step—not only to reduce overall carbon emissions, but also to alleviate pressure on the electricity grid and enable decentralized, resilient energy systems.

5.4.1. Integration of RES

Integrating RES into e-bus charging infrastructure increases the share of clean energy in public transport while improving energy independence and stability. Among the various RES technologies available, solar energy stands out as the most practical and scalable solution, especially in urban settings with high solar irradiance. Wind and hydropower also offer high efficiency but are often constrained by site-specific requirements and initial investment costs.

5.4.2. Solar Energy as the Core RES

Solar installations are a significant driving force in the transition towards a decentralized energy policy, offering great potential for energy independence and sustainability. While solar energy generation is inherently intermittent, combining it with efficient energy storage systems allows for effective management of this intermittency. Energy storage solutions enable greater on-site consumption and ensure reliable power availability, even when sunlight is not directly available.

Solar electricity storage can also decouple electricity consumption from production. This has the added effect of reducing the need to expand local power grids for the absorption of high volumes of renewable energy sources. Combined with photovoltaic installations, solar electricity storage could double the amount of solar power consumed directly on site.

5.4.3. Efficiency of Solar Panels

The efficiency of solar panels refers to the percentage of sunlight that is converted into usable electricity. This efficiency is crucial as it determines how much energy can be generated in a given area.

Typical Efficiency: Most solar panels on the market have efficiencies ranging from 15 % to 22 %, whereas high-efficiency panels can reach up to 24-26 %.

Solar Insolation and Energy Production

Solid Potential: Regions receiving 5,5 kWh/m²/day of solar insolation are considered having ideal potential for solar energy production. Although even areas with levels of 3-4 kWh/m²/day can still be suitable, though they may require larger panel installations to meet the same energy needs as regions with higher sunlight exposure.

Factors Affecting Efficiency

Solar panel efficiency is a dynamic measure influenced by panel technology, installation conditions, and ongoing maintenance. Maximizing efficiency involves optimal panel placement, keeping panels clean and clear of obstructions, and using high-quality inverters.

- **Installation Angle and Orientation**: Panels need to be correctly angled towards the sun to capture maximum sunlight. The optimal tilt and orientation vary by location and time of year.
- **Shade and Obstructions**: Even minimal shading can significantly reduce output, as it blocks the sunlight needed for energy generation.
- **Inverter Efficiency**: The efficiency of inverters, which convert the direct current (DC) from the panels to alternating current (AC) for home use, typically ranges between 95 % and 99 %. Losses here affect the overall system efficiency.

Calculation of Daily Energy Output:

For example, with a solar panel efficiency of 20 % and receiving 4 hours of peak sun per day, a 1 m² panel would receive about 4 kWh/m²/day of sunlight. At 20 % efficiency, the panel would convert this to 0,8 kWh of electricity per day (20 % of 4 kWh/m²/day).

To produce 1 kWh of electricity per day, approximately 5 m² of panels would be needed under these conditions. Considering real-world inefficiencies the required area might increase to 8-10 m².

Defining Efficiency

Sun Peak Hours: This refers to the hours during which the sunlight intensity is strong enough to be considered at its peak (around 1.000 W/m²). It is not the total sunlight duration but the equivalent number of full-intensity hours that count towards energy production.

Real case perspective: Maribor CE4CE pilot action

For Maribor CE4CE's pilot action, it was calculated that solar panels for charging buses, with a solid daily efficiency of 1.367 kW and an average daily irradiation period, would require 750 m² of panels to achieve full self-sufficiency for a bus line consuming 650 kWh per day. The investment would be recouped within a couple of years — without the cost implementing for a battery storage system.

Best practice: Integrate Solar with Existing Infrastructure

Vienna, Austria - Ottakring Metro Station (Wiener Linien & Wien Energie)

Figure 16. Solar panels at Vienna metro station. Source: https://positionen.wienenergie.at/en/proje

Innovation: Installation of lightweight, foil-based photovoltaic (PV) films on the roof of the Ottakring U3 metro station as part of the Interreg EfficienCE project. These flexible PV films are significantly lighter than traditional panels, making them suitable for retrofitting existing structures without extensive structural modifications.

Impact: In its first full year of operation, the 60 kWp system generated approximately 58,377 kWh of green electricity, covering about 5.7% of the station's annual energy consumption. During peak spring and summer days, the system supplied up to 50% of the station's energy needs. This initiative led to an annual reduction of over 21 tons of CO_2 emissions.

Challenges: The pilot project addressed several challenges, including ensuring the PV system's compatibility with existing electrical grounding systems and managing the structural load on the station's roof. Additionally, the specialized nature of the PV films resulted in higher initial costs compared to conventional PV systems.

Transferable Lessons: This project demonstrates the feasibility of integrating renewable energy solutions into urban public transport infrastructure, even in existing facilities. The use of lightweight PV films offers a viable option for similar retrofitting projects where traditional solar panels may not be suitable due to weight constraints. The success of this pilot has prompted Wiener Linien to evaluate the potential for PV installations across other metro stations, aiming to expand the use of renewable energy within Vienna's public transport network.

Sources: https://programme2014-20.interreg-central.eu/Content.Node/Webinar-held-on-energy-efficient-metro-stations--with-vir.html

https://sump-central.eu/2021/03/16/first-full-year-results-of-the-vienna-pv-system/

Best practice: Integrate Solar with Existing Infrastructure

Barcelona, Spain – Solar-Powered Smart Bus Shelters

Innovation: In 2019, Barcelona implemented a network of 100 solar-powered bus shelters designed to enhance sustainability and passenger experience. Each shelter is equipped with photovoltaic (PV) panels that generate electricity to power integrated features such as LED lighting, USB charging ports, and digital real-time information displays. The shelters also incorporate battery storage systems, ensuring uninterrupted operation during nighttime or cloudy conditions.

Impact: The solar shelters have significantly improved energy efficiency and passenger satisfaction. The project has led to a 30% reduction in municipal energy costs associated with bus stop operations. Additionally, passenger satisfaction rates have increased by 85%, attributed to enhanced amenities and reliable information services.

Challenges: Implementing the solar shelters required addressing several challenges, including integrating the PV systems with existing urban infrastructure and ensuring the durability of components in varying weather conditions. The initial investment was higher compared to traditional shelters, primarily due to the cost of solar technology and battery storage systems.

Transferable Lessons: Barcelona's initiative demonstrates the feasibility and benefits of integrating renewable energy solutions into public transport infrastructure. The success of the solar-powered bus shelters highlights the potential for similar projects in other urban settings, promoting energy independence and enhancing the commuter experience. Key takeaways include the importance of combining solar generation with energy storage to ensure reliability and the value of incorporating passenger-centric features to increase public engagement.

Source: https://www.euro-inox.org/solar-powered-bus-stops-transform-european-public-transit/

5.5. Recapture wasted energy

Objective: Capture and repurpose braking energy for grid support or e-bus charging.

5.5.1. Recuperating braking energy from trains

Recuperating braking energy from trains and integrating it into urban energy systems presents a significant opportunity to enhance energy efficiency and reduce waste. In light rail systems, regenerative braking converts kinetic energy into electrical energy when a tram slows down. Although a portion of this energy is reused to power tram auxiliary systems, such as lighting and heating, a significant amount is often wasted due to the limitations of existing power supply systems in redistributing the energy effectively. This excess energy can cause a rise in distribution system voltage, leading to its dissipation as heat through resistors.

To address this inefficiency, one innovative solution involves linking the light rail network with nearby electric vehicle (EV) charging hubs. By doing so, the regenerative braking energy that would otherwise be wasted can be stored in EVs, which act as temporary energy storage. This stored energy can subsequently be utilized to reduce the demand on substations during tram acceleration or to charge fleet EVs based on predictable usage patterns, effectively creating a vehicle-to-grid (V2G) system.

Furthermore, stationary energy storage systems (ESS) can be employed along the trackside or at substations to capture and store excess energy generated during braking. These systems not only help stabilize the voltage in the railway's catenary system and reduce peak power demands but also support catenary-free operation for electric buses (e-buses). By providing charging support to e-buses, ESS reduces dependency on the grid during peak hours, optimizes energy consumption, and extends the range of e-buses, offering a versatile solution to improve energy efficiency across multiple modes of public transportation.

Regenerative Braking in Trains

When trains slow down, their kinetic energy is converted into electrical energy via regenerative braking systems. This energy is typically reused to power train auxiliary systems like lighting and heating, but a large portion is often wasted due to limitations in power supply systems and inefficient redistribution of energy.

Energy Storage and Redistribution

EV Charging Hubs: To address this inefficiency, excess energy can be captured and stored in nearby EVs. These vehicles act as temporary energy storage, reducing demand on substations and contributing to a **vehicle-to-grid (V2G)** system.

Stationary Energy Storage Systems (ESS): ESS placed along the track or at substations can capture and store excess energy. This improves grid stability, reduces peak power demand, and supports catenary-free operation for electric buses (e-buses), optimizing energy use across public transport systems.

Table 4 Challenges and Technical Barriers

Category	Barrier	Description
Legal Constraints	Use Restriction	Regulations restrict the reuse of regenerative braking energy to within railway networks, preventing redistribution to e-buses or EV infrastructure.
	Cross-Operator Issues	Legal complexities arise when foreign or third-party operators access national rail infrastructure or energy systems.
Technical Limitations	Network Compatibility	Railway and EV infrastructure may operate on different current types (AC vs. DC), requiring costly converters for energy transfer.
	Energy Withdrawal Points	Optimal energy extraction occurs at traction substations, which may be located far from urban e-bus routes, complicating direct energy transfer.
	Synchronization	Braking events are unpredictable and not aligned with e-bus charging schedules, requiring energy storage systems (ESS) to buffer supply and demand.
	High-Power Charging Requirements	E-buses often need over 300 kW charging power, exceeding what can reliably be supplied from regenerative braking alone without supplementary storage.
	Voltage Fluctuations	Voltage levels vary during regenerative braking; systems must manage these changes to avoid inefficiencies or potential damage to the grid and devices.
	Proximity to Rail Lines	Many urban areas lack suitable space or infrastructure near rail lines to install charging hubs, leading to increased transmission losses.
Infrastructure Limitations	Energy Storage Integration	Strategically placed ESS is essential for capturing and reusing energy efficiently, but identifying and implementing such locations can be complex and costly.

5.5.2. Efficiency of recuperation

Efficiency ratios for regenerative braking systems in trains are generally defined by how much of the kinetic energy during braking can be converted back into usable electrical energy. Here are some typical findings from other studies.

Efficiency Range: Regenerative braking systems in trains can achieve energy recovery efficiencies ranging from **20% to 45%** for conventional train systems and up to **70% to 80%** for systems specifically optimized for energy recovery, such as those in urban metro systems or light rail.

Train Type	Efficiency Range	Weight	Operational Velocity	Braking Acceleration	Braking Distance
Urban Metro Trains	60-80 %	30-50 t	30-80 km/h	0.8-1,5 m/s^2	100-300m
Light Rail/Tram Systems	50-75 %	30-50 t	30-80 km/h	0,8-1.5 m/s^2	100-300m
Intercity Trains	20-40 %	200-500 t	120-160 km/h	0.6-1.2 m/s^2	500-1200m
High-Speed Trains	10-20 %	>400 t	200-300 km/h	0.5-1.0 m/s^2	800m+
Freight Trains	5-15 %	1,000-3,000 t	60-100 km/h	0.3-0.6 m/s^2	1500m+

Notes:

- **Efficiency Range:** Refers to the percentage of kinetic energy during braking that can be converted back into usable electrical energy.
- **Weight:** Includes the weight of the train itself and, where applicable, passengers or cargo.
- **Braking Distance:** The distance required for a train to come to a complete stop, depending on speed and other factors like track gradient.

Input data

To accurately calculate the energy recovered during train braking, we need the following input parameters:

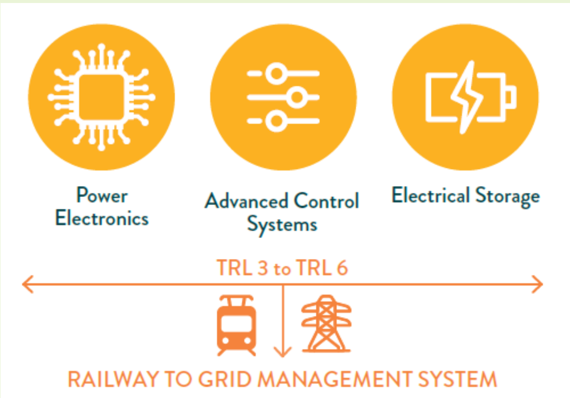
Parameter	Symbol / Unit	Description
Mass of the Train	m (kg or t)	Total mass of the train, including carriages, passengers, and cargo.
Initial Velocity	v_i (m/s or km/h)	Speed of the train before braking begins.
Final Velocity	vf (m/s)	Speed of the train after braking. Typically 0 m/s for a complete stop.
Braking Time	t (s)	Time duration over which the braking occurs.
Braking Distance	d (m)	Distance the train travels while decelerating to a stop.

Regenerative Braking Efficiency	η (%)	Proportion of kinetic energy recovered and converted into usable electrical energy (10–80%).
Type of Train & Braking System	—	Type of rolling stock (e.g., metro, tram, intercity) and its braking technology affect efficiency.
Type of Electrical Network	AC / DC	Determines compatibility and losses during energy recovery and transfer.
System Resistances & Losses	—	Includes losses from electrical resistance, inverter inefficiencies, and grid integration limits.

The efficiency of regenerative braking in train systems depends on several factors, including the type of train, its operational environment, braking distance, braking acceleration, and the technology used to capture and store the energy. Studies generally report that regenerative braking can recover between 20% to 80% of braking energy, with higher efficiencies achieved in systems designed for frequent stopping, such as urban metros and light rail. High-speed and freight trains typically show lower recovery rates due to longer braking distances and less frequent stops.

Innovative Project: E-LOBSTER

The **E-LOBSTER project**, funded by the European Union's **Horizon 2020 research and innovation programme**, aims to redefine energy management in **urban railway systems** by turning regenerative braking energy—traditionally lost as heat—into a valuable resource for nearby consumers such as **electric vehicles (EVs)** or the **local power grid**. This innovative approach contributes directly to **energy efficiency**, **grid resilience**, and the broader goal of **urban decarbonization**.



At the core of the project is the concept of establishing a **synergistic energy ecosystem** between railway infrastructure and power distribution networks. Instead of allowing excess energy from train braking to dissipate unused, **E-LOBSTER captures and redirects it** using depot-based **Battery Energy Storage Systems (BESS)** and advanced power electronics.

One of the project's most significant technological advancements is the **Smart Soft Open Point (sSOP)**—a smart, bi-directional power electronic interface that dynamically manages energy flow among three key components: the **railway network**, the **energy storage system**, and the **power grid**. By balancing power flows in real-time, the sSOP enhances **voltage stability**, mitigates peak loads, and facilitates the **integration of renewable energy sources**.

The system operates in two flexible modes:

- **Rail + Grid Mode**: During train operation, braking energy is harvested and redistributed.
- **Grid Mode**: When no trains are running, stored energy can support the grid or charge electric vehicles independently.

In live demonstrations, the E-LOBSTER system achieved up to **10% improvements in overall energy efficiency**, significantly **reduced grid losses**, and increased the viability of **decentralized charging infrastructures** for urban e-mobility. Its successful deployment sets a precedent for broader applications across Europe, fostering **smarter, cleaner, and more resilient transportation-energy networks**.

Best Practice: Smart Braking for Energy Recovery and Emission Reduction

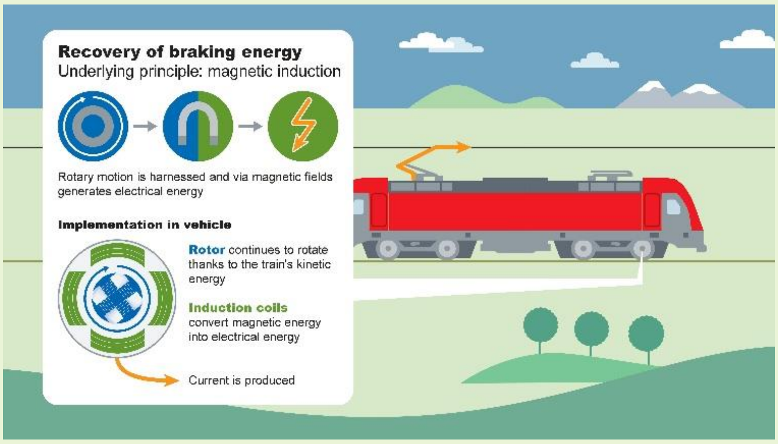
Germany – Deutsche Bahn

Innovation: Deutsche Bahn has implemented regenerative braking technology across its fleet of modern electric trains and an increasing number of buses. In electric trains, this system allows the traction motors to function as generators during braking, converting kinetic energy into electricity that is fed back into the overhead power line and reused by other trains. For buses, the recovered energy is stored on board and later used to power auxiliary systems such as lighting, even when the engine is turned off.

Impact: In 2023, regenerative braking systems installed on Deutsche Bahn's trains generated approximately 1,440 gigawatt hours of electricity. This amount of recovered energy is equivalent to the annual electricity consumption of around 350,000 four-person households. In buses, the stored energy contributes to reduced fuel consumption and lower CO_2 emissions, supporting Deutsche Bahn's wider climate goals and energy efficiency strategies.

Challenges: The integration of regenerative braking systems requires advanced technical coordination, especially for feeding electricity back into the grid on rail infrastructure. On the bus side, optimizing the onboard energy storage systems and ensuring long-term reliability in various operational conditions presents both engineering and cost-related challenges.

Transferable Lessons: Deutsche Bahn's experience illustrates that regenerative braking is a practical and scalable solution for reducing energy consumption and emissions in both rail and bus transport. The dual application shows how similar principles can be adapted across transport modes. Other operators can draw on this example to retrofit or upgrade their fleets, particularly where energy recovery can deliver measurable economic and environmental benefits without extensive infrastructure modifications.



5.5.3. Waste-to-Energy for Public Transport

Waste-to-Energy (WtE) systems offer various technologies for converting waste materials, including organic waste, into useful energy forms like electricity and heat. Key WtE technologies include Anaerobic Digestion, Incineration, Gasification, Pyrolysis, and Landfill Gas Recovery, each with distinct processes and efficiencies:

- **Anaerobic Digestion (AD)**: Organic waste is broken down by microorganisms in the absence of oxygen, producing biogas (mainly methane and carbon dioxide). This biogas can be used for electricity generation, heat production, or upgraded to biomethane for vehicle fuel. The conversion efficiency of biogas to electricity typically ranges from 30-40%, with combined heat and power (CHP) systems potentially reaching an overall efficiency of up to 85%.
- **Incineration**: Waste combustion at high temperatures generates heat, which is used to produce steam that drives turbines to generate electricity. Modern incineration plants incorporate advanced emissions control systems to minimize pollutants. Typical energy efficiency for electricity-only generation ranges from 20-30%. However, when combined with heat production in CHP systems, the overall efficiency can exceed 70%.
- **Gasification and Pyrolysis**: These thermal processes convert organic material into synthetic gas (syngas), which can be used to produce electricity, fuels, or chemicals. The electrical efficiency of gasification is around 25-30%, with potential increases when syngas is used in CHP systems or upgraded for fuel production.

- **Landfill Gas Recovery**: Methane produced from the decomposition of waste in landfills is captured and used as a fuel for electricity generation. This process helps reduce greenhouse gas emissions and recovers valuable energy from waste.

Using WtE to power public transport, particularly electric buses (e-buses), is still emerging but holds (significant) potential. Energy generated from WtE processes can be stored in battery banks or used directly to charge e-buses, contributing to a more circular and sustainable energy system.

To implement Waste-to-Energy (WtE) systems for powering e-buses, infrastructure must include waste collection, processing facilities, and integration with charging stations and power grids. Compliance with regulatory requirements involves obtaining necessary permits, conducting environmental impact assessments, and adhering to waste management and energy production standards. Effective integration with public transport systems requires careful infrastructure planning and stakeholder engagement to align WtE projects with existing transport networks and broader sustainability goals.

Best Practice: Waste-to-Energy (WtE) Conversion to Fuel Public Transport

Lille, France - Ilevia Transport Operator

Innovation: The city of Lille has implemented an advanced Waste-to-Energy (WtE) system that links municipal waste management with sustainable mobility. Organic household waste and sewage sludge are processed in anaerobic digesters to generate biogas. This raw biogas is then purified into **biomethane**, a renewable fuel that is fully compatible with natural gas-powered vehicles.

Impact: The biomethane produced from local waste is used to fuel Lille's bus fleet, operated by Ilevia. This transition from diesel to biomethane has **substantially reduced greenhouse gas emissions**, cut reliance on fossil fuels, and closed local resource loops. The city processes around 108,000 tons of organic waste annually, with enough biomethane production to fuel more than **150 buses**. This system contributes to climate targets while showcasing a model of circular integration between waste and mobility sectors.

Challenges: Ensuring a consistent feedstock supply for anaerobic digestion and maintaining fuel quality standards required close coordination between waste and transport departments. The investment in purification infrastructure and adaptation of the bus fleet for biomethane use also presented initial financial and technical hurdles.

Transferable Lessons: Lille's experience demonstrates how municipalities can turn organic waste into a **clean, locally produced transport fuel**, aligning with circular economy principles. The integration of WtE with public transport systems provides a replicable model for cities aiming to decarbonize their fleets while managing waste sustainably. This approach highlights the co-benefits of sectoral collaboration and investment in renewable energy systems.

Sources: https://www.europeanbiogas.eu/, https://www.bioenergy-news.com/

Benefits and Challenges of WtE in Public Transport

Typically, the anaerobic digestion process converts approximately 50-60% of organic waste into biogas. After purification, the biomethane produced meets the standards for vehicle fuel, with high-quality output and minimal impurities. Biomethane provides energy efficiency comparable to diesel, with an energy density of about 35-40 MJ/m^3. While slightly less than diesel, it remains effective for transportation.

Despite high initial investments, emissions management, and public concerns about environmental impacts, waste-to-energy (WtE) systems remain crucial for sustainable waste management.

6. Monitoring and evaluating circular economy

This section provides a framework of indicators at the intersection of transport assets and the circular economy. The framework presents a curated yet evolving list of indicators, continuously refined based on new insights and practical experience. It acknowledges existing gaps and the need for further discussion, aiming to serve as a foundation for dialogue, refinement, and harmonization with stakeholders across different levels—from individual companies to government policies.

Circular economy principles, such as recycling, reusing, and energy recuperation, are not yet fully integrated into the energy management of public transport systems, particularly in the context of charging electric buses. While initiatives exist to recycle and repurpose batteries for energy storage, these practices remain limited and have not yet reached mainstream adoption.

6.1. Importance and scope of circularity indicators for public transport

The integration of circular economy principles into energy management requires effective monitoring and evaluation, which relies on well-defined circularity indicators. These indicators help assess progress in adopting circular practices, such as battery reuse, energy efficiency, and renewable energy integration in public transport systems.

To the best of our knowledge, limited work has been done in proposing a comprehensive set of circularity indicators specifically addressing the energy dimension in public transport. Circular energy indicators differ from conventional energy metrics by shifting focus beyond simple consumption or efficiency—they assess how well energy systems manage the entire energy lifecycle, including sourcing from renewables, reducing dependency on finite resources, extending the life of energy assets (e.g. batteries), and reintegrating energy or materials back into the system.

This does not mean starting from scratch. PTOs and related stakeholders already monitor many energy-related indicators such as total electricity use, energy cost, vehicle energy efficiency, and fuel mix. Many of these, when viewed through a circularity lens, become powerful tools to assess progress toward decarbonization, resource efficiency, and resilience. Therefore, the approach taken in developing the indicator list was to build on what is already being measured, refining or adapting these metrics to better reflect circular energy goals.

This focus on existing and achievable data serves as a starting point—what can be considered the “low-hanging fruit” of circular energy management. However, the long-term goal is more ambitious: to expand the range of indicators, incorporate lifecycle thinking, and stimulate collaboration across stakeholders to build a deeper, more circular energy system for public transport.

We propose classifying indicators according to their scope of implementation, which helps clarify how responsibility and data access are distributed:

- **Indicators within the PTO's scope of work**: These are metrics that PTOs either already track or can reasonably start tracking with minor adjustments. They typically relate to operations, energy management systems, vehicle usage, and depot infrastructure.
- **Indicators outside the PTO's direct scope of work**: These include metrics where the primary responsibility lies with other actors (e.g. municipalities, energy suppliers, infrastructure owners), but which remain essential to assessing the full circularity of energy use in public transport. PTOs are therefore encouraged to initiate partnerships and data-sharing agreements to help fill these gaps—particularly for decentralized energy systems, renewable integration, battery recycling, and grid resilience.

By combining practical metrics with a clear understanding of their applicability, this framework aims to support both short-term action and long-term systemic change in how energy is used, stored, reused, and valued across the public transport sector.

6.2. Overview of Current State of the Debate and Advancements in Circular Economy Indicators

Numerous indicator frameworks to measure the implementation of circular economy exist in literature and practice. However, a lack of standardisation exists with respect to methodological and conceptual foundation for the same. This section gives an overview of the different circular economy indicator systems widely referred to.

A good starting point is the recent Bellagio Declaration, which was endorsed in December 2020 by the Heads of the Environment Protection Agency of Germany, France, Slovakia, Switzerland, the Netherlands, Austria, Italy and the European Environment Agency (EEA). According to ISPRA & EEA (2020), it is a set of principles on how to ensure that a monitoring of the transition to a circular economy captures all relevant aspects and involve all relevant parties.

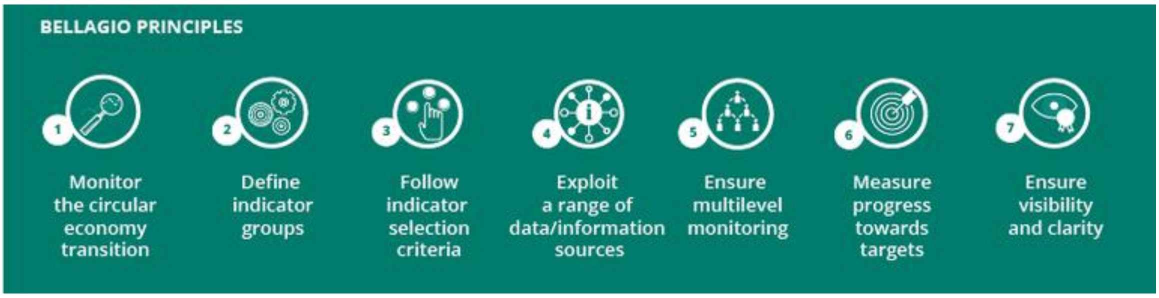


Figure 17. The 7 Bellagio Principles on Circular Economy indicators. Source: bellagio-declaration.pdf

Figure 17 describes the brief outline of the 7 Bellagio principles. Within the indicator development framework, it defines the following 4 indicator groups:

- **Material and waste flow indicators**: To monitor changes throughout the material life cycle, including resource efficiency dimensions. Although originally intended for tracking physical materials, this group can be extended to include energy source flows, battery material circularity and energy waste reduction.

- **Environmental footprint indicators**: To capture the impacts across the full life cycle of products and materials, ensuring that spill-over effects are assessed, and planetary boundaries are respected.
- **Economic and social impact indicators**: These capture both positive and negative impacts that may occur during the structural changes of the circular economic transition.
- **Policy, process, and behavior indicators**: These track the implementation of specific circular economy policy measures and initiatives.

Another popular indicator system is the European Circular Economy Monitoring Framework[20], established by the European Commission and Eurostat to monitor progress towards a circular economy using available statistical data. The key components of this framework include:

- **Material footprint:** Measuring the total amount of raw materials used.
- **Consumption footprint:** Assessing the environmental impact of consumption.
- **Circular material use rate:** Calculating the percentage of materials that are reused or recycled**.**
- **Waste generation and decoupling:** Tracking the amount of waste generated and efforts to decouple economic growth from waste production

The next case in point is the Circularity Transition Indicators (CTI)[21] framework by the World Business Council for Sustainable Development (WBCSD). Originally developed in collaboration with more than 50 companies and organizations, the framework aims to provide a credible and standardized methodology for assessing a company's contribution to circularity. While primarily focused on material flows, the logic and structure of the CTI framework can also be meaningfully applied to energy use—especially in public transport systems undergoing a transition to circular and renewable energy models.

In this context, the CTI framework can be interpreted through three key intervention points relevant for energy circularity:

- Energy Inflow Assessment:
    - Share of renewable energy: Evaluates the percentage of energy inputs sourced from renewable sources (e.g. solar, wind, hydro). This reflects the system's reliance on naturally replenished energy, reducing dependency on fossil fuels.

[20] European Commission. (n.d.). *Circular economy monitoring framework*. https://ec.europa.eu/eurostat/web/circular-economy/monitoring-framework
European Environment Agency. (n.d.). *Measuring Europe's circular economy*. https://www.eea.europa.eu/en/topics/in-depth/circular-economy/measuring-europes-circular-economy

[21] World Business Council for Sustainable Development. (2025, March). *Circular Transition Indicators (CTI): Enabling solutions*. https://www.wbcsd.org/wp-content/uploads/2025/03/WBCSD_CTI_enabling_solutions.pdf

- Use of second-life or recovered energy systems: Measures the share of energy stored or managed using non-new systems, such as second-life batteries, reused in stationary storage, or recovered braking energy from vehicles. This promotes the reuse of infrastructure and components, minimizing the need for virgin energy technologies.

- Energy System Design Assessment:
    - Design for energy flexibility and integration: Assesses whether infrastructure and systems are designed for integration with decentralized and renewable sources, enabling bidirectional flows, smart grid compatibility, and modular upgrades.
    - Battery and system modularity: Evaluates the design of battery systems and charging infrastructure for easy replacement, refurbishment, or reuse, supporting long-term energy asset circularity.
- Energy Outflow Assessment:
    - Actual energy recovery: Measures the real efficiency and usage of energy recovery systems, such as regenerative braking or heat recovery in depots. It focuses on how much of the potential recoverable energy is truly captured and reused.
    - End-of-life recovery of energy assets: Tracks the percentage of energy infrastructure (e.g., batteries, panels, inverters) that is properly recycled, refurbished, or repurposed at the end of its lifecycle, instead of being discarded.

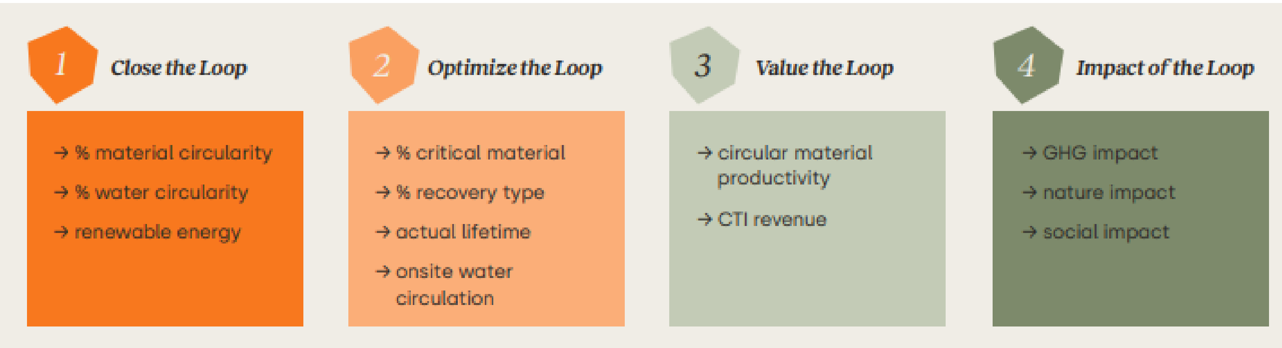


Figure 18: CTI indicators retrieved from CTI v4.0. Source: WBCSD_CTI_enabling_solutions.pdf

6.3. Evolving list of indicators for monitoring circularity in public transport

This section presents a non-exhaustive and evolving set of indicators that can be used to measure or assess the extent of implementation of circular economy principles in the domain of energy use within public transport systems. In alignment with the Circularity Compass, the indicators have been classified into the following categories:

AVOID (Upfront stage): These indicators assess strategies aimed at promoting circularity by avoiding the use of high-emission energy sources and maximizing the use of renewable or low-carbon energy from the outset. They focus on the share of renewable energy input, secondary energy usage (e.g., recovered braking energy), and low-carbon energy procurement, promoting energy sources with a reduced environmental impact.

EXTEND (Operational stage): These indicators focus on the performance and efficiency of energy use during the operational phase of public transport services. Metrics include energy consumption per passenger-kilometre, efficiency of energy distribution systems, peak load management, and operational emission intensity. The goal is to optimize energy efficiency, reduce energy losses, and minimize the overall carbon footprint of transport operations.

TRANSFORM (End-of-life stage): These indicators assess circularity strategies for energy systems at the end of their lifecycle. This includes the reuse or repurposing of energy storage components, recycling of battery systems, and decommissioning of energy infrastructure in an environmentally responsible way. They emphasize the importance of sustainable recovery and waste reduction in energy assets.

ENABLE: These indicators evaluate the effectiveness of enabling systems and tools that support circular energy practices. This includes the application of digital tools such as energy monitoring systems, life cycle energy assessments (LCEA), predictive analytics for load optimization, and integration of smart grid technologies. These practices enhance energy efficiency and system resilience throughout the energy lifecycle.

It is important to note that the proposed categorization of energy circularity indicators is not rigid. Different approaches may be used to classify and assess circularity in public transport energy systems. While the framework presented here is designed to be comprehensive and reflect a wide range of circularity dimensions, it remains adaptable. This flexibility allows indicators to be tailored to specific operational contexts and policy goals, ensuring relevance and effectiveness in guiding the transition to a more sustainable and circular energy ecosystem in public transport.

Table 5. Non-exhaustive list of circular indicators for PTE.

Category	Indicator	Unit	Description	Measurement Methodology	Data Required	Significance of the Indicator	Scope of Implementation for PTOs
Avoid	Share of Electrified Fleet	%	Share of electric vehicles in the total public transport fleet.	Count of electric vehicles / total fleet size.	Fleet inventory, vehicle registration data.	Key for tracking progress in fleet electrification.	Easily trackable, within PTO responsibility.
	Renewable Energy Share	%	Share of electricity sourced from renewable energy.	Estimated via energy bills and metering systems.	Electricity bills, supplier contracts.	Reduces emissions and fossil fuel dependency.	Within PTO scope, commonly available data.
	Infrastructure Electrification Readiness	%	Share of facilities equipped for electric operations.	Inventory of charging units / total depots or stations.	Equipment lists, technical documentation.	Indicates readiness for electrified operations.	Within PTO control, often covered in planning documents.
Extend	Energy Efficiency Gains from Optimization Measures	kWh saved / %	Amount of energy saved through measures such as eco-driving, smart timetabling, and vehicle priority.	Comparison of energy consumption before and after implementation (control group).	Energy consumption per vehicle/trip, timetable data, driving behavior monitoring systems.	Quantifies the impact of soft measures without requiring new hardware.	Fully within PTO competence; low-tech measures with high potential.

	Smart Charging Usage	%	Share of charging events using optimized strategies (e.g., off-peak hours).	Charging log analysis with time stamps.	Charging infrastructure data, tariff schedules.	Optimizes costs and grid load.	Requires smart chargers; otherwise difficult to track.
	Battery Health Monitoring Coverage	%	Share of vehicles equipped with battery health monitoring systems.	Availability and function of SoH diagnostics.	Battery reports, vehicle logs.	Crucial for extending battery lifespan.	Requires technical systems, but feasible.
	Off-Peak Energy Use	%	Share of electricity used during lower-tariff periods.	Analysis of charging times relative to tariffs.	Electricity bills, charging schedules.	Reduces costs and grid strain.	Requires access to tariff data and time logs.
	Energy Savings from Energy Management	kWh saved / % / €	Amount of energy or cost saved by storing energy from cheaper or renewable sources for later use.	Compare energy cost and consumption with and without storage.	Tariff schedules, storage system logs, time-of-use charging data.	Demonstrates economic and operational benefits of storage systems.	Within PTO scope; dependent on energy market and ESS implementation.
Transform	Second-Life Battery Use	%	Share of used batteries repurposed in stationary energy systems.	Number of reused batteries / total end-of-life batteries.	Decommissioning reports, installed storage systems.	Enhances sustainability and reduces waste.	Within PTO scope, dependent on partnerships and strategy.

	Battery Recycling Rate	%	Share of batteries recycled at end-of-life.	Recycled batteries / total batteries used.	Disposal records, contracts with recycling firms.	Key for closing the resource loop.	Trackable via contractual obligations.
	Energy Recovery Rate	%	Share of energy recovered through regenerative systems.	Recovered energy / total energy used.	Technical data from recovery systems (trains, buses).	Reduces net energy demand.	Technically complex, but increasingly feasible.
	Energy Self-Sufficiency Level	%	Share of total energy consumption covered by on-site or stored renewable energy sources.	(Energy generated + stored energy used) / Total energy consumption.	On-site generation data, ESS discharge logs, total energy use data.	Measures independence from external grid; key for resilience and cost control.	Within PTO scope, depends on renewable and storage capacity.
	Energy Conversion Efficiency	%	Ratio between usable energy output and total energy potential (e.g. solar panels, regenerative braking, etc.).	Usable output energy / Total potential or captured energy.	System logs from solar panels, regenerative systems, inverters.	Indicates technical efficiency of energy systems.	Technically measurable; growing relevance with more energy systems.
Enable	Digital Energy Monitoring Coverage	%	Share of operations/systems monitored using digital tools.	Analysis of smart meter and digital system coverage.	Device inventories, software systems, reports.	Enables optimization and rapid response.	Requires initial investment, implementable over time.

	Lifecycle Energy Assessment Use	Qualitative / Y/N	Use of LCA or LCC methods in energy planning and procurement.	Review of planning documentation.	Tenders, project documentation.	Supports energy-informed decisions.	More difficult to implement, but strategically important.
	System Integration Flexibility	Qualitative	Ability of infrastructure to integrate new energy solutions.	Technical compatibility assessments and expert reviews.	Infrastructure condition reports, upgrade potential.	Key for long-term adaptability.	Within PTO scope, assessment required during upgrades.
Economic	Return on Investment (ROI) per Energy Measure	%	Financial return for each implemented energy-related measure or project.	(Total savings - investment cost) / investment cost * 100.	Investment costs, operational savings, energy bills.	Justifies investment decisions; supports prioritization of measures.	Fully implementable by PTOs; requires financial tracking and evaluation.

The indicators presented in this chapter offer a structured yet adaptable framework for assessing the implementation of circular economy principles in energy use within public transport systems. These indicators are also rated according to their current scope of implementation by Public Transport Operators (PTOs) or their future potential for adoption. Within the circularity framework of Avoid-Extend-Transform-Enable, the indicators aim to capture a wide range of lifecycle stages—from energy sourcing and operational consumption to energy recovery and reuse. These indicators provide practical entry points for public transport authorities and other stakeholders to monitor, evaluate, and enhance circularity in energy management practices. While not exhaustive, this set is intended to evolve alongside technological innovations, regulatory developments, and industry best practices. Ultimately, the use of such indicators can support more informed energy-related decision-making, ensure compliance with climate and sustainability goals, and drive innovation in the shift toward a more energy-efficient and circular public transport ecosystem.

7. Conclusions and recommendations

This strategy examines **energy use in public transport (PTE)** through the lens of the AETE circularity framework, offering a life cycle-based approach that can drive transformative change in how energy is sourced, used, monitored, and managed. It promotes a systemic perspective that moves beyond technology upgrades alone—toward reducing resource intensity, improving energy resilience, and aligning with climate, social, and economic objectives.

The strategy provides a flexible basis for developing **CE4CE Action Plans and beyond**, supporting broader uptake of circular energy practices among European public transport operators. In addition to specific technical recommendations in each section, this document concludes with overarching messages to guide the development of local and actionable energy transition strategies in the public transport sector.

7.1. Adopt a Life Cycle Approach to Energy Planning and Use

Public transport operators (PTOs) are encouraged to move beyond short-term efficiency measures and adopt a life cycle, system-oriented perspective for managing energy. This means integrating planning, sourcing, use, storage, and end-of-life aspects into a coherent energy strategy. Decision-making should be based on data and life-cycle impacts—not just focusing on cost or CO_2 but also on resource circularity, self-sufficiency, grid dependency, and long-term energy resilience.

Even if PTOs do not directly control energy generation or policy, they can act as enablers and influencers through their procurement choices, operational decisions, and by collaborating with energy providers, local authorities, and technology suppliers.

7.2. Consolidate existing improvements in the operational stage of PTE

Electrification is the cornerstone of the energy transition in public transport. With increasing numbers of electric vehicles entering fleets, charging solutions are evolving in tandem. These two elements—vehicles and infrastructure—form an interdependent system that must be developed cohesively to ensure efficiency and long-term scalability.

As electrification expands, effective energy management becomes essential. Many PTOs have already begun implementing soft optimization measures, such as eco-driving programs and smart scheduling. These low-tech, high-impact initiatives improve energy efficiency without the need for major infrastructure upgrades. At the same time, digitalization is opening new avenues for improvement. Digital energy monitoring tools enable operators to track, analyze, and respond to consumption patterns in real time—supporting dynamic adjustments and continual efficiency gains.

A key emerging area is energy storage, which enables the temporal and spatial decoupling of energy production and consumption. Storage systems open the door to optimized use of electricity from diverse sources—especially during off-peak hours and from renewables such as solar or wind. Importantly, these storage solutions align with the second-life use of batteries, repurposing batteries from electric vehicles to stationary applications. Although this field remains largely underdeveloped and currently limited to pilot initiatives, early trials demonstrate strong potential and serve as testbeds for future scaling.

Energy storage also enables the use of recovered or “wasted” energy, most notably through regenerative braking in rail systems. While regenerative braking is already widely implemented, it typically functions as a real-time energy return mechanism, with limited capture or redistribution. The establishment of multimodal hubs—capable of sharing energy across modes, such as from trains to buses—would unlock more of this latent potential.

In addition, the role of renewable energy sources (RES) is growing. While extensively applied in other sectors, their integration into PT operations—particularly when combined with local storage—can significantly reduce reliance on grid electricity. Another potential energy source is waste-to-energy, which remains at a conceptual stage in most public transport contexts due to the need for large-scale infrastructure and investment. However, where applicable, such systems could complement circular energy strategies in the long term.

Lastly, the end-of-life phase for energy-related assets, especially batteries, remains a critical blind spot. The current battery recycling rate is low and largely managed by manufacturers. Yet, with rising global demand for batteries and their reliance on rare-earth elements, recycling and material recovery are becoming strategic priorities. Developing local or regional capabilities for battery processing and re-use will be essential for circularity and supply chain resilience in the coming years.

Altogether, these components—optimization, digitalization, energy storage, renewable integration, recovery systems, and responsible end-of-life management—form the backbone of a mature, circular energy strategy. PTOs are well-positioned to lead in this area by building on current progress and scaling solutions that are both technologically and institutionally within reach.

7.3. Advocate for transformative policy measures to break linear models

Last but not least, real circularity cannot be achieved without ambitious policies that promote innovative approaches and create a level playing field, which are essential to overcoming the structural barriers maintaining the linear model. While some progress has been made through existing regulations, more work is needed. Current policy discussions that are moving in the right direction, revolve around including strengthening green public procurement with concrete incentives to prioritize assets with better life-cycle environmental performance over price, regulations that opt out waste by making recycling and recovery standard practices. These measures would help pave the way for national and local public authorities to implement and enforce policies tailored to their specific local contexts.

7.4. Foster Cross-Sector Collaboration

Advancing circular energy use in public transport cannot be achieved in isolation. It requires coordinated collaboration across sectors, departments, and organizations. Many of the most impactful solutions—such as the development of second-life battery systems, integration of renewable energy sources, or establishment of energy-sharing infrastructure—demand joint planning and aligned strategies between PTOs, energy providers, technology developers, and municipal authorities.

For example, stationary energy storage systems using repurposed EV batteries rely not only on operational capacity from PTOs, but also on partnerships with battery manufacturers, recyclers, and grid operators. Similarly, regenerative braking technologies offer greater benefits when integrated into intermodal hubs capable of redistributing recovered energy between transport modes—such as from trains to buses. These kinds of solutions require both technical integration and institutional cooperation.

In addition, while PTOs may lead in implementing smart charging infrastructure, they depend on distribution network operators (DSOs) and policy makers to ensure regulatory and grid capacity support. Real-time energy management and dynamic load shifting cannot be scaled without such enablers.

The same is true for energy sourcing. To increase the share of locally generated renewable energy, PTOs must collaborate with municipal energy agencies, solar developers, and land use planners. Buildings and depots can serve as hosts for solar panels or other distributed energy systems—but only if designed with these future integrations in mind.

Ultimately, circular energy transition in public transport is not simply a technological shift—it is an institutional challenge. It requires shared intent, transparent dialogue, and long-term collaboration across the energy and mobility ecosystem. PTOs can act as catalysts by consolidating demand, initiating pilot projects with external partners, and helping shape common standards that guide industry-wide transformation.