DELIVERABLE D.T2.3.1 STATE OF THE ART & PEER REVIEW FOR ENERGY-EFFICIENT PT INFRASTRUCTURE TECHNOLOGIES DEPLOYMENT

(3) Energy storage in public transport infrastructure

Project index number and acronym	CE1537 EfficienCE
Lead partner	PP1 – City of Leipzig
Deliverable number and title	D.T2.3.1 STATE OF THE ART & PEER REVIEW FOR ENERGY-EFFICIENT PT INFRASTRUCTURE TECHNOLOGIES DEPLOYMENT
Responsible partner(s)	PP11 Redmint
Project website	www.interreg-central.eu/efficience
Delivery date	
Status	Final version 3
Dissemination level	Public

Document history of revisions				
Version	***Date***	***Partner***	***Name***	***Action***
template	17.11.2020	PP11 Redmint	Gabriele Grea	Structure and brief content description
1	16.02.2021	PP11 Redmint	Anja Seyfert	contents
2.1	11.03.2021	PP11 Redmint	Anja Seyfert	contents
2.2	15.10.2021	PP11 Redmint	Anja Seyfert	contents
2.3	01.12.2021	PP11 Redmint	Anja Seyfert	contents
3	15.12.2021	PP11 Redmint	Gabriele Grea	Contents and finalisation
	15.12.2021	Rupprecht Consult	Marlene Damerau	Review, final

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Executive summary

The European Union is focusing on accelerating decarbonisation of the transport sector based on renewable energy sources. Electric Vehicles (EVs), Fuel Cell Electric Vehicles (FCEVs). and energy storage can greatly foster this effort and at the same time foster also cost efficiency and grid stabilization for public transport infrastructure.

The role of public transport infrastructure strongly depends on its ability to foster the efficient use of electricity in the networks, as well as to enable the integration of Renewable Energy Sources (RES).In this process, storage technologies play a very important role, with applications in depots, stations and stops, and along the lines which form transport networks.

The present report analysis the main relevant technologies for energy storage that can be applied to public transport infrastructure, identifying their potential and challenges, and proposes a review of geed practices for their concrete allocation.

The state of the art study is completed by the identification of three use cases, which represent the basis for the development of the Transnational handbook for energy-efficient PT infrastructure Technologies deployment dedicated to energy storage (D.T2.3.2).

1. Functionalities for energy storage in public transport infrastructure

The presence of electrified vehicles and infrastructure in public transport represents an important opportunity for the decarbonization process in transport, and at t he same time sets relevant technical challenges related to the stability of the grid, in particular in presence of growing shares of RES to be integrated and exploited.

Energy storage can have a variety of functionalities in public transport infrastructure depending on the respective frame conditions and needs.

1.1. Optimisation of consumption

Energy storage technologies provide different possibilities in order to optimise the consumption. Power purchase can be optimized to minimize demand charges by buffering needs between peak hours and low demand times for example in depots and stations or for charging infrastructure.

Another possibility is the better integration of renewable energies to maximise the own consumption, for example from PV power plants or to improve the energy efficiency by recovering and re-using breaking energy of vehicles.

With the integration of renewable or breaking energy as well as fast charging stations, power quality becomes even more important, and storage technologies can provide grid stability for short-duration power loss or variations in frequency and voltage.

Depending on the location (depot, station, onboard etc.), the voltage, energy and time for the storing, different technologies are suitable.

1.2. System operation (e.g. grids for trolley buses, metros, trams)

Energy grids for public transport have to deal with high power demands for acceleration, and in case of collecting breaking energy also with high supply at different times. Energy storage systems can provide ancillary services to the grid:

- primary response to stabilise frequency and voltage changes in the network
- secondary response to correct imbalances between load and generation
- peaker replacement to ensure sufficient generation capacity during peak demand periods

Storage systems with low reaction times connected to the grid improve grid stability and can be installed either directly onboard of vehicles to balance the demand and supply towards the grids or stationary as way side storage or in stations or substations.

Ancillary services, especially peaker replacement can ensure sufficient generation capacity during peak demand periods and can therefore postpone or avoid network infrastructure upgrades and related investments.

1.3. Prosumers - Integration of renewable energies

Many public transport providers invest in photovoltaic or other technologies to use renewable energy sources in order to lower CO_2 emissions and energy related costs by increasing the share of renewables.

Big roofs of depots or stations/stops are convenient to be used for photovoltaic, but the time of energy generation does not necessarily match the demand. Since the status as prosumer feeding energy into the general grid is not as convenient as self-consumption, energy storage technologies can better integrate and maximise the share of renewables used. In any case consumption profiles should be analysed in detail and compared with possible generation to estimate the needed storage capacity as well as the storage type.

Depending on the cost of the storage and proposed energy/cost savings it might be necessary to include other options as providing charging infrastructure also to external parties.

As prosumer with available storage capacities also energy arbitrage is possible, and therefore gain from low-price energy purchases which can be sold in high price periods.

2. Technologies for Energy storage

This chapter gives an overview of the most relevant storage technologies for the use in public transport. As Figure 1 shows, suitable technologies vary depending on power capacity, energy density and discharge time.

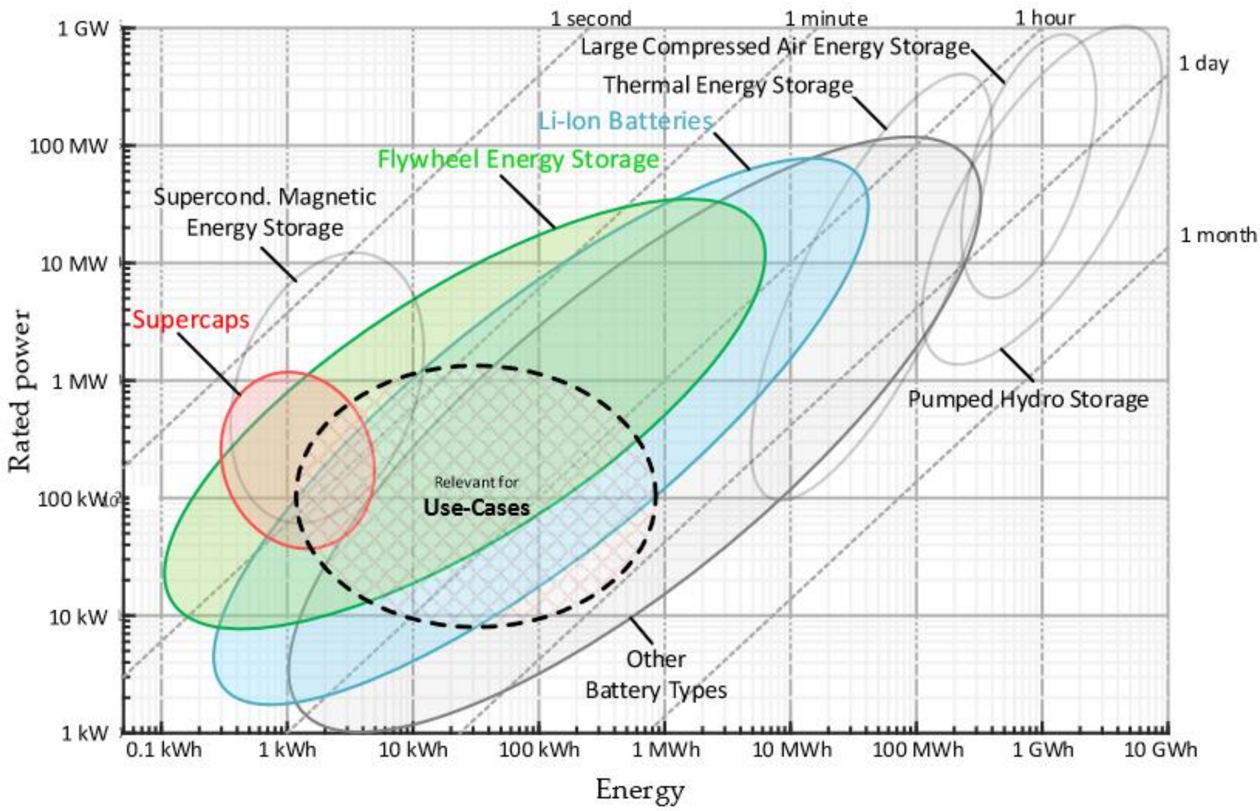

Figure 1: Power rating, energy capacity and discharge time of different energy storage systems for stationary and mobile transportation applications. (Haidl et al. 2019)

2.1. Batteries

Batteries can be used either on vehicles for propulsion or other services within the vehicle (as auxiliaries, recuperation of breaking energy etc.) or as stationary storage. For stationary batteries requirements are lower for light weight and safety, they allow a wider range of battery technologies.

Lead-Acid

Lead acid batteries are the oldest type of rechargeable batteries, it provides a rather low energy density and large power to weight ratio. Low costs and possible deep discharge allow lead acid batteries as applications for back-up power systems, off-grid applications but also as grid energy storage.

Recent research results state, that for stationary storage for example for the integration of PV Li-ion batteries provide reliable power supply for lower costs. (Kebede et al. 2021)

Vanadium Redox Flow

Compared to Li-ion batteries Vanadium Redox Flow batteries have a longer lifetime (25 years and more) without capacity degradation but provide less energy density. Therefore, applications are larger and only stationary. Vanadium Redox Flow energy storage systems are used mainly for longer (over 10 h) energy storage in big scale utility or commercial applications to facilitate the integration of renewable energies. (Rapier, 2020)

The technology is less mature as Li-ion batteries and has around the same costs. (George, 2021)

Lithium-ion battery

Lithium-ion batteries allow high energy density and lower cost per energy capacity but also less power density and high costs per power capacity, for which they are used most for weight-sensitive applications requiring high energy capacities such as automotive or consumer electronics.

Available lithium-Ion batteries differ very much according to cell format and chemistry and therefore also performance, cost and safety characteristics, but still allow for the highest energy density compared to other battery types.

Disadvantages are, besides the fire hazard of the inflammable electrolytes in case of damage or incorrect charging, the rather low power density, relatively long charging times and the limited life cycles and lifetime up to 15 years, which is influenced very much by external conditions as temperature and state of charge. (Meishner et al. 2019)

Li-ion batteries have a very wide range of applications onboard and stationary:

a) As part of propulsion systems of electric vehicles;

b) As mobile storage in vehicle-to-grid;

c) as stationary storage to provide ancillary services for grid stability and security, integration and maximisation of self-consumption of renewable energies, recovery and reuse of breaking energy, bill management and energy arbitrage.

- Expected benefits

Due to the properties as high energy density and low self-discharge.

- Relevant investments

From 2010 Lithium-ion battery pack prices dropped from average $1.100/kWh by 89% to $137/kWh in 2020. For battery electric vehicles (BEV) average volume-weighted prices are around $126/kWh, whilst cells themselves count for around four fifth of the price ($100/kWh), one fifth of the total price is allocated to the battery pack. Lowest prices can be found for e-bus batteries in China.

A battery price survey of BNEF 2020 expects a price development of BEVs for 2030 around $101/kWh which would allow car producers mass production of electric vehicles for prices comparable to vehicles with combustion engine. Further reductions due to different chemical compositions and further developments in the battery technology might allow further reduction down to $58/kWh in 2030 (BloomberNEF 2020).

According to estimations li-ion batteries might be more cost-competitive than alternative solutions for most applications after 2030. (Xiaojun Li, 2021).

The technical and price development of Li-ion batteries explains the wide field of applications.

- Possible technical barriers

In order avoid degradation a favourable environment/application should be chosen, considering temperature, number of charging cycles, depth of discharge, current. Furthermore, safety standards due to the fire hazard should be considered.

Second life batteries

According to the global EV-outlook 2021 of the IEA the global electric vehicle stock including all transport modes (except two/three-wheelers) will increase from more than 11 million in 2020 to around 145 million vehicles in 2030, a share of 7 % of road vehicles. This development causes a significant increase lithium-ion battery production from around 160 GWh in 2020 to 1.6 to 3.2 TWh in 2030 depending on different scenarios, of which a demand of 120 GWh is estimated for buses.

With increasing numbers of EVs, the demand for charging infrastructure grows. Second life battery storage systems can reduce peak power consumption and related costs from the grid for fast charging, enable charging in areas with grid limitations and support further services, for example the integration of renewable energies.

With dropping prices for new EVs expectations would be, that costs of used batteries are significantly lower. However, this is momentarily not the case because batteries which end their first life in vehicles, are hardly available at the market, and if rather for pilot/DIY than for standard applications due to the following reasons (Circular Energy Storage 2021/1):

- the average battery lifetime for the first use in light duty vehicles is estimated to be 14.7 years (Circular Energy Storage 2021/2) with average warranties over 8 years, whilst e-bus batteries are assumed to reach their end-of-life after seven years (to have 80% capacity left);
- batteries which fail within the warranty time are taken back by the car producer and remanufactured or reused in other applications;
- car producers offer battery upgrades to vehicle owners and take back battery packs in very good conditions to be used in other solutions;
- batteries of vehicles which were involved in accidents are often sold by insurance companies to authorised treatment facilities which will move it to countries with cheaper repairs and high demand of electric vehicles and most likely sell it to the highest bidder.

Due to the fact that there are many different kinds of battery packs and modules in markets of different countries all over the world, prices vary much, up to $1.000/kWh, not all of them even find buyers (Circular Energy Storage 2021/1).

Very few battery types have a global or even regional market, amongst which are the ones from Tesla Model S/X, Nissan Leaf and to some extent Mitsubishi Outlander, BMW i3 and Chevrolet Volt, with most consistent but over average prices for Tesla. Due to long warranties and good access often battery modules are harvested and sold back to the automotive market (IEA, 2021).

Therefore, the market for used batteries is not effective or liquid but changing a lot over time and geographic region and depends also on market maturity and preference. With the growth of the EV-production within the next years, the market for second life batteries will change (Circular Energy Storage 2021/1).

- Expected benefits

The extension of the useful life of batteries, in addition to all the benefits of battery stationary storage (integration of renewable energy, collection of recuperated energy, stabilisation of the grid, smart charging, etc.).

- Relevant investments

So far not feasible to purchase at the market due to the availability and prices equal to or higher than new battery packs.

- Possible technical barriers

On the market is a very wide range of different modules and battery packs available, with very different volume – weight relation, different charging standards and often available not tested regarding the remaining capacity.

- Possible regulatory barriers

Besides fiscal rules, energy taxes, missing charging standards and protocols, second life batteries are challenged by regulatory barriers, which results in the need for revision of the European regulatory framework to foster commercial business models for second life batteries. (EASE 2020)

2.2. Supercapacitors

Supercapacitors or ultracapacitors is based on the Helmholtz electric double-layer. Compared to batteries with electro-chemical systems Supercapacitors provide high power capability also at low temperatures and a very high number of charging/discharging cycles without efficiency loss. (Meishner, et al. 2019)

Due to the very short recharge time supercapacitors allow to supply for high and frequent power demand peaks. Similar to FESS supercapacitors can be produced in different sizes for various applications as electric or hybrid vehicles improving performance, efficiency and economic viability, storage systems for the improvement of power quality in distribution and transport systems, for example in railways, for the integration of renewable energies and other applications. (Guerrero et al.)

Examples for applications

Besides hybrid applications for the reuse of breaking energy in railways and diverse vehicles, supercapacitors can also replace batteries in electric vehicles entirely. Also, stationary storages for power quality and voltage changes are feasible, even if the technology is not mature yet. For the integration of renewable energies, they are used especially in wind power plants. (Castro-Gutierrez, 2020)

» Electric tram

Supercapacitors provide charging times for trams around 30 seconds which allows for charging at each stop without the need for overhead cables, along with a long lifetime. Furthermore, breaking energy can be reused to around 85%. Examples are:

- Changshui International Airport, Yunnan province, Southwest China: in 2020 the autonomous supercapacitor tram was produced for the airport line, comprising 7 carriages and a speed up to 70 km/h.

» Electric bus

Latest generation supercapacitors in place of batteries in electric buses provide ranges of up to 40 km due to reduced weight and up to 35% of breaking energy recovery.

- The SmartBUS in Turin, Italy is running on a 17 km line with 10 minutes charging time.

- Expected benefits

Similar to FESS, supercapacitors are suited for applications regarding high voltage and relatively short time and can be customised.

- Relevant investments

Supercapacitors have comparative high investment costs of around 10.000 $/kWh, but low installation and maintenance costs.

- Possible technical barriers

Supercapacitors providing a very high power capacity require large and heavy systems and still provide only a low energy density. Not much information is available yet for stationary storage based on supercapacitors.

2.3. Flywheel Energy Storage Systems (FESS)

Flywheels are mechanical devices to store kinetic energy and release it by applying torque to a mechanical load. To reduce friction the rotors spin in a vacuum shell at 20,000 to over 50,000 rpm. Small-sized flywheels can be used as storage devices in uninterruptible power supplies (UPS) as well as in vehicles.

Flywheels are used for energy storage since the eighteenth century, where the first flywheels were made out of cast iron and had rather low rotational velocity. When new materials with greater strength and higher rotational velocity were developed, also applications in transport became common, for example on ships and trains. With further development in the twentieth century Flywheels were used in electric vehicles for energy back up.

With growing importance of energy storage solutions new research in flywheels results in lighter new materials, optimised in uniform strengths and shapes, in order to avoid friction loss flywheels are in most cases supported by active magnetic bearing (Xiaojun Li, 2021). A new generation of flywheel systems with energy efficiencies up to 90 %, storage potential of up to 500 MJ and a power domain from KW to GW provides a wide range of functions.

The use of Flywheels Energy Storage System (FESS) has become more popular in the last years, mainly due to the following characteristics (Arabkoohsar et al. 2021):

» Long lifetime without capacity losses (very high number of charging and discharging cycles)

» High power quality (voltage stability, fast response)

» No temperature dependencies

» Precise verification of state of charge / state of health

» No risk for transportation, no deep discharge problems

» Minimal environmental impact (No toxic or limited resources required)

According to their characteristics flywheels are most suitable for applications which require frequent charge/discharge at a large number of cycles storing energy at a high efficiency. According to estimations about lithium-ion batteries being the most cost-competitive application after 2030, FESS can still be competitive for applications related to grid regulation, also connected to the fluctuation of renewable energy generation (Xiaojun Li, 2021).

Examples for applications:

Flywheels in vehicles in public transport are used since around 80 years, an example is the Gyrobus developed in the 1940s in Switzerland, which was running until 1960 . The first buses made 4 to 6 km distances with speeds up to 50 or 60 km per hour, but with rather heavy and large flywheels which besides safety issues and long charging times also caused challenges in operation, for example for the change of direction. (Patowary, 2019).

In newer applications FEES can reduce 10-15% of energy consumption in rolling stock. In electrified railways onboard applications they can support the voltage and reduce power demand during acceleration, in trams FESS can store breaking energy for acceleration in a hybrid system to improve the energy efficiency or be the only propulsion system with charging in every stop.

» On-board FESS for battery lifetime prolongation for electric buses

Simulations on real bus lines in daily operation considering different energy management systems and flywheel configurations show that a hybrid energy storage system consisting of a FESS supporting a battery results in 20% of lifetime increase on average. The FESS is buffering power spikes during operation. (Glücker et al. 2021)

» Stationary FESS for grid stability and fast charging applications

In the Austrian research project “FlyGrid”, a FESS is developed for a fully automated EV charging station One module of this prototype will be used as the reference case and will deliver 5 kWh at 100 kW peak power. (Haidl et al. 2019).

- Expected benefits

Due to the characteristics FESS are well suited for applications regarding high voltage and relatively short time, as storing of breaking energy and releasing it for acceleration, providing services for grid stability or/ and the integration of renewable energies. Due to very different sizes and capacities FESS can be part of stationary storage, increase energy efficiency in rolling stock, support batteries to extend their lifetime in electric vehicles or be the main propulsion system. FESS can be installed in retrofits and new lines.

- Relevant investments

Flywheels with a rapid charge-discharge process and long lifetime/lifecycle (20 years to nearly unlimited) are comparably in performance to supercapacitors but provide a slightly higher energy density, unfortunately investment costs are still high even though lifetime costs are lower as well as service requirements.

- Possible technical barriers

Flywheels with recent improvements of materials and power electronics accompanied by falling prices are available in different sizes for various applications also in the transport sector, unfortunately use cases so far are not on big scale but rather pilots or demonstrations, why also detailed data is hard to find.

Safety issues have to be considered.

2.4. Overview of benefits and barriers

The following table summarizes the main expected benefits and barriers of the reviewed technologies, in order to assess their opportunity of application in the use cases to be developed in the transnational handbook.

Technology	Expected benefits	Possible technical barriers	Possible regulatory barriers
Li-Ion-batteries	high energy density, low self-discharge	degradation, temperature sensitive, safety standards	related to second life reuse
Second life batteries	extension of the lifetime of batteries	missing standardisation, also for remaining capacity and charging	no regulatory framework, fiscal rules, energy taxes
Supercapacitor	no capacity loss, long lifetime, very low charging times, high voltage	high investment costs, low energy density, large and heavy systems for high power capacity	n.a.
Flywheels	no capacity loss, long lifetime, low charging times, high voltage, retrofitting	high investment costs, low energy density	possible safety regulations

Figure 2: Storage technologies, benefits and barriers (EffcienCE, 2021)

3. Good practices across Europe and beyond

In this chapter, we provide relevant examples of the application of storage technologies in public transport operations and infrastructure, that will represent the basic reference for the development of use cases for the transnational handbook on energy storage in public transport infrastructure.

The review includes good practices developed within the EfficienCE project pilots in Maribor, Pilsen and Gdynia, and a shortlist of worldwide cases broadening the range of examples of storage technologies applications in public transport infrastructure.

3.1. Experiences from the EfficienCE project

As mentioned, the first group of good practices has been selected among the EfficienCE pilot actions. These examples, although focusing on different specific purposes (recuperation of breaking energy, multipurpose use of charging infrastructure, energy buffering in trolleybus networks), are all characterized by the use of storage technologies in depots, along lines, in stations.

Maribor - Multipurpose use of public infrastructure for e-Bus charging

The objective of the Maribor pilot action is to implement e-bus fast chargers in multipurpose charging facilities located by an existing cable car station and by the railway station. The infrastructures for multipurpose charging are placed at the termini of the bus line.

The approach for the implementation follows three steps. In the first one, a spatial planning analysis has been run in order to identify criteria for Bus route priority for electrification. Secondly, the technical feasibility of the solution has been explored on the basis of real life data and and analysis of the energetic performance of electric solutions. The third step consisted in the analysis of the total cost of ownership of different solutions (based on mumber of buses, battery capacities, and number of chargers) to identify the most economiclly viable option.

The solution identified for the analyzed route according to spatial planning, technicl feasibility and economic viability analyses envisages the instattation of two fast chargers (150 kW and 300 kW), and the acquisition of two 12 meter e-buses with 73 kWh LTO batteries.

Focusing on the cable car station, the modernization involves the integration of a fast charger for multipurpose use of the existing public transport (PT) infrastructure. The power of the cable car substation used for the operation of the cable car can also be shared for the charging of an e-bus as well as e-cars. The substation has a capacity of 630 kVA, and given the current load and the capacity of one charging station, 230 kVA would be sufficient to build two charging stations.

Pilsen - buffer storage station in trolley network for energy efficiency

Deployment of a large number of in-motion charging trolleybuses means higher electricity consumption in the sections where these vehicles move and charge (so far 8 articulated and 22 12 meter battery vehicles).

In-motion charging trolleybuses and their consumption can generate a reduction in the voltage at higher loads and therefore short-term mains failures or instantaneous failures of the trolleybus drive units.

To avoid that, the construction of a new substation or cables reinforcement would require high investment costs and long-term preparation. The public transport operator identified as possible technical solution the installation of a buffer storage station along the line.

The chosen alternative has been to install a buffer storage station based on high power batteries and intelligent computer control, a galvanic separated traction drive unit (DC 600 V / DC 600 V) assuring safe and reliable transfer of energy to and from the traction.

Possible future upgrades may include the use of high capacity batteries (and second hand) and/or the integration of a small photovoltaic power plant for energy provision on site.

Gdynia recuperated braking energy and RES to power trolley depot building

In Gdynia, the pilot action focuses on the optimization of energy resources within the trolleybus depot building, through a mix of technological applications.

The depot is equipped with a 0,5MW peak PV-power plant on the roof generating annually roughly 450MWh to be fed directly to the trolleybus grid (5% of total usage). Moreover, the braking energy from the buses is recuperated thanks to an energy inverter allowing to feed the otherwise wasted energy directly into the building's energy system.

The device also controls the level of energy consumption in the traction network, detects unused energy and thoroughly controls the energy consumption of the depot building, further enhancing its already existing energy monitoring system (EMS).

The inverter system is equipped with an innovative storage energy system, which can accumulate recovered unused recuperation energy in case there is no load on AC output. For this purpose, one battery module from a trolleybus traction battery is used (second life application).

3.2. Energy storage applications in PT infrastucture around the world

In this section we propose a review of good practices on energy storage applications in public transport infrastructure, in some cases integrating the already reviewed approaches with functions such as vehicle to grid, wayside energy recovery systems, integration of renewable energies.

London - Bus2Grid

Although vehicle to grid applied to public transport is considered by experts as one of the transport applications with most potential due to the characteristics and size of batteries as well as the operational patterns of buses, no significant test results have been made available to the public so far.

The Bus2Grid project is a first of a kind initiative aiming at exploring the potential benefits of V2G technologies applied to bus fleet, highlighting not only their commercial potential but also the environmental and social benefits related to both the energy and passenger transportation systems.

The project is led by SSE Enterprise in partnership with the Mayor of London, Transport for London (TfL) and Go-Ahead London. It is funded by the Department for Business, Energy and Industrial Strategy (BEIS) and the Office for Low Emission Vehicles (OLEV) with support from Innovate UK. The project started in 2021 and will run for three years.

So far, London Bus2Grid is the world's largest V2G project and it is located in the Northumberland Park garage, where a fleet of 100 new zero-emission electric buses is stored and the depot is equipped with bidirectional chargers.

The buses are AC charged with 2 x 40kW on-board-chargers, and therefore equipped with mobile discharge facility. This choice differs from most of the ongoing V2G projects, which opted for DC charging where the certification required interests the charge point rather than the vehicle. The technological choice, although more complex, is aimed at better exploiting the potential of bus fleets, as well as the economic benefits of large scale V2G.

Hamburg - Hamburg goes electric (direct use of wind power in bus batteries)

In the Hamburg Alsterdorf depot, two of the six carports have been equipped with smart infrastructure for e-bus charging, consisting in 96 charging points and 240 parking spaces.

The charging concept is modular, consisting of in: scalable charging infrastructure design (expandable), electricity supply - ring circuit connected to the Hamburg power grid via a substation; Modular standard transformers (1,600 KVA) supply power to up to 16 buses.

Buses will be charged overnight, with a maximum charging capacity of 150kW per bus and average charging time of 4-5 hours. One notable characteristics of the project is that in this case buses are charged in times where the excess wind energy generated can be used, therefore enhancing the integration of renewable sources in the grid.

Madrid - eLobster (H2020)

The eLobster project aims at improving the synergies between light railway infrastructure and electricity distribution networks, in order to reduce electricity losses and increase the grid stability especially in scenarios where a high integration of renewable energies is possible.

The solution proposed is based on the development of an integrated Railway + Grid Management System which starting from the real time analysis of energy losses will be able to optimize the interexchange of electricity between the networks maximizing local RES self-consumption.

The demonstrator site of E-LOBSTER is the Metro de Madrid as its underground railway is connected to a local power distribution network with a high penetration of RES.

Coventry - recycled bus battery cells in an onsite battery energy storage system

Recycled bus power cells are being reused by the transport provider National Express in a stationary battery solution to provide power to electric vehicles and thus greatly extend their useful life. The stationary battery is a Time Shift B.V. 1MW/1.2MWh battery with second life BYD cells that were originally from buses operating in the Nordics. The application, provided by the energy equipment and solutions company Zenobe. Are expected to allow the battery life to be extended by around 30% resulting in less waste and lower replacement costs.

Solingen (DE) - Project BOB

Within the BOB project, funded by the German Ministry for transport and digital infrastructure, the catenary network of trolleybuses will be integrated into the city's electricity network.

The overhead line network is coupled to the medium-voltage network, allowing braking energy to be fed back into the network. Photovoltaic systems along the overhead line can feed the direct current generated directly into the grid without loss. Batteries installed in substations can store electricity and deliver it when required. Charging points for electric cars can be customers.

Los Angeles, United States – Way Side Energy Storage System (WESS)

The project Way Side Energy Storage System (WESS), based on five years of research and development, integrated the VYCON REGEN flywheel-based system into the Red and Purple Line Traction Power Substation (TPSS) at the Westlake/McArthur Park station.

The system collects the breaking energy of the metros in curves or when entering the passenger station near WESS TPSS, stores this energy and provides it to the next train that needs it. Therefore, it lowers the peak power demand and realizes a 10-18% reduction of the traction power energy. The system is running in daily full operation since August 2014. The annual savings are estimated at around 541 MWh which equals the energy supply for 100 average California homes.

4. Identification of use cases for the transnational handbook

In this chapter, three relevant use cases are identified according to the analysis of functionalities and technologies and to the review of good practices carried out in the previous chapters. The cases will be developed and described in detail within the in the Transnational handbook for energy-efficient PT infrastructure Technologies deployment (D.T2.3.2), and cover the main application areas of energy storage technologies in public transport infrastructure.

For the design of the use cases, the transnational handbook will consider as framework blueprint the context of the City of Bergamo, where the SUMP implementation envisages the renovation of an important mobility node for the transport network, the construction of new light rail and eBRT lines, and the development of a multipurpose recharging network for electric vehicles.

The case of Bergamo, where an action plan for a better integration of renewable energies and storage systems in the public transport infrastructure is being developed within the EfficienCE project, represents a suitable framework representing a model context for the allocation of storage facilities for different purposes and to different types of infrastructure.

4.1. Energy efficient depot

Description

This use case will consider, analyse and compare different technological options for both the construction of new depots and the refurbishing of existing ones. The focus will be on the enhancement of the energetic performance of the depot through a better use of renewable sources where available (including braking) as well as a more efficient consumption, as well as on the contribution to energy autonomy and to the grid (e.g. Bus to Grid).

The planning of an energy efficient depot may involve a broad range of stakeholders such as the local authority, public transport operators and other providers (e.g. e-carsharing), energy TSOs and DSOs, as well as the citizens.

According to the use case background, the design and implementation of energy efficiency solutions for depots based on storage are mainly based on battery storage (new and second life), and investments include also PV systems and other renewable generation solutions, charging facilities (also V2G), monitoring systems, etc.

The main expected impacts are related to a higher energy efficiency through self generation and decrease of losses, a better integration of renewable sources, and the related environmental and economic benefits.

The following table summarizes a first selection of expected relevant Key Performance Indicators that may be analysed within the use case development.

D.T2.4.1 - Definition of evaluation framework

COD	DOMAIN	KPI	Description	Measurement Unit
T1	Technical	Degree of energetic self-supply by RES	Ratio of locally produced energy from RES and the energy consumption over a period of time (e.g. month, year); the quantity of locally produced energy is interpreted as by renewable energy sources (RES) produced energy	%
T2	Technical	Reduced energy curtailment of RES and DER	Reduction of energy curtailment due to technical and operational problems; the integration of ICT will have an impact on producers, as the time for curtailment will be reduced, and the operative range will be wider	%
T3	Technical	Average number of electrical interruptions per customer per year	Average number of electrical interruptions per year	N*year
T6	Technical	Energy savings	Reduction of the energy consumption due to the implementation	kWh, %
T7	Technical	Storage Capacity	Energy storage technologies installed capacity	kWh
T8	Technical	Battery Degradation Rate	Capacity losses of the batteries, through use (some cycles) and through time (some years); the conclusions of this KPI concern the effectiveness of this technology, the need for maintenance and thus, gives useful data concerning the financial feasibility of its integration	kW, %
T9	Technical	Storage Energy Losses	Losses generated by battery storage, including the added voltage transformations	kWh, %
T16	Technical	EVs charging stations, solar powered, V2G enabled	Number of EV charging stations installed (rapid-ultrarapid, fast <22kW, slow <10kW) and density	N, N*Km2
E1	Environmental	Increase in Local Renewable Energy Generation	Renewable Energy generataed by the project	kWh*year, %
E2	Environmental	Carbon dioxide Emission Reduction	CO2 emissions reduction achieved by the project, and percentage on the relevant context	Tonnes*year, %
E3	Environmental	Decreased emissions of Particulate matter	PM10 and PM2,5 emissions reductions achieved by the project	Tonnes*year, %
EC1	Economic	Reduction of energy expenditure	Economic benefits of the intervention in terms of reduced cost of the consumed energy	€*kWh, €*year
EC2	Economic	Return on Investment (ROI)	Ratio between the total incomes/net profit and the total investment of the project	%
EC3	Economic	Payback	Time needed to cover investment costs. Payback period is usually considered as an additional criterion to assess the investment, especially to assess the risks	N of years
EC4	Economic	Carbon dioxide Emission Reduction cost efficiency	External costs saved per year	€
EC5	Economic	Particulate matter reduction cost efficiency	External costs saved per year	€
EC7	Economic	Total Investments	Value of asset or item that is purchased or implemented with the aim to generate payments or savings over time	€*m2 or €*kW
EC8	Economic	Total Annual costs	Sum of capital-related annual costs (e.g. interests and repairs caused by the investment), requirement-related costs (e.g. power costs), operation related costs (e.g. costs of using the installation) and other costs (e.g. insurance)	€*year

Figure 3: KPIs for the evaluation of impacts in use case storage (EffcienCE, 2021)

Challenges/barriers

The implementation of storage solutions for energy efficient depots can face different orders of challenges and in some cases barriers, in particular related to the regulatory context when talking about V2G and energy dispatching, and related to the evaluation of costs and benefits of investments needed. Moreover, social acceptance represents a relevant element to be taken into account when planning for new infrastructure in densely populated neighbourhood and the challenges related to storage and V2G can bring benefits to be considered.

The use case description will be completed with the identification of conditions for the evaluation and scaling up of solutions in the network and at urban and FUA level.

4.2. Smart node

The second use case focuses on the design of a smart node, as a station, stop or multimodal hub where storage can be adopted to enable the efficient use of renewable sources as well as well as the multipurpose use of charging infrastructure. Different approaches will be considered, from the pure improvement of the energy efficiency and performance of the infrastructure to the active contribution of vehicles and generation to the stability of the grid.

The engagement of stakeholders will focus in particular to the technical side both concerning mobility (public transport operators and other providers), and energy (TSOs and DSOs).

The selection of solutions for smart nodes based on storage will consider a variety of technological options including batteries, flywheels and supercapacitors and assessing their potential according to the characteristics of the nodes and systems.

The main expected impacts are related to the integration of renewable sources, the support to the grid and energy efficiency, in order to improve operational efficiency and therefore enhance the environmental and economic performance of the infrastructure.

Challenges/barriers

The implementation of storage solutions for smart nodes may face in particular challenges and technical barriers due to the complexity and interactions among different systems. In particular, the implementation of multipurpose charging systems and the energy exchanges among different services may require in depth regulatory and business models analyses.

The use case description will be completed with the identification of conditions for the evaluation and scaling up of solutions in the network and at urban and FUA level.

The following table summarizes a first selection of expected relevant Key Performance Indicators that may be analysed within the use case development.

D.T2.4.1 - Definition of evaluation framework

COD	DOMAIN	KPI	Description	Measurement Unit
T1	Technical	Degree of energetic self-supply by RES	Ratio of locally produced energy from RES and the energy consumption over a period of time (e.g. month, year); the quantity of locally produced energy is interpreted as by renewable energy sources (RES) produced energy	%
T6	Technical	Energy savings	Reduction of the energy consumption due to the implementation	kWh, %
T7	Technical	Storage Capacity	Energy storage technologies installed capacity	kWh
T8	Technical	Battery Degradation Rate	Capacity losses of the batteries, through use (some cycles) and through time (some years); the conclusions of this KPI concern the effectiveness of this technology, the need for maintenance and thus, gives useful data concerning the financial feasibility of its integration	kW, %
T9	Technical	Storage Energy Losses	Losses generated by battery storage, including the added voltage transformations	kWh, %
E1	Environmental	Increase in Local Renewable Energy Generation	Renewable Energy generataed by the project	kWh*year, %
E2	Environmental	Carbon dioxide Emission Reduction	CO2 emissions reduction achieved by the project, and percentage on the relevant context	Tonnes*year, %
E3	Environmental	Decreased emissions of Particulate matter	PM10 and PM2,5 emissions reductions achieved by the project	Tonnes*year, %
E4	Environmental	Decreased emission of oxides (NOx)	Percentage reduction in NOx emissions (NO and NO2) achieved by the project	Tonnes*year, %
EC1	Economic	Reduction of energy expenditure	Economic benefits of the intervention in terms of reduced cost of the consumed energy	€*kWh, €*year
EC2	Economic	Return on Investment (ROI)	Ratio between the total incomes/net profit and the total investment of the project	%
EC3	Economic	Payback	Time needed to cover investment costs. Payback period is usually considered as an additional criterion to assess the investment, especially to assess the risks	N of years
EC4	Economic	Carbon dioxide Emission Reduction cost efficiency	External costs saved per year	€
EC5	Economic	Particulate matter reduction cost efficiency	External costs saved per year	€
EC7	Economic	Total Investments	Value of asset or item that is purchased or implemented with the aim to generate payments or savings over time	€*m2 or €*kW
EC8	Economic	Total Annual costs	Sum of capital-related annual costs (e.g. interests and repairs caused by the investment), requirement-related costs (e.g. power costs), operation related costs (e.g. costs of using the installation) and other costs (e.g. insurance)	€*year

Figure 4: KPIs for the evaluation of impacts in use case smart node (EffcienCE, 2021)

4.3. Linear infrastucture

Description

The last use case analyses possible applications of storage technologies to the linear infrastructure, mainly with the purpose of supporting and balancing the grid, taking into account both stationary and in motion approaches.

Application like stationary and in motion batteries, as well as flywheels and supercapacitors will be considered in order to investigate the range of benefits that can be generated for the grid by the use of storage technologies, and their benefits and limitations.

The engagement of stakeholders will focus in particular to the technical side both concerning mobility (public transport operators and other providers), and energy (TSOs and DSOs).

The main expected impacts are related to the support to the grid, in order to improve operational efficiency and therefore enhance the environmental and economic performance of the infrastructure through economically viable solutions.

Challenges/barriers

The implementation of storage solutions for linear infrastructure may face in particular economic challenges related to the investments needed, but at the same time can represent opportunities for deferring relevant investments on the grid and to fine more flexible solutions for the stabilization of the grid. In some case specific regulatory barriers might be in place for different technological applications (e.g. safety regulations on flywheels).

The use case description will be completed with the identification of conditions for the evaluation and scaling up of solutions in the network and at urban and FUA level.

The following table summarizes a first selection of expected relevant Key Performance Indicators that may be analysed within the use case development.

Interreg CENTRAL EUROPE EfficienCE D.T2.4.1 - Definition of evaluation framework

COD	DOMAIN	KPI	Description	Measurement Unit
T1	Technical	Degree of energetic self-supply by RES	Ratio of locally produced energy from RES and the energy consumption over a period of time (e.g. month, year); the quantity of locally produced energy is interpreted as by renewable energy sources (RES) produced energy	%
T2	Technical	Reduced energy curtailment of RES and DER	Reduction of energy curtailment due to technical and operational problems; the integration of ICT will have an impact on producers, as the time for curtailment will be reduced, and the operative range will be wider	%
T3	Technical	Average number of electrical interruptions per customer per year	Average number of electrical interruptions per year	N*year
T4	Technical	Average length of electrical interruptions (in hours)	Sum of the duration of interruptions in hours (numerator) divided by the total number of interruptions (denominator); the result shall be expressed as the average length of electrical interruptions in hours	Hours
T6	Technical	Energy savings	Reduction of the energy consumption due to the implementation	kWh, %
T7	Technical	Storage Capacity	Energy storage technologies installed capacity	kWh
T8	Technical	Battery Degradation Rate	Capacity losses of the batteries, through use (some cycles) and through time (some years); the conclusions of this KPI concern the effectiveness of this technology, the need for maintenance and thus, gives useful data concerning the financial feasibility of its integration	kW, %
T9	Technical	Storage Energy Losses	Losses generated by battery storage, including the added voltage transformations	kWh, %
T15	Technical	Efficient vehicles deployed	Number of efficient vehicles (electric/hybrid buses/trolleybuses) deployed, and percentage on total fleet	N, %
E1	Environmental	Increase in Local Renewable Energy Generation	Renewable Energy generataed by the project	kWh*year, %
E2	Environmental	Carbon dioxide Emission Reduction	CO2 emissions reduction achieved by the project, and percentage on the relevant context	Tonnes*year, %
E3	Environmental	Decreased emissions of Particulate matter	PM10 and PM2,5 emissions reductions achieved by the project	Tonnes*year, %
E4	Environmental	Decreased emission of oxides (NOx)	Percentage reduction in NOx emissions (NO and NO2) achieved by the project	Tonnes*year, %
EC1	Economic	Reduction of energy expenditure	Economic benefits of the intervention in terms of reduced cost of the consumed energy	€*kWh, €*year
EC2	Economic	Return on Investment (ROI)	Ratio between the total incomes/net profit and the total investment of the project	%
EC3	Economic	Payback	Time needed to cover investment costs. Payback period is usually considered as an additional criterion to assess the investment, especially to assess the risks	N of years
EC4	Economic	Carbon dioxide Emission Reduction cost efficiency	External costs saved per year	€
EC5	Economic	Particulate matter reduction cost efficiency	External costs saved per year	€
EC6	Economic	Oxides (NOx) reduction cost efficiency	External costs saved per year	€
EC7	Economic	Total Investments	Value of asset or item that is purchased or implemented with the aim to generate payments or savings over time	€*m2 or €*kW
EC8	Economic	Total Annual costs	Sum of capital-related annual costs (e.g. interests and repairs caused by the investment), requirement-related costs (e.g. power costs), operation related costs (e.g. costs of using the installation) and other costs (e.g. insurance)	€*year

Figure 5: KPIs for the evaluation of impacts in use case linear infrastucture (EffcienCE, 2021)

5. Conclusions

The classification of functionalities, the analysis of technologies and the review of relevant good practices and projects in the field of energy storage for public transport infrastructure lead to the identification of three relevant use cases covering the main exemplary applications enabling a higher energy efficiency, a higher integration of renewable sources and a more effective contribution to the grid by public transport infrastructure.

The combination of energy efficient depots, smart nodes and linear infrastructure for public transport highlights the potential of innovative solutions development in optimizing the relationship between mobility and the energy grid.

The outline of the use cases, main result of the present deliverable, will represent the central element of the structure for the Transnational handbook for energy-efficient PT infrastructure Technologies deployment dedicated to energy storage (D.T2.3.2), where the experience of analyses and pilot actions from the projects will be catalyzed into guidance for the implementation of storage based solutions in public transport.

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