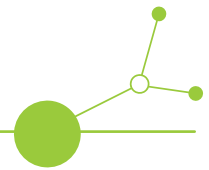


Deliverable D3.1.1

Report on pilot joint requirements,
preparation, implementation and evaluation

**Pilot: Simulation of e-corridor, energy
flows to simulate circular scenarios for
electrification upscaling in Gdynia, Poland**



Version 3
03 2025





DELIVERABLE D3.1.1

Pilot action Gdynia, Poland

Project index number and acronym	CE0100250 CE4CE
Lead partner	LP LVB
Deliverable number and title	D3.1.1 Report on pilot joint requirements, preparation, implementation and evaluation. Pilot: Simulation of e-corridor, energy flows to simulate circular scenarios for electrification upscaling in Gdynia, Poland
Responsible partner(s) (PP name and number)	PKA Gdynia (PP2), UG (PP3), Kruch (PP6)
Contributing experts	Dominika Kowalkowska, Marcin Wotek, Mikołaj Bartłomiejczyk, Jan Röhl, Agnieszka Szmelter-Jarosz, Aleksander Jagiełło
Project website	https://www.interreg-central.eu/projects/ce4ce/
Delivery date	31.03.2025
Status	Final
Dissemination level	Confidential



Authors and log change of the document

Partner No.	Partner Acronym	Name of the author	Action	Version
PP 7	UM	Danijel Hojski	Template design for reporting	V.0
PP2	PKA	Dominika Kowalkowska	Provided content and data, coordinated input of PP2 PKA	V.1
PP3	UG	Marcin Wołek	Provided content and data, coordinated input of PP3 UG	V.1
PP6	Kruch	Jan Röhl	Provided content and data	V.1
PP3	UG	Mikołaj Bartłomiejczyk	Provided content	V.1
PP3	UG	Agnieszka Szmelter-Jarosz	Provided content	V.1
PP3	UG	Aleksander Jagiełło	Provided content	V.1
PP 7	UM	Danijel Hojski	Review	V.2
LP	LVB	Ana-Maria Baston	Review and finalisation	V.3



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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.

The implementation of the CE4CE pilot in Gdynia followed a phased and collaborative approach, aligning closely with its initial design. The project aimed to test and optimize electrification strategies for public transport using a Digital Twin of the city's Western Corridor—a critical section of Gdynia's trolleybus network. Overall, the deployment process was smooth, supported by strong institutional coordination, technical preparedness, and access to reliable operational data from the existing public transport system.

The CE4CE pilot in Gdynia has demonstrated measurable impacts in reducing energy consumption, optimizing infrastructure investments, and promoting environmentally and economically sustainable public transport. Its digital planning foundation ensures that these benefits could extend beyond the pilot period, enabling long-term circular mobility strategies in Gdynia and beyond.

This document is a report on pilot action in Gdynia 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 addresses relevant regions concerned by the pilot action.

Chapter 3 briefly explains the implementation of circular economy principles in the Gdynia pilot project, which focuses on the electrification of public road transport.

Chapter 4 is about key development phases of the pilot action, starting from the design phase to the reporting and documentation phase.

Chapter 5 focuses on preparation and technical requirements for each phase.



Chapter 6 contains the 4 phases of the pilot action implementation.

Chapter 7 explains the operational launch as part of the evaluation.

Chapter 8 presents the monitoring and evaluation phase as a continuous process following the operational launch.

Chapter 9 offers an overview of best practices among Europe that integrate circular economy principles.

Chapter 10 focuses on risks identification that helps define mitigation measures.

Chapter 11 is about the key impacts of the pilot project.

Chapter 12 addresses the possibility of the pilot project to be implemented in other cities and regions.

Chapter 13 contains the references of the document.

2. NUTS region(s) concerned by the pilot action (relevant NUTS level)

The region that is covered by the pilot action refers to the city of Gdynia.

Country (NUTS 0)	PL
Macroregion (NUTS 1)	Polish Northern macroregion
Region (NUTS 2)	Pomorskie (PL63)
Sub-region (NUTS 3)	Trójmiejski (PL633)

3. Basic pilot concept

The CE4CE pilot project in Gdynia focused on advancing circular economy principles through the electrification of public road transport. Building upon Gdynia's longstanding trolleybus network—operational since 1943 and modernised with In-Motion Charging (IMC) technology since 2015—the project seeks to develop a Digital Twin to model, simulate, and optimise electrification strategies.

Introducing electric buses into operation in 2022 accelerated the electrification process of the public transport fleet in Gdynia. The choice of the operational model (opportunity charging) and specific bus lines was preceded by thorough analyses and a negotiation process between the city authorities, the transport organizer, and the transport operator.

The simultaneous operation of electric buses and trolleybuses potentially allows them to leverage their advantages in serving a city as functionally and spatially diverse as Gdynia. Table 1 presents the advantages and disadvantages of both road-based public transport systems. In practice, purely "opportunity charging" systems are not encountered; instead, a mixed system is used, including overnight bus charging. However, due to the smaller battery capacity and, as a result, shorter range, such buses require additional charging at terminal stops during the day.



Table 1. Advantages and disadvantages of particular electric public road transport systems solutions

SYSTEM	ADVANTAGES	DISADVANTAGES
Trolleybus IMC	<p>Smaller size of the battery.</p> <p>No need for additional charging infrastructure.</p> <p>Possibility to integrate PV with the catenary network.</p>	<p>Higher cost of vehicle purchase.</p> <p>A substantial amount of infrastructure needs to be developed if a new system is being deployed.</p>
Opportunity charging e-bus	<p>No need for overhead charging.</p> <p>Highest flexibility of service.</p>	<p>Fast chargers are needed in specific locations in a city.</p> <p>Limited daily mileage.</p> <p>Mileage impacted by heating / air conditioning.</p>
Overnight charging e-bus	<p>No need for overhead charging.</p> <p>Highest flexibility of service.</p>	<p>The largest battery capacity.</p> <p>Mileage impacted by heating / air conditioning.</p>

Therefore, choosing a specific solution for serving a city or transport corridor is a strategic decision, as it determines the mode of operation for a minimum of 12 to 15 years.

This results from the expected vehicle lifecycle (12-15 years), and in the case of trolleybus infrastructure, even up to 30 years. Making decisions with such a long-term perspective requires considering many variables, but it always involves the risk of being unable to foresee all of them.

Advancements in machine learning have enabled the development of new risk optimisation methods. One is the creation of digital twins, which allows for replicating numerous variables under typical operating conditions for a specific location.

The pilot focuses on the Western Corridor of Gdynia’s public transport system, selecting specific lines for detailed analysis. A digital model using EFS (Energy Flow Simulation) has been used to simulate the electrification of the Western Corridor using the following options:

- trolleybus IMC (In Motion Charging),
- trolleybus,
- electric bus (e-bus).

The main simulation objective was to simulate how much OCS (Overhead Contact System) and substation infrastructure is needed for IMC trolleybuses and how many additional e-buses are required for full electrification with the battery buses option.

The general project structure included three subcomponents:

- development of the digital model,
- validation of the model with real-world measurements on line 190,
- simulation-based study of the electrification of the Western Corridor.



3.1. Development of the digital model

Only the minimum necessary infrastructure for the mentioned lines was modelled. Possible extensions of the trolleybus infrastructure were previously defined with local partners (PKA Gdynia and UG). They were limited to areas between Gdynia Centrum, Kielecka, and Chwarzno-Wiczlino (so-called Western Corridor—Fig. 1).



Fig. 1. The spatial layout of the Western Corridor in Gdynia

The analysis considered existing bus lines 121, 140, 147, 160, and 190, with 12 m and 18 m in length vehicles. All other lines and external influences were excluded.

As part of the preparation for the simulation, three types of road sections were defined (Fig. 2):

- road sections with OCS (Overhead Contact System) - red colour,
- road sections without OCS, where buses operate using battery power - blue color,
- road sections with potential OCS extensions, indicating where new infrastructure could be added - green colour.

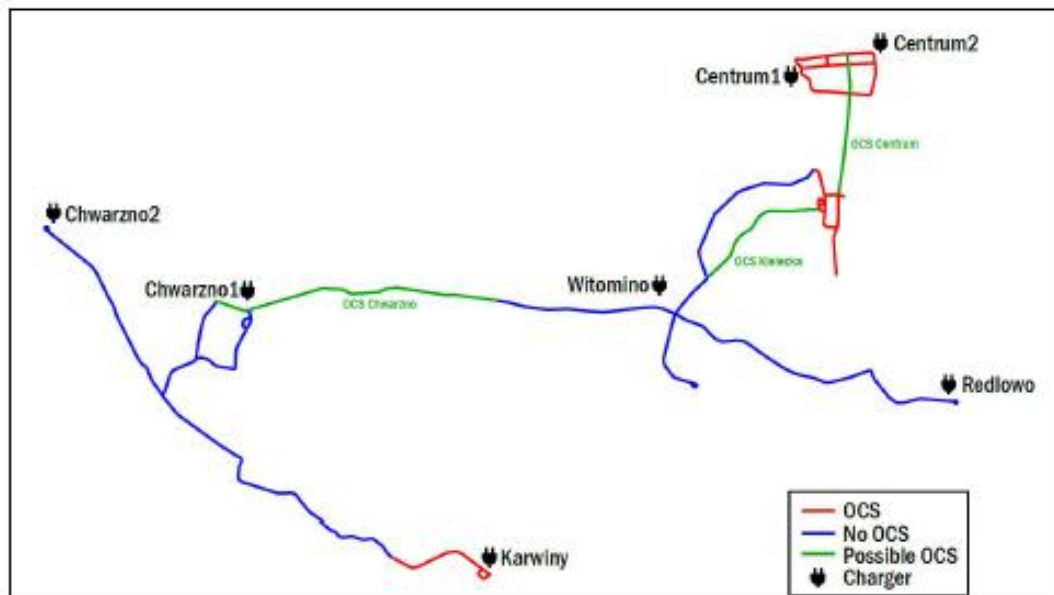


Fig. 2. The Western Corridor in Gdynia simulation scheme

PKA Gdynia and KRUCH have agreed to add three areas where OCS can be installed, allowing trolleybuses to charge while in motion. Table 2 presents the distance of each possible OCS extension.

Table 2. Length of possible road sections with OCS in the Western Corridor in Gdynia

Road section	Length [km]
OCS Centrum	1,51
OCS Chwarzno	3,12
OCS Kielecka	1,54

The chargers have been placed in seven locations, allowing only one vehicle to be charged simultaneously. However, this parameter can be modified on the EFS website in the charger's features.

Moreover, the EFS model has also introduced four new substations to feed the possible overhead network extensions.

Table 3 displays the frequency values, and the number of vehicles required for each line within the Western Corridor.



Table 3. Basic parameters of bus lines within the Western Corridor

LINE	FREQUENCY [MIN]	START TIME [MIN]	OFFSET [MIN]	NUMBER OF VEHICLES
121	20	19	5	3
140	13	11	9	7
147	15	11	7	7
160	20	4	1	3
190 Loop	10	0	9	6

It is essential to precisely define the departure times and the schedules, considering that the time at the end of the line will be the available time to charge the battery.

3.2. Validation

Simulation results have been compared with real-world measured data in the validation process. Real data extracted from buses operating on line 190 onboard computers have been used for validation. During validation, unexpected extra stops of vehicles between passenger stops were observed. To reflect reality more accurately, traffic lights were added to the simulation. A total of 32 traffic lights were incorporated into the model. Their locations were determined using satellite imagery (Google Earth and Google Street View). Most of the traffic lights are concentrated in the city centre (Fig. 3).

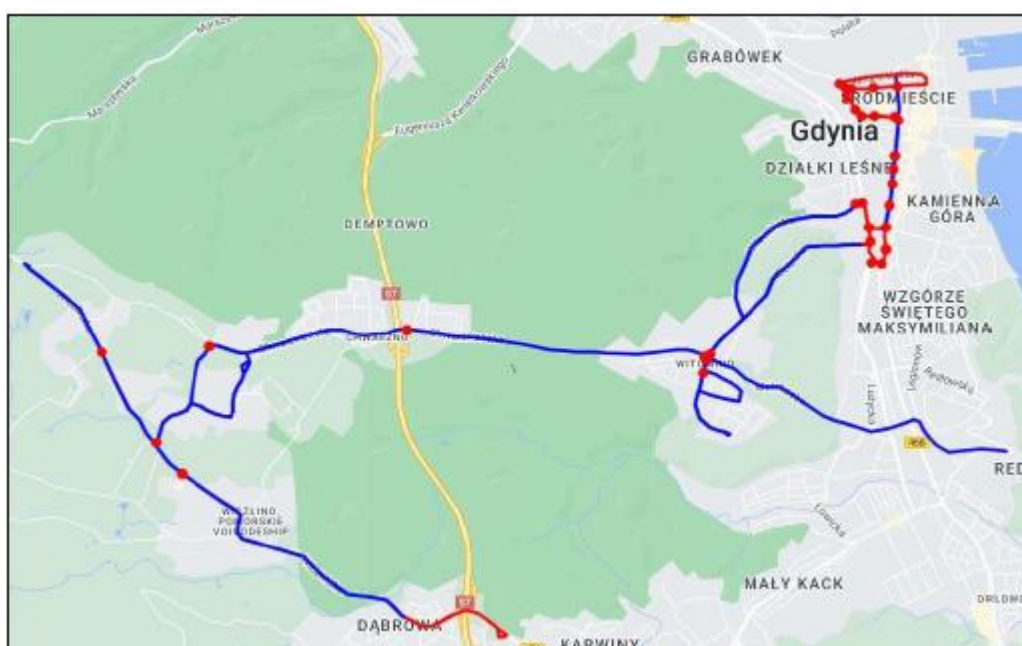


Figure 3. Traffic lights in the Western Corridor in Gdynia (as red points in the model).



Finally, the speed, energy consumed, and battery measurements compared to the EFS results showed a good correlation. Therefore, the validation process proved to be successful.

3.3. Simulation-based study of the electrification of the Western Corridor

The research approach involves running simulation scenarios using e-buses and IMC (In-Motion Charging) trolleybuses. Different configurations of the possible OCS (Overhead Contact System) have been tested, enabling and disabling specific segments. The following table presents which scenarios must be studied for each line. For instance, line 121 is just running through the possible OCS extension of Chwarzno, so the scenario of just running with e-bus and the scenario enabling the OCS Chwarzno will be investigated.

Table 4. EFS scenarios for the Western Corridor in Gdynia

Line	E-bus	OCS						
		OCS Centrum	OCS Kielecka	OCS Chwarzno	OCS Centrum + Kielecka	OCS Centrum + Chwarzno	OCS Kielecka + Chwarzno	OCS Centrum + Kielecka + Chwarzno
121	o			o		o	o	o
140	o	o	o	o	o	o	o	o
147	o	o	o	o	o	o	o	o
160	o	o	o	o	o	o	o	o
190 Loop	o	o			o	o		o

The worst scenario has been selected for the study. Table 5 contains the values maintained for all of the simulations conducted for the Western Corridor in Gdynia. The most “unfriendly” assumptions from the daily operational perspective are limited mileage under the trolleybus network (30%), challenging road conditions (“traffic jam”, resulting in less reliable service), fully deployed HVAC and full passenger load.

Table 5. Main assumptions for the EFS model

Parameter	Value
Wear contact wire	30 %
Temperature OCS	70 °C
Temperature feeding	90 °C
Mode	Traffic jam
Stopping time at stations	Random
Initial SOC	80%
HVAC	100 %
Passenger load	100 %
Charger power (12 and 18m)	250 kW
Number of vehicles charging at a charger position	1



3.4. Simulation results

Table 6 shows the number of buses to run each line according to the timetable. The first column shows the minimum number of vehicles needed to execute the timetable for the ideal case, or for the case, where batteries would be big enough to run the lines. The second and third columns present the real number of buses needed to run each of the lines taking into account battery size and SOC requirements after 10 hours of operation.

Table 6. Number of vehicles needed for each of the lines in the Western Corridor: e-bus option [results for the 12 meters vehicles]

Line	Number of vehicles needed (ideal/base)	Number of 12m-vehicles needed (real)	Number of 18m-vehicles needed (real)
121	3	3	3
140	7	9*	10*
147	7	10	10*
160	3	5	6*
190 Loop	6	9	9
Total	26	36	38

Table 7. Number of vehicles and simulation scenarios for the IMC trolleybuses [results for the 12 meters vehicles]

Line	Vehicles	IMC without OCS		IMC with extra OCS in Centrum		IMC with extra OCS in Chwarzno		IMC with extra OCS in Kielecka		IMC with extra OCS in Centrum and Chwarzno		IMC with extra OCS in Centrum and Kielecka		IMC with extra OCS in Chwarzno and Kielecka	
		SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]	SOC [%]	Battery [h]
121	3	20	1,4	20	1,4	49	>10	20	1,4	48,9	>10	20	1,4	49,1	>10
140	7	20	1	20	1	59,4	>10	20	2,7	59,8	>10	24,2	>10	64,2	>10
147	7	20	4	31,6	>10	66,4	>10	40,9	>10	68,8	>10	41,5	>10	71,1	>10
160	3	20	2	41	>10	67	>10	52	>10	68,8	>10	51,9	>10	78,8	>10
190Loop	6	54	>10	60,1	>10	54,7	>10	55,1	>10	60,3	>10	60,3	>10	56,1	>10

Table 8 shows the results of the different scenarios conducted for the e-buses and IMC trolleybuses in the Western Corridor in Gdynia. Viable scenarios are marked with a check, as the SOC of the vehicles operating on a particular line is above 20% in a 10-hour simulation.



Line	E-bus base	E-bus extra	IMC No extra OCS	IMC OCS Centrum	IMC OCS Kielecka	IMC OCS Chwarzno	IMC OCS Centrum + Kielecka	IMC OCS Centrum + Chwarzno	IMC OCS Kielecka + Chwarzno	IMC OCS Centrum + Kielecka + Chwarzno
121	✓		✗			✓		✓	✓	✓
140	✗	✓+2	✗	✗	✗	✓	✓	✓	✓	✓
147	✗	✓+3	✗	✓	✓	✓	✓	✓	✓	✓
160	✗	✓+2	✗	✓	✓	✓	✓	✓	✓	✓
190 Loop	✗	✓+3	✓	✓			✓	✓		✓
Total vehicles	26	36	26	26	26	26	26	26	26	26
Total chargers	7	7								
Extra Substations				1	1	2	2	3	3	4
Extra OCS km				1,51	1,54	3,12	3,05	4,63	4,66	6,17

Table 8. Final evaluation of scenarios for the Western Corridor in Gdynia

Conclusions from the EFS modelling

- The pilot project was initiated in September 2023 with the definition of its collaborative framework and scope.
- From December 2023 to October 2024, the project team focused on building the Digital Twin, simulating energy flows, validating different electrification options, and optimizing operational strategies based on socio-economic analyses.
- The findings from simulations performed using the Energy Flow Simulation (EFS) tool developed by KRUCH have been validated. It is possible to simulate various scenarios independently by the PKA or city authorities.
- In summary there have been over 110 simulations conducted using the digital model.
- All studied lines can be operated with either electric buses or IMC trolleybuses.
- Electric buses on lines 140, 147, 160, and 190 require more vehicles than IMC model of operation. Only line 121 shows no difference in vehicle requirements between the two options.
- IMC trolleybus operation on lines 121, 140, 147, and 160 requires OCS infrastructure extensions, especially including the Chwarzno section. No other setup ensures 10 hours of operation for both 12m and 18m IMC buses.
- Line 190 is the only one that can operate without extending the existing OCS infrastructure.
- 18-meter vehicle scenarios are less favorable compared to 12-meter ones.
- Ultimately, the CE4CE pilot in Gdynia demonstrates how the use of digital tools and real operational data can significantly support the transition toward more sustainable, cost-effective, and circular public transport systems.



3.5. Further development of scenarios

Multiple scenarios were tested within the EFS, including variations in service frequency (7-minute and 15-minute intervals) and traffic conditions (with and without congestion). Different charging strategies were evaluated, such as stationary charging, standard IMC charging, high-power IMC charging, and hybrid solutions combining these methods.

Key findings indicate that traffic congestion significantly increases operational costs by requiring a higher number of vehicles and larger battery capacities. Battery lifetime and the frequency of battery replacement emerged as crucial factors influencing the total cost of ownership (TCO) for electric buses. Additionally, the study revealed that prioritizing electric vehicles in traffic, for example through dedicated lanes, can help reduce battery size requirements, thus lowering overall investment costs. Furthermore, higher service frequency improves the cost-effectiveness of overhead IMC infrastructure.

4. Key pilot development phases

This section describes the key phases of the pilot, planning steps, activities, and the corresponding results, providing a timeline and an overview of progress.

Fig. 4. Presents the EFS development as a process.

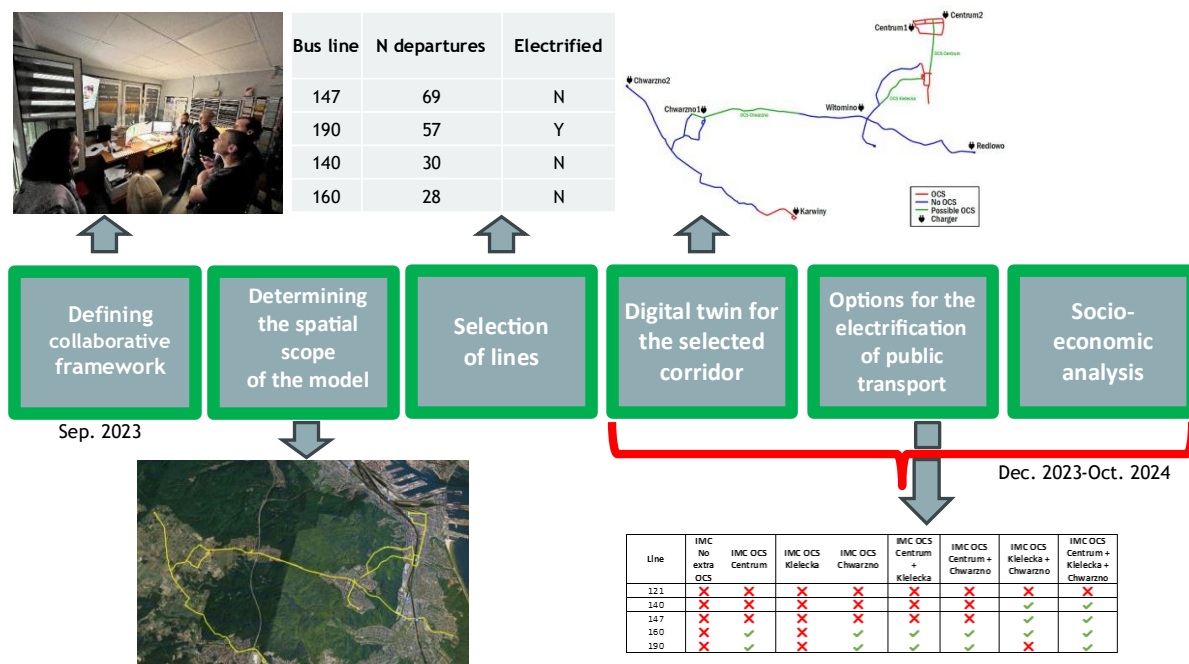


Fig. 4. The process of the EFS development for the Western Corridor in Gdynia



Table 9. Crucial milestones of the EFS pilot in Gdynia

Main milestones of the pilot project	Description	Duration of the stage	Calendar term	Responsible partner
Pilot Design	Defining the overall concept and design of the pilot project, including objectives, scope, and key deliverables. This stage also includes initial planning and resource allocation.	4 months	09.2023-12.2023	PP3 UG PP2 PKA PP6 Kruch
Stakeholders Engagement and joint development	Engaging key stakeholders through workshops, hackathons, and other meeting forms to gather feedback, validate assumptions, and align expectations.	14 months	03.2024-05.2025	PP3 UG PP2 PKA PP6 Kruch
Feasibility Study and Preparation	Conducting feasibility studies to assess technical, financial, and operational feasibility. This also includes securing necessary funding and permits.	8 months	01.2024-08.2024	PP3 UG PP2 PKA PP6 Kruch
Procurement Process(es)	Initiating the procurement process for the goods, services, or equipment required for the pilot project. Includes issuing tenders and selecting vendors.	Not applicable	Not applicable	Not applicable
Pilot Implementation	Overseeing the work of the contractors and ensuring that the implementation follows the project plan.	2 months	10.2024 - 12.2024	PP3 UG PP2 PKA PP6 Kruch
Operational Launch	Ensuring that all systems are fully functional, providing initial training for users and operators, and solving any initial operational challenges.	4 months	08.2024 - 12.2024	PP3 UG PP2 PKA PP6 Kruch
Monitoring and Evaluation	Collecting data and performance metrics to assess the pilot's effectiveness. This stage focuses on the monitoring of the system in real-time and evaluating its performance against objectives.	9 months	10.2024-06.2025	PP3 UG PP2 PKA PP6 Kruch
Reporting and Documentation	Compiling findings, data, and analyses into comprehensive reports. This includes both interim and final reports to document progress, results, challenges, and lessons learned.	6 months	03.2025-08.2025 (ongoing)	PP2 PKA PP3 UG PP6 Kruch



5. Preparation and technical requirements

5.1. Preparation for the CE4CE Pilot: meeting technical, social, environmental, and economic requirements

The preparation phase of the CE4CE pilot in Gdynia involved addressing a comprehensive set of **technical, social, environmental, and economic requirements** to ensure the successful implementation of electrified public transport using Digital Twin technology.

5.1.1. Technical requirements

- **Equipment Compliance:** All vehicle and charging systems—such as IMC (In-Motion Charging), high-power IMC, and stationary charging solutions—were required to meet **EU and national safety and interoperability standards** for electric public transport.
- **Digital Infrastructure:** The development of the Digital Twin demanded robust data integration frameworks, including real-time traffic, energy consumption, and operational data from Gdynia’s bus and trolleybus network.
- **Compatibility:** Charging infrastructure needed to be compatible with existing trolleybus systems, requiring retrofitting strategies and technical harmonization.
- **Simulation Accuracy:** Modelling tools had to accurately replicate real-world conditions, including congestion patterns and energy dynamics, requiring validation with historical data. This was delivered by one of the project partners (PP6 Kruch).

5.1.2. Social requirements

- **Stakeholder Engagement:** Early involvement of key stakeholders—including public transport operator (PKA), public transport authority (ZKM Gdynia), and trolleybus operator (PKT), and city authorities—was essential to build support and gather input for scenario design and policy recommendations.
- **User Acceptance:** Public awareness and ongoing public discussions were considered to ensure acceptance of potential changes, such as new charging stations or bus lane prioritization.
- **Operational Training:** PKA staff responsible for operating and maintaining the new systems required training on electrification technologies and battery management.

5.1.3. Environmental requirements

- **Regulatory compliance:** The pilot had to align with local and EU environmental policies, especially those related to **air quality, emissions reduction, and circular economy principles**.
- **Battery sustainability:** Battery technologies were assessed for **lifecycle impact**, including sourcing, energy efficiency, and end-of-life handling, with a preference for solutions that support second-life use or recycling.
- **Infrastructure footprint:** Charging station locations and overhead infrastructure extensions were planned to minimize disruption to urban green space and comply with environmental planning regulations.



5.1.4. Economic requirements

- **Cost-Benefit Analysis:** The Digital Twin simulations are based on multiple scenarios to ensure economic viability, including battery replacement frequency, vehicle requirements, and energy consumption.
- **Funding sources:** The pilot leveraged **EU sustainability funding**, local government contributions, and potential public-private partnerships to finance development and infrastructure deployment.
- **Operational efficiency:** Scenario testing aimed to minimize financial outlays through optimized fleet management, efficient energy use, and prioritization strategies that reduce battery size and infrastructure costs.

6. Implementation phase

The implementation of the CE4CE pilot in Gdynia was carefully structured to align with goals of PKA and public transport authority, and also broader EU climate and mobility policies. The process was organized into several distinct phases, beginning with the definition of the collaborative framework in September 2023, followed by technical development, stakeholder coordination, and simulation work carried out from December 2023 to October 2024.

Although the pilot primarily focused on digital modelling and scenario testing rather than immediate large-scale infrastructure deployment, it laid an important groundwork for future investment undertakings. As such, the project did **not involve a full public procurement or open tender process** during the pilot phase. However, **preliminary assessments of equipment and services** (e.g. charging system designs) were conducted in line with **Gdynia's internal public sector procurement policies**, ensuring transparency, competitiveness, and alignment with Polish and EU regulations. The project partner's software was used to prepare and carry out the simulation.

The pilot adhered to relevant **technical standards for digital infrastructure**, including data privacy, interoperability, and modeling accuracy, as well as **environmental and transport sector guidelines**. The project aligned with the EU's Green Deal objectives and the Polish National Urban Mobility Policy, particularly with respect to sustainable urban transport and digital innovation.

Key **stakeholders** involved in the implementation included:

- **PKA Gdynia (public transport operator)**, leading the technical integration and operational analysis
- **ZKM Gdynia** (the municipal transport authority), monitoring the correctness of operations done by PTO.
- **PKT Gdynia** - municipal trolleybus operator, providing the valuable data for comparison
- **Technology partner - Kruch Railway Innovations from Austria, who was also the project partner in CE4CE**, providing expertise for the Digital Twin modeling and simulation work
- **Research institution**, a project partner - University of Gdańsk, providing expertise for public transport operations, their modeling and simulation.
- **External policy advisors and mobility consultants**, offering input on socio-economic and regulatory implications, who were consulting and validating the results.

While direct regulatory constraints were limited at the pilot stage, the initiative remained mindful of future regulatory requirements related to electric vehicle infrastructure, battery management, and public transport emissions standards. The structured, multi-actor coordination during implementation ensured that the pilot's outcomes are actionable and scalable in future phases requiring formal procurement and infrastructure investment.



7. Process evaluation

7.1. Implementation Process and Execution

The pilot began with a clearly defined scope and partnership framework in September 2023. From December 2023 to October 2024, the project focused on developing the Digital Twin, running scenario simulations, and analyzing data. The PKA, UG and Kruch team succeeded in integrating real-time and historical operational data to simulate different traffic conditions, service frequencies, and charging strategies.

Scenarios tested included 7- and 15-minute service frequencies, varying congestion levels, and multiple charging configurations—such as stationary, standard IMC, high-power IMC, and hybrid models. The implementation remained largely faithful to the original plan, thanks to early stakeholder alignment and robust project management.

7.2. Challenges and Adjustments

Despite the overall success, the pilot encountered several challenges:

- **Data quality and integration:** Some initial delays occurred due to data formatting inconsistencies between different systems (e.g., traffic data vs. energy usage data). These were addressed through collaborative troubleshooting and technical support from research partners.
- **Battery modelling:** Accurately forecasting battery degradation and replacement cycles proved more complex than anticipated. As a result, sensitivity analyses were expanded to account for wider performance ranges.
- **Traffic modelling under congestion:** Simulating congestion scenarios with high precision required iterative calibration of the Digital Twin, which extended the timeline slightly in that module.

Minor adjustments were made to the simulation parameters and model calibration strategies, but the core objectives and methodology remained intact. Importantly, the iterative design of the Digital Twin allowed for flexible adaptation without compromising the integrity of the analysis.

7.3. Outcomes vs. Expectations

The pilot met or exceeded most expectations. It demonstrated the viability of using digital tools to inform electrification strategies and provided valuable insights into the trade-offs between battery size, service frequency, and infrastructure investment. The ability to evaluate total cost of ownership (TCO) under multiple scenarios, including congestion, was particularly impactful.

In summary, the CE4CE pilot was implemented effectively, with high technical rigor, responsive problem-solving, and valuable outputs that support the transition to a circular and sustainable public transport system.

8. Testing and evaluation phase

The evaluation of the CE4CE pilot in Gdynia was grounded in simulation-based testing using a Digital Twin of the Western Corridor public transport network. The goal was to assess various electrification strategies under realistic operational scenarios, with a focus on energy efficiency, infrastructure use, vehicle performance, and economic viability.



8.1. Testing Approach

The testing process involved simulating multiple operational scenarios over a projected service period, comparing performance under:

- **Different service frequencies** (7-minute vs. 15-minute intervals)
- **Traffic conditions** (congested vs. uncongested)
- **Charging strategies** (stationary, standard IMC, high-power IMC, hybrid models)

Digital simulations ran over periods equivalent to **annual operational cycles**, allowing for seasonal variation and long-term impact projections. The Digital Twin incorporated real operational data from Gdynia's trolleybus network, ensuring the accuracy and relevance of performance metrics.

8.2. Key Performance Indicators (KPIs)

Performance was evaluated using KPIs across technical, operational, environmental, and financial dimensions. Data was collected through a combination of:

- Simulation outputs from the Digital Twin model
- Historical operational and energy use data from PKA Gdynia
- Manufacturer specifications and lifecycle estimates (for batteries and charging systems)

Below is a table summarizing the primary KPIs used in the evaluation:

Table 10. KPIs proposed for the evaluation of the EFS pilot

Category	Indicator	Unit
Energy/Infrastructure	Energy consumption per vehicle-km	kWh/km
	Cost of charging infrastructure	EUR
Vehicles	Average battery size required per vehicle	kWh
	Battery lifetime (cycles)	Number of cycles
Operation	Number of vehicles required per scenario	Vehicles
Costs	Investment in charging infrastructure	EUR
	Battery replacement cost per year	EUR/year



8.3. Evaluation Robustness

The simulations covered both peak and off-peak periods, representing full operational conditions. KPI data was collected over virtual timelines replicating **multi-year operations**, allowing the team to assess lifecycle performance, cost dynamics, and energy efficiency. This robust dataset enabled sensitivity analysis, particularly regarding the influence of congestion and battery degradation on long-term costs.

In summary, the CE4CE pilot used a rigorous and data-driven evaluation method to test electrification strategies, producing actionable insights for sustainable and cost-effective public transport planning.

9. Best practices

Until now, no similar simulation has been conducted as part of previous projects.

10. Risks and contingency approach

Below there is a structured **Risk Assessment and Analysis** for the **CE4CE pilot project in Gdynia**, focused on the electrification of public road transport through Digital Twin simulation and optimization:

10.1. Strategic Risks

Risk	Description	Impact	Likelihood	Mitigation
Inadequate stakeholder engagement	Failure to effectively involve all key actors (transport operators, city planners, energy providers) could limit adoption.	Medium	Medium	Strengthening communication strategy and collaborative planning among stakeholders.

10.2. Technical Risks

Risk	Description	Impact	Likelihood	Mitigation
Digital Twin inaccuracies	Model limitations or data errors may lead to suboptimal or misleading strategy recommendations or longer time of simulations than expected.	High	Medium	Complex validation with real operational data; iterative model refinement.
Charging infrastructure mismatch	Selected charging strategies may not scale or integrate well with existing trolleybus infrastructure.	Medium	Medium	Pilot testing of hybrid and high-power IMC options before full deployment.



Battery degradation uncertainty	Real-world battery lifespans may differ significantly from simulated expectations.	High	High	Include safety margins in battery replacement planning; invest in battery health monitoring.
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10.3. Operational Risks

Risk	Description	Impact	Likelihood	Mitigation
Traffic congestion unpredictability	Congestion scenarios heavily impact cost models; real traffic may vary unpredictably.	High	High	Collaborate with urban mobility planners; consider adaptive priority measures for electric buses.
Resource constraints	Insufficient technical or financial resources may slow implementation.	Medium	Medium	Leverage EU funding opportunities and public-private partnerships.

10.4. Financial Risks (for the future deployment)

Risk	Description	Impact	Likelihood	Mitigation
Cost overruns from infrastructure upgrades	Overhead IMC or hybrid charging system expansion may exceed initial budget estimates.	High	Medium	Conduct phased investment with clear KPIs and milestones.
TCO underestimation	Battery replacement and energy costs may prove higher than forecast.	High	Medium	Build conservative assumptions into financial models; reevaluate TCO scenarios regularly.

10.5. Environmental & Social Risks (for the future deployment)

Risk	Description	Impact	Likelihood	Mitigation
Environmental impact of battery disposal	Increased battery use requires responsible end-of-life management.	Medium	High	Partner with certified recyclers; explore second-life battery use.
Public resistance to infrastructure changes	Introduction of priority lanes or charging stations could face local opposition.	Medium	Low	Engage community early; transparently share sustainability benefits.



10.6. Summary of Key Risks:

- **High-impact areas:** Battery lifecycle uncertainty, congestion variability, infrastructure cost.
- **Most influential factors:** Traffic conditions and battery management dominate the total cost and feasibility.
- **Critical enablers:** Real-time data validation, cross-sectoral collaboration, and proactive stakeholder communication.

11. Pilot impact and sustainability

11.1. Expected Impact and Benefits

The CE4CE pilot is expected to generate substantial **environmental, social, and economic benefits** for Gdynia and potentially other cities seeking to transition to circular, low-emission public transport systems.

Environmental Impact:

- By optimizing electrification strategies using a EFS, the pilot reduces dependency on oversized batteries, less efficient charging schedules and optimises number of vehicles needed for the service in a given area.

Social Impact:

- Enhanced service reliability through electrification and smart planning improves **public satisfaction** and **mobility equity**, particularly in dense urban corridors.
- The pilot also fosters **institutional learning and interdepartmental collaboration**, helping build long-term capacity in digital and sustainable mobility planning.

Economic Impact:

- Scenario testing indicated that higher service frequencies, while initially more costly, result in better utilization of infrastructure and can be economically justified through increased ridership and operational efficiency.
- These economic insights provide a foundation for leveraging **additional public and EU funding** for infrastructure investments.

11.2. 2. Sustainability of Results Beyond the Project

Long-Term Viability:

- The pilot's core output—the Digital Twin model—will remain a **reusable, updatable planning tool** for Gdynia's transport operators and urban planners.
- This allows the city to continuously refine strategies, adapt to changing mobility needs, and scale the solution to other transport corridors or city regions.



Environmental Sustainability:

- By promoting **modular infrastructure upgrades** (e.g., high-power IMC in targeted areas rather than full coverage), the project advances **resource-efficient planning**.
- Lower battery requirements translate into **fewer raw materials, reduced lifecycle emissions**, and improved alignment with **EU circular economy goals**.

Social and Policy Integration:

- The pilot supports Gdynia's long-term Sustainable Urban Mobility Plan (SUMP) and contributes to **policy shifts favoring data-driven, low-impact mobility solutions**.
- Public engagement and stakeholder inclusion throughout the pilot create the foundation for sustained political and community support.

Scalability Potential:

- The approach is **highly replicable**, especially for cities with legacy trolleybus systems or existing electrified public transport.
- The modular nature of Digital Twin deployment and scenario-based planning enables **cost-effective scaling**, both geographically and across transit modes.

12. Transferability of the pilot action

The CE4CE pilot project in Gdynia demonstrates a strong potential for transferability and scalability to other cities, regions, and even countries aiming to modernize and decarbonize their public transport systems while embedding circular economy principles.

12.1. Aspects Applicable and Adaptable to Other Regions

- **Digital Twin Approach:** The creation and use of a Digital Twin to simulate energy flows, traffic dynamics, and charging strategies is highly adaptable. Any city with access to basic transport operational data (fleet characteristics, service frequencies, traffic patterns) can replicate this model to support informed decision-making.
- **Scenario Testing:** Testing multiple operational and infrastructure scenarios (e.g., different service intervals, congestion levels, and charging options) allows flexibility depending on local conditions, such as traffic patterns, energy grid stability, and fleet composition.
- **Charging Strategy Optimization:** The combination of stationary, standard IMC, and high-power IMC charging is modular and can be adapted depending on urban density, road infrastructure, and fleet renewal plans.
- **Circular Economy Focus:** Minimizing battery sizes, extending asset lifetimes, and planning for battery recycling are universal strategies that align with broader European and global sustainability targets.

12.2. How Outcomes, Lessons, and Strategies Can Be Transferred

- **Knowledge Sharing:** The results and lessons learned from Gdynia can be shared through technical guidelines, workshops, and toolkits targeted at urban transport operators and city planners.



- **Template for Feasibility Studies:** The pilot methodology—data collection, Digital Twin modeling, scenario development, and KPI analysis—can serve as a template for initial feasibility studies elsewhere.
- **Policy Integration:** Insights on the socio-economic impacts (e.g., cost of congestion, importance of traffic prioritization for electric buses) provide arguments for policy reforms favoring sustainable transport initiatives in other cities.

12.3. Potential for Scaling

- **Geographic Scaling:** Cities with legacy electric transport networks (trolleybus, tram) are natural candidates for scaling.

12.4. Challenges in Transferability

- **Data Availability and Quality:** Successful Digital Twin development requires good-quality, comprehensive data. Cities lacking digitalized fleet and infrastructure data may face initial barriers.
- **Infrastructure Differences:** Cities with no overhead wire systems (non-trolleybus cities) may need to adapt the charging strategy model more heavily toward stationary fast-charging networks.
- **Institutional Readiness:** Effective transfer requires capable municipal bodies willing to invest in digital infrastructure, interdisciplinary collaboration, and change management processes.
- **Financial Resources:** Some regions may find initial investments into Digital Twin development and detailed simulations challenging without external funding support (e.g., EU programs).



Fig. 5. First meeting in the PKA depot to establish collaboration between PKA, KRUCH and UG in September 2023. Picture by M. Wotek

The CE4CE pilot offers a highly adaptable and scalable model for sustainable public transport transformation. With proper adaptation to local contexts and support for capacity-building and data infrastructure development, its outcomes and strategies can drive circular, low-carbon mobility transitions across many different regions.