Deliverable 3.2: Applied Demonstration Pilots for Green Transition in SMSPs

DigiTechPort2030

Within the frame of the South Baltic Programme

Work Package: 3

WP Leader: PP4 Blekinge Institute of Technology

Task: Implementing Decarbonization Pilot Applications in SMPS (Activity 3.3). Testing and Monitoring of Running Pilots in SMPS (Activity 3.4).

These tasks focuses on implementing and evaluating pilot applications aimed at accelerating decarbonization in small and medium-sized ports (SMSPs). Two pilot initiatives will be deployed to test practical electrification measures and assess their operational and environmental impact.

The pilots combine the implementation of an Energy Twin framework with a Port Electrification plan, enabling the analysis of energy demand, operational efficiency, and the integration of smart energy management layers that optimize the use and distribution of green energy within port operations.

The pilot actions include: (1) the full electrification of a forklift truck at PP9 – Terminal Świnoujście, and (2) the transition from fuel-based vehicles to electrified equipment used in ship unloading operations at PP6 – Port of Karlshamn.

The results will be monitored and evaluated to measure improvements in energy efficiency, operational performance, and the scalability of electrification solutions for SMSPs.

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Applied Pilot Demonstrations for Green Transition in Small and Medium-Sized Ports (SMSPs)

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Acknowledgement

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1. Introduction

The DigiTechPort2030, *Digital Excellence for Decarbonisation of Port-City Ecosystems for Efficient Environmental and Energy Management towards South Baltic Fit for 55*), project supports small and medium-sized ports (SMSPs) across the South Baltic Sea Area (SBA) in their green transition by implementing pilot demonstrations and capacity building strategies aligned with the EU Green Deal, IMO Fit for 55, and upcoming EU maritime fuel regulations.

This report documents Deliverable 3.2 under Work Package 3 (WP3), which focuses on the preparation and execution of the green decarbonisation pilots in SMSPs. The report provides the framework and analysis required to ensure informed, effective, and scalable pilot demonstrations.

1.1 Strategic Role of WP3

Work Package 3 (WP3) plays an important role in the implementation phase of the project. It focuses on the design, deployment, and evaluation of two distinct types of green pilot initiatives within participating SMSPs. These pilots are scheduled to be executed and fully assessed by the end of June 2026.

The outcomes of WP3 are integral to two flagship outputs of the DigiTechPort2030 project:

- **The Green Energy Harmonisation Toolbox for SMSPs**, which provides operational models and best practices for port decarbonisation.
- **The EU Regulation and Green Policy Compliance Development Roadmap**, which assists SMSPs in navigating and aligning with emerging EU environmental directives and climate policies.

Drawing upon the insights and tools developed in earlier work package,s especially the structured training, technology mapping, and decision-support instruments that are outlined in the Green Transition Capacity Building Portfolio, WP3 transitions the project from planning to real-world validation.

1.2 Deliverable 3.2 – Applied Demonstration Pilots for Green Transition in SMSPs

Deliverable 3.2 sets the foundation for all WP3 pilot activities. It focuses on the preparation, feasibility assessment, and scenario modelling necessary to successfully implement green technologies and systems in complex operational ecosystems that characterize small ports.

Implementing new systems or equipment in a “live” or operating port environment is inherently challenging due to the interconnectedness of port actors, logistics workflows, and energy infrastructure. Therefore, pilot demonstrations require thorough preparation, including:

- **Contractual and Regulatory Readiness:** Activities such as stakeholder engagement, procurement planning, legal compliance checks, and site-specific regulatory assessments are addressed under Activity 3.1.
- **Scenario Development and Analysis:** Under Activity 3.2, multiple decarbonisation and energy transition models are developed and tested against real-world data from the selected pilot sites. Each scenario is evaluated based on economic feasibility, environmental performance, and social impact, with the most suitable one selected for implementation.

This deliverable (3.2), synthesizes technical, regulatory, and strategic dimensions to ensure that the forthcoming pilots are not only viable but replicable across the South Baltic region. It also builds directly on the methodologies and frameworks laid out in Deliverables 2.1, 2.2, and 2.3.

Table 1. DigiTechPort2030 Project – WP 3 Description of Deliverables and Activities

1.2.1 Relation to the Capacity Building Portfolio

The Green Transition Capacity Building Portfolio (compiled in prior deliverables and summarized in Section 7 of the main report) underpins Deliverable 3.1 by equipping SMSPs with knowledge, tools, and institutional capacity to carry out pilot projects effectively. This includes:

- Technical readiness training in AI, blockchain, and AR
- Renewable energy integration guidelines
- Use of tools such as the Green Energy Compass
- Stakeholder engagement methodologies
- Workforce development and certification tracks

By combining this foundational training with localised scenario planning and pilot testing, Deliverable 3.1 ensures that SMSPs are fully prepared to move from conceptual green transition strategies to practical, measurable action.

2 Enabling technologies for Green Transition in SMSPs.

As the second Deliverable of WP 3, deliverable 3.2 is covering all “hands-on” activities needed to implement the decarbonisation pilots in SMSPs of the SBA - South Baltic Area (Activities 3.3 - 3.5). To drive substantial decarbonisation in port ecosystems, two demonstration pilot streams will be developed, implemented, and systematically evaluated: **Energy Twin digital modelling** and **Port Electrification strategies**.

2.1 Energy Twin

Digital Twins are already well-known in port industry. As part of WP 3, Deliverable 3.2 will design, implement, and validate an **Energy Twin framework** for Small and Medium-Sized Ports (SMSPs) to support their transition toward low-carbon and electrified operations. Building upon the CHESSCON Digital Twin environment, the Energy Twin will extend operational simulation models by embedding dynamic energy consumption parameters, grid interaction constraints, charging behavior of electrified equipment (e.g., e-RTGs, terminal tractors, shore power), and renewable energy integration scenarios. The objective is to create a data-driven decision-support tool capable of modelling realistic energy demand profiles under stochastic operational conditions.

The Energy Twin will enable participating ports in the pilots to simulate peak load behavior, charging congestion risks, and emissions intensity per container or cargo move. By linking operational performance metrics (throughput, equipment utilization, vessel service time) with energy performance indicators (kWh consumption, CO_2 reduction potential, cost per move), the framework will provide an integrated view of operational and environmental efficiency. This approach allows SMSPs to evaluate electrification roadmaps, renewable integration strategies, and Total Cost of Ownership (TCO) scenarios before capital investment decisions are made.

This work will include applied demonstration pilots in selected partner ports, where the Energy Twin models will be calibrated using “real - world” operational and telemetry data. Results will be evaluated against baseline scenarios to quantify decarbonisation impact, grid feasibility, and financial viability. The validated framework will serve as a transferable methodology for other South Baltic ports seeking structured, simulation-driven pathways toward Fit-for-55 compliance and long-term energy resilience.

2.2 Port Electrification

Complementing the analytical capabilities of Energy Twin, this group of actions foresees to apply practical implementation and validation of electrification measures in port operations by proposing to electrify current port operations by using different approaches. While the transition from diesel-powered vehicles, cranes, and yard equipment to electrified alternatives is recognized as a critical decarbonisation pathway, implementation remains limited in SMSPs due to financial risk, infrastructure constraints, and operational uncertainty.

As part of WP 3, this deliverable will develop and execute applied electrification pilots that demonstrate technical feasibility, operational continuity, and economic viability. Activities will include phased replacement scenarios for terminal tractors, RTGs, and auxiliary equipment; assessment of charging infrastructure requirements; evaluation of grid capacity and load balancing strategies; and comparison of Total Cost of Ownership (TCO) across alternative transition pathways.

By combining real-world validation with simulation-driven insights from the Energy Twin, this will reduce hesitation within the port sector and provide actionable electrification roadmaps for SMSPs. The results will generate measurable indicators of emissions reduction, energy efficiency improvement, and operational performance stability, supporting a structured and scalable transition toward low-emission, future-ready port ecosystems.

2.3 Challenges in Introducing Enabling technologies in SMSPs

As part of the preparatory activities under Work Package 3 (WP3) of the DigiTechPort2030 project, a comprehensive review of technical conditions, capacity-building outcomes, and stakeholder consultations revealed a set of persistent digital challenges that hinder the successful deployment and scaling of decarbonisation technologies in Small and Medium-Sized Ports (SMSPs). These findings are based on the synthesis of prior deliverables, including the *Green Transition Capacity Building Portfolio* and pilot preparation assessments conducted across the South Baltic region.

This section outlines the primary digital barriers SMSPs face in aligning their operational environments with the EU Green Deal, IMO Fit for 55, and forthcoming maritime fuel regulations. Addressing these barriers is essential to ensure the effective implementation of pilot activities, including those planned under Deliverable 3.2 and beyond.

1. **Fragmented Digital Infrastructure.** Most SMSPs operate with legacy information systems and siloed data environments, where Terminal Operating Systems (TOS), energy management systems (EMS), and equipment telemetry platforms lack integration. This fragmentation leads to:
   - Limited real-time visibility into energy consumption or emissions.
   - Inability to model “what-if” decarbonisation scenarios accurately.
   - Challenges in conducting baseline measurements necessary for pilot benchmarking.

2. **Low Maturity in Data Governance and Standardizatio.** Ports often lack standardized data protocols for critical operational and environmental parameters such as fuel consumption, equipment cycles, and energy source mix. Consequences include:
   - Difficulty in harmonizing datasets for cross-border comparison and EU reporting.
   - Incompatibility with digital twin simulation software (e.g., CHESSCON).
   - Inadequate documentation of carbon accounting or performance metrics.

3. **Insufficient IoT and Connectivity Readiness.** Many pilot sites reported limited or unreliable connectivity across terminal areas, impeding the deployment of IoT sensors and smart equipment. Specific issues identified include:
   - Inadequate Wi-Fi or 5G coverage across yard and quay zones.
   - Poor integration of crane, forklift, or battery data into central EMS platforms.
   - Lack of infrastructure for real-time performance tracking and anomaly detection.

4. **Underdeveloped Digital Twin Capabilities.** While digital twin technologies such as CHESSCON were introduced as part of the pilot design phase, several implementation barriers were discovered:
   - SMSPs do not have access to high-resolution geospatial data (e.g., LiDAR-based terrain models).
   - Technical staff are often unfamiliar with simulation tools, limiting in-house use.
   - Telemetry datasets are often incomplete or not exportable in structured formats.

5. **Cybersecurity and Data Privacy Concerns.** Introducing new digital technologies into port ecosystems raises legitimate concerns about:
   - Data breaches related to operational telemetry, energy use, or cargo handling.
   - GDPR compliance when sharing personnel or tracking data across EU member states.
   - Trust issues between ports and solution providers regarding intellectual property and performance transparency.

6. **High Dependency on External Technology Vendors.** Many SMSPs lack internal IT departments or digital innovation teams, resulting in:
   - Overreliance on external vendors for critical functions such as software integration and analytics.
   - Difficulty in assessing the credibility, interoperability, and cost-effectiveness of vendor solutions.
   - Limited capacity to troubleshoot or adapt technologies post-deployment.

7. **Financial Constraints for Digitalisation.** Even when digital technologies demonstrate long-term energy and cost savings, many SMSPs:
   - Struggle to fund upfront capital investments in smart infrastructure.
   - Face gaps in knowledge regarding eligibility and application for EU funding schemes (e.g., CEF, Horizon Europe).
   - Encounter misalignment between funding cycles and port infrastructure project timelines.

8. **Knowledge Gaps in Emerging Technologies**
   - Despite rising interest, digital literacy across the port ecosystem—particularly in smaller facilities—remains low. Key insights from capacity-building sessions showed:
   - Artificial Intelligence (AI) is viewed as too complex or not directly applicable.
   - Blockchain applications are poorly understood, particularly in energy certification and traceability.
   - Digital twins are often perceived as research tools rather than operational assets.

9. **Strategic Implications for WP3 Pilot Deployment**

- The above challenges underscore the need for deep digital readiness assessments as part of pilot planning (Activity 3.1) and targeted technical support during pilot execution (Activity 3.2). Specifically:
- Scenario modelling and electrification simulation tools (e.g., CHESSCON) must be coupled with training for local teams to foster digital literacy.
- Energy monitoring infrastructure (e.g., sensors, EMS, cloud dashboards) should be prioritized alongside physical upgrades.
- Cross-border knowledge exchange platforms can help SMSPs learn from more digitally mature peers, accelerating replication.
- These insights also reinforce the value of the *Green Transition Capacity Building Portfolio*, which includes digital enablement tracks and decision-support tools tailored to SMSP needs.
- Ultimately, without addressing these digital barriers, decarbonisation technologies may be underutilized or fail to achieve measurable results, limiting the impact and scalability of the pilots.

2.4 Statement

To effectively implement green energy transition in SMSPs of the South Baltic, ports must create enabling conditions rooted in regulatory clarity, ecosystem coordination, local context adaptation, and strategic investment. Pilot implementations must be systematically prepared, ensuring they not only demonstrate feasibility but also generate replicable insights that feed into both a harmonisation toolbox and a regulatory compliance roadmap for wider adoption.

3 Implementing Pilot Projects under Activity 3.3

As part of Activity 3.1 of Work Package 3 (WP3)**, the** DigiTechPort2030 project has launched several pilot initiatives designed to test and evaluate decarbonisation strategies through digital innovation in Small and Medium-Sized Ports (SMSPs) across the South Baltic Sea Region. Each pilot aims to address specific challenges related to operational efficiency, energy consumption, and environmental performance.

The following pilot projects are currently under implementation. Though still in progress, they are advancing through structured methodologies involving stakeholder engagement, data acquisition, modelling, and simulation using the CHESSCON platform and other digital/energy twin tools.

3.1.1 EuroTerminal (Świnoujście, Poland) – Energy Twin for Operational Efficiency

Objective: Implement a fast-track ENERGY Twin pilot within a 2–3 week timeframe, focusing on the tracking of forklift activity, crane operations, and cargo-handling efficiency through the CHESSCON simulation platform. The initiative will include collaboration with Liebherr to digitally integrate mobile harbor crane operations into the simulation environment. Additionally, a fully operational electric forklift (E-Forklift) will be deployed, with its performance data imported into the Energy Twin model of the EuroTerminal yard. This model will enable detailed battery performance and energy consumption analysis, with the goal of evaluating and comparing energy efficiency between diesel and electric driven equipment in terminal operations.

Key Processes:

- Deployment and testing of E-Forklift.
- Elaborating data requirements and flight planning protocol for RGB vision and lidar sensors data collection procedures to cover a 1000 x 100 m terminal area as show in Figure 1.
- Execute terminal layout scan(s) with Lidar mapping sensor by RTK Drone.
- Import Mapping data into Web-based data processing software to process the data, generate visual 3D model of terminal and identify cargo objects.
- Execute sample tracking in real-world, with forklifts and mobile harbour cranes during cargo movement to collect performance indicators from telematic data.
- Use of CHESSCON to simulate and optimize CHE energy efficiency.

Figure 1. EuroTerminal area layout with facilities map (Euroterminal, Poland).

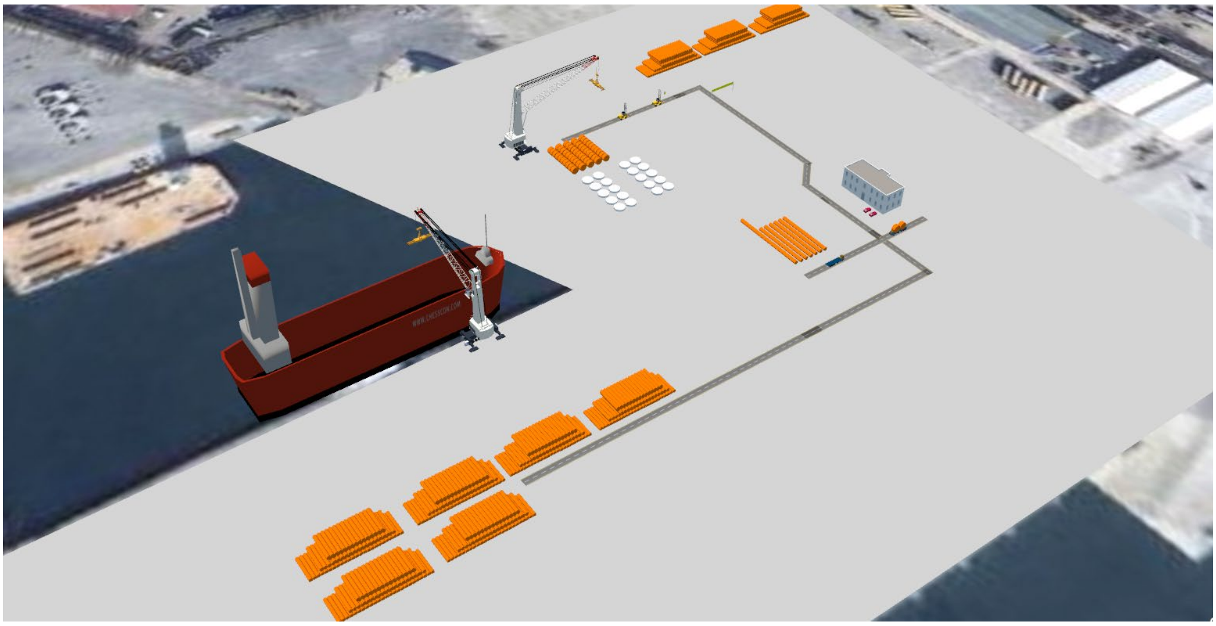


Figure 2. CHESSCON software screenshot, 3D Viewer output for Euro-terminal terminal layout.

Expected Outcome: First phase will be the testing results of the E-Forklift to be input for phase 2, which is a 3D simulation-based performance assessment leading to recommendations for operational improvements and energy reduction for electric equipment, including battery driven.

Figure 3 4. Pilot Project on Electric Forklift and EnergyTwin

3.1.2 Port of Karlshamn (Sweden) – Energy Twin Implementation

Objective: To implement a high-fidelity Energy Twin to assess CHE operations and simulate the impact of transitioning to electric systems.

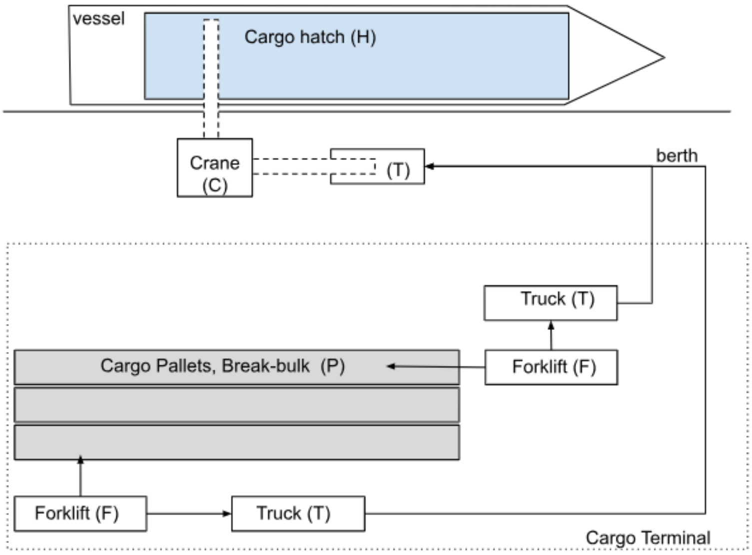


Figure 5. Pilot scenario model for cargo operations.

Key Processes:

- Asset and equipment modeling (trucks, tractors, reach stackers, cranes) for sample scenario model presented in Figure 6.
- Integration of real-time electric equipment telemetry (telematic data) and terminal mapping.
- Scenario analysis for diesel vs. electric operation using simulations.

Expected Outcome: Operational decision support tools for port planners targeting reduced energy use and increased equipment efficiency

Figure 6. Pilot Project on EnergyTwin at Port of Karlshamn

3.1.3 Seaport of Klaipėda (Lithuania) – Vessel Arrival Digital Twin for Berth Optimization

Objective: To reduce vessel idle time and energy consumption through the development of a digital twin focused on vessel traffic and berth coordination.

Key Processes:

- Integration of AIS (Automatic Identification System) data into the Klaipėda Vessel Management System (VMS).
- Development of a Digital Twin for real-time monitoring and simulation of ship arrivals.
- Coordination between pilots, port control, terminal operators, and tugboat services to optimize berth allocation and reduce waiting times.

Strategic Focus This pilot directly addresses decarbonisation goals by:

- Minimizing engine idle time at anchor and in port approaches.
- Improving berth scheduling and enhancing port call predictability.
- Reducing overall fuel consumption and emissions from both vessels and port support services.

Expected Outcome: A replicable model for integrating digital twins into port-wide traffic management systems, contributing to the overarching DigiTechPort2030 goal of optimising energy and resource use in maritime operations.

Figure 7. Pilot Project on Digital Twin of Vessels for Intelligent Vessel Management System

3.1.4 Port of Elbląg (Poland) – Renewable Energy Integration through Solar Power

Objective: To reduce dependency on grid electricity through the implementation of solar panel systems tailored for port infrastructure.

Key Challenges:

- Procurement Barriers: Difficulty identifying port-ready solar technology suppliers with suitable equipment for coastal environmental conditions.
- Installation Expertise Gaps: Lack of local specialists experienced in designing and installing solar PV systems in port environments, which include structural integration with warehouses, cranes, and administrative buildings.

Collaborative Impact: A critical success factor was the exchange of technical knowledge and experience with EuroTerminal Świnoujście, which had previously implemented its own solar panel installation. Through this collaboration:

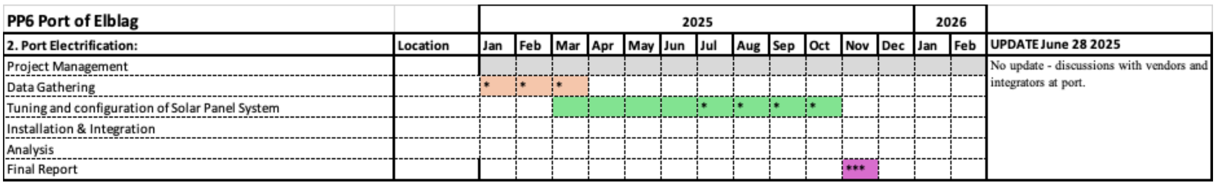
- EuroTerminal achieved 14% of its energy supply from solar within the first operational year.

- EuroTerminal has set a target of 50% solar energy use by 2026.
- Elbląg port was able to fast-track its feasibility studies and vendor engagement, benefitting from templates and insights shared by Euroterminal.

Expected Outcome: While the solar implementation in Elbląg is still underway, the pilot represents a significant step in enabling smaller Polish ports to participate meaningfully in national and EU-wide decarbonisation efforts. The port aims to position itself as a lighthouse example of renewable energy adaptation in inland SMSPs, aligned with Fit for 55 targets.

3.1.5 Liebherr Mobile Habor Cranes – In progress

Objective: The ambition is to use the telemetry data from Liebherr from one or more of their crane units that are deployed in a port or terminal so as to use as input for an Energy Twin. The vision for the Energy Twin, is by using Digital Twin technology, there is increased visibility of the data so as to help improve the reduction of decarbonization by management. In addition the data, is expected to be useful so as to help validate the existing digitalise simulations from using CHESSCON. **This work is in progress.** Expected results are by Q3 2026.



PP6 Port of Elblag		2025												2026		
2. Port Electrification:	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	UPDATE June 28 2025
Project Management		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	No update - discussions with vendors and integrators at port.
Data Gathering		🟧 *	🟧 *	🟧 *												
Tuning and configuration of Solar Panel System				🟩	🟩	🟩	🟩	🟩 *	🟩 *	🟩 *	🟩 *					
Installation & Integration																
Analysis																
Final Report												🟪 ***				

Figure 8. Pilot Project with Port of Elblag on Solar Panel system

3.1.6 Cross-Pilot Insights and Observations

One of the most prominent cross-cutting insights from the DigiTechPort2030 pilot activities is the critical role of data-driven modeling in supporting decarbonisation and energy efficiency across small and medium-sized ports (SMSPs). In some of the pilots, Energy twin technology, enabled through tools such as CHESSCON, has been used to simulate port equipment performance, cargo flows, vessel movements, and energy consumption. These virtual environments allow port operators to test decarbonisation scenarios without disrupting ongoing operations, offering a safe and cost-effective pathway to transition planning.

Another important observation is the value of collaborative innovation among diverse stakeholders. Each pilot has benefited from the coordinated input of port authorities, terminal operators, equipment manufacturers like Liebherr, software providers such as Akquinet, and academic research teams. This multi-actor approach enables the sharing of domain expertise, operational knowledge, and technical tools, resulting in scalable, replicable strategies that can be adapted to different port contexts. The collaboration also accelerates learning cycles and lowers barriers for ports with limited internal capacity to undertake digital transformation.

Initial results from the pilots have already revealed tangible benefits, including measurable improvements in energy efficiency, increased operational transparency through telemetry and real-time tracking, and stronger digital readiness across participating sites. Ports that had previously operated without systematic energy performance data are now able to visualize and assess their energy footprint, identify inefficiencies, and prepare for future electrification investments with a clear evidence base.

Collectively, these pilot projects serve a dual purpose: they are both proof-of-concept experiments and living laboratories. They not only validate the feasibility of decarbonisation technologies in real port environments but also generate valuable data, methodologies, and templates that feed directly into the development of the Green Energy Harmonisation Toolbox. Moreover, the lessons learned from these early-stage implementations contribute directly to the formulation of compliance strategies for upcoming EU regulatory frameworks, particularly those tied to the EU Green Deal and Fit for 55 initiatives.

In summary, these pilot studies offer a critical foundation for scaling green transition strategies across the South Baltic Region and beyond, reinforcing the importance of digitalisation as a key enabler of maritime decarbonisation.

4 Testing and Monitoring of Running Pilots under activity 3.4

In this section, we describe four running pilots Euro-Terminal Energy Twin, Karlshamn Simulation of hybrid model, Klaipeda Digital-Twin and Elblag Solar Panels.

4.1 Euro-Terminal (Świnoujście, Poland) – Energy Twin

The final Pilot is represented by two separate simulation software projects on the defined terminal area layout. The aim is to simulate the amount of CO_2 savings after transitioning to battery-driven CHE. The project includes layout visualization focused on processes and operational capacity of the terminal area for break bulk cargo operations. In conducting the simulation projects the need for developing a robust simulation model was supported by employing CHESSCON®, which is a Port Terminal modelling and simulation Software as a Service (**SaaS**), that helped in modelling by using any of the number of CHESSCON® modules setup: Layout, Input, Simulation and 3D layout. The main screen of CHESSCON® is represented in Figure, and the example of the project screen in Layout Editor is represented in Figure 4

Figure 9. CHESSCON® SaaS application main screen (Source: Final Results – Euro-Terminal , 2025)

4.1.1 Main scenario

The cargo handling operation takes place at a general cargo terminal equipped with two adjacent storage facilities, berth 50m width and 500 m long. The incoming vessel 10000 TEU is equipped with a side-door ramp enabling direct horizontal cargo transfer between ship and quay. As presented in Figure 11 The handling process comprises two sequential logistics flows Discharge flow (Import) Load flow (Export). During Import flow 1,000 pallets, each with a unit weight of 1.0 tonne, are discharged from the vessel. Each pallet is received by a battery-electric forklift at the vessel side-door ramp. The pallet is transported over a horizontal distance of 50 m to the storage facility receiving door (S3).

During export flow 1,000 big bags, each with a unit weight of 1.0 tonne, are collected from the storage facility export door (S1). Each unit is transported over a horizontal distance of 50 m to the vessel side-door ramp and loaded onboard. A fleet of four battery-driven electric forklifts is deployed to perform both discharge and loading operations.

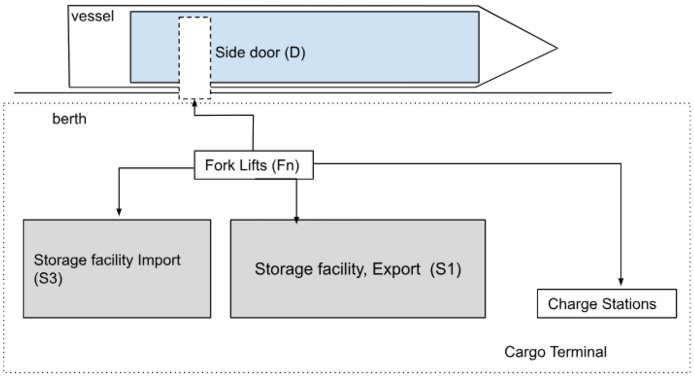


Figure 10. Cargo handling operations model (Source: Final Results – Euro-Terminal , 2025)

The forklift is equipped with a battery that allows a few hours of continuous operation per charge cycle. Charging capabilities include 2 fixed charging stations located within the cargo terminal area at a distance of 200 meters. Forklifts require charging rotations to maintain uninterrupted cargo flow.

The Pilot objective is to calculate CO_2 emissions saved by using battery-electric forklifts instead of diesel forklifts. We assume EU Emission Factors (EF) as follows:

EF Diesel CO_2 Factor (Diesel) = 2.68 kg/L

Diesel consumption for cargo terminal Forklift, for 150 kWh: 10 L/h, Thus, hourly emissions per diesel forklift:

$$E=10\cdot 2.68\approx 26.8 \text{ kg } CO_2/h$$

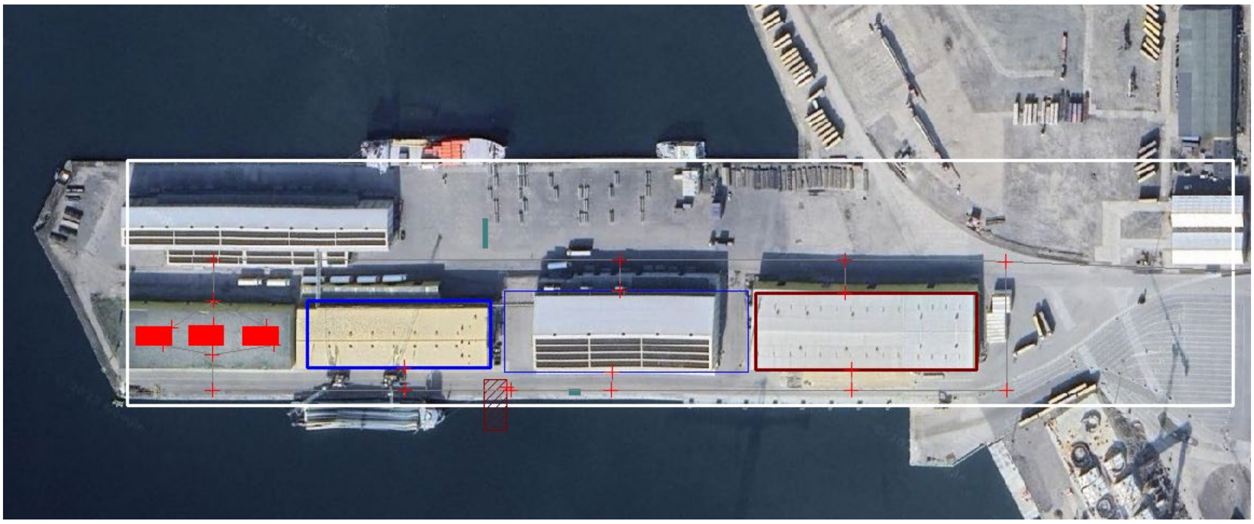


Figure 11 EuroTerminal terminal view in CheessCon Layout Editor, with terrain layer set visible. (Source: Final Results – Euro-Terminal , 2025).

Figures 12 and 13 represent more detailed break-bulk cargo terminal geometry including quay, location of two deposit facilities (Import and Export) and position of charging stations. We exported the schema of the area by using Google Maps software and then added arrows on top of it to confirm our assumptions regards the size of cargo and container stack in the terminal with the Euro-Terminal representatives. The layout includes the following elements: two cranes, two stacks for break-bulc cargo (area A , B), one mechanical station to check and refuel conventional diesel driven CHE, two charging stations for Electric , battery driven CHE.

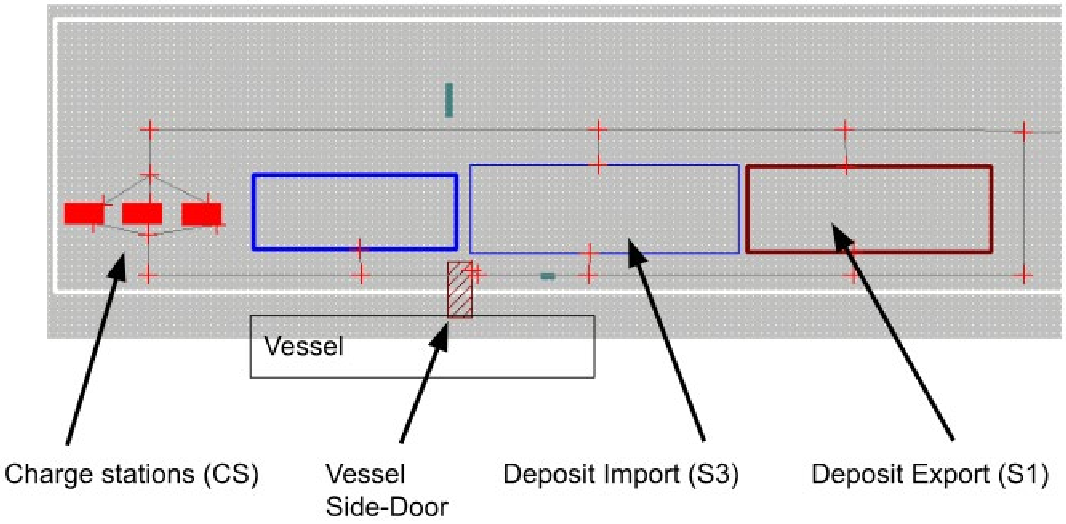


Figure 12. Euro-Terminal terminal layout designed in CheessCon Layout Editor (Source: Final Results – Euro-Terminal , 2025)

After interviewing Euro-Terminal a simulation scenario was created based on Import/Export case described in table 1. The cargo scenario consists of two sequential flows: unloading (import) and loading (export), each comprising 1,000 cargo units with an individual mass of approximately 1.0 tonne per unit. Handling is performed using four battery-electric forklifts with a nominal performance of 40 tonnes per hour. The forklifts are specified as Jungheinrich EFG 550 models, representing modern industrial electric CHE. The forklifts operate in a shuttle transport mode between the vessel side-door ramp and the storage facility doors.

Vessel A	Cargo (A)	Port Equipment (B)	Handling rate (C=A/B)	Simulation criteria
Simulation #1				
Sided door vessel. 10000 GWT	Unloading: 1000 pallets of aluminium ingots, 980 kg/pall, single pall per lift. Loading: 1000 t of big bags with fish feed.	4 x 40t/hour Batery-driven forklifts Jungheinrich EFG 550	Unloading: 25 hours Loading: 25 hours	Energy use for electric forklift, kWh. Equipment active hours.
Simulation #2				
		Diesel driven forklift, 150 kWh , 10 L/hour consumpition		Equipment active hours

Table 2. The simulation scenario for bulk-bulk cargo operation. (Source: Final Results – Euro-Terminal , 2025)

In the illustration presented in Figure 13, a Jungheinrich EFG 550 forklift, and its working characteristics presented in Table 4.

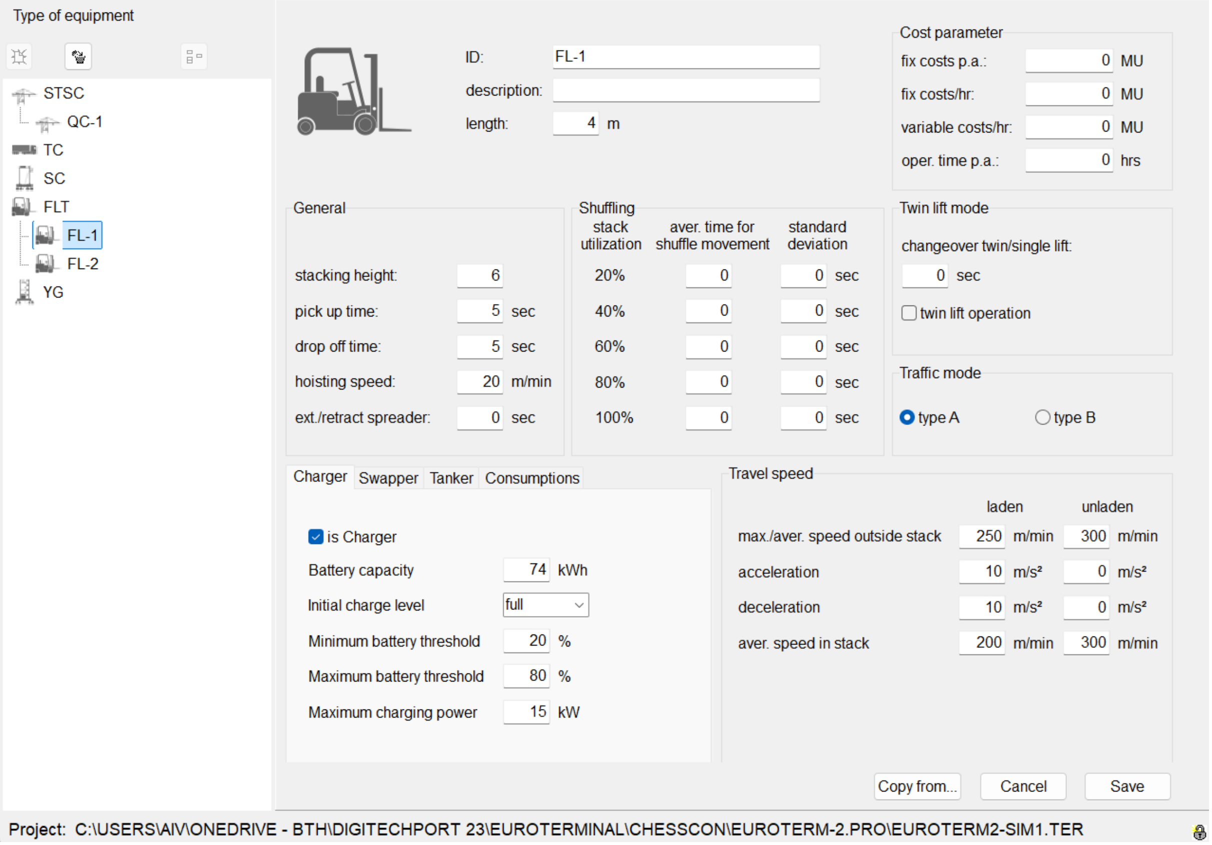
Figure 13. Jungheinrich EFG 550 forklift (Source: https://www.jungheinrich.com/)

Battery capacity	74 kWh
Lifting	20 kWh
Traveling	14.5 kWh
Running time:	
Charger	12,8 kWh
Charge time , linear / by vendor	5,7 / 7,5 Hour
Travel speed (Loaded)	12 km/h
Travl Speed (unloaded)	15 km/h
Driving motor	14,5 kW
Lifting Motor	20 kW

Table 3. Performance characteristics of Jungheinrich EFG 550 forklift. (Source: Final Results – Euro-Terminal , 2025)

Apart from the spatial layout of the break-bulk stack, CHESSCON® Input editor allows defining detailed parameters of the cargo scenario, such as the number of involved equipment, Its characteristics, and volume of cargo flow between yard, waterside, and landside. CHESSCON® Input editor also allows defining the simulation duration and equipment strategies, for example how much moves each crane needs to make to server a number of cargo hatches in a vessel.

In Figure 14 screenshot from CHESSCON describes the Forklift parameters to define the main characteristics for charger and forklift energy consumption in Figure 15.



Type of equipment

- STSC
  - QC-1
- TC
- SC
- FLT
  - FL-1
  - FL-2
- YG

ID: FL-1
description:
length: 4 m

Cost parameter
fix costs p.a.: 0 MU
fix costs/hr: 0 MU
variable costs/hr: 0 MU
oper. time p.a.: 0 hrs

General
stacking height: 6
pick up time: 5 sec
drop off time: 5 sec
hoisting speed: 20 m/min
ext./retract spreader: 0 sec

Shuffling

stack utilization	aver. time for shuffle movement	standard deviation
20%	0	0 sec
40%	0	0 sec
60%	0	0 sec
80%	0	0 sec
100%	0	0 sec

Twin lift mode
changeover twin/single lift: 0 sec
☐ twin lift operation

Traffic mode
● type A ○ type B

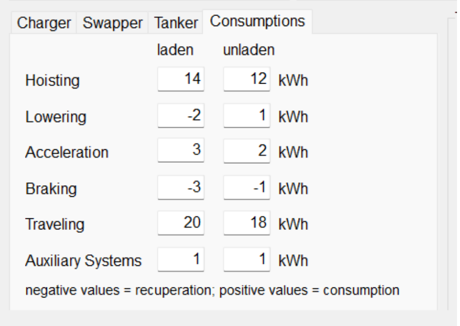
☑ is Charger
Battery capacity 74 kWh
Initial charge level full
Minimum battery threshold 20 %
Maximum battery threshold 80 %
Maximum charging power 15 kW

Travel speed

	laden		unladen	
max./aver. speed outside stack	250	m/min	300	m/min
acceleration	10	m/s²	0	m/s²
deceleration	10	m/s²	0	m/s²
aver. speed in stack	200	m/min	300	m/min

Project: C:\USERS\AIV\ONEDRIVE - BTH\DIGITECHPORT 23\EUROTERMINAL\CHESSCON\EUROTERM-2.PRO\EUROTERM2-SIM1.TER

Figure 14. Simulation parameters for EFG 550 forklift represented in CHESSCON Input module (Source: Final Results – Euro-Terminal , 2025)

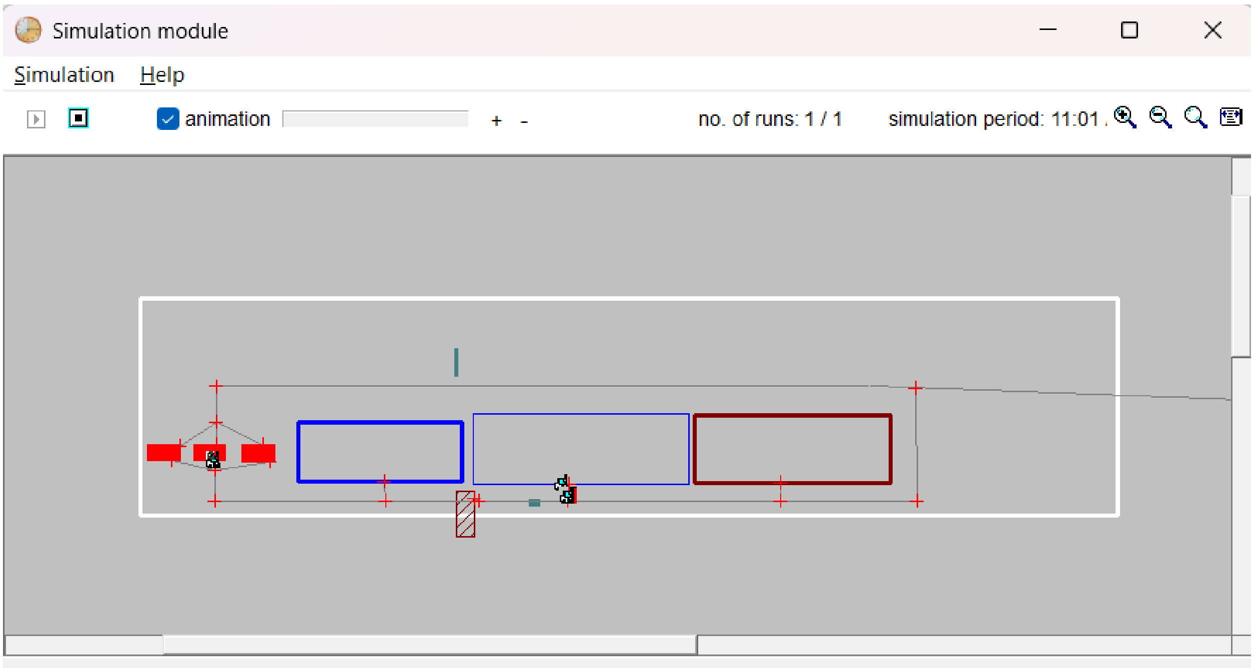


	laden	unladen	
Hoisting	14	12	kWh
Lowering	-2	1	kWh
Acceleration	3	2	kWh
Braking	-3	-1	kWh
Traveling	20	18	kWh
Auxiliary Systems	1	1	kWh

negative values = recuperation; positive values = consumption

Figure 15. Energy consumption per activity for EFG 550 forklift represented in CHESSCON Input module (Source: Final Results – Euro-Terminal , 2025)

In Figure 16 a screenshot of the Simulation module in CHESSCON® software is presented. It allows simulating cargo flow a number of times with the parameters defined in Input module and Layout module. The results are being recorded and stored with the project data.



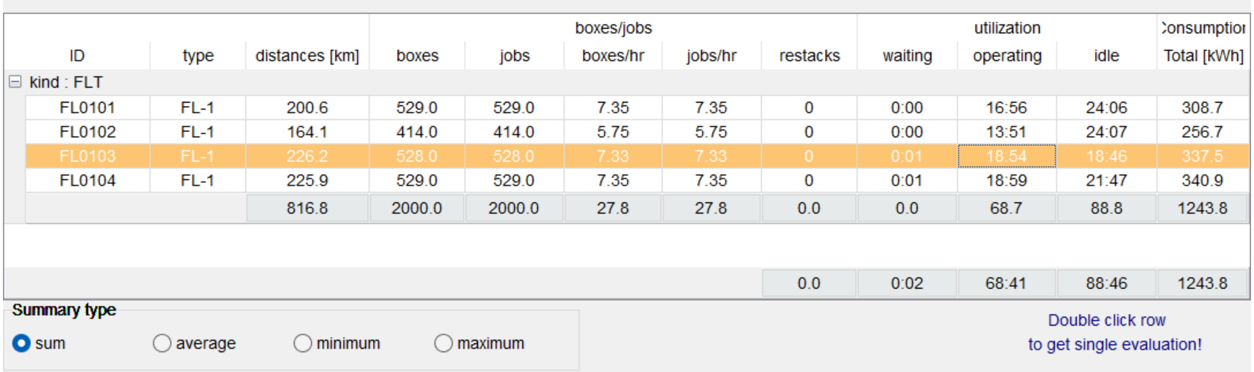
no. of runs: 1 / 1

simulation period: 11:01 .

Figure 16. CHESSCON Simulation module running (Source: Final Results – Euro-Terminal , 2025)

Results from the EuroTerminal Pilot

To understand the savings for CO_2 emissions for the cargo scenario, we have elaborated a cargo terminal layout and flow scenario, including landside storage stacks. We then executed Simulation #1 times to get average values. Figure 18 shows the evaluation results of simulation #1, where it is indicated that total of 2000 packages were handled during a simulation time defined as 55 hours. 4 forklifts consumed 1243,8 kWh of energy during 68 hours in total. The average battery use is 18,2 kWh per hour, which is 14 %.



			boxes/jobs					utilization			onsumptio
ID	type	distances [km]	boxes	jobs	boxes/hr	jobs/hr	restacks	waiting	operating	idle	Total [kWh]
⊟ kind : FLT											
FL0101	FL-1	200.6	529.0	529.0	7.35	7.35	0	0:00	16:56	24:06	308.7
FL0102	FL-1	164.1	414.0	414.0	5.75	5.75	0	0:00	13:51	24:07	256.7
FL0103	FL-1	226.2	528.0	528.0	7.33	7.33	0	0:01	18:54	18:46	337.5
FL0104	FL-1	225.9	529.0	529.0	7.35	7.35	0	0:01	18:59	21:47	340.9
		816.8	2000.0	2000.0	27.8	27.8	0.0	0.0	68.7	88.8	1243.8
							0.0	0:02	68:41	88:46	1243.8

Summary type

● sum ○ average ○ minimum ○ maximum

Double click row
to get single evaluation!

Figure 17. Electric forklift performance results in CHESSCON Evaluation module (Source: Final Results – Euro-Terminal , 2025)

Stacks, Storage area S3 -Import

The model included key operational components such as quay-side cargo movements, landside transport flows, and designated storage stacks located in Storage Area S3 (Import). In Figure 18, the number of imported boxes used into the simulation is presented.

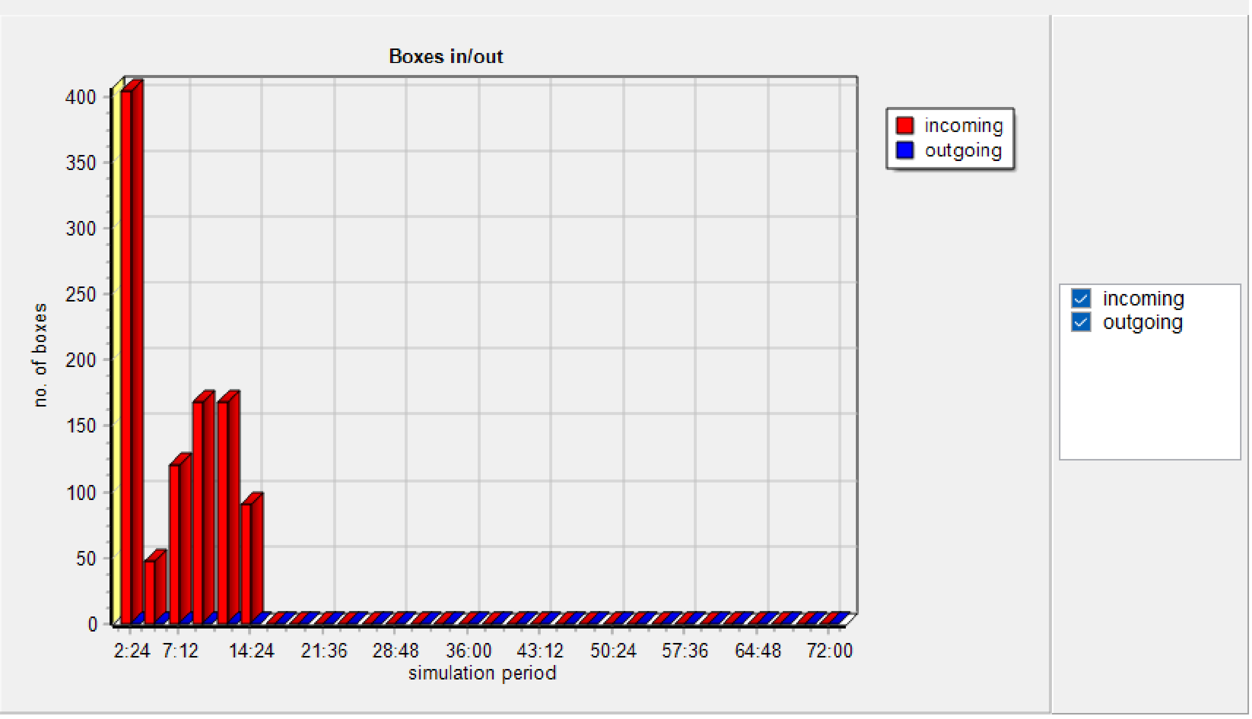


Figure 18. Imported Packages throughput in CHESSCON Evaluation module (Source: Final Results – Euro-Terminal , 2025)

Stacks, Storage area S1 – Export
In Figure 19 the number of exported boxes used into the simulation is presented for Storage Area S1 (Export).

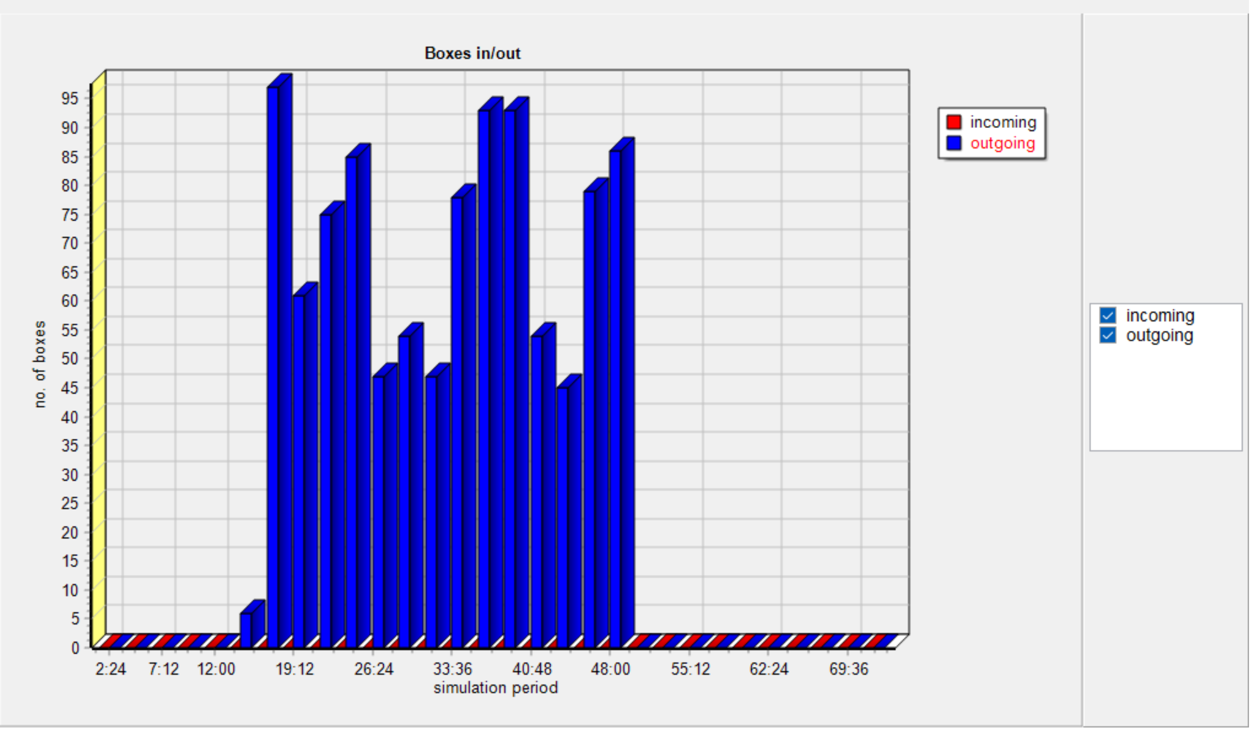
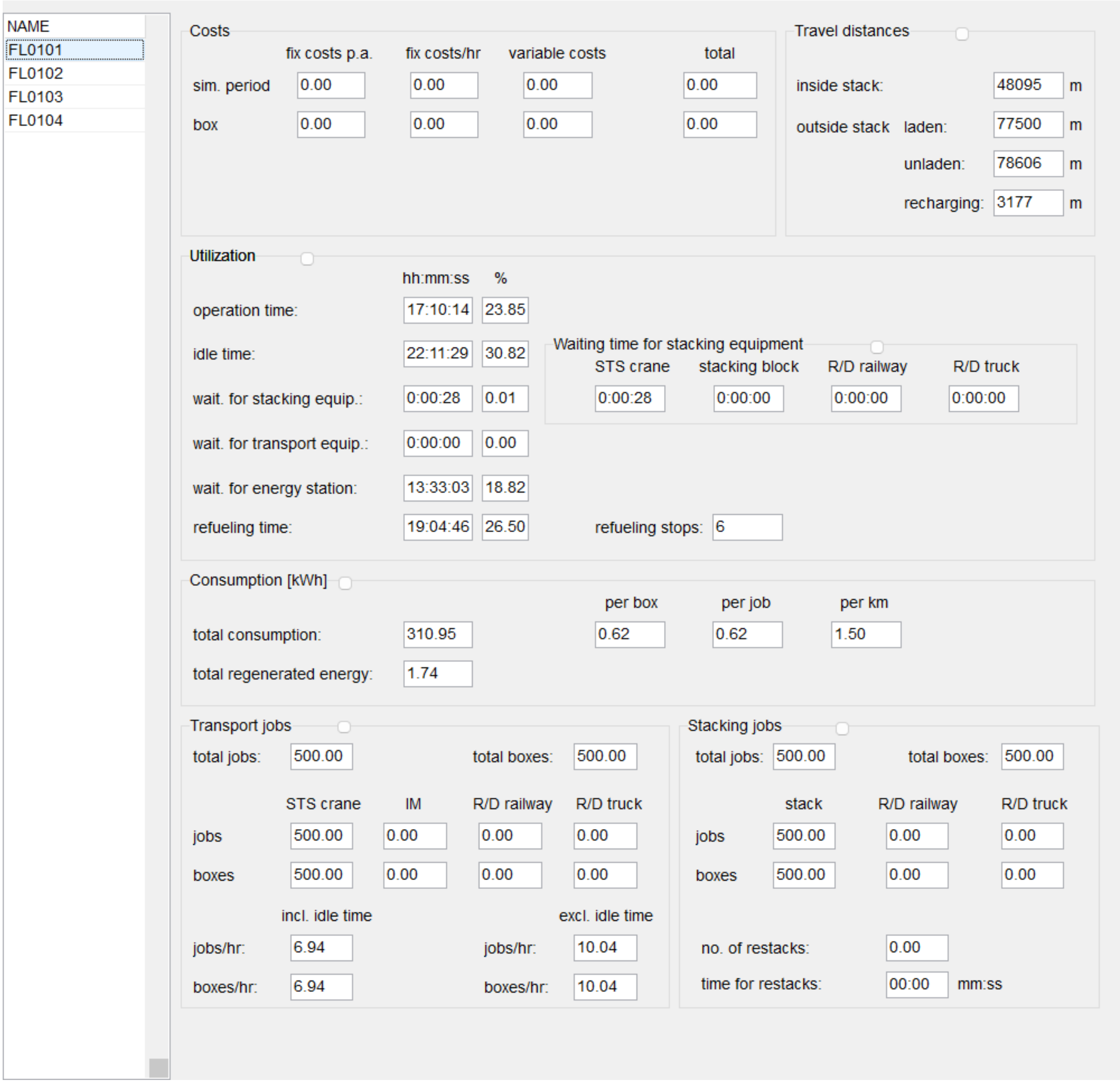


Figure 19. Exported Packages throughput in CHESSCON Evaluation module (Source: Final Results – Euro-Terminal , 2025)

Electric equipment – average:
Within the DigiTechPort2030 pilot, the CHESSCON simulation model was used (c.f., Figure 20) to evaluate the performance and energy consumption of electric forklifts operating in the terminal. The simulation results show that 500 cargo units were handled, with a total energy consumption of 328.95 kWh, equivalent to 0.65

kWh per box and 1.48 kWh per kilometer traveled e.g., forklifts represented in Figure 21. The equipment recorded an operational utilization of 23.85%, with 11 charging events during the simulation period, c.f. Figure 22. These results provide insight into the energy demand and operational efficiency of electrified cargo-handling equipment, supporting the evaluation of port electrification strategies within the DigiTechPort2030 project.



NAME
FL0101
FL0102
FL0103
FL0104

Costs

	fix costs p.a.	fix costs/hr	variable costs	total
sim. period	0.00	0.00	0.00	0.00
box	0.00	0.00	0.00	0.00

Travel distances

inside stack:		48095	m
outside stack	laden:	77500	m
	unladen:	78606	m
	recharging:	3177	m

Utilization

	hh:mm:ss	%
operation time:	17:10:14	23.85
idle time:	22:11:29	30.82
wait. for stacking equip.:	0:00:28	0.01
wait. for transport equip.:	0:00:00	0.00
wait. for energy station:	13:33:03	18.82
refueling time:	19:04:46	26.50

refueling stops: 6

Waiting time for stacking equipment

STS crane	stacking block	R/D railway	R/D truck
0:00:28	0:00:00	0:00:00	0:00:00

Consumption [kWh]

		per box	per job	per km
total consumption:	310.95	0.62	0.62	1.50
total regenerated energy:	1.74			

Transport jobs

total jobs: 500.00
total boxes: 500.00

	STS crane	IM	R/D railway	R/D truck
jobs	500.00	0.00	0.00	0.00
boxes	500.00	0.00	0.00	0.00

	incl. idle time		excl. idle time
jobs/hr:	6.94	jobs/hr:	10.04
boxes/hr:	6.94	boxes/hr:	10.04

Stacking jobs

total jobs: 500.00
total boxes: 500.00

	stack	R/D railway	R/D truck
jobs	500.00	0.00	0.00
boxes	500.00	0.00	0.00

no. of restacks: 0.00
time for restacks: 00:00 mm:ss

Figure 20. Electric forklift performance and consumption breakdown (Source: Final Results – Euro-Terminal , 2025)

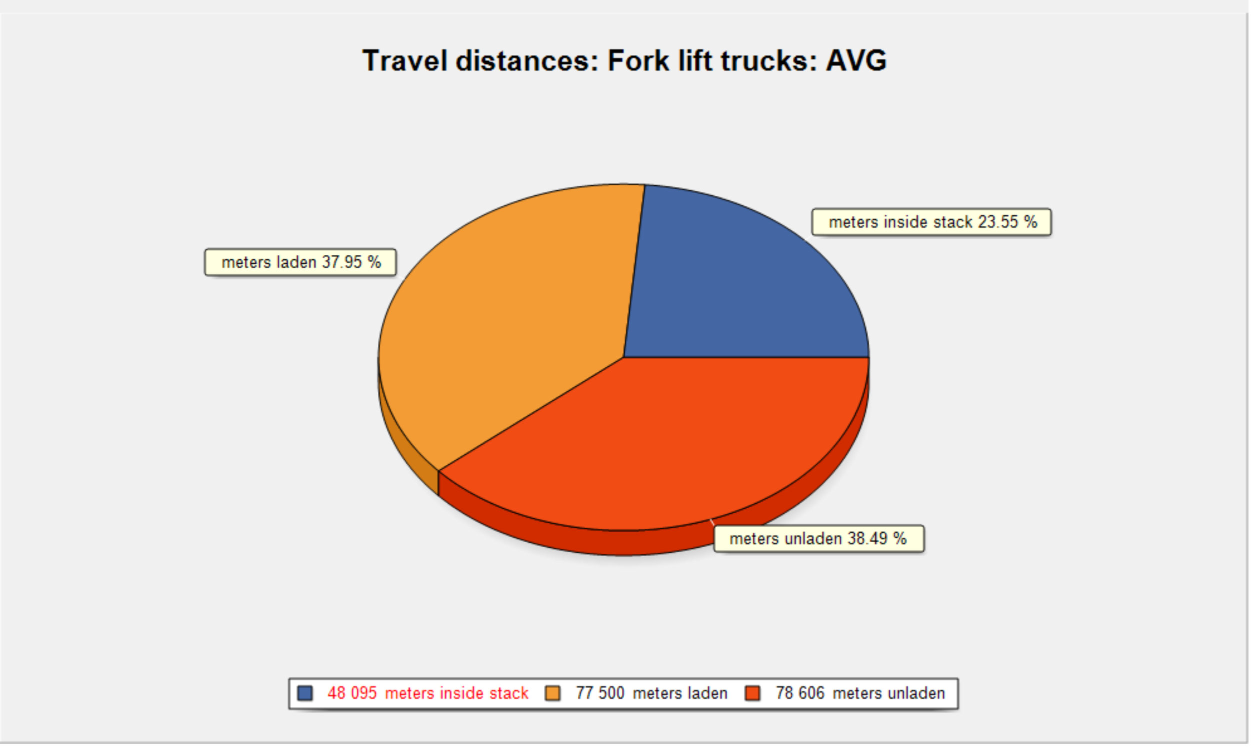


Figure 21. Electric forklift travel distances (Source: Final Results – Euro-Terminal , 2025)

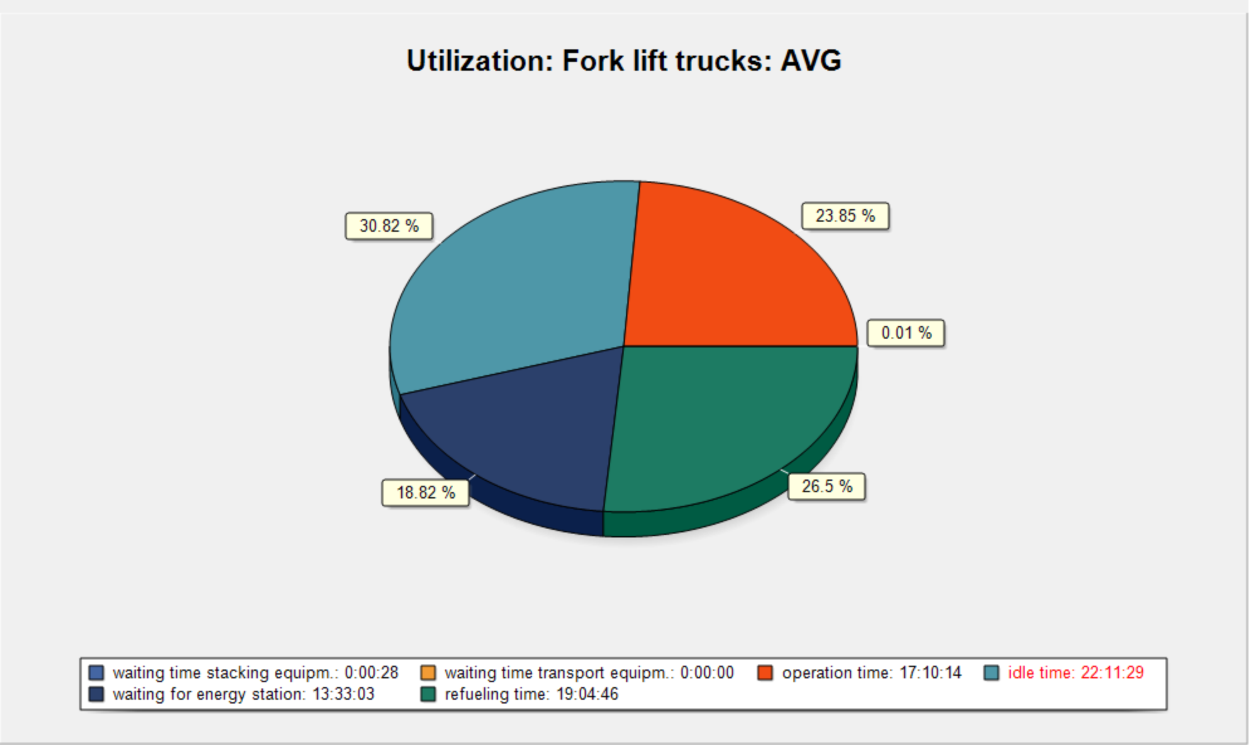
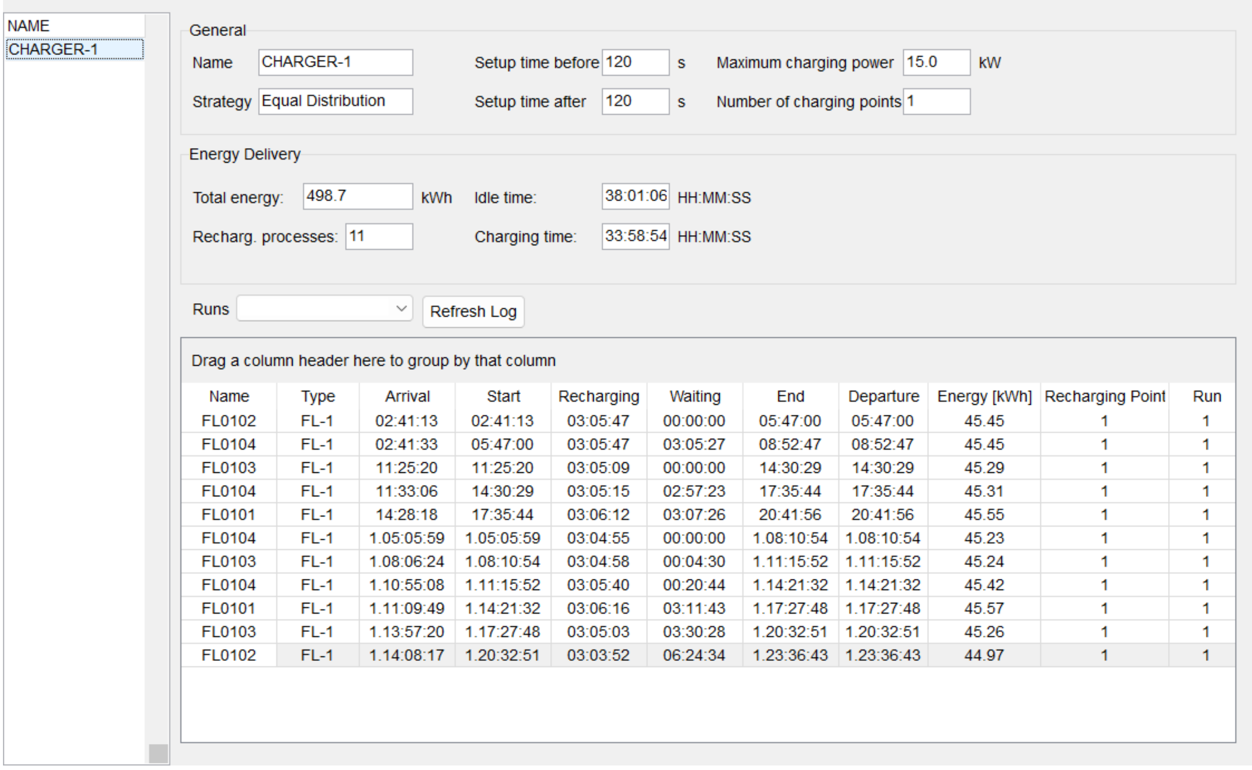


Figure 22. Electric forklift utilization (Source: Final Results – Euro-Terminal , 2025)

Energy – Charging Stations averages

In the EuroTerminal pilot, CHESSCON simulation results show (c.f., Figure 23) that the charging station delivered 498,7 kWh of energy across 11 charging events. The total charging time was 34 hours, with 38 hours of idle time. The charging infrastructure was configured with a maximum power of 15.0 kW and one charging point, providing insights into charging demand and infrastructure utilization for electrified port equipment.



Name CHARGER-1
Strategy Equal Distribution
Setup time before 120 s
Setup time after 120 s
Maximum charging power 15.0 kW
Number of charging points 1

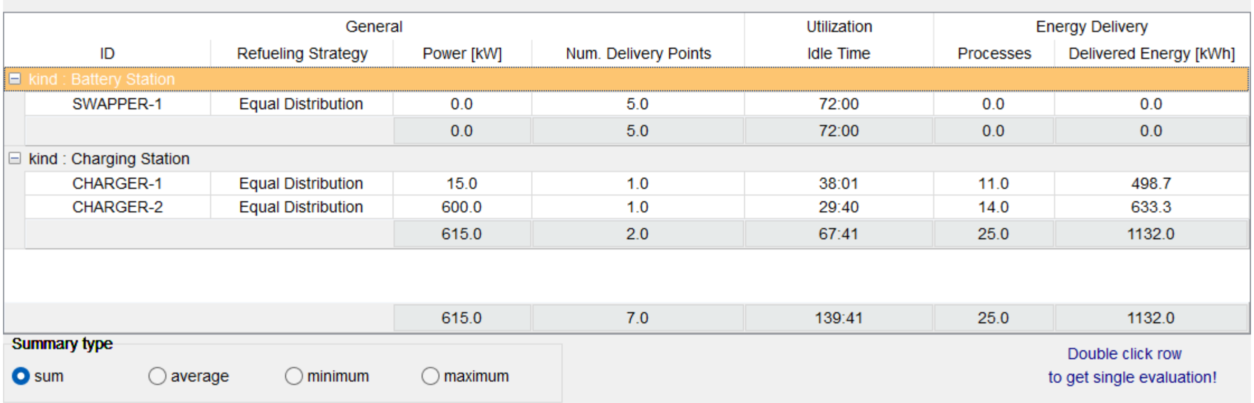
Total energy: 498.7 kWh
Recharg. processes: 11
Idle time: 38:01:06 HH:MM:SS
Charging time: 33:58:54 HH:MM:SS

Name	Type	Arrival	Start	Recharging	Waiting	End	Departure	Energy [kWh]	Recharging Point	Run
FL0102	FL-1	02:41:13	02:41:13	03:05:47	00:00:00	05:47:00	05:47:00	45.45	1	1
FL0104	FL-1	02:41:33	05:47:00	03:05:47	03:05:27	08:52:47	08:52:47	45.45	1	1
FL0103	FL-1	11:25:20	11:25:20	03:05:09	00:00:00	14:30:29	14:30:29	45.29	1	1
FL0104	FL-1	11:33:06	14:30:29	03:05:15	02:57:23	17:35:44	17:35:44	45.31	1	1
FL0101	FL-1	14:28:18	17:35:44	03:06:12	03:07:26	20:41:56	20:41:56	45.55	1	1
FL0104	FL-1	1.05:05:59	1.05:05:59	03:04:55	00:00:00	1.08:10:54	1.08:10:54	45.23	1	1
FL0103	FL-1	1.08:06:24	1.08:10:54	03:04:58	00:04:30	1.11:15:52	1.11:15:52	45.24	1	1
FL0104	FL-1	1.10:55:08	1.11:15:52	03:05:40	00:20:44	1.14:21:32	1.14:21:32	45.42	1	1
FL0101	FL-1	1.11:09:49	1.14:21:32	03:06:16	03:11:43	1.17:27:48	1.17:27:48	45.57	1	1
FL0103	FL-1	1.13:57:20	1.17:27:48	03:05:03	03:30:28	1.20:32:51	1.20:32:51	45.26	1	1
FL0102	FL-1	1.14:08:17	1.20:32:51	03:03:52	06:24:34	1.23:36:43	1.23:36:43	44.97	1	1

Figure 23. Electric Charging station utilization (Source: Final Results – Euro-Terminal , 2025)

Costs – Energy - Charging stations

The simulation results, shown in Figure 24, indicate that two charging stations with a combined capacity of 615 kW delivered a total of 1132 kWh of energy across 25 charging events. CHARGER-1 (15 kW) supplied 498.7 kWh in 11 sessions, while CHARGER-2 (600 kW) delivered 633.3 kWh in 14 sessions. The results illustrate the energy demand and utilization of charging infrastructure supporting electrified terminal equipment in the pilot scenario.



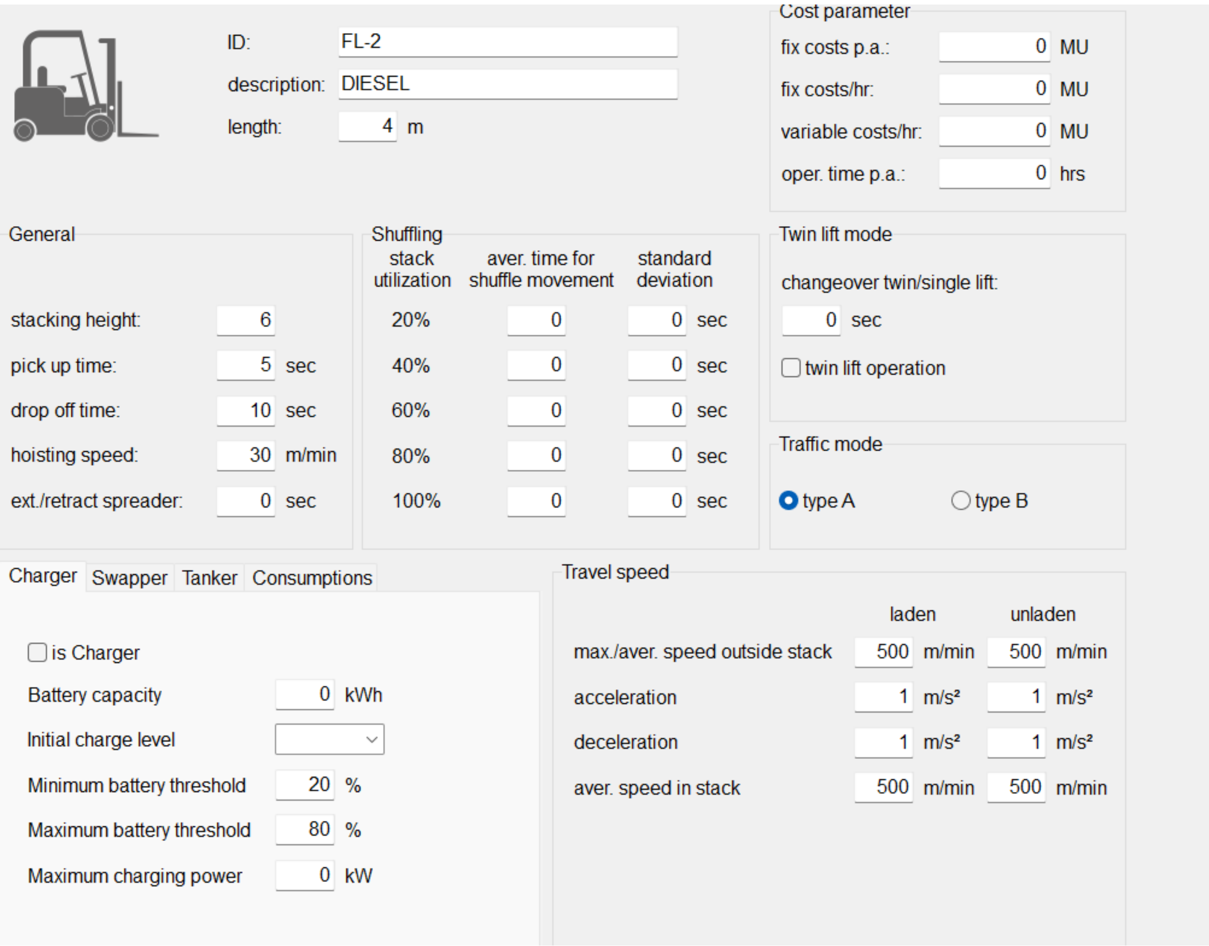
General				Utilization	Energy Delivery	
ID	Refueling Strategy	Power [kW]	Num. Delivery Points	Idle Time	Processes	Delivered Energy [kWh]
⊟ kind : Battery Station						
SWAPPER-1	Equal Distribution	0.0	5.0	72:00	0.0	0.0
		0.0	5.0	72:00	0.0	0.0
⊟ kind : Charging Station						
CHARGER-1	Equal Distribution	15.0	1.0	38:01	11.0	498.7
CHARGER-2	Equal Distribution	600.0	1.0	29:40	14.0	633.3
		615.0	2.0	67:41	25.0	1132.0
		615.0	7.0	139:41	25.0	1132.0

Summary type
● sum ○ average ○ minimum ○ maximum

Figure 24. Electric Charging Station electricity consumptions and delivery breakdown (Source: Final Results – Euro-Terminal , 2025)

Results for EuroTerminal Simulation, Scenario 2

In Figure 25, the screenshot represents the baseline scenario that used a diesel-powered forklift (FL-2) to perform cargo-handling operations in the terminal. The model parameters define a forklift with a stacking height of 6 levels, a pick-up time of 5 seconds, and a drop-off time of 10 seconds, with a hoisting speed of 30 m/min. The equipment operates with an average travel speed of 500 m/min, both inside and outside the storage stacks. This configuration represents the conventional fuel-based cargo-handling operation, serving as a reference case for comparison with the electrified equipment scenario evaluated in the EuroTerminal pilot. The results of this simulation are shown in Figure 26, which provides the baseline operational performance parameters used to assess the potential efficiency improvements and CO_2 emission reductions achievable through the electrification of terminal equipment.



ID: FL-2
description: DIESEL
length: 4 m

Cost parameter
fix costs p.a.: 0 MU
fix costs/hr: 0 MU
variable costs/hr: 0 MU
oper. time p.a.: 0 hrs

General
stacking height: 6
pick up time: 5 sec
drop off time: 10 sec
hoisting speed: 30 m/min
ext./retract spreader: 0 sec

Shuffling

stack utilization	aver. time for shuffle movement	standard deviation
20%	0	0 sec
40%	0	0 sec
60%	0	0 sec
80%	0	0 sec
100%	0	0 sec

Twin lift mode
changeover twin/single lift: 0 sec
☐ twin lift operation

Traffic mode
● type A ○ type B

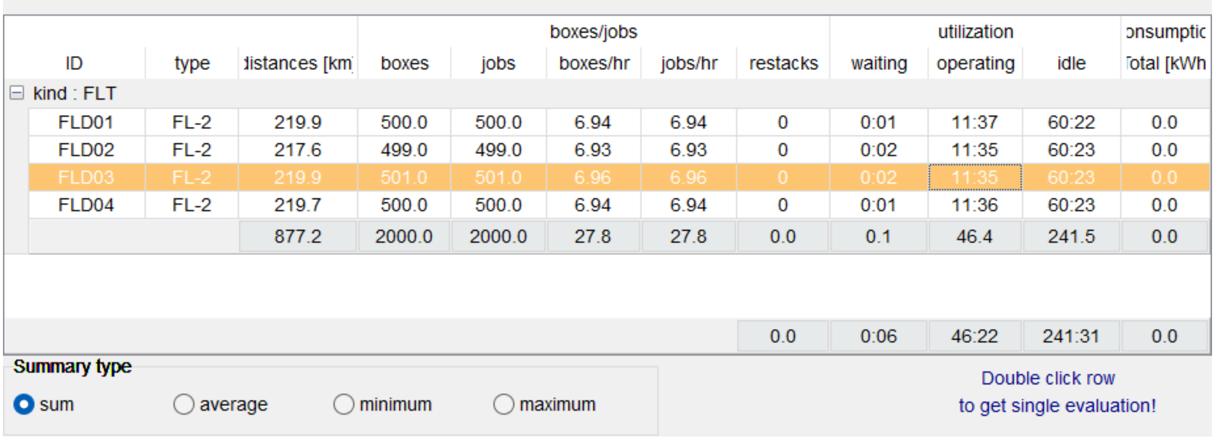
Charger | Swapper | Tanker | Consumptions

☐ is Charger
Battery capacity 0 kWh
Initial charge level
Minimum battery threshold 20 %
Maximum battery threshold 80 %
Maximum charging power 0 kW

Travel speed

	laden	unladen
max./aver. speed outside stack	500 m/min	500 m/min
acceleration	1 m/s²	1 m/s²
deceleration	1 m/s²	1 m/s²
aver. speed in stack	500 m/min	500 m/min

Figure 25. Simulation parameters of diesel-driven forklift (Source: Final Results – Euro-Terminal , 2025)



			boxes/jobs					utilization			onsumptic
ID	type	listances [km	boxes	jobs	boxes/hr	jobs/hr	restacks	waiting	operating	idle	Total [kWh
⊟ kind : FLT											
FLD01	FL-2	219.9	500.0	500.0	6.94	6.94	0	0:01	11:37	60:22	0.0
FLD02	FL-2	217.6	499.0	499.0	6.93	6.93	0	0:02	11:35	60:23	0.0
FLD03	FL-2	219.9	501.0	501.0	6.96	6.96	0	0:02	11:35	60:23	0.0
FLD04	FL-2	219.7	500.0	500.0	6.94	6.94	0	0:01	11:36	60:23	0.0
		877.2	2000.0	2000.0	27.8	27.8	0.0	0.1	46.4	241.5	0.0
							0.0	0:06	46:22	241:31	0.0

Summary type

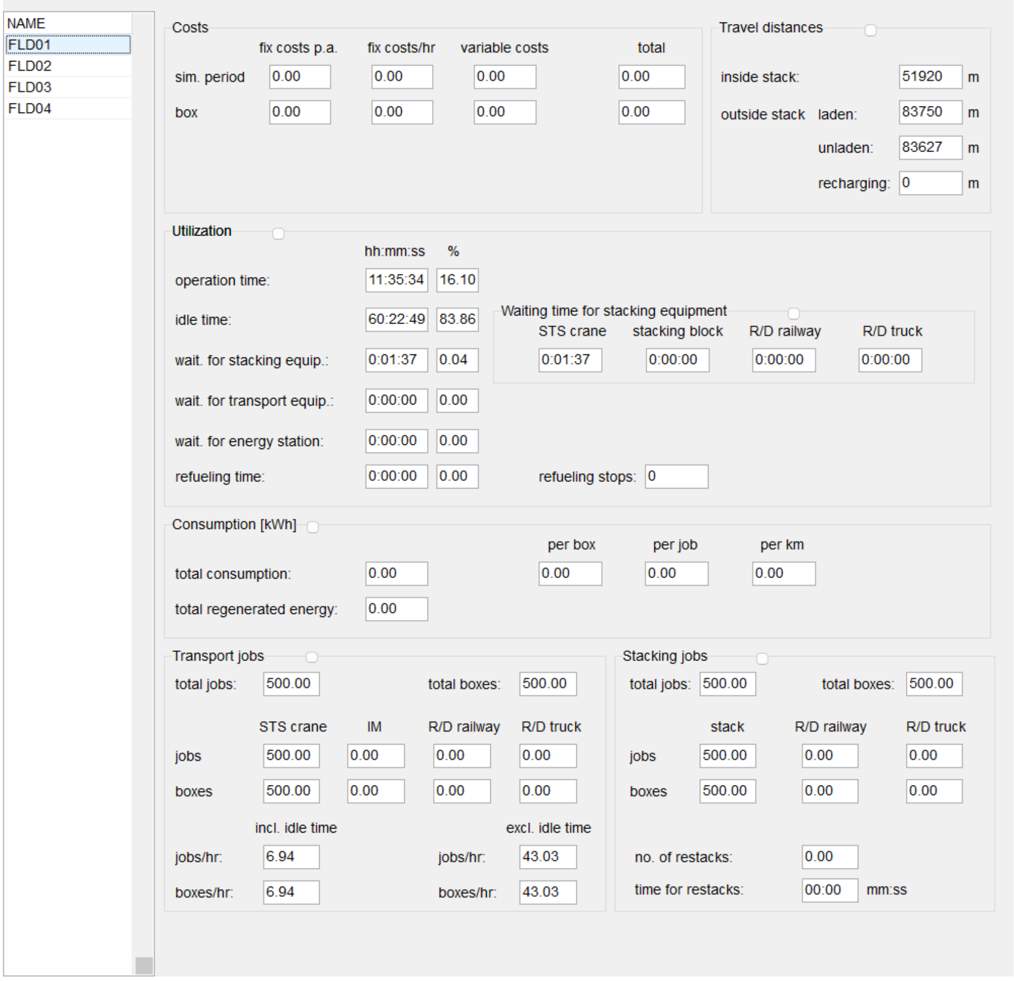
● sum ○ average ○ minimum ○ maximum

Double click row
to get single evaluation!

Figure 26. Diesel-driven forklift performance results (Source: Final Results – Euro-Terminal, 2025

Equipment - Forklifts – average:

The simulation results for the diesel forklift scenario shown in Figure 27 indicate that four forklifts handled a total of 500 cargo units during the operational period. The forklifts traveled approximately 51,920 m within the storage stacks, 83,750 m while loaded, and 83,627 m while unloaded outside the stack areas. The equipment recorded an active operation time of 11:35:34 hours (16.10%), while remaining idle for 60:22:49 hours (83.86%), indicating that forklift availability exceeded the operational demand in this scenario. Waiting time related to stacking equipment was minimal (1 minute and 37 seconds), and no waiting for transport equipment or refueling was recorded. Overall, the forklifts achieved an operational throughput of 6.94 jobs per hour including idle time, and 43.03 jobs per hour when idle time is excluded, providing a baseline operational performance for comparison with electrified equipment scenarios in the EuroTerminal pilot.



NAME
FLD01
FLD02
FLD03
FLD04

Costs

	fix costs p.a.	fix costs/hr	variable costs	total
sim. period	0.00	0.00	0.00	0.00
box	0.00	0.00	0.00	0.00

Travel distances

inside stack: 51920 m
outside stack laden: 83750 m
unladen: 83627 m
recharging: 0 m

Utilization

	hh:mm:ss	%
operation time:	11:35:34	16.10
idle time:	60:22:49	83.86
wait. for stacking equip.:	0:01:37	0.04
wait. for transport equip.:	0:00:00	0.00
wait. for energy station:	0:00:00	0.00
refueling time:	0:00:00	0.00

Waiting time for stacking equipment

STS crane	stacking block	R/D railway	R/D truck
0:01:37	0:00:00	0:00:00	0:00:00

refueling stops: 0

Consumption [kWh]

total consumption: 0.00
total regenerated energy: 0.00

per box	per job	per km
0.00	0.00	0.00

Transport jobs

total jobs: 500.00
total boxes: 500.00

	STS crane	IM	R/D railway	R/D truck
jobs	500.00	0.00	0.00	0.00
boxes	500.00	0.00	0.00	0.00

	incl. idle time		excl. idle time
jobs/hr:	6.94	jobs/hr:	43.03
boxes/hr:	6.94	boxes/hr:	43.03

Stacking jobs

total jobs: 500.00
total boxes: 500.00

	stack	R/D railway	R/D truck
jobs	500.00	0.00	0.00
boxes	500.00	0.00	0.00

no. of restacks: 0.00
time for restacks: 00:00 mm:ss

Figure 27. Diesel-driven forklift performance and consumption breakdown (Source: Final Results – Euro-Terminal , 2025)

Travel Distances

The simulation shown in Figure 28 indicate that 23.68% of forklift travel occurs inside storage stacks, while the majority occurs outside the stacks, with 38.19% loaded movements and 38.13% unloaded return trips. This indicates that most travel distance is related to transport operations outside stack areas, suggesting opportunities to improve efficiency through optimized routing and terminal layout.

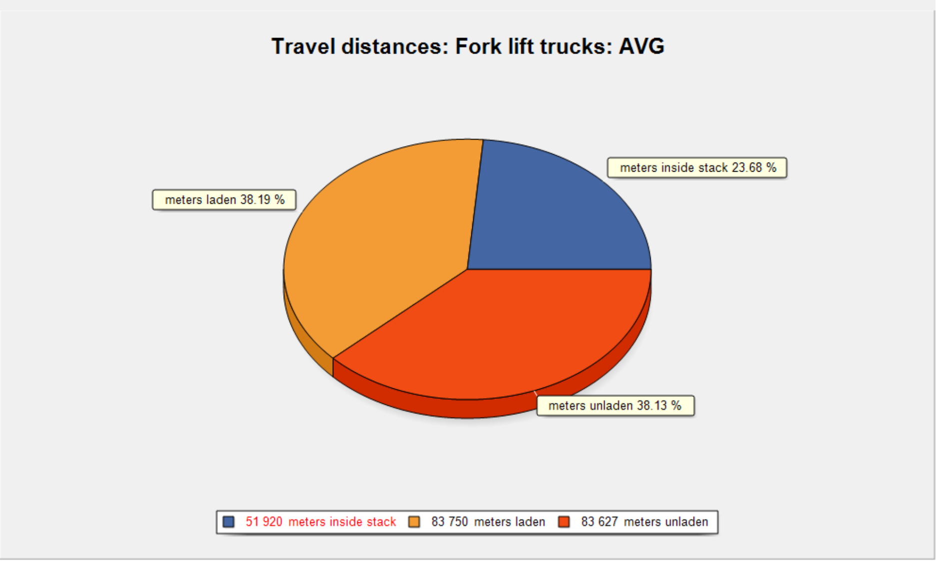


Figure 28. Diesel-driven forklift travel distances (Source: Final Results – Euro-Terminal , 2025)

(Stacks) Storage area S3 -Import

The simulation results for Storage Area S3 (Import) shown in Figure 29 that the flow of incoming and outgoing cargo boxes during the simulation period. Most cargo units enter the stack during the early stages of the simulation, with a high number of incoming boxes followed by corresponding outgoing movements. This pattern reflects the temporary storage function of the import stack, where cargo is first received and then gradually retrieved for further transport. Overall, the results illustrate the dynamic inflow and outflow of containers within the storage area, supporting efficient cargo handling and distribution within the terminal.

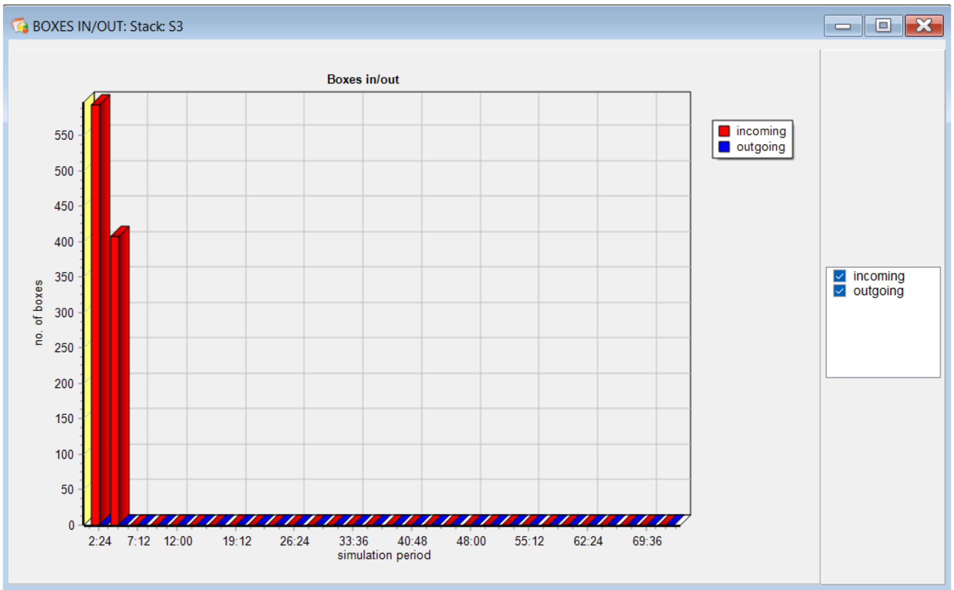


Figure 29. Imported Packages throughput in CHESSCON Evaluation module (Source: Final Results – Euro-Terminal , 2025)

S1 – Export

The simulation results presented in Figure 30 are for Storage Area S1 – Export shows the flow of cargo boxes leaving the terminal during the simulation period, which required 11,37 hours for handling. The chart indicates that most activity consists of outgoing boxes, reflecting the export function of this storage area where cargo is retrieved from the stack and transported to the vessel. The majority of outgoing movements occur within the early phase of the simulation period, after which activity stabilizes with minimal additional flows. This pattern reflects the operational role of the export stack in supporting the timely delivery of cargo to the quay for vessel loading.

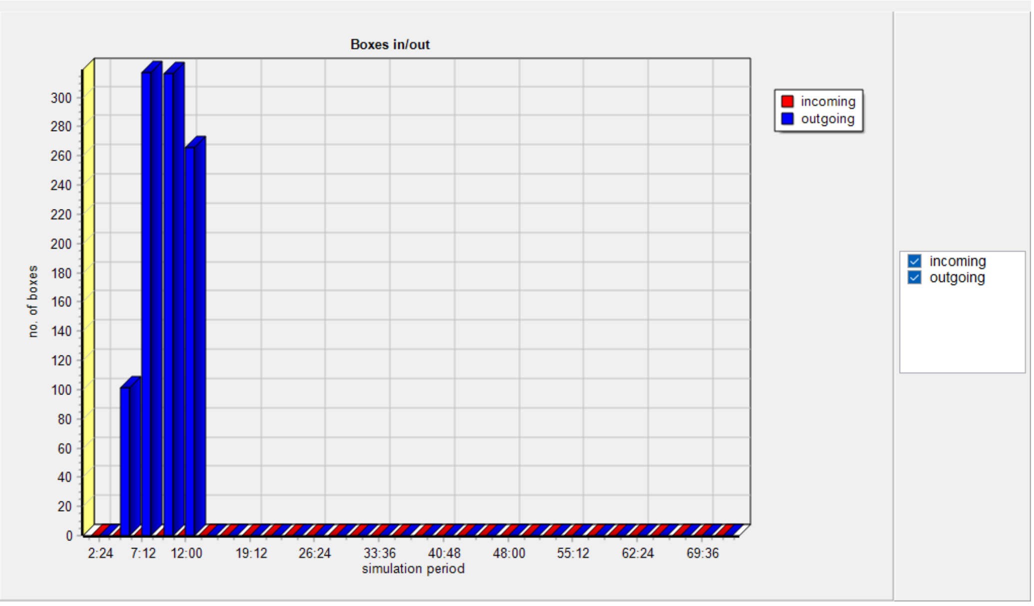


Figure 30. Exported Packages throughput in CHESSCON Evaluation module (Source: Final Results – Euro-Terminal , 2025)

According to Konecranes specification (Konecranes SMV 15-1200) – average fuel consumption is 10L/hour. Thus we can calculate the amount of liters of consumed Diesel by using the formula for 4 vehicles worked in total :

4 * 11,37 hrs * 10 liter/hour = 454,8 liters

liters of diesel for scenario of 11,37 hrs according to average fuel consumption by forklift specification. Total scenario time: 11,37 Hrs

According to the Report "PREPARING FOR THE TRANSITION TO GREEN ENERGY IN SMALL AND MEDIUM-SIZED PORT ECOSYSTEMS (WP2 A2.4; A2.5)", table 7.3 [3] , average emission factor for diesel is 3,2. Also For **diesel (EN590 / ISO 8217 DMA)**, EU MRV and IPCC we use:

$$\mathrm{EF}_{\mathrm{diesel}} = 3.206 \text{ kg CO}_2 \text{ per kg of fuel}$$

Diesel density (EU standard reference):

$$\rho = 0.84 \text{ kg/L}$$

Thus we calculate amount of emissions as follows:

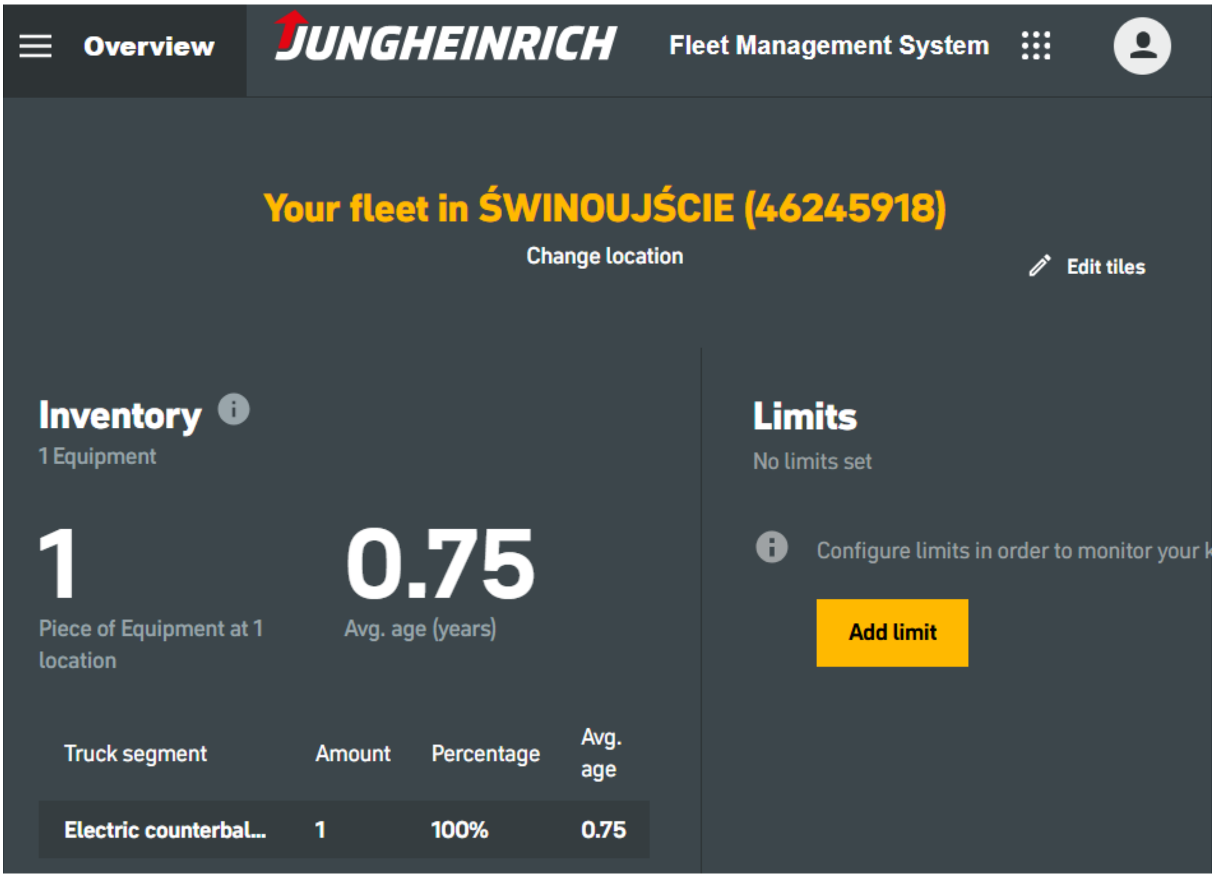
$$\boxed{1\ \text{L diesel} \approx 2.69\ \text{kg CO}_2}$$

454,8 liters of diesel x 2.69 kg CO_2 = 1223,4 Kg CO_2

4.1.2 Monitoring running pilot

EuroTerminal provided access to the Jungheinrich© fleet management system (FMS). Monitoring of the running pilot was possible by auxiliary data: Operating hours and Battery Monitoring.

https://fleetmanagement.jungheinrich.com/



Your fleet in ŚWINOUJŚCIE (46245918)

Inventory

1 Equipment

1

Piece of Equipment at 1 location

0.75

Avg. age (years)

Truck segment	Amount	Percentage	Avg. age
Electric counterbal...	1	100%	0.75

Limits

No limits set

Configure limits in order to monitor your k

Figure 31. Forklift fleet management system (Source: Final Results – Final Results - Euro-Terminal running pilot, 2026)

Jungheinrich© FMS (**FMS** = Fleet Management System) includes pages that allows to review the detailed list of equipment by Jungheinrich in the port. The FMS allows to manage the vehicles, define locations, provide analysis tools and check various safety metrics.

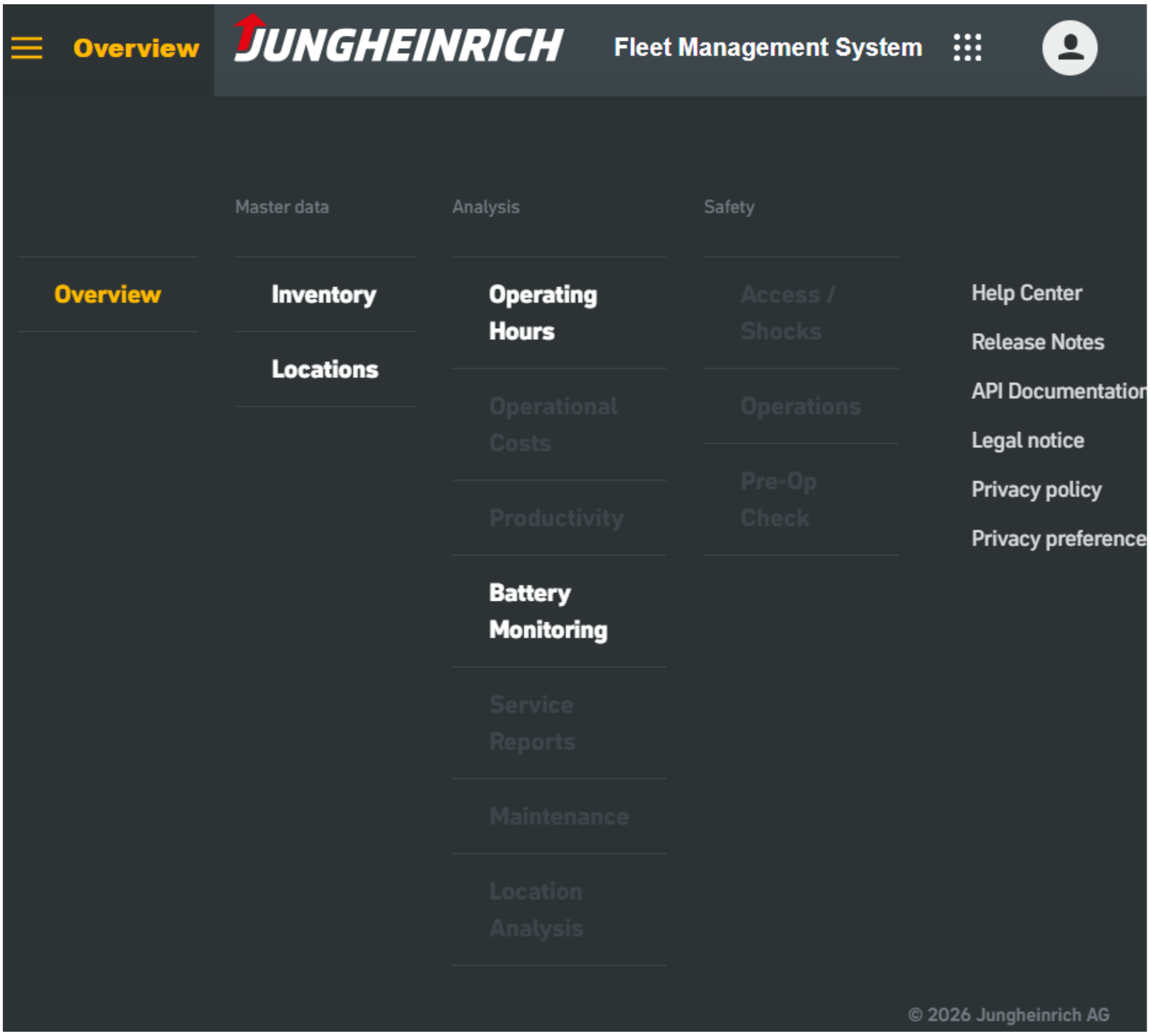


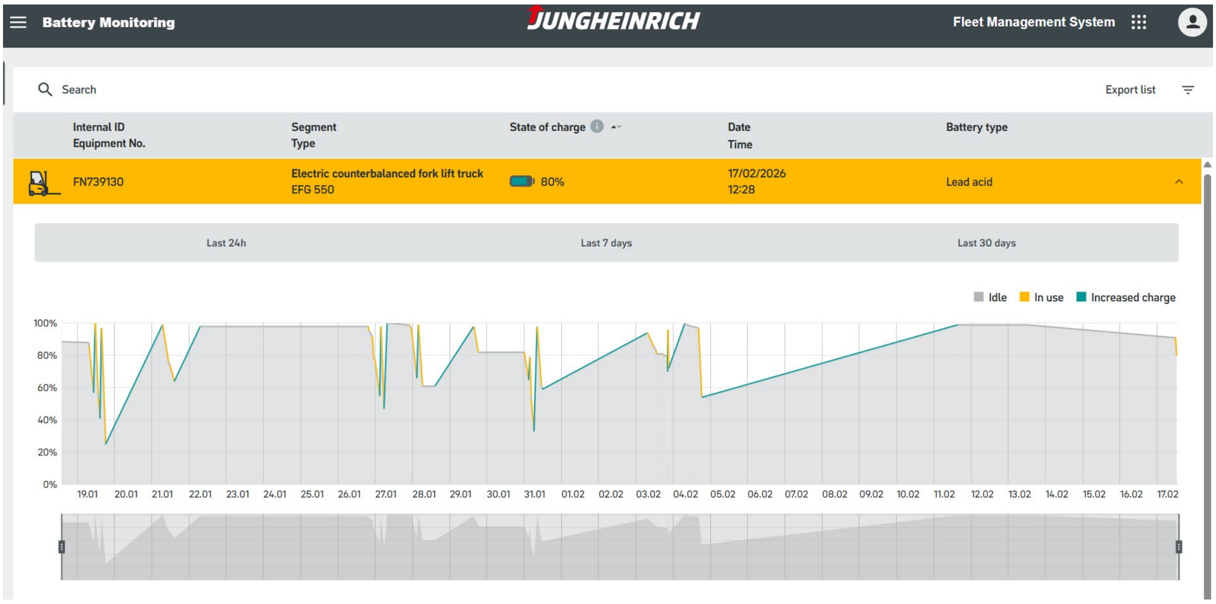
Figure 32. Forklift fleet management system (Source: Final Results – Final Results - Euro-Terminal running pilot, 2026)

Figure represents the battery monitoring module of the Jungheinrich fleet management system. The module provides operational visibility into the performance, utilization patterns, and charging behavior of electric forklift batteries over time.

At the top of the screen, each battery or forklift battery pack is uniquely identified by an internal ID number and assigned to a segment (e.g., electric counterbalanced forklift truck EFG 550). Additional metadata displayed includes the following: State of charge in percentage, representing the current battery energy level.

Timestamp of the latest recorded status. Battery type (e.g., lead-acid), enabling differentiation between battery technologies (lead-acid, lithium-ion, etc.) for lifecycle and performance analysis.

This data also supports cargo handling operations traceability and maintenance planning, allowing for linking battery performance to specific operations.



Battery Monitoring

JUNGHEINRICH

Fleet Management System

Search

Export list

Internal ID Equipment No.	Segment Type	State of charge	Date Time	Battery type
FN739130	Electric counterbalanced fork lift truck EFG 550	80%	17/02/2026 12:28	Lead acid

Last 24h

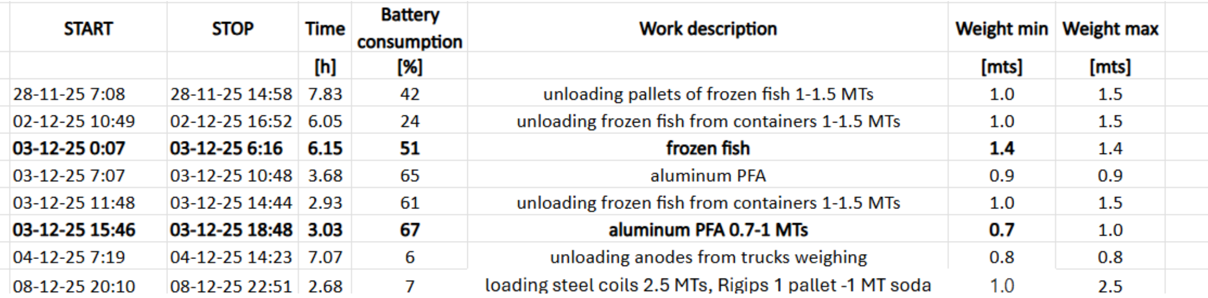
Last 7 days

Last 30 days

Figure 33. Battery usage diagram in Forklift FMS (Source: Final Results – Final Results - Euro-Terminal running pilot, 2026)

This battery monitoring page has been used as a validation tool for testing running pilot, linking forklift operational activity with energy consumption and charging behavior. Euro-Terminal representative provided information about actual activity per hour: transported weights and battery consumption that allows to validate simulations results.

Figure 34. Battery usage visualization in Forklift fleet management system (Source: Final Results – Final Results - Euro-Terminal running pilot, 2026)



START	STOP	Time	Battery consumption	Work description	Weight min	Weight max
		[h]	[%]		[mts]	[mts]
28-11-25 7:08	28-11-25 14:58	7.83	42	unloading pallets of frozen fish 1-1.5 MTs	1.0	1.5
02-12-25 10:49	02-12-25 16:52	6.05	24	unloading frozen fish from containers 1-1.5 MTs	1.0	1.5
03-12-25 0:07	**03-12-25 6:16**	**6.15**	**51**	**frozen fish**	**1.4**	1.4
03-12-25 7:07	03-12-25 10:48	3.68	65	aluminum PFA	0.9	0.9
03-12-25 11:48	03-12-25 14:44	2.93	61	unloading frozen fish from containers 1-1.5 MTs	1.0	1.5
03-12-25 15:46	**03-12-25 18:48**	**3.03**	**67**	**aluminum PFA 0.7-1 MTs**	**0.7**	1.0
04-12-25 7:19	04-12-25 14:23	7.07	6	unloading anodes from trucks weighing	0.8	0.8
08-12-25 20:10	08-12-25 22:51	2.68	7	loading steel coils 2.5 MTs, Rigips 1 pallet -1 MT soda	1.0	2.5

Figure 35. Actual Forklift activity per hour : transported weights and battery consumption   (Source: Final Results – Final Results - Euro-Terminal running pilot, 2026)

According to the data from table in Figure 36 Average battery use per hour is 8.19 % which is 6.5 Kwh per hour. This validation support simulation results of 18 Kwh per hour or 14% .

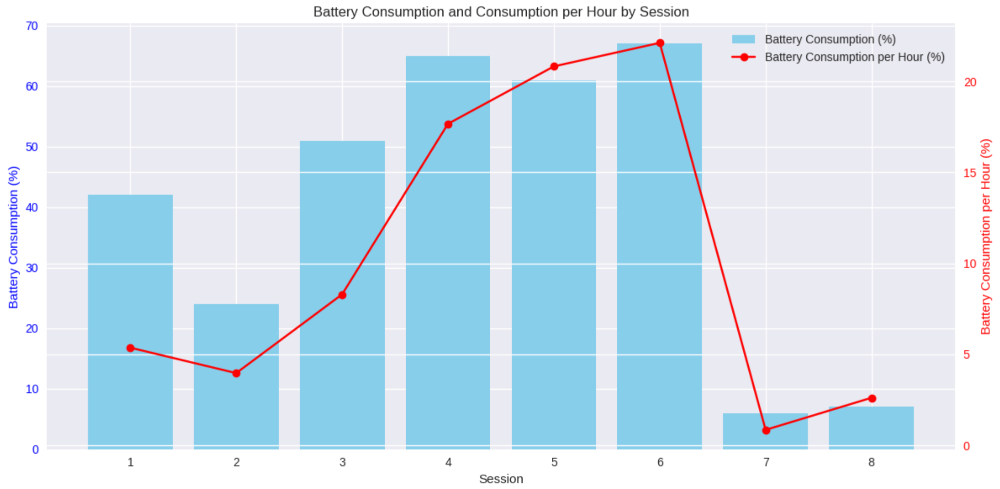


Figure 36. Forklift Battery Consumption and Consumption per Hour by Session (Source: Final Results – Final Results - Euro-Terminal running pilot, 2026)

The produced visualization shows that there is no strong positive correlation between load weight and battery drain. Heavier loads do not consistently lead to higher battery consumption per hour. The largest battery-drain events occurred at moderate weights. For example: Sessions with ~0.9–1.0 MT loads show some of the highest battery-per-hour values. Meanwhile, the heaviest load (2.5 MT) had very low battery drain per hour.

Operational factors likely matter more than weight. The pattern suggests that battery drain is influenced by: Type of material (e.g., aluminum PFA sessions were very energy-intensive), Driving patterns (short bursts vs continuous movement), Lifting frequency, Temperature (frozen fish handling may involve cold environments, Idle time or travel distance. Load weight alone does not predict battery consumption. Forklift's energy usage is more sensitive to task type and operational behavior than to the weight being lifted.

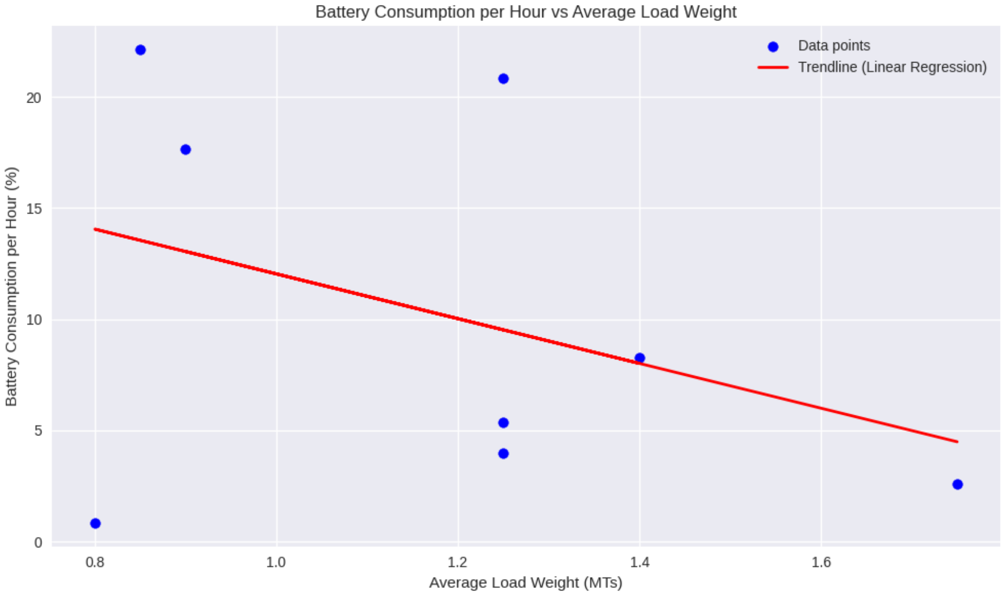


Figure 37b. Dependency of Battery Consumption by load weight (Source: Final Results – Final Results - Euro-Terminal running pilot, 2026)

4.2 Karlshamn (Sweden)

The pilot in Sweden is represented by two separate simulation software projects on the defined terminal area layout. The aim is to simulate the impact of transitioning to electric CHE in hybrid scenarios. The projects include layout visualization focused on processes and operational capacity of the terminal area for soft-wood cargo operations. In conducting the simulation projects the need for developing a robust simulation model was supported by employing CHESSCON®, which is a Port Terminal modelling and simulation software that helped in modelling by using any of the number of CHESSCON® modules setup: Layout, Input, Simulation and 3D layout. The main screen of CHESSCON® is represented in Figure, and the example of the project screen in Layout Editor is represented in Figure 4

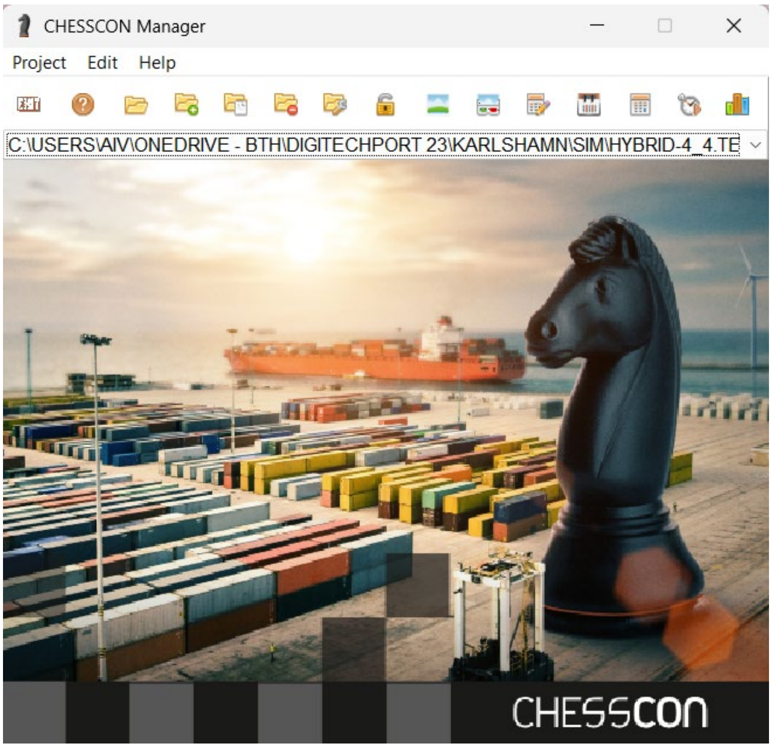


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Figure 38. CHESSCON® SaaS application main screen (Source: Final Results – Karlshamn, 2025)

4.2.1 Main scenario and Requirements

Karlshamn port representatives provided the information about cargo terminal parameters, equipment, and description of a cargo operations. Figure 5 represents the schematic representation of cargo scenario including terminal area, break-bulk stacking area CHE disposition.

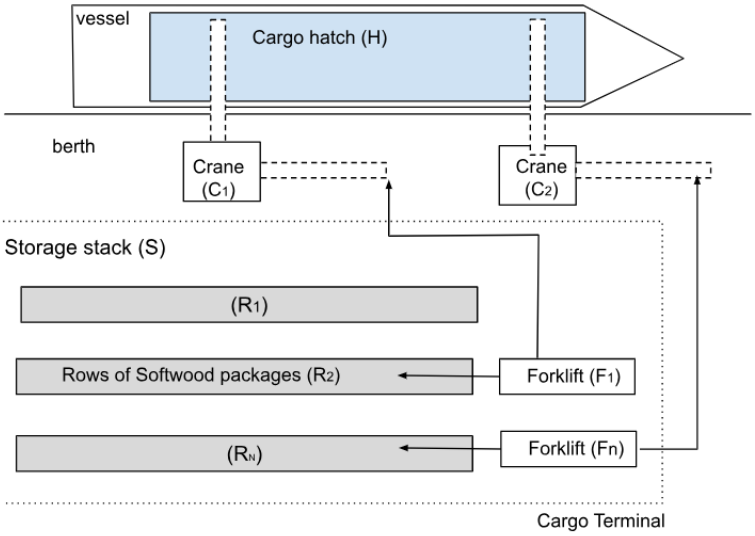


Figure 39. Cargo handling operations model (Source: Final Results – Karlshamn, 2025)

Figure 5 represent the planned cargo terminal area within the designated port area.

The analyzed export scenario at Figue1 represents a general cargo terminal operation handling packaged softwood cargo for maritime shipment. A container-capable vessel with a nominal capacity of 2,000 TEU and an overall length of 200 m is berthed at the quay. Cargo handling operations are conducted within a two cargo terminal areas of 160 m × 500 m in total, which includes quay-side handling zones, internal transport corridors, and landside storage areas.

The terminal is equipped with two mobile harbour cranes, which perform ship-to-shore and shore-to-ship lifting operations, and eight forklifts, which provide horizontal transport and stacking operations within the terminal. The cargo consists of 7,500 packaged softwood units, representing break-bulk forest products prepared for export.

These areas are used for intermediate storage and staging of softwood packages prior to loading. The average transport distance between the stacking areas and the quay crane interface is approximately 100 m, which defines the internal horizontal transport leg for forklift operations.

The operational process flow comprises: (i) internal transport of packages from stacking areas to the quay at crane lifting zone, and (ii) vertical loading onto the vessel's cargo holds. This configuration represents a typical export logistics layout for break-bulk forest products, with separated functional zones for storage, internal transport, and ship interface operations

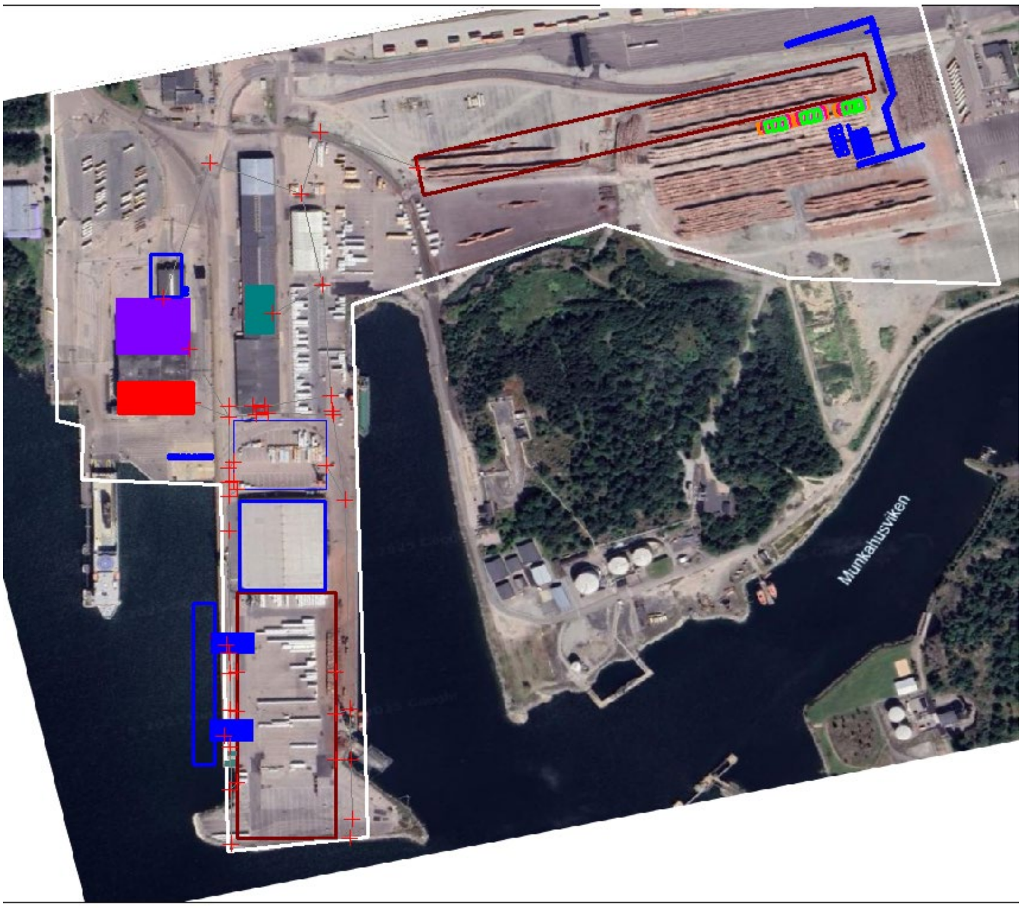


Figure 40. Euro-Terminal terminal view in CheessCon Layout Editor, with terrain layer set visible. (Source: Final Results – Karlshamn, 2025)

Figure 20 represent the Karlshman terminal layout designed in CheessCon Layout Editor.

Figure 6 represent more detailed break-bulk cargo terminal geometry including quay, location of two storage stacks (in yellow and black color) and position of mobile harbour cranes. We exported the schema of the area by using Google Maps software and then added arrows on top of it to confirm our assumptions regards the size of cargo and container stack in the terminal with the Port of Karlshamn representatives. The layout includes the following elements: two cranes, two stacks for break-bulc cargo (area A , B), one mechanical station to check and refuel conventional diesel driven CHE, two charging stations for Electric, battery driven CHE.

After interviewing Karlshamn port we have created simulation scenario based on export case of MS Saga Faith vessel in 2020 having 65,417 m³ of softwood boards exported from Sweden/ Karlshamn Port. According to the provided scenario, the only type of cargo that will be used in the simulation are softwood packages.

https://www.timberindustrynews.com/sweden-record-batch-of-softwood-lumber-sent-to-the-united-states/

According to a questionnaire, Karlshamn cargo terminal uses the conventional berthing facilities for break-bulk cargo vessels are usually berthed at a dedicated berth with a quay line of 150 meters. Due to limited size of the terminal area, exist a solution to reuse berth area for warehouse purposes thus saving space in the main warehouse for other types of cargo. For this purpose, we have modified the loading operations and elaborated new handling schema presented on Figure 12. Simulation model assumes that berth area is used partially as a warehouse to stack 6000 packages of softwood before ship arrival. Another small area behind the building is also used to stack 2000 packages. During ship loading , forklifts bring packages from both areas to the cranes at the berth directly and drop them in front of the crane. Crane lifts packages from the ground by using the special attachment.

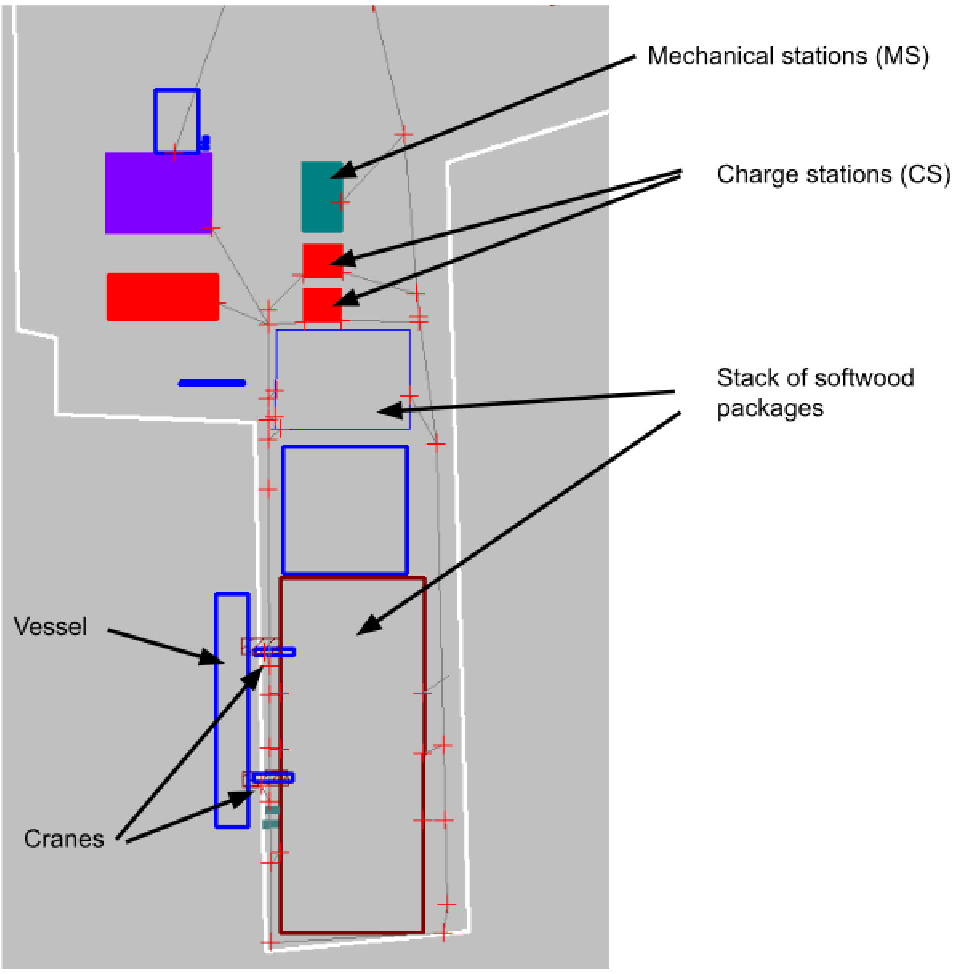


Figure 41. Euro-Terminal terminal layout designed in CheessCon Layout Editor (Source: Final Results – Karlshamn, 2025)

Two dedicated stacking areas are defined within the terminal:
Stacking Area A: 110 m × 300 m
Stacking Area B: 110 m × 80 m

Table 1 represents two simulations for the same single cargo scenario focusing on CO_2 emissions for two sets of cargo handling equipment. Each simulation focuses on energy consumption of forklift loaders to transport cargo from storage stack to harbour crane. To understand the outcomes of CO_2 emissions savings depending on the rate of Electrified cargo handling equipment, we have introduced an additional vessel with 250 containers

Simulation #1	Independent variables			Dependent variables
Vessel A	Cargo (A)	Port Equipment (B)	Handling rate (C=A/B)	Simulation criteria
Saga Faith IMO 9808651	Loading:	Mobile harbour crane	Unloading: XX hours	Total energy consumption converted to Kwh. Equipment active hours - diesel usage

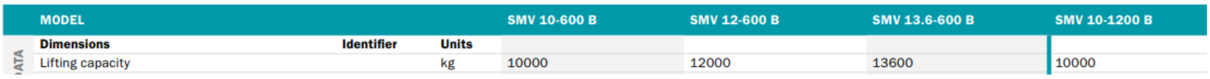
2000 TEU 65,417 m³ softwood	7500 softwood packages (6 meters long) 6m x 1m x 1m , 6 m^3	2 x Mantsinen 160ES crane (4,6 m² grab) 8 x 40t/hour Diesel forklift Konecranes SMV 15-1200	Loading: XX hours?	in liters and total weight of CO₂ emissions in Kg.
Simulation #2	Independent variables			Dependent variables
		4x Electric Forklifts 4 x 40t/hour Diesel forklift Konecranes SMV 15-1200		Total energy consumption converted to Kwh. Equipment active hours - diesel usage in liters and total weight of CO₂ emissions in Kg.

Table 4. The simulation scenario for bulk-bulk cargo operation. (Source: Final Results – Karlshamn, 2025)

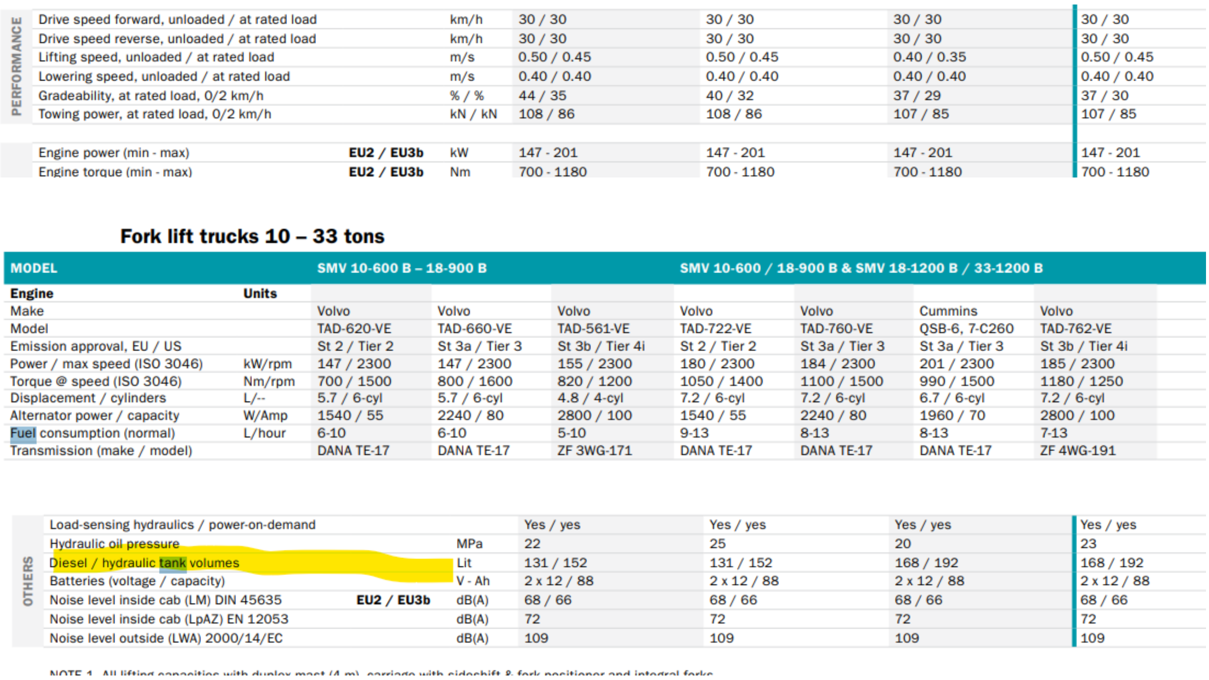
Figure 42. Forklift Konecranes SMV 15-1200 (Source: https://www.konecranes.com)

https://www.konecranes.com/sites/default/files/download/konecranes_brochure_lifttrucks_flt_en_2015_8809008-1.pdf

Equipment Performance, from



MODEL			SMV 10-600 B	SMV 12-600 B	SMV 13.6-600 B	SMV 10-1200 B
Dimensions	**Identifier**	**Units**				
Lifting capacity		kg	10000	12000	13600	10000



PERFORMANCE	Drive speed forward, unloaded / at rated load		km/h	30 / 30	30 / 30	30 / 30	30 / 30
	Drive speed reverse, unloaded / at rated load		km/h	30 / 30	30 / 30	30 / 30	30 / 30
	Lifting speed, unloaded / at rated load		m/s	0.50 / 0.45	0.50 / 0.45	0.40 / 0.35	0.50 / 0.45
	Lowering speed, unloaded / at rated load		m/s	0.40 / 0.40	0.40 / 0.40	0.40 / 0.40	0.40 / 0.40
	Gradeability, at rated load, 0/2 km/h		% / %	44 / 35	40 / 32	37 / 29	37 / 30
	Towing power, at rated load, 0/2 km/h		kN / kN	108 / 86	108 / 86	107 / 85	107 / 85
	Engine power (min - max)	**EU2 / EU3b**	kW	147 - 201	147 - 201	147 - 201	147 - 201
	Engine torque (min - max)	**EU2 / EU3b**	Nm	700 - 1180	700 - 1180	700 - 1180	700 - 1180

Fork lift trucks 10 – 33 tons

MODEL		**SMV 10-600 B – 18-900 B**			**SMV 10-600 / 18-900 B & SMV 18-1200 B / 33-1200 B**			
Engine	**Units**							
Make		Volvo	Volvo	Volvo	Volvo	Volvo	Cummins	Volvo
Model		TAD-620-VE	TAD-660-VE	TAD-561-VE	TAD-722-VE	TAD-760-VE	QSB-6, 7-C260	TAD-762-VE
Emission approval, EU / US		St 2 / Tier 2	St 3a / Tier 3	St 3b / Tier 4i	St 2 / Tier 2	St 3a / Tier 3	St 3a / Tier 3	St 3b / Tier 4i
Power / max speed (ISO 3046)	kW/rpm	147 / 2300	147 / 2300	155 / 2300	180 / 2300	184 / 2300	201 / 2300	185 / 2300
Torque @ speed (ISO 3046)	Nm/rpm	700 / 1500	800 / 1600	820 / 1200	1050 / 1400	1100 / 1500	990 / 1500	1180 / 1250
Displacement / cylinders	L/--	5.7 / 6-cyl	5.7 / 6-cyl	4.8 / 4-cyl	7.2 / 6-cyl	7.2 / 6-cyl	6.7 / 6-cyl	7.2 / 6-cyl
Alternator power / capacity	W/Amp	1540 / 55	2240 / 80	2800 / 100	1540 / 55	2240 / 80	1960 / 70	2800 / 100
Fuel consumption (normal)	L/hour	6-10	6-10	5-10	9-13	8-13	8-13	7-13
Transmission (make / model)		DANA TE-17	DANA TE-17	ZF 3WG-171	DANA TE-17	DANA TE-17	DANA TE-17	ZF 4WG-191

OTHERS	Load-sensing hydraulics / power-on-demand			Yes / yes	Yes / yes	Yes / yes	Yes / yes
	Hydraulic oil pressure		MPa	22	25	20	23
	Diesel / hydraulic tank volumes		Lit	131 / 152	131 / 152	168 / 192	168 / 192
	Batteries (voltage / capacity)		V - Ah	2 x 12 / 88	2 x 12 / 88	2 x 12 / 88	2 x 12 / 88
	Noise level inside cab (LM) DIN 45635	**EU2 / EU3b**	dB(A)	68 / 66	68 / 66	68 / 66	68 / 66
	Noise level inside cab (LpAZ) EN 12053		dB(A)	72	72	72	72
	Noise level outside (LWA) 2000/14/EC		dB(A)	109	109	109	109

NOTE 1. All lifting capacities with duplex mast (4 m), carriage with sideshift & fork positioner and integral forks.

Figure 43. Forklift Konecranes Performance comparison (Source: https://www.konecranes.com)

Parameter	Value	Source
Forklift Model	Konecranes SMV 15-1200 C	Konecranes, Volvo
Load Capacity	15 tons at 1200 mm	Konecranes
Engine	Volvo Diesel, 150 kW	Volvo
Travel Speed (Loaded/Unloaded)	30 km/h	Konecranes
Fuel Consumption Estimate	8–12 L/hour	Konecranes Models
CO_2 Factor (Diesel)	2.68 kg/L	EU Emission Factors
CO_2 Factor (Electric)	0.05 kg/kWh	Swedish Grid Avg.
Hoisting Speed	~0.35–0.4 m/s	Comparable to similar models; varies with load and hydraulic system.
Pickup Time	~5–7 seconds	Time to engage forks and lift load; depends on operator skill and load.
Drop-off Time	~5–7 seconds	Time to lower and disengage load; influenced by load weight and mast type.
Acceleration	~0.5–0.7 m/s^2	Estimated based on engine power and weight; varies with terrain.

Table 5. Performance characteristics of Konecranes SMV 15-1200 forklift. (Source: Final Results – Karlshamn, 2025)

Operation	Typical Power (kW)	Engineering Rationale
Idle / positioning	12 kW	Engine auxiliaries + hydraulic standby
Lifting 5 t	45 kW	~60% of 50% operational ceiling
Loaded acceleration	60 kW	Traction transient peak
Loaded travel (25 km/h)	35 kW	Rolling resistance + drivetrain losses

Operation	Typical Power (kW)	Engineering Rationale
Braking / deceleration	5 kW	Mostly mechanical braking
Lowering load	12 kW	Controlled hydraulic descent
Empty return travel	25 kW	Lower mass, reduced traction load

Table 6. Energy consumptions of Konecranes SMV 15-1200 forklift. (Source: Final Results – Karlshamn, 2025)

Table. SMV 15-1200 Forklift energy consumption.

According to report „PREPARING FOR THE TRANSITION TO GREEN ENERGY IN SMALL AND MEDIUM-SIZED PORT ECOSYSTEMS (WP2 A2.4; A2.5)“ the average power utilization factor of the specified equipment during operation. It is between 0.2 and 0.7, which is normal practice in multi-functional SMSPs or terminals.
If We assume 0.5 (i.e. 50%) for average power utilization factor for “Konecranes SMV 15-1200 ” 150kWh.
power utilization =

$$150 \times 0.5 = 75 \text{ kWh.} * 34 \text{ hrs} * 0.2 \text{ (kg/kWh)} = 510 \text{ Kg diesel}$$

Converting diesel Kg to CO_2:

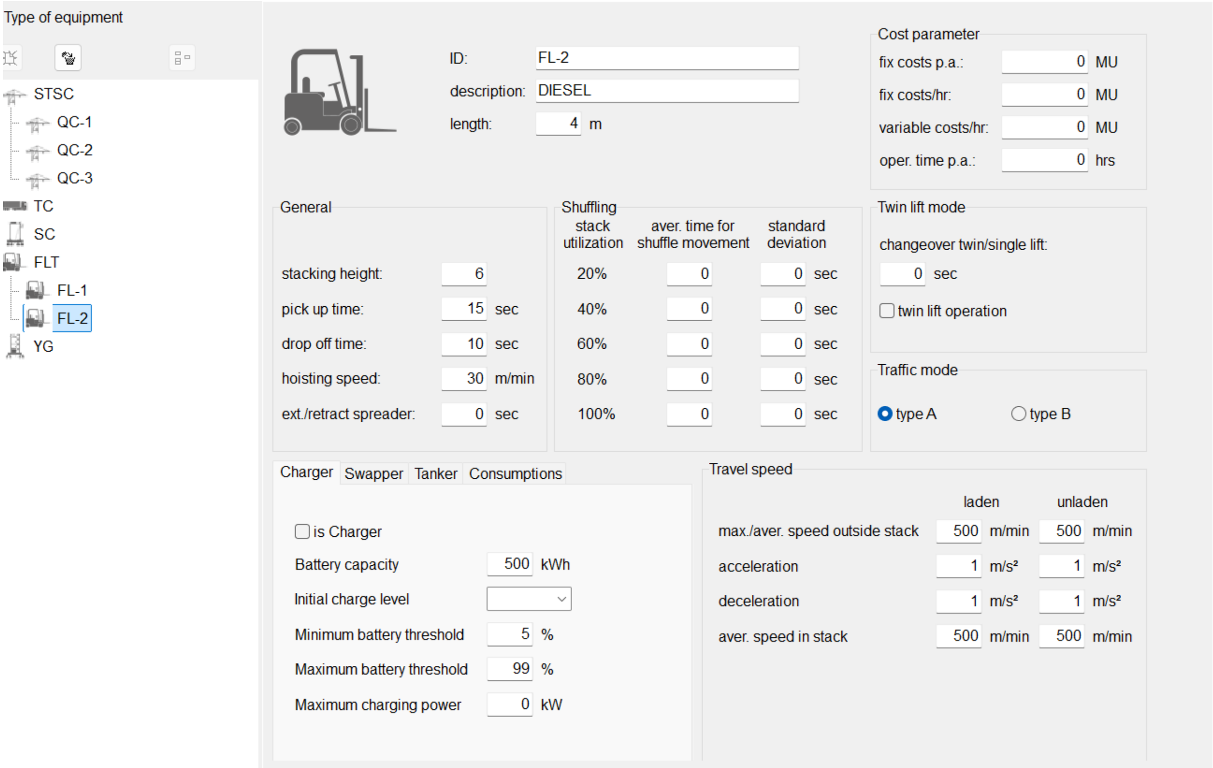
$$510 \text{ kg} * 3{,}2 \text{ (}CO_2\text{ emission factor per kg)} = 1632 \text{ Kg } CO_2$$

for a single Forklift and Total emission according to average power util. Factor:

$$1632 \text{ Kg } CO_2 * 8 \text{ vehicles} = \mathbf{13056\ kg}\ CO_2$$

Apart from the spatial layout of the break-bulk stack, CHESSCON® Input editor allows defining detailed parameters of the cargo scenario, such as the number of involved equipment, Its characteristics, and volume of cargo flow between yard, waterside, and landside. CHESSCON® Input editor also allows defining the simulation duration and equipment strategies, for example how much moves each crane needs to make to server a number of cargo hatches in a vessel.

Figure 44 contains the screenshot of the Ship parameters where we define 7500 packages for for Export served by two cranes. Each crane may have various parameters such as number of served containers with a defined distribution, number of allocated bays, container lifting time for discharging and loading, time waste after each cycle tier.



ID: FL-2
description: DIESEL
length: 4 m

Cost parameter
fix costs p.a.: 0 MU
fix costs/hr: 0 MU
variable costs/hr: 0 MU
oper. time p.a.: 0 hrs

General
stacking height: 6
pick up time: 15 sec
drop off time: 10 sec
hoisting speed: 30 m/min
ext./retract spreader: 0 sec

Shuffling

stack utilization	aver. time for shuffle movement	standard deviation
20%	0	0 sec
40%	0	0 sec
60%	0	0 sec
80%	0	0 sec
100%	0	0 sec

Twin lift mode
changeover twin/single lift: 0 sec
☐ twin lift operation

Traffic mode
● type A ○ type B

Charger | Swapper | Tanker | Consumptions

☐ is Charger
Battery capacity 500 kWh
Initial charge level
Minimum battery threshold 5 %
Maximum battery threshold 99 %
Maximum charging power 0 kW

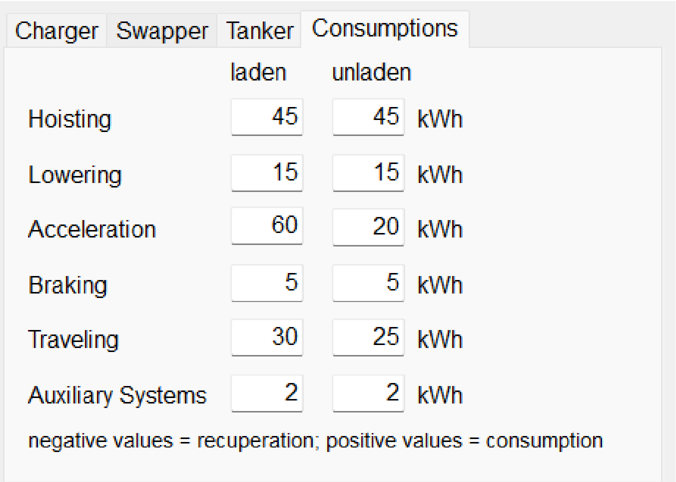
Travel speed

	laden	unladen
max./aver. speed outside stack	500 m/min	500 m/min
acceleration	1 m/s²	1 m/s²
deceleration	1 m/s²	1 m/s²
aver. speed in stack	500 m/min	500 m/min

Figure 44. Simulation parameters for SMV 15-1200 forklift represented in CHESSCON Input module (Source: Final Results – Karlshamn, 2025)

Key diesel forklift parameters configured in the simulation model.

Figure 42 represent the parameters of forklifts such as length, various type of speed, container pickup and drop-off time, as well as energy consumption per each operation. The values for each parameter is extracted from Forklift manufacturer specification provided in Figure 45 below

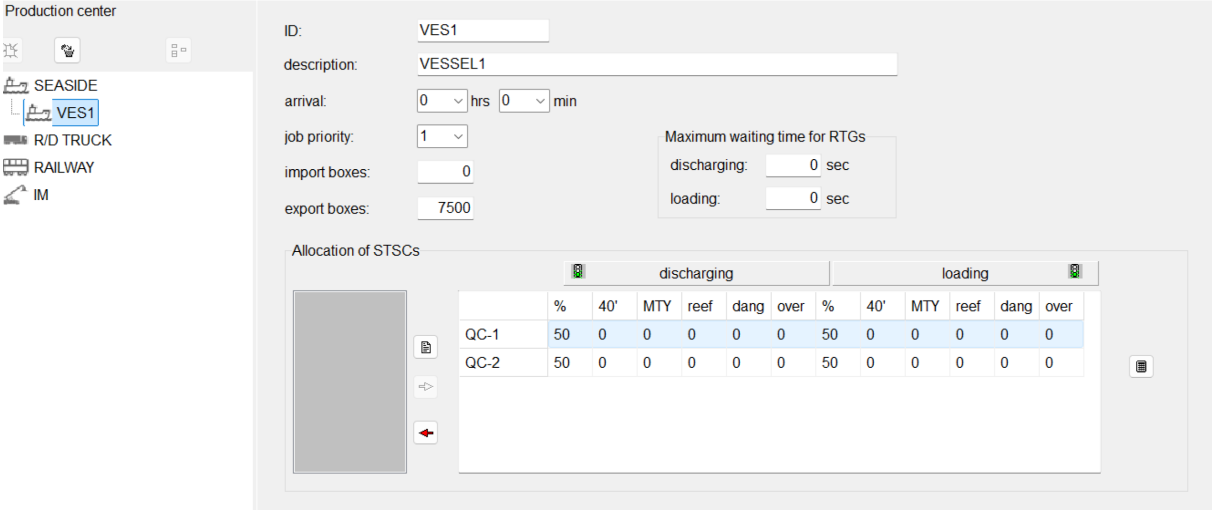


	laden	unladen	
Hoisting	45	45	kWh
Lowering	15	15	kWh
Acceleration	60	20	kWh
Braking	5	5	kWh
Traveling	30	25	kWh
Auxiliary Systems	2	2	kWh

negative values = recuperation; positive values = consumption

Figure 45. Energy consumption per activity for SMV 15-1200 forklift represented in CHESSCON Input module (Source: Final Results – Karlshamn, 2025)

Figure Energy Consumption.



ID: VES1
description: VESSEL1
arrival: 0 hrs 0 min
job priority: 1
import boxes: 0
export boxes: 7500

Maximum waiting time for RTGs
discharging: 0 sec
loading: 0 sec

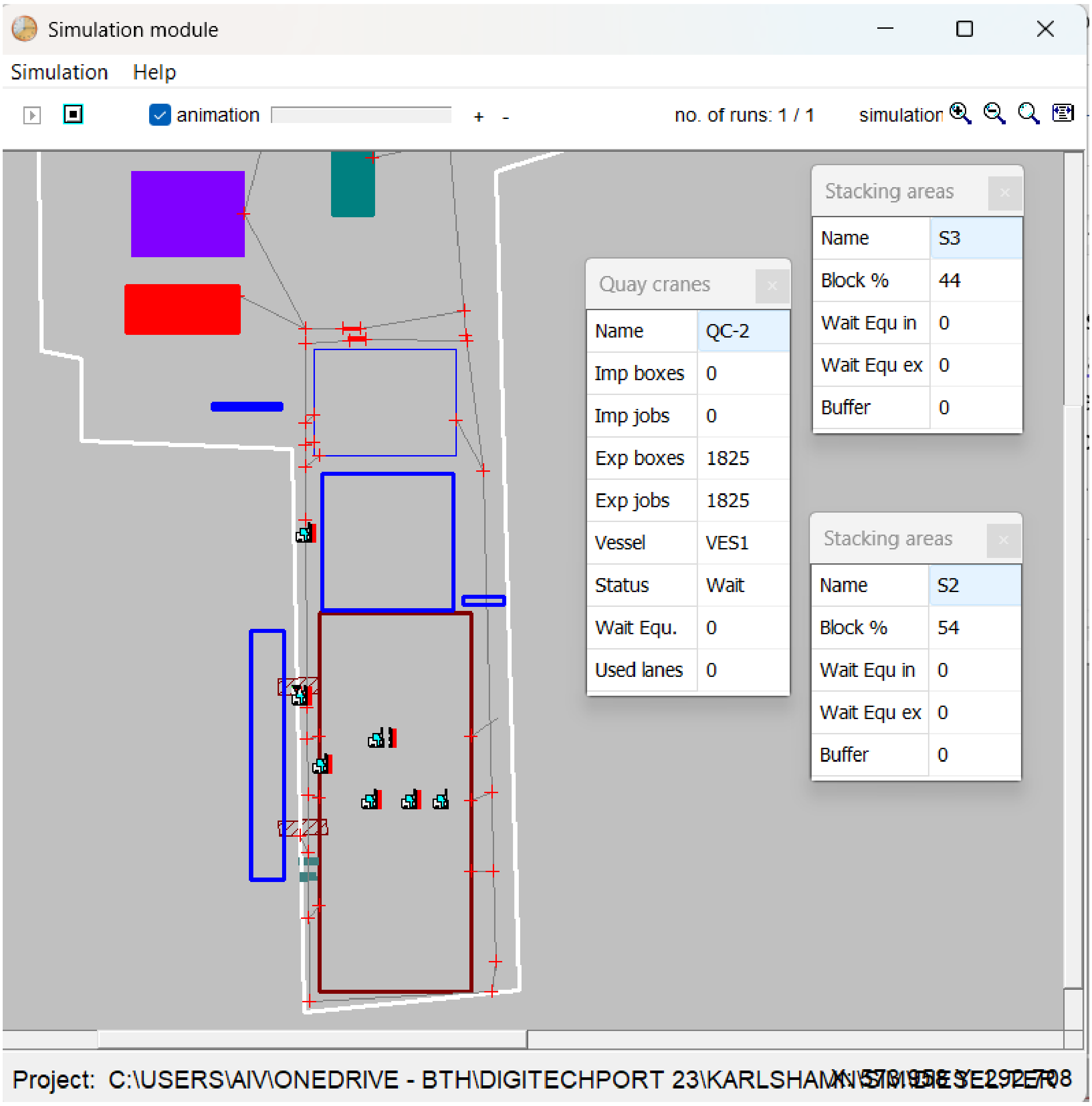
Allocation of STSCs

	discharging						loading					
	%	40'	MTY	reef	dang	over	%	40'	MTY	reef	dang	over
QC-1	50	0	0	0	0	0	50	0	0	0	0	0
QC-2	50	0	0	0	0	0	50	0	0	0	0	0

Figure 46. Mobile harbor cranes represented in CHESSCON Input module (Source: Final Results – Karlshamn, 2025)

Figure Mobile harbor cranes.

From the data in Figure 23 , which contains the screenshot of the Simulation module in CHESSCON® software. It allows simulating cargo flow a number of times with the parameters defined in Input module and Layout module. The results are being recorded and stored with the project data. As shown, Simulation module allows to thoroughly investigate the size of queue or waiting status for each equipment by using “Animation” checkbox and Equipment view dialog, such as “Quay Cranes“.



Quay cranes

Name	QC-2
Imp boxes	0
Imp jobs	0
Exp boxes	1825
Exp jobs	1825
Vessel	VES1
Status	Wait
Wait Equ.	0
Used lanes	0

Stacking areas

Name	S3
Block %	44
Wait Equ in	0
Wait Equ ex	0
Buffer	0

Stacking areas

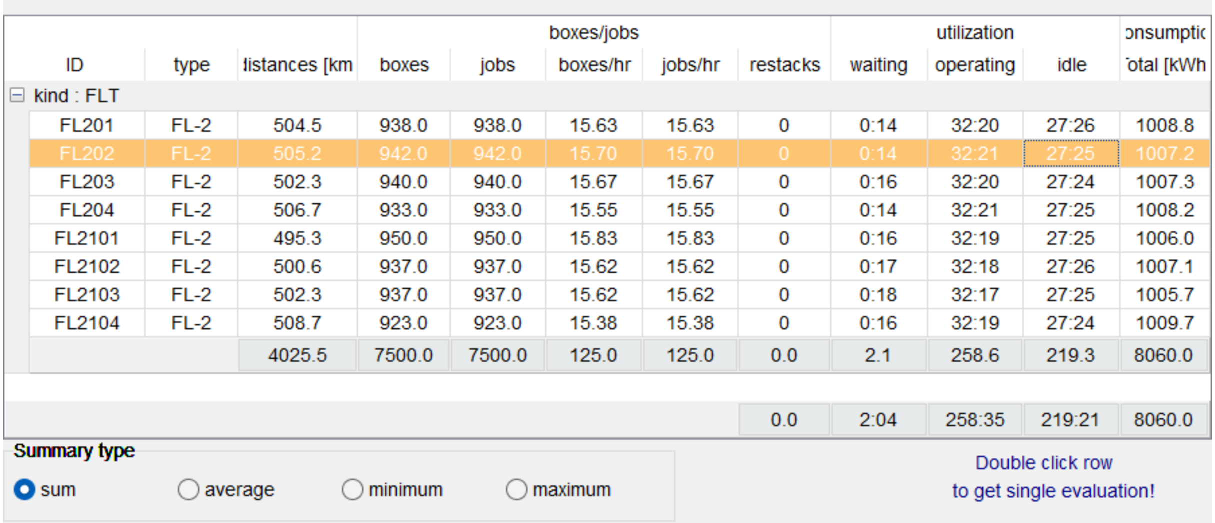
Name	S2
Block %	54
Wait Equ in	0
Wait Equ ex	0
Buffer	0

Project: C:\USERS\AIV\ONEDRIVE - BTH\DIGITECHPORT 23\KARLSHAMN [illegible]

Figure 47. CHESSCON Simulation module running (Source: Final Results – Karlshamn, 2025)

Results from Karlshamn Pilot

To simulate the CO_2 emissions for the cargo scenario, we have elaborated cargo terminal layout and flow scenario including landside storage stacks. We then executed Simulation module 10 times to get average values. Figure 25 shows the results of simulation, where it is indicated that total of 7500 packages was loaded during a simulation time defined as 5 hours. 8 Diesel-driven forklifts consumed 8060 kWh of energy during 258 hours in total.



					boxes/jobs				utilization		onsumptic
ID	type	listances [km	boxes	jobs	boxes/hr	jobs/hr	restacks	waiting	operating	idle	otal [kWh
⊟ kind : FLT											
FL201	FL-2	504.5	938.0	938.0	15.63	15.63	0	0:14	32:20	27:26	1008.8
FL202	FL-2	505.2	942.0	942.0	15.70	15.70	0	0:14	32:21	27:25	1007.2
FL203	FL-2	502.3	940.0	940.0	15.67	15.67	0	0:16	32:20	27:24	1007.3
FL204	FL-2	506.7	933.0	933.0	15.55	15.55	0	0:14	32:21	27:25	1008.2
FL2101	FL-2	495.3	950.0	950.0	15.83	15.83	0	0:16	32:19	27:25	1006.0
FL2102	FL-2	500.6	937.0	937.0	15.62	15.62	0	0:17	32:18	27:26	1007.1
FL2103	FL-2	502.3	937.0	937.0	15.62	15.62	0	0:18	32:17	27:25	1005.7
FL2104	FL-2	508.7	923.0	923.0	15.38	15.38	0	0:16	32:19	27:24	1009.7
		4025.5	7500.0	7500.0	125.0	125.0	0.0	2.1	258.6	219.3	8060.0
							0.0	2:04	258:35	219:21	8060.0

Summary type

● sum ○ average ○ minimum ○ maximum

Double click row
to get single evaluation!

Figure 48. Forklifts performance results in CHESSCON Evaluation module (Source: Final Results – Karlshamn, 2025)

Simulation results from the Karlshamn Pilot
The simulation results provided the average of kWh consumed per forklift and working time:
1007,5 kWh / 34 hours = 29,6 kWh (20%) is calculated as real power utilization factor. By using this value we could calculate the total emissions for 8 forklifts as follows:

29,6 kWh. * 34 hrs * 0.2 (kg/Kwh) * 3,2 =644 Kg CO_2 * 8 = **5152,1 Kg co2**

According to real power utilization factor.

If we use the assumption of a relative fuel consumption of 0.2 kg/kWh then:

1007 kWh * 0.22 / 0.84 (coefficient to convert Kg to Liters) = 263,7 liters

The amount of diesel in liters consumed bye ach forklift. According to Konecranes specification (Konecranes SMV 15-1200) – average fuel consumption is 10L/hour.
33 hrs / 13 hours without refuel = 3 refuels. Thus we can calculate the amount of liters of consumed Diesel by using formula:

33 hrs * 10 liter/hour 330 Liters of diesel.

8 vehicles worked in total :

258,6 hrs * 10 liter/hour = 2586 liters

liters of diesel for scenario of 34 hrs according to average fuel consumption by forklift specification.

Total scenario duration: 34 Hrs

According to Simulation results provided 8060 kWh total energy use , we could calculate total CO2 by formula:

8060 kWh *** 0,2 (kg/kWh) = 1612 Kg diesel * 3,2** (CO_2 emission factor per kg) **= 5158,4Kg CO_2.**

CO_2 calculation also can be done by Reference Emission Factor :

From [3] the average emission factor for diesel is 3,2. Also For **diesel (EN590 / ISO 8217 DMA)**, EU MRV and IPCC use:

$$\mathrm{EF}_{\mathrm{diesel}} = 3.206 \text{ kg CO}_2 \text{ per kg fuel}$$

Diesel density (EU standard reference):

$$\rho = 0.84 \text{ kg/L}$$

Thus:

$$\boxed{1 \text{ L diesel} \approx 2.69 \text{ kg CO}_2}$$

2586 liters of diesel x 2.69 kg CO_2 = 6956,34Kg CO_2

Source of data	Methodology	Sensitivity	CO_2 emission, Tons
Manufacturer manual ,engine kWh and Report [1].	Average power utilization factor		13
Simulation	Realistic power utilization factor by Simulation		5,1
Simulation	Total energy consumed by all equipment in kWh		5,1
Manufacturer's manual, engine consumption per hour.	Average diesel consumption by engine, per hour.		6,9

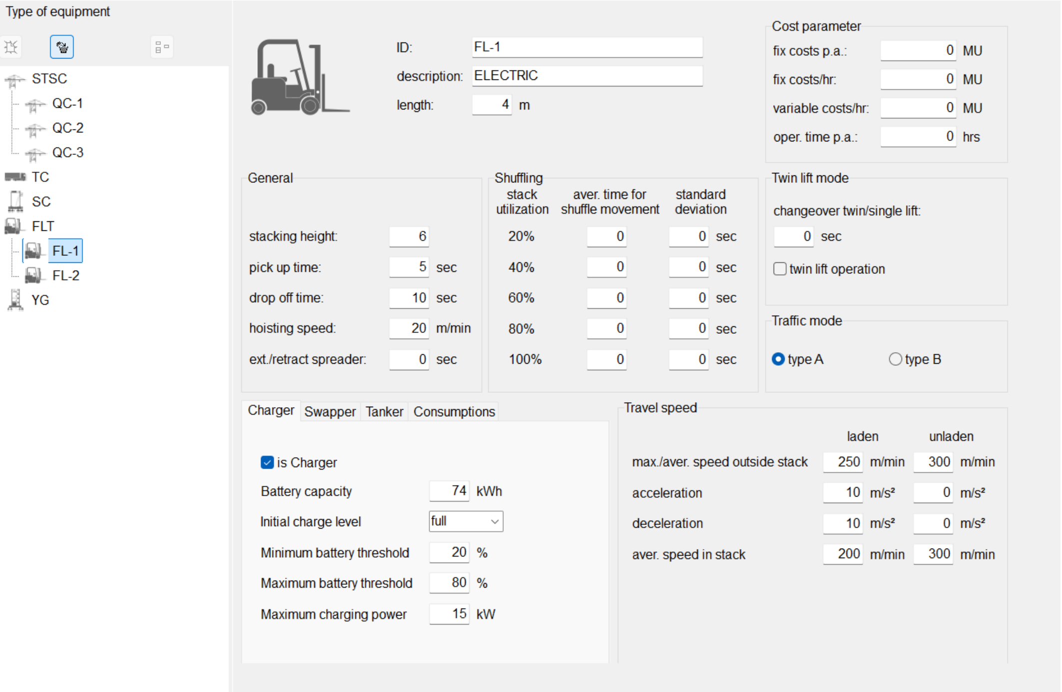
Table 7. Comparison of CO_2 emission calculations for the cargo scenario (Source: Final Results – Karlshamn, 2025)

4.2.2 Hybrid scenario and results

According to the Karlshamns port strategy, the hydrid mode of CHE usage is most promising for future needs. This assumes the use of conventional CHE, diesel driven and Electrified equipment.
To define parameters for Hybrid mode, we used cargo scenario from Table X and split the total number of forklift into equal proportion for Diesel and Electric forklifts.
As a reference we used the performance data for Jungheinrich EFG 550 electric forklift from table 3 (Source: Final Results – Euro-Terminal , 2025).

For the hybrid scenario, we adopted loading operations and handling schema presented in Figure 12 from the initial simulation. The layout includes the following elements: two cranes, two stacks for break-bulc cargo (area A , B), one mechanical station to check and refuel conventional diesel driven CHE, two charging stations for Electric , battery driven CHE. New simulation model assumes that packages will be transported to the crane area by 4 diesel forklifts and 4 electric forklifts. Since electric forklifts are battery-driven, we allocated 2 charge stations (CS) at a distance of 500 meters from the storage stack.

We defined the new model in , CHESSCON® Input editor. Here we outline the proposed changes in the Simulation project nr1 . Figure 23 represents the parameters of Electric forklifts, such as energy consumption for each operation. The value for each parameter is extracted from Jungheinrich specification provided in table



ID: FL-1
description: ELECTRIC
length: 4 m

Cost parameter
fix costs p.a.: 0 MU
fix costs/hr: 0 MU
variable costs/hr: 0 MU
oper. time p.a.: 0 hrs

General
stacking height: 6
pick up time: 5 sec
drop off time: 10 sec
hoisting speed: 20 m/min
ext./retract spreader: 0 sec

Shuffling

stack utilization	aver. time for shuffle movement	standard deviation
20%	0	0 sec
40%	0	0 sec
60%	0	0 sec
80%	0	0 sec
100%	0	0 sec

Twin lift mode
changeover twin/single lift: 0 sec
☐ twin lift operation

Traffic mode
● type A ○ type B

Charger | Swapper | Tanker | Consumptions

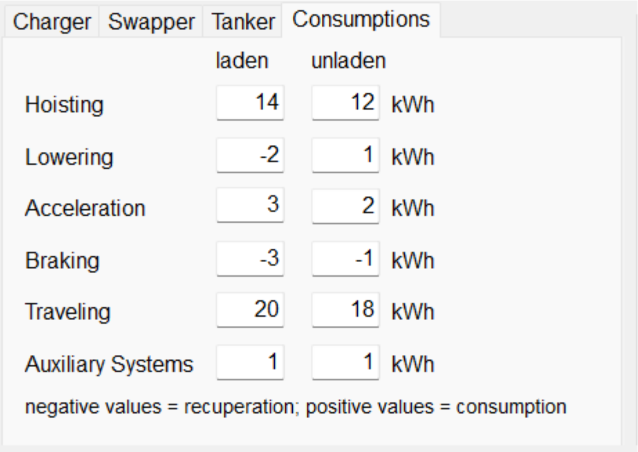
☑ is Charger
Battery capacity 74 kWh
Initial charge level full
Minimum battery threshold 20 %
Maximum battery threshold 80 %
Maximum charging power 15 kW

Travel speed

	laden	unladen
max./aver. speed outside stack	250 m/min	300 m/min
acceleration	10 m/s²	0 m/s²
deceleration	10 m/s²	0 m/s²
aver. speed in stack	200 m/min	300 m/min

Figure 49. Simulation parameters for battery driven forklift represented in CHESSCON Input module (Source: Final Results – Karlshamn, 2025)

Figure. CHESSCON® Input editor and electric forklift parameters .



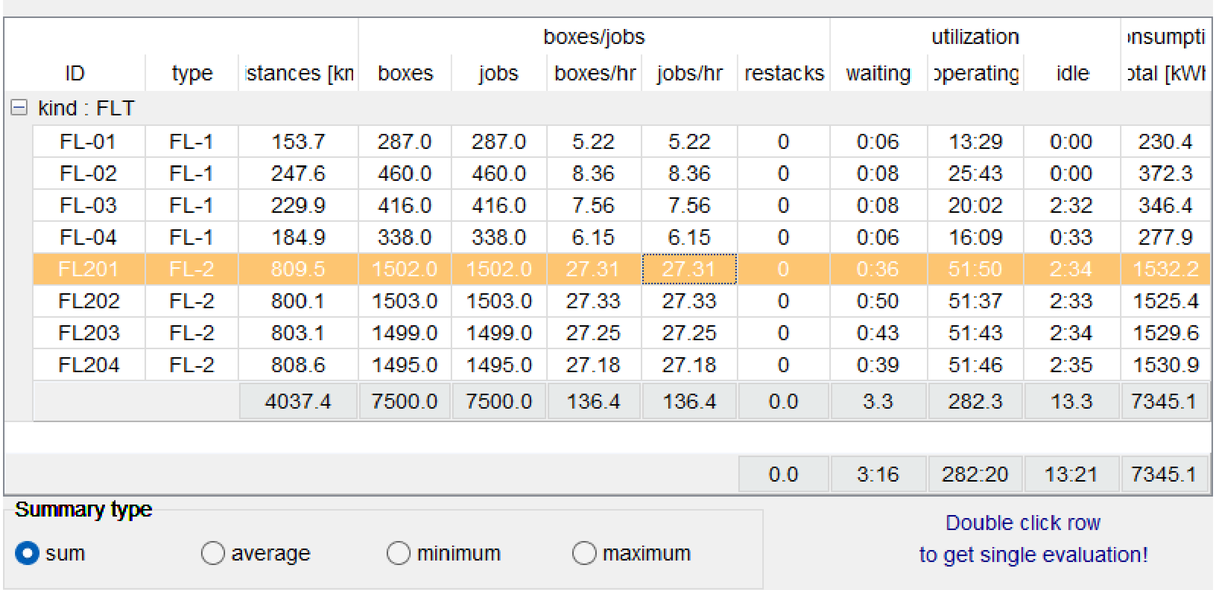
	laden	unladen	
Hoisting	14	12	kWh
Lowering	-2	1	kWh
Acceleration	3	2	kWh
Braking	-3	-1	kWh
Traveling	20	18	kWh
Auxiliary Systems	1	1	kWh

negative values = recuperation; positive values = consumption

Figure 50. Energy consumptions for battery driven forklift represented in CHESSCON Input module (Source: Final Results – Karlshamn, 2025)

Simulation Results from Karlshamn Pilot

To simulate the CO_2 emissions for the cargo scenario for hybrid mix of CHE we used CHESSCON® Simulation module. We performed 10 runs of simulation to get average values. Figure 25 shows the results of simulation, where it is indicated that total of 7500 packages was loaded during a simulation time defined as 5 hours. 4 Diesel-driven forklifts consumed 6118 kWh of energy in total.



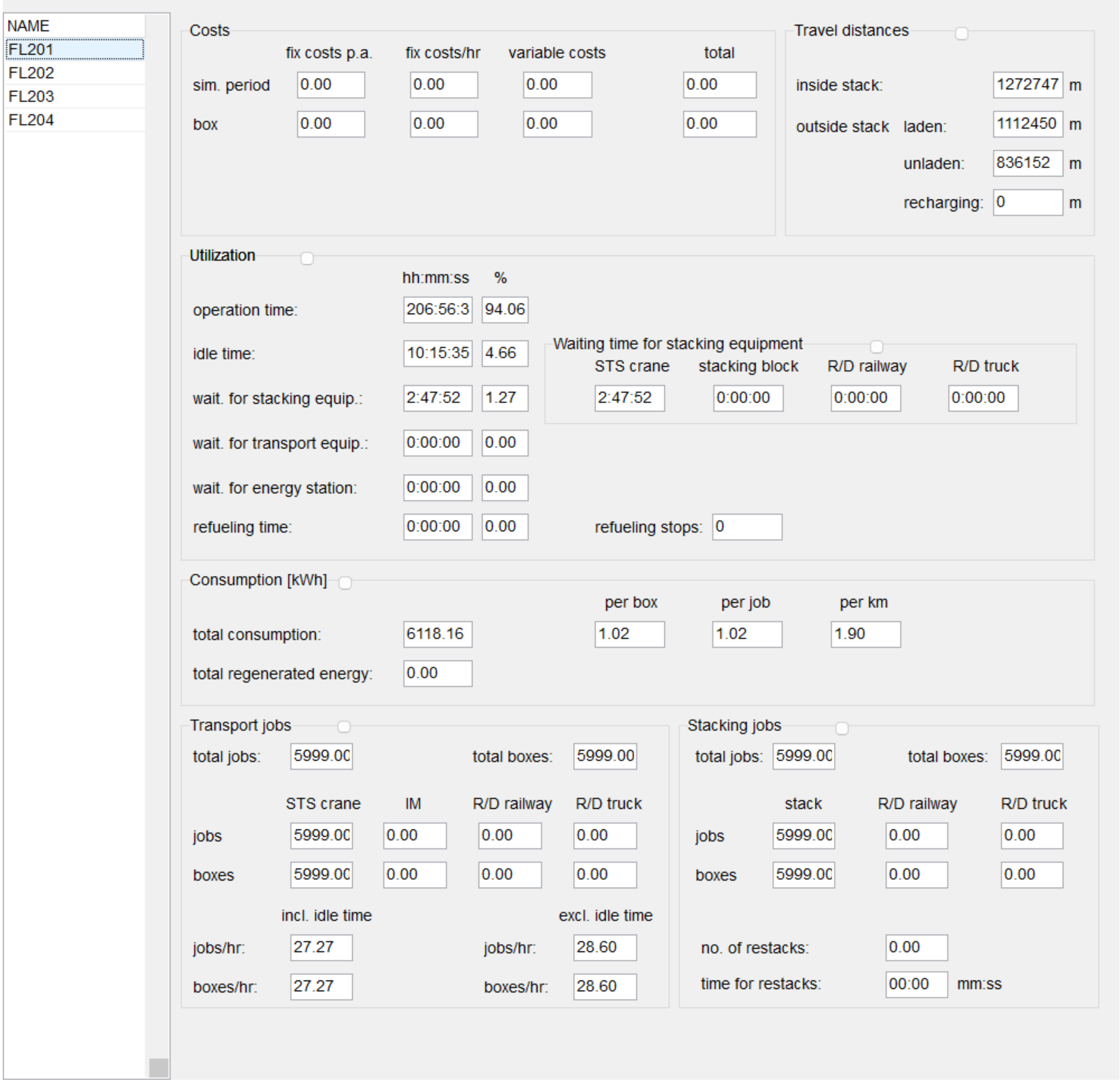
			boxes/jobs					utilization			nsumpti
ID	type	stances [kn	boxes	jobs	boxes/hr	jobs/hr	restacks	waiting	operating	idle	otal [kW
⊟ kind : FLT											
FL-01	FL-1	153.7	287.0	287.0	5.22	5.22	0	0:06	13:29	0:00	230.4
FL-02	FL-1	247.6	460.0	460.0	8.36	8.36	0	0:08	25:43	0:00	372.3
FL-03	FL-1	229.9	416.0	416.0	7.56	7.56	0	0:08	20:02	2:32	346.4
FL-04	FL-1	184.9	338.0	338.0	6.15	6.15	0	0:06	16:09	0:33	277.9
FL201	FL-2	809.5	1502.0	1502.0	27.31	27.31	0	0:36	51:50	2:34	1532.2
FL202	FL-2	800.1	1503.0	1503.0	27.33	27.33	0	0:50	51:37	2:33	1525.4
FL203	FL-2	803.1	1499.0	1499.0	27.25	27.25	0	0:43	51:43	2:34	1529.6
FL204	FL-2	808.6	1495.0	1495.0	27.18	27.18	0	0:39	51:46	2:35	1530.9
		4037.4	7500.0	7500.0	136.4	136.4	0.0	3.3	282.3	13.3	7345.1
							0.0	3:16	282:20	13:21	7345.1

Summary type

● sum ○ average ○ minimum ○ maximum

Double click row
to get single evaluation!

Figure 51. Forklifts performance results in hybrid scenario in CHESSCON Evaluation module (Source: Final Results – Karlshamn, 2025)



NAME
FL201
FL202
FL203
FL204

Costs

	fix costs p.a.	fix costs/hr	variable costs	total
sim. period	0.00	0.00	0.00	0.00
box	0.00	0.00	0.00	0.00

Travel distances

inside stack: 1272747 m
outside stack laden: 1112450 m
unladen: 836152 m
recharging: 0 m

Utilization

	hh:mm:ss	%
operation time:	206:56:3	94.06
idle time:	10:15:35	4.66
wait. for stacking equip.:	2:47:52	1.27
wait. for transport equip.:	0:00:00	0.00
wait. for energy station:	0:00:00	0.00
refueling time:	0:00:00	0.00

Waiting time for stacking equipment

STS crane	stacking block	R/D railway	R/D truck
2:47:52	0:00:00	0:00:00	0:00:00

refueling stops: 0

Consumption [kWh]

total consumption: 6118.16
total regenerated energy: 0.00

per box	per job	per km
1.02	1.02	1.90

Transport jobs

total jobs: 5999.0
total boxes: 5999.00

	STS crane	IM	R/D railway	R/D truck
jobs	5999.0	0.00	0.00	0.00
boxes	5999.0	0.00	0.00	0.00

	incl. idle time		excl. idle time
jobs/hr:	27.27	jobs/hr:	28.60
boxes/hr:	27.27	boxes/hr:	28.60

Stacking jobs

total jobs: 5999.0
total boxes: 5999.0

	stack	R/D railway	R/D truck
jobs	5999.0	0.00	0.00
boxes	5999.0	0.00	0.00

no. of restacks: 0.00
time for restacks: 00:00 mm:ss

Figure 52. Diesel-driven forklift performance and consumption breakdown (Source: Final Results – Karlshamn, 2025)

Total scenario time: 54 Hrs
Simulation results show the energy use :

6118 kWh *** 0,2 (kg/Kwh) * 3,2** (CO_2 **emission factor per kg) = 3915,52 Kg** CO_2**.**

Compared to 5,1 Tons of CO_2 emissions in Simulation #1, we observe that „50/50" hybrid scenario provided 23% savings in terms of CO_2, i.e. 1,1 tons CO_2 saving. This savings per 7500 Packages or 2,000 TEU, can be recalculated per TEU or Tons of cargo.

4.3 Seaport of Klaipėda (Lithuania) – Digital Twin

Seaport of Klaipėda (Lithuania) – Vessel Arrival Digital Twin for Berth Optimization
The implementation of the Digital Twin project (2024–2025) represents the culmination of key research objectives aimed at enhancing port operations through advanced digital technologies. The project delivered a comprehensive 3D port model developed in Unreal Engine, featuring detailed representations of water, quays, vessels, buildings, and critical infrastructure such as the Fleet Base and Hydrogen Facilities, along with realistic terrain modeling.

Real-time integration of data from the local Geoinformation System (PortGIS) enabled dynamic visualization of vessel positions and bathymetric information, providing an accurate and up-to-date digital reflection of the port environment. User interaction capabilities were implemented to facilitate intuitive navigation within the port, allowing users to select objects and access detailed information seamlessly.

The project also incorporated various vessel types and their movements within the port area, including route tracking, vessel classification, and position monitoring. Furthermore, integration with the LUVIS Port Shipping Management Information System enriched the digital twin with cargo vessel details, agent information, cargo data, weight metrics, and visual representations categorized by cargo type.

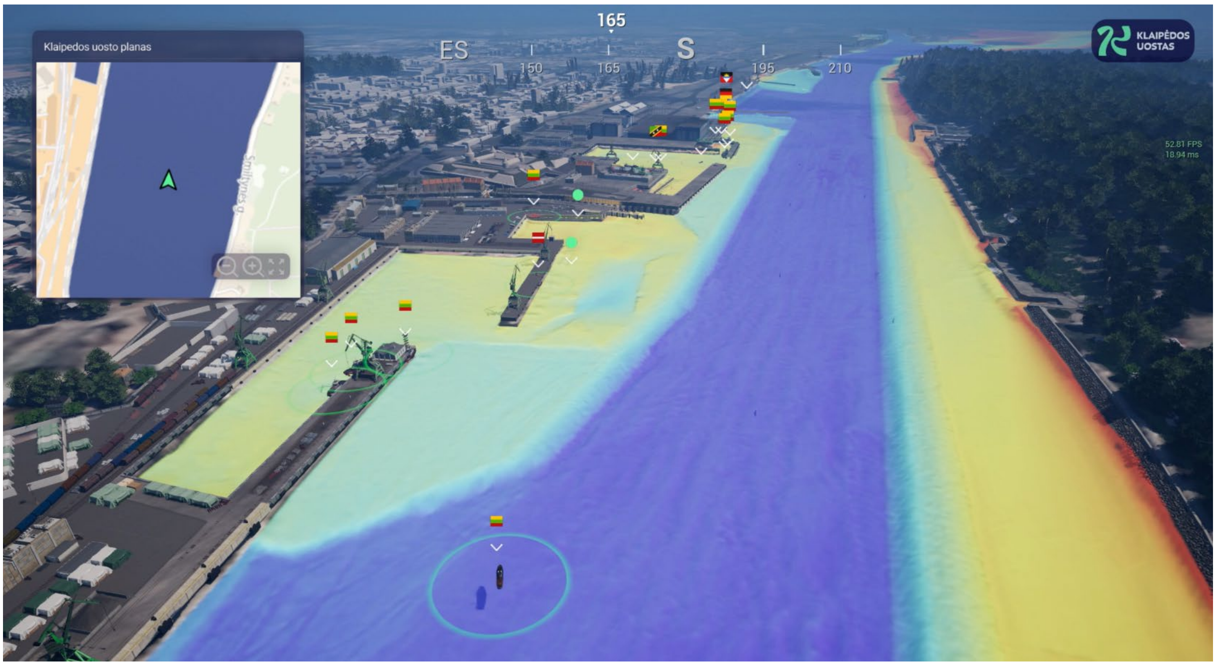
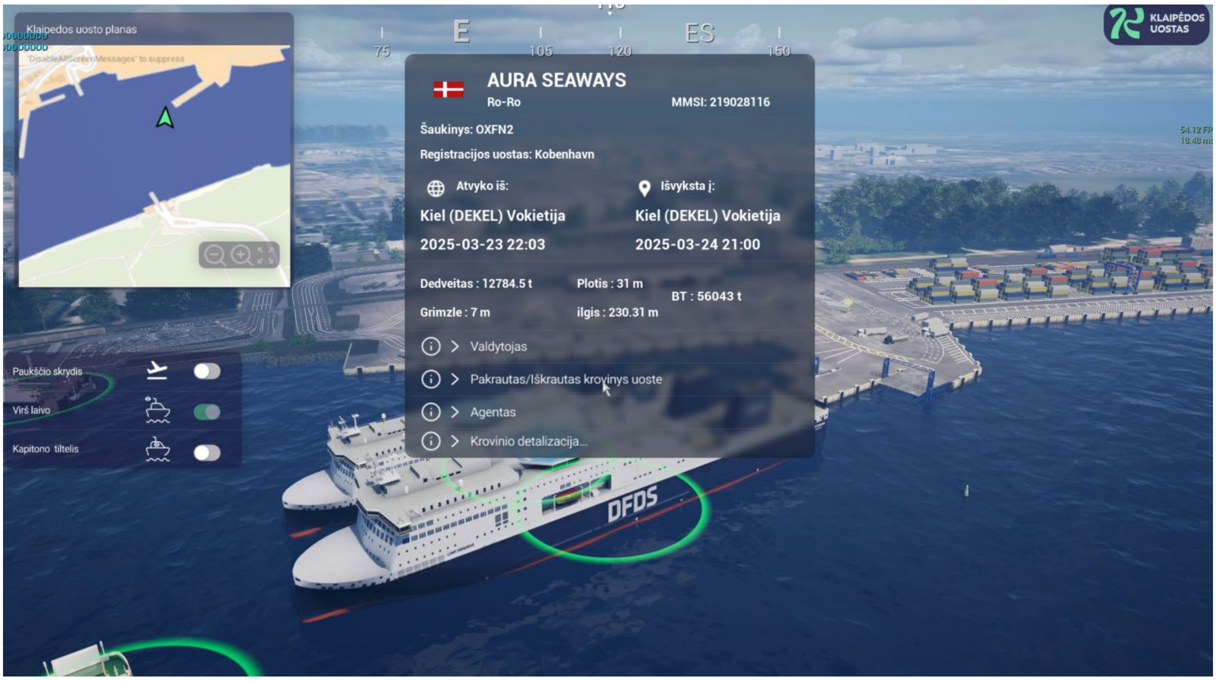


Figure 53. Klaipeda Digital-Twin 3D view (Source: Port_Digital_Twin_Implementation_Plan – Klaipeda, 2025)



AURA SEAWAYS
Ro-Ro
MMSI: 219028116
Šaukinys: OXFN2
Registracijos uostas: Kobenhavn
Atvyko iš: Kiel (DEKEL) Vokietija 2025-03-23 22:03
Išvyksta į: Kiel (DEKEL) Vokietija 2025-03-24 21:00
Dedveitas : 12784.5 t
Plotis : 31 m
BT : 56043 t
Grimzle : 7 m
ilgis : 230.31 m

Figure 54. Klaipeda Digital-Twin 3D view (Source: Port_Digital_Twin_Implementation_Plan – Klaipeda, 2025)

Completed (2024–2025)

1. Developed a 3D Port Model in Unreal Engine:
   - water, quays, vessels, buildings, and infrastructure 3D models (Fleet Base, Hydrogen Facilities), terrain.
2. Integrated real-time data from PortGIS (local Geoinformation System)
   - vessel positions, bathymetry.
3. Implemented user interaction
   - navigation within the port, object selection and information display.
4. Integrated various vessel types and their movement within the port area
   - routes, types, positions.
5. Integrated cargo vessel information from the LUVIS (local Port Shipping Management Information System)
   - showing vessel details, agent, cargo data, weight and visual representation by cargo type.

Planned (2025–2026 – 'Energy Twin' Phase) Energy Twin

1. Integration of Onshore Power Supply (OPS) stations:
   - real-time indicators and CO_2 emission charts.
   - Hydrogen plant and refueling station models with SCADA data integration.
   - Vessel emission model – comparison between 'with OPS connection' and 'without OPS connection' scenarios.
2. Operational Data and Monitoring
   - Visualization of quay occupancy via Power BI reports.
   - Camera visibility simulation tool – for planning new cameras and analyzing blind spots.
   - Cargo visualization – hazardous and non-hazardous cargo locations and data displayed on the port map.
   - Automatic update of port depths.
   - Integration of sensors – air pollution, meteorology, currents, waves, and water level (charts and historical data).
3. Environmental and Risk Modelling
   - Water level rise (flood) simulation.
   - Hazardous substance dispersion model – analysis of spill scenarios and impact zones.

4. Other Improvements
    - Seasonal visualization (e.g., snow, vegetation, precipitation based on sensor data).
    - Radar-type display on a separate screen.
    - Ability to upload additional GIS layers (e.g., new projects or plans).

4.4 Port of Elbląg (Poland) –Solar Power

The Port of Elbląg’s solar installation was engineered to meet the demanding conditions of a maritime environment while delivering reliable, high-yield performance. After detailed site surveys and rooftop and land assessments, 78 RISEN RSM108-10-450BNDG panels were mounted on a robust Corab WS-026 ground-mount system. Each 450-watt panel employs advanced TOPCon technology to withstand salt air and variable weather, and module-level power optimisers ensure that each string contributes maximum output even under shading or orientation variances. Commissioning was completed on 12 June 2025, with the Huawei SUN2000-17KTL-M2 inverter integrating smart grid compatibility and real-time cloud monitoring that illuminates energy flows and drives proactive maintenance and performance optimisation (Figure 1).

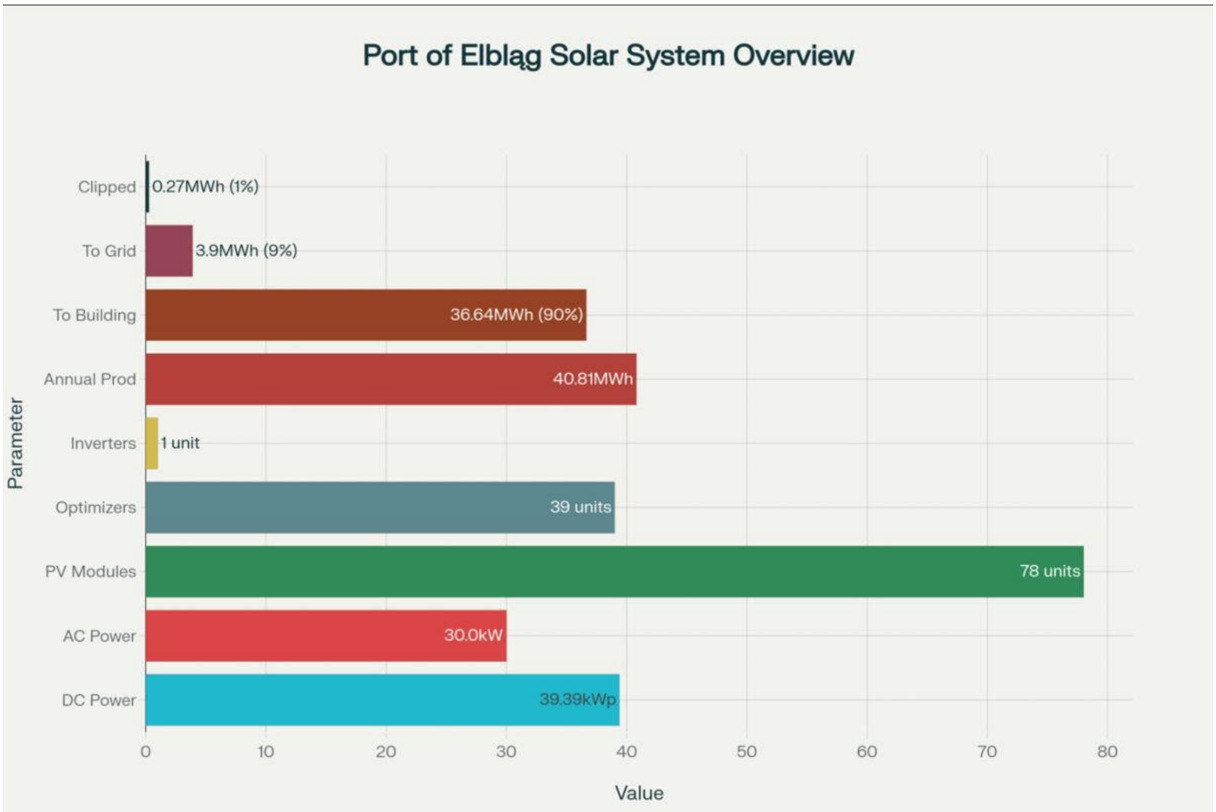


Figure 55. Technical specifications and energy flow distribution of the Port of Elbląg solar panel installation
Source: Own elaboration of Elbląg Sea Port Authority based on data provided by Voltaic System

From its 39.39 kWp of installed DC capacity, the system delivers up to 30.0 kW of AC power at peak, channelling 90 per cent of its 40.81 MWh annual output directly into port operations while exporting the balance to the grid. To maximise the use of available space, the array was laid out in two orientations: seven panels facing 294 degrees azimuth at a 10 degree tilt yield 3.5 kWp, and twelve oriented at 52 degrees produce 6.1 kWp. Although this dual-axis setup initially prompted warnings about potential mismatch losses, the suite of 39 optimisers successfully mitigates those effects, delivering actual production equal to 100.6 per cent of the projected yield.

78
PV modules

1
inverter

39
optimisers

A transparent, competitive procurement process led to the selection of VOLTAIC SYSTEM from Olsztyn, whose turnkey contract encompassed design, procurement, installation, testing, grid-connection approvals, and comprehensive warranty coverage—15 years for panels, 30 years for performance, and whole inverter and service support. Rigorous quality-assurance protocols, including detailed electrical testing and performance verification, ensured seamless integration with the port's existing 50 kW C23-tariff electrical network. From inception through installation, each step followed robust engineering standards, resulting in a reliable, durable solar energy solution that has rapidly become a cornerstone of the port's decarbonization strategy.

5 Site location and layout

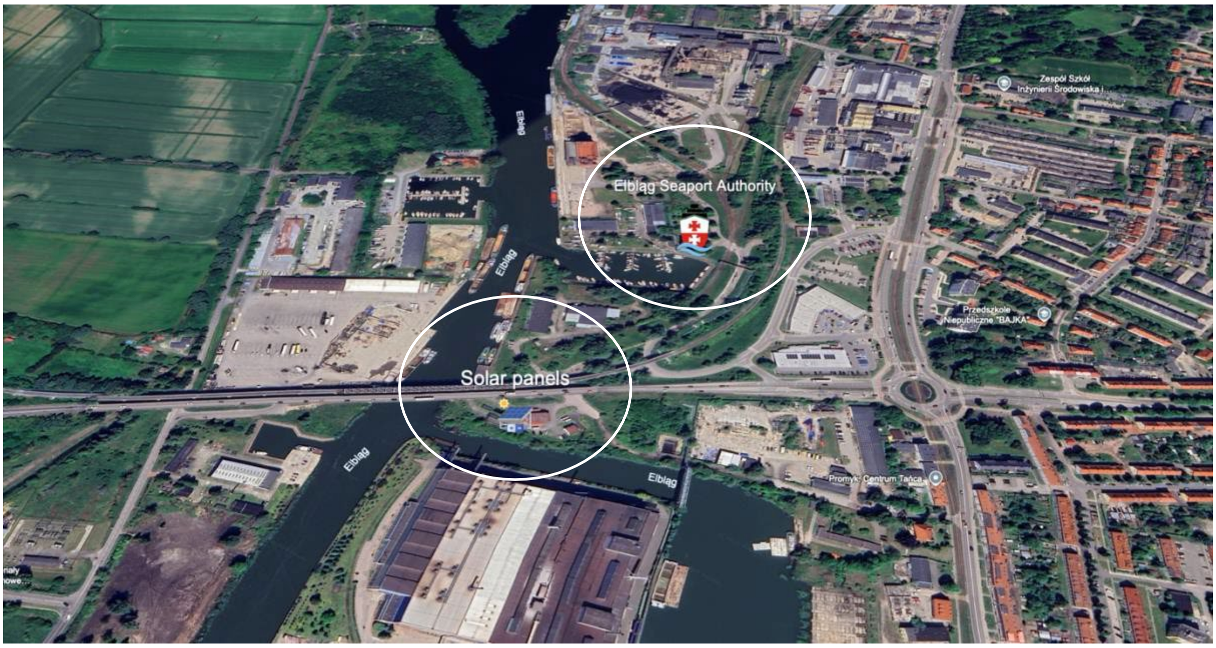


Figure 56. Location of the solar panels in the Port of Elbląg area
Source: Google Earth

The photovoltaic array at the Port of Elbląg is positioned within the port complex at ul. Portowa 7, making optimal use of available land while minimising operational disruptions. The solar panels are installed on an open ground area adjacent to the main port infrastructure, allowing for direct integration with the port's electrical network and providing ease of maintenance. The aerial view (Figure 2) highlights the precise location of the solar installation relative to the Elbląg Seaport
Authority headquarters and other key port facilities, confirming the proximity to administrative centres and transportation arteries.

This site was selected based on a comprehensive analysis of sun exposure, accessibility, and minimal shading from nearby structures or vegetation. The layout ensures high yield and operational reliability by taking advantage of the unobstructed southern aspect along the riverbank, while maintaining convenient access for port personnel. The placement alsofacilitates real-time system monitoring and rapid response for technical interventions, thereby supporting the port's ongoing decarbonization and energy management initiatives.

The visual map (Figure 3) provides a detailed, three-dimensional representation of the solar panel distribution within the port area, illustrating the relationships between the photovoltaic array, main administrative buildings, and surrounding infrastructure. This representation highlights the systematic approach to site planning, which combines technological requirements with spatial and logistical considerations to maximise energy efficiency and sustainability at the Port of Elbląg.

Figure 57. Visual presentation of the solar panels' placement in the Port of Elbląg Source: Voltaic System

Energy performance and cost analysis

As the Port of Elbląg solar panels settled into operation, their performance quickly proved both reliable and surprisingly robust. In the first full year of service, the array generated 40.81 MWh of electricity, slightly exceeding the 40.55 MWh predicted in the design phase and delivering an extra 260 kWh of clean power. This positive variance reflects the accuracy of the initial energy resource assessment, the durability of the TOPCon modules, and the precision of the engineering work. Throughout that year, 90 per cent of every kilowatt-hour produced—36.64

MWh—was consumed directly on-site, neatly matching the port's daytime energy demands and shielding the operation from price volatility on the wholesale market Figure 2. Only a modest 3.90 MWh (9 per cent) found its way back to the grid. In comparison, a mere 0.27 MWh (1 per cent) was clipped, highlighting both the sound system sizing and the effectiveness of module-level power optimisers in mitigating mismatch and shading losses.

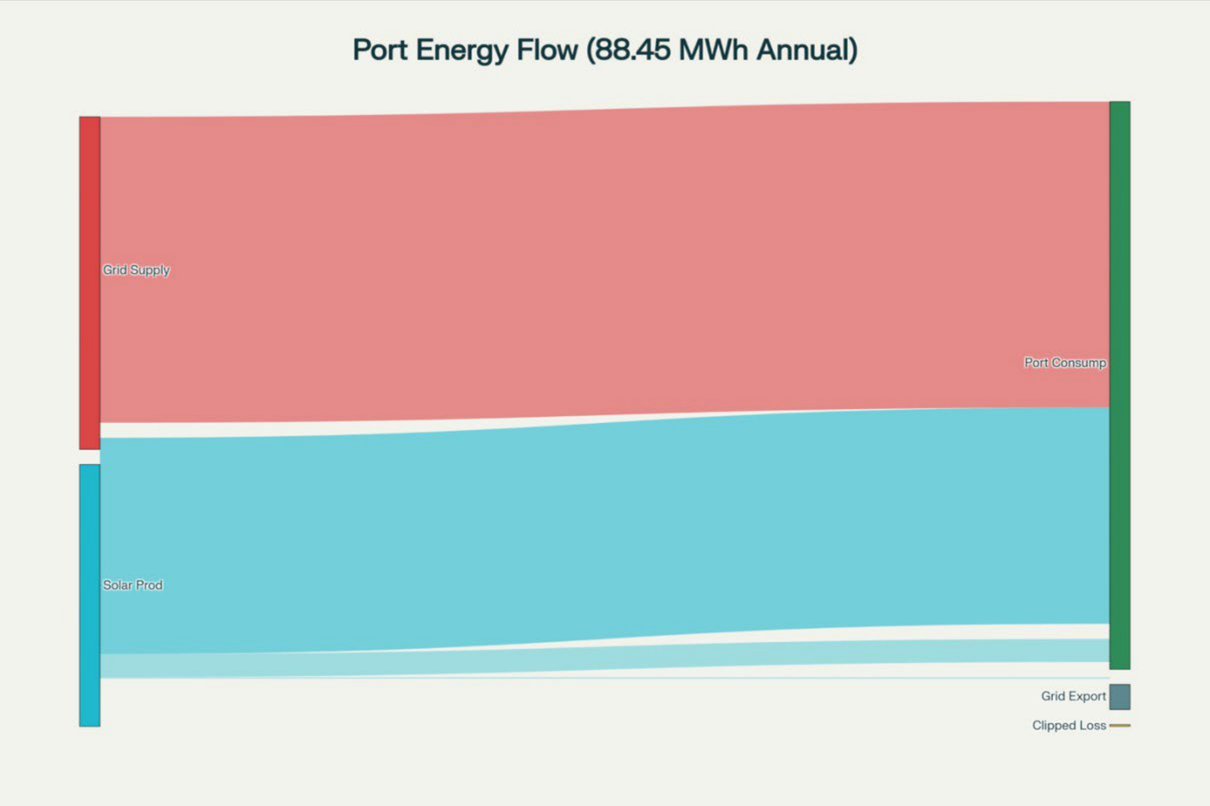


Figure 58.Annual energy flow analysis for the Port of Elbląg, showing solar production distribution and consumption sources
Source: Own elaboration of Elbląg Sea Port Authority based on data provided by Voltaic System

Over the course of twelve months, the installation's output matched the characteristic seasonal rhythm of Northern Europe Figure 3, rising to 6.5 MWh in June, because of longer daylight hours, and tapering off to 1–2 MWh per month in the winter. Meanwhile, the port's consumption averaged between 6.3 and 8.8 MWh each month, creating a nearly perfect synergy with solar production peaks and troughs. This alignment allowed the installation to maintain a capacity factor of 11.9 per cent, a value calculated by dividing the actual annual production by the theoretical maximum output if the system had run at full rated capacity around the clock. Such a figure is entirely in line with expectations for a high-quality PV installation in Poland's climate, confirming that the design and installation were executed with careful planning.

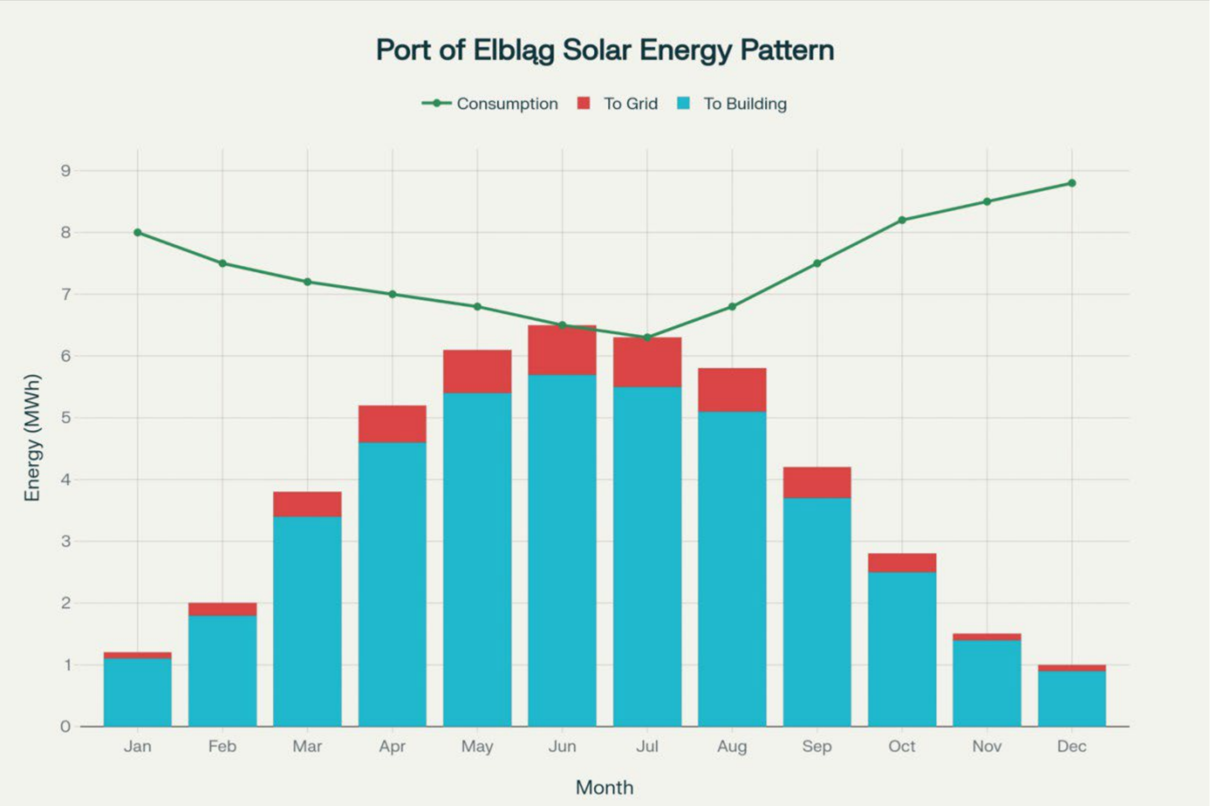


Figure 59. Monthly energy production and consumption patterns at the Port of Elbląg throughout the year Source: Own elaboration of Elbląg Sea Port Authority based on data provided by Voltaic System

When benchmarked against typical commercial photovoltaic plants, the Port of Elbląg system stands out for 100.6 per cent production accuracy, 90 per cent self-consumption, and only 1 per cent clipping losses Figure 4. These metrics far exceed industry norms and underscore the project's superior technical performance. Having displaced over 35 per cent of the port's annual electricity needs, the installation also demonstrates how small and medium-sized ports can meaningfully advance energy independence. With 64.6 per cent of the remaining load still drawn from the grid, there remains fertile ground for future capacity expansions and energy management improvements. Still, the current performance already marks a dramatic step toward a greener, more self-reliant port operation.

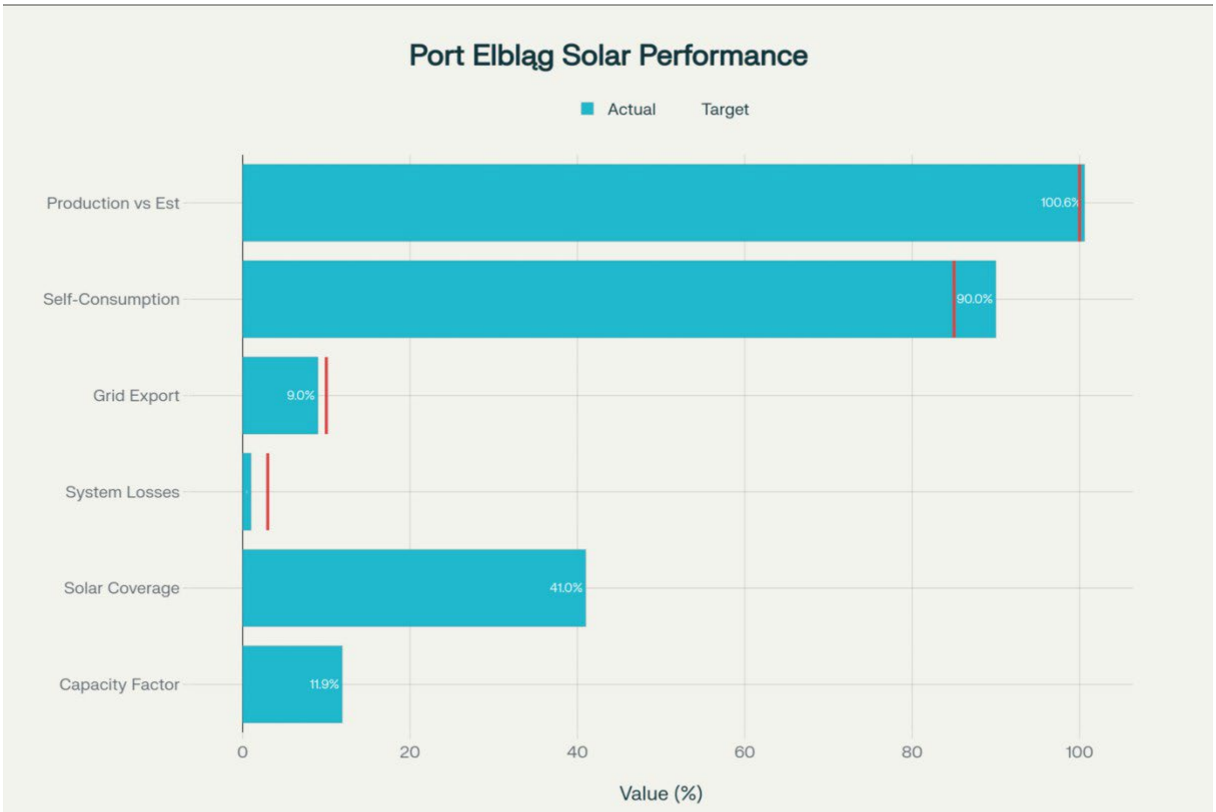


Figure 60. Key performance indicators and system efficiency metrics for the Port of Elbląg solar installations
Source: Own elaboration of Elbląg Sea Port Authority based on data provided by Voltaic System

6 Energy consumption and cost analysis post-solar panel installation

Following the commissioning of the 39.39 kWp solar photovoltaic installation at the Port of Elbląg on June 12, 2025, a marked reduction in grid electricity consumption and associated costs is evident from the utility invoices.

7 Consumption trends

Before the installation, monthly electricity consumption typically ranged between approximately 7,000 kWh in October 2024 and peaked at over 13,000 kWh in the coldest months of winter and early 2025. This reflected the port's baseline energy demand, serviced entirely by the grid.

Post-installation invoices from June and July 2025 show a significant decrease in energy drawn from the grid. For example, July 2025 consumption dropped to 2,155 kWh, representing roughly an 80% reduction compared to winter pre-installation levels. This transition is attributed to the solar array effectively offsetting a large portion of daytime electricity usage, reducing the port's reliance on external energy supplies.

8 Cost reduction

Electricity costs have mirrored the decrease in consumption. Pre-installation monthly expenses averaged between approximately 5,500 PLN and 8,200 PLN, depending on seasonal demand and tariff factors. Post-installation, costs have declined substantially, with the July 2025 invoice reporting a payment of 4,830 PLN — a reduction of nearly 40% from the highest earlier monthly costs.

Additionally, peak power usage remained well within the contracted 50 kW limit, avoiding surcharge penalties. Enhanced power factor and reactive power management through the solar inverter system contributed to further cost efficiency by mitigating reactive energy charges.

Month	Consumption (kWh)	Installation status
October 2024	6 991	Pre-installation
December 2024	13 013	Pre-installation
March 2025	12 431	Pre-installation
May 2025	5 470	Pre-installation
June 2025	3 302	Post-installation
July 2025	2 155	Post-installation

Table 8. Comparison of energy consumption before and after solar panels installation

Source: Elbląg Seaport Authority

The robust technical performance of the photovoltaic installation—demonstrated by high self-consumption, minimal losses, and seasonal reliability—not only advances the port's energy independence but also delivers direct financial benefits. The relationship between the system's energy yield and the port's electricity bills is clear: every kilowatt-hour produced and consumed on-site translates into measurable cost savings and revenue opportunities. The following section examines how these technical results have reshaped the port's energy expenditures, reduced reliance on external suppliers, and improved overall financial performance.

9 Economic benefits

As the solar panels settled into operation, the Port of Elbląg immediately began to see the financial advantages of generating its own electricity. A detailed review of eight months of electricity bills from Energa-Operator S.A. revealed that before solar, the port's annual consumption of 103,620 kWh cost a total of 72,518 PLN, an effective rate of 0.700 PLN per kilowatt-hour once all distribution charges, taxes, and fees were included. With the 39.39 kWp system fully operational on 12 June 2025, the port displaced 36,640 kWh of grid-purchased power through self-consumption, yielding immediate savings of 25,648 PLN in avoided electricity costs. In addition, the 3,900 kWh of surplus energy exported to the grid generated 1,560 PLN in feed-in revenue. Taken together, these savings and revenues produced a total annual benefit of 27,208 PLN (Figure 5), reducing the port's energy expenditure from 72,518 PLN to 46,870 PLN—a 37.5 per cent drop that insulated operations from price volatility.

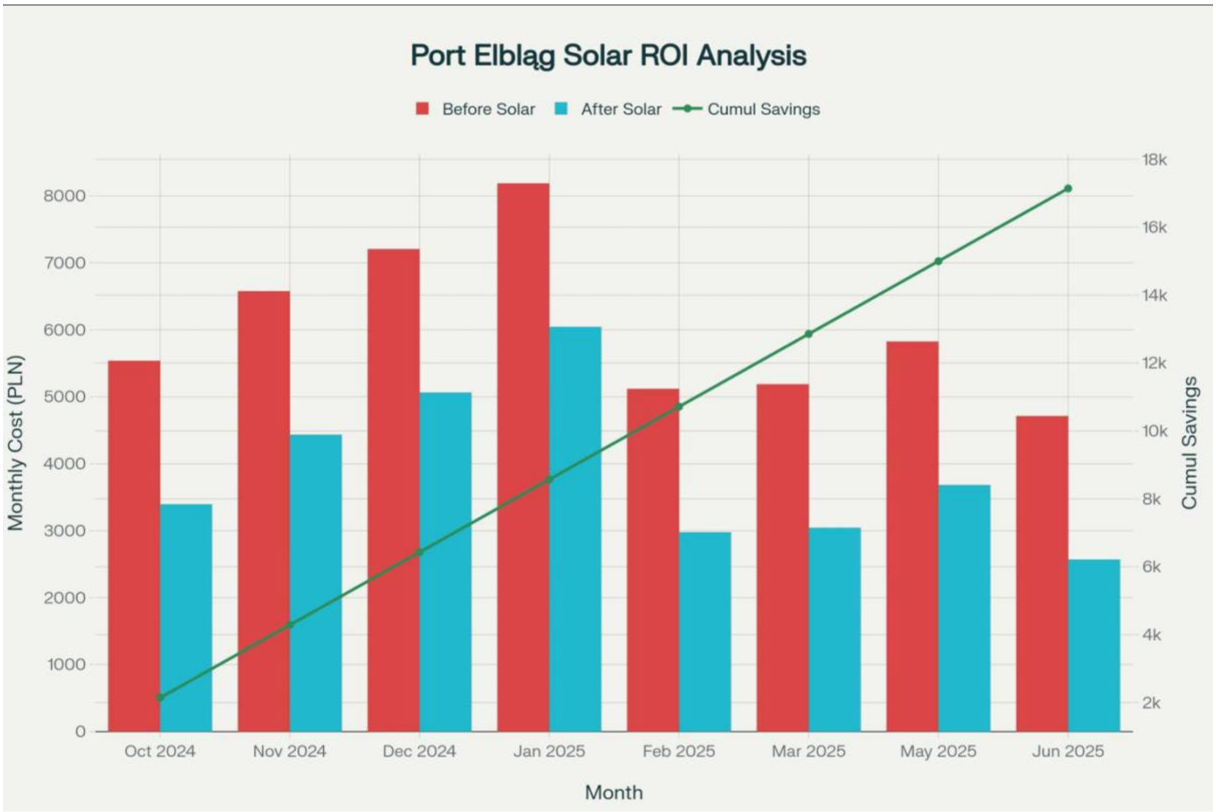


Figure 61. Economic impact analysis of solar installation at the Port of Elbląg based on actual electricity bills
Source: Own elaboration of Elbląg Sea Port Authority based on data provided by Voltaic System

This level of year-one savings translated into a financial turnaround. The initial investment of 114,800 PLN was recovered in just 4.2 years, a payback period far shorter than the 6–8 years typically seen in commercial solar projects. Equally striking was the annual return on investment: 23.7 per cent, a figure that dwarfs benchmark yields from real estate (6–8 per cent), government bonds (4–5 per cent), or bank deposits (2–3 per cent). The solar array immediately boosted operational cash flow by roughly 2,267 PLN per month, freeing up working capital, smoothing budget forecasts, and reducing exposure to fluctuating energy markets.

Looking ahead over the technology's 25-year lifespan, a straightforward projection of 27,208 PLN in annual savings yields cumulative savings of 680,200 PLN and a net profit of 565,400 PLN once the initial cost is subtracted. That represents a total ROI of 493 per cent. Moreover, sensitivity analysis underlines the investment's robustness—a conservative scenario assuming 10 per cent lower performance still delivers a 4.7-year payback and nearly 500,000 PLN in net profit. Meanwhile, even modest annual energy price increases of 3 per cent would further elevate returns, as fixed solar generation costs act as a built-in inflation hedge.

Beyond these headline figures, the installation has driven more financial benefits. By slicing peak-time consumption and lowering contracted grid power levels, the port unlocked additional savings on network charges. Reducing grid dependency from 100 per cent to 64.6 per cent also cut exposure to reactive-power fees and demand-charge penalties. In practice, the solar project has not only slashed energy costs but also delivered greater budgeting certainty, improved liquidity, and provided a replicable blueprint for renewable investments in similar port operations across the South Baltic region.

Environmental impact assessment for The Port of Elbląg

Figure 62. The Port of Elbląg solar installation delivers exceptional environmental benefits, preventing

Over 28.71 tonnes of CO_2 emissions annuall, which is equivalent to the environmental impact of planting 1,319 trees each year. This represents the most critical outcome of the project, directly supporting EU climate targets while improving local air quality."

The solar installation's measurable technical and economic performance delivers more than immediate operational and financial rewards. Significantly, this transformation has catalysed substantial environmental benefits for the Port of Elbląg, its surrounding community, and the broader South Baltic region. By leveraging clean energy production to replace fossil-based grid electricity, the port is now actively reducing its carbon footprint and supporting EU-wide decarbonisation targets. The following chapter examines the comprehensive scope of environmental impacts, ranging from reductions in greenhouse gas emissions to improvements in local air quality and long-term ecological resilience.

The Port of Elbląg's shift to solar energy has yielded environmental benefits that extend well beyond simple carbon accounting. By replacing electricity that would otherwise be supplied by Poland's largely fossil fuel–fired grid, the photovoltaic system prevents an estimated 28.71 tonnes of CO_2 emissions each year, based on an emission factor of 0.70 kg CO_2 per kilowatt-hour and an annual production of 40.81 MWh. This level of greenhouse gas avoidance directly advances the European Green Deal's ambition of reducing emissions by at least 55 per cent by 2030 relative to 2015 levels, while positioning the port as a proactive contributor to EU climate targets. Over the course of its 25-year design life, the solar array will avert roughly 717.8 tonnes of CO_2, the equivalent of removing more than 150 passenger vehicles from the road each year, or planting 32,975 mature trees—a living forest's worth of carbon sequestration and a vivid illustration of the project's lasting climate impact.

Beyond carbon dioxide reductions, the solar installation drives improvements in local air quality by displacing power generation sources that emit harmful pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM_{10} and $PM_{2.5}$). While precise figures depend on the regional generation mix, the substitution of 40.81 MWh of fossil-based electricity with solar power appreciably lowers the cumulative load of these pollutants, delivering cleaner air for port workers and neighbouring communities. This benefit is particularly significant in urbanised port environments, where industrial emissions can concentrate and exacerbate respiratory health risks. By providing a steady, predictable supply of zero-pollution energy, the photovoltaic system helps the port contribute to regional efforts to meet air quality standards and public health goals.

The ecological advantages of solar energy extend to resource conservation, as the system operates with negligible water usage—a stark contrast to thermoelectric power plants that often depend on large-scale water withdrawals and cooling systems. Additionally, the installation's power optimisers and high-efficiency inverters not only maximise energy yield but also enhance component longevity, minimising electronic waste over the system's lifetime. By selecting durable, marine-grade materials and implementing rigorous maintenance protocols, the port has ensured that the solar array will continue to generate clean power with a minimal environmental footprint, from reduced material consumption to lower lifecycle emissions.

In operation, the photovoltaic system is silent, emissions-free, and generates no operational waste, starkly differing from diesel backup generators or fossil-fuel boilers that produce noise, exhaust fumes, and hazardous byproducts. Routine maintenance involves only periodic panel cleaning and inverter inspections, generating minimal non-hazardous waste such as used gloves or cleaning supplies. This quiet, low-impact form of energy production enhances the port's ability to operate 24/7 without disturbing nearby residents or wildlife, aligning operational efficiency with environmental stewardship.

Crucially, the diversification of the port's energy supply through on-site solar generation has strengthened resilience against grid outages, volatile fossil fuel prices, and tightening environmental regulations. During periods of grid instability or peak price events, the port benefits from its own generation capacity, enabling it to maintain critical operations such as lighting, cargo handling, and administrative functions without interruption. This resilience not only safeguards the port's logistical reliability but also insulates its financial planning from sudden energy cost spikes, supporting broader supply chain stability in the South Baltic region.

From a policy standpoint, the installation exemplifies how small and medium-sized ports can align with multiple environmental frameworks simultaneously. It contributes directly to the European Green Deal and the Fit for 55 package while reinforcing local ecological strategies and fulfilling the operational goals of the DigiTechPort2030 initiative. By documenting each phase of the project—from feasibility assessments to performance monitoring—the Port of Elbląg offers a replicable case study for neighbouring ports, regional authorities, and national policymakers.

This knowledge transfer accelerates the adoption of renewable energy across the South Baltic area, amplifying collective progress toward net-zero targets. Over its whole 25-year lifespan, the cumulative environmental benefits will be substantial. Avoiding over 717 tonnes of CO_2, conserving water resources, reducing pollutant emissions, and mitigating noise and waste, the solar array will continuously reinforce the port's role as a green innovator. These long-term gains not only elevate the Port of Elbląg's operational sustainability but also demonstrate the real-world impact of combining sound engineering, strategic investment, and forward-thinking policy alignment. As EU regulations tighten and decarbonization becomes ever more critical, the port's solar success story will serve as a powerful blueprint for sustainable infrastructure development in maritime and industrial settings alike.

5 Iterating and Improving Port Pilots through Corrective Measures and Monitoring Compliance Checklists

The transition to low-carbon maritime operations is a critical objective for the South Baltic Sea Area, where dense shipping traffic, port activities, and industrial operations contribute significantly to greenhouse gas emissions. Within the DigiTechPort2030 project, decarbonization pilot initiatives are being implemented to test innovative solutions aimed at reducing carbon footprints in maritime transport and port operations. To ensure the effectiveness and consistency of these pilots, it is essential to establish a structured framework that guides implementation, monitors progress, and ensures compliance with environmental and sustainability standards.

This activity focuses on the development of tailored measures and compliance monitoring checklists that will support the decarbonisation pilots throughout their lifecycle. These measures will cover multiple criteria, such as evaluation criteria, target compliance, energy efficiency, operational impact, and environmental effects. Additionally, corrective measures and stakeholder feedback mechanisms will be provided. By providing clearly defined actions and standards, the checklists will serve as practical tools for project participants, enabling them to integrate sustainability principles directly into operational processes. This activity is connected to the outcomes of previous activities 3.3 Implementing Decarbonnisation Pilots Application in SMSPs and 3.4 Testing and Monitoring of Running Pilots in SMSPs which were essentail foundation for the research. In addition to guiding implementation, the compliance monitoring checklists will establish a standardized system for tracking progress and evaluating outcomes. This system will allow stakeholders to identify performance gaps, document successes, and generate comparable data across pilot sites. Regular monitoring will facilitate adaptive management, allowing adjustments to measures where necessary and ensuring that the decarbonisation objectives are achieved effectively. The checklists will also provide a structured basis for reporting results to project partners, authorities, and relevant stakeholders, increasing transparency and accountability.

Moreover, this activity will foster knowledge exchange and capacity building among project partners. By participating in the development and application of the measures and checklists, stakeholders—including port authorities, municipal authorities, and technical partners—will gain insights into practical approaches for emissions reduction and sustainability monitoring. This will not only strengthen the operational capability of the pilots but also support the broader dissemination of lessons learned and best practices, contributing to long-term regional sustainability strategies.

Finally, the activity aligns with overarching environmental and policy objectives, ensuring that decarbonisation efforts comply with national and EU-level regulations. By integrating robust, standardized, and practical monitoring tools, the project will enhance the credibility, replicability, and impact of the pilots. Ultimately, this activity will contribute to the successful implementation of decarbonisation strategies in maritime transport, supporting the Baltic Sea Area in its transition toward a sustainable and climate-resilient future.

5.1 Methods and Materials

In this research the secondary data analysis was used, based on the analysis of already existing articles and materials on decarboniasation and pilots implementations. In adddition, the research was based on the real case-study data taken from DigiTechPort2030 initiative.

5.2 Monitoring Compliance and Proposed Corrective Measures: Checklist Template

In the framework of our project, several pilots in different locations have been examined and are currently being implemented. At the moment, we have six different pilots in six different locations. The list of them as well as objectives can be found below:

1) One is in Euroterminal (Świnoujście, Poland) –possible extendion of EnergyTwin forOperational Efficiency Objective: Implement a fast-track ENERGY Twin pilot within a 2–3 week timeframe, focusing on the tracking of forklift activity, crane operations, and cargo-handling efficiency through the CHESSCON simulation platform.
2) Liebherr Multi-Site Pilot –Energy Twin for CHE Decarbonisation Locations: Świnoujście, Karlshamn, Rostock
   Objective: To compare diesel and electric cargo-handling equipment performance using telemetry data and simulation models
3) Port of Karlshamn (Sweden) –Energy Twin Implementation
   Objective: To implement a high-fidelity Energy Twin to assess CHE operations and simulate the impact of transitioning to electric systems.
4) Seaport of Klaipėda (Lithuania) –Vessel Arrival Digital Twin for Berth Optimization
   Objective:To reduce vessel idle time and energy consumption through the development of a digital twin focused on vessel traffic and berth coordination.
5) Port of Elbląg (Poland) –Renewable Energy Integration through Solar Power
   Objective:To reduce dependency on grid electricity through the implementation of solar panel systems tailored for port infrastructure.
6) Port of Vordingborg (Denmark) –Energy Simulation for Strategic Decarbonization
   Planning Objective:To perform a comprehensive energy simulation study of Vordingborg Port to identify operational and infrastructural areas for decarbonization, based on electrification potential and digital twin modeling.

The six pilots cover a wide range of decarbonisation actions, from digital twins for operational efficiency and berth optimisation to renewable energy integration and strategic energy simulations. Each of these pilots involves different technologies, stakeholders, and operational contexts, which makes it difficult to compare progress and ensure that all activities are aligned with project objectives.

Monitoring compliance checklists are therefore necessary to:

- Provide a standardized framework for assessing whether pilots meet agreed sustainability and decarbonisation targets.
- Ensure consistency and comparability of results across different ports and technologies.
- Track key performance indicators (KPIs) such as energy efficiency, emissions reduction, and operational impacts.
- Facilitate transparent reporting and accountability for all project partners.
- Support knowledge transfer, enabling lessons learned from one pilot to be applied in others.

By applying compliance checklists, the project will ensure that all pilots are monitored in a systematic, transparent, and comparable way, strengthening the credibility of the results and supporting their replication in other ports and maritime contexts.

5.3 Monitoring Compliance Checklist Template

In this chapter, it is essential to provide a list of monitoring compliance criteria to enable pilot owners to analyse how efficient and effective their pilots are in terms of evaluation criteria, energy efficiency, operational impact, and related aspects. This chapter will also include corrective measures and stakeholder feedback at the end. The main idea is that all pilot owners should provide their feedback on the pilots, allowing us to analyse how effective these pilots have been overall.

This checklist will help track key performance indicators (KPIs) and ensure pilots are meeting their objectives. It will also create a standardised framework across all pilot sites, making results comparable and transparent, regardless of differences in scale, technology, or location.

The monitoring compliance checklist is not only a tool for control but also a support instrument, helping pilot owners identify strengths, weaknesses, and opportunities for improvement during the implementation phase. Furthermore, the checklist will incorporate both quantitative data (such as energy savings, emissions reduction, equipment efficiency, or reduction in idle time) and qualitative feedback (such as stakeholder acceptance, operational challenges, and lessons learned). This dual approach ensures that the monitoring process captures not only measurable outcomes but also the practical experiences of those involved in operating and managing the pilots.

By systematically applying the checklist, the project will be able to:

- Verify compliance with agreed sustainability and decarbonisation targets.
- Assess the real impact of pilots on energy efficiency and operational practices.
- Document best practices and transferable solutions for other ports and stakeholders.
- Strengthen accountability and transparency among all partners.

Category	Criteria	Status (✓ / X / N/A)	Comments/Observations
Evaluation Criteria	Are the pilot projects meeting set objectives?	✓ / X / N/A	
Target Compliance	Are targets for green energy use met?	✓ / X / N/A	
Energy Efficiency	Reduction in fossil fuel consumption (%)	✓ / X / N/A	Remarks: (we have to put some numbers)

Operational Impact	Are port operations unaffected by the changes?	✓ / X / N/A	Remarks: (are the port operation efficiency increased or decreased? What is the change in port operations efficiency?)
Environmental Impact	Are emissions reduced as per project goals?	✓ / X / N/A	Remarks: (CO_2 reduction in %)
Corrective Measures	Are issues identified and addressed?	✓ / X / N/A	
Stakeholder Feedback	Is the pilot operator satisfied with results?	✓ / X / N/A	Remarks: (answer can be yes or no)

Table 9. Monitoring Compliance Checklist (own elaboration)

The list of monitoring compliance criteria will be provided below and will serve as a living tool that can be updated and refined throughout the project's lifetime, ensuring it remains relevant, practical, and effective. After the pilot owners provide their feedback, it will be possible to see how effective these pilots are.

5.4 Proposed corrective measures

In this section will show and provide the feedback on how the implementation of green energy pilot projects at port facilities has demonstrated measurable progress in reducing fossil fuel consumption and greenhouse gas emissions while maintaining stable operational efficiency. However, several technical and operational challenges were identified during the pilot phase. The proposed corrective measures focus on enhancing energy storage capacity, improving grid integration, and optimizing load management to ensure a consistent supply of renewable energy. Additional measures will include refining monitoring systems for real-time performance tracking and engaging stakeholders for continuous feedback to align outcomes with operational needs. These corrective actions will be expected to further increase the effectiveness of the pilot projects, strengthen environmental performance, and provide a replicable framework for scaling sustainable energy solutions across port operations.

5.5 Key problems observed in pilot implementations

Pilot implementations of green energy solutions in port operations often face a range of potential challenges that may influence their effectiveness. Common areas of concern include technical limitations such as energy storage capacity, variability in renewable energy supply, and the complexity of integrating new systems with existing infrastructure. Operational impacts may also arise, requiring careful monitoring to ensure efficiency is maintained. Furthermore, effective data collection, stakeholder engagement, and clear communication are essential to evaluate outcomes accurately. Identifying and addressing these key problems is critical for ensuring that pilot projects achieve their intended environmental and operational objectives.

5.6 Efficiency Assessment

5.6.1 Effectiveness of corrective measures

This section evaluates how well the corrective measures implemented during the pilots addressed identified gaps or challenges. It examines whether these actions improved performance, enhanced compliance with decarbonisation targets, and resolved operational issues. Feedback from pilot owners and stakeholders is also considered to assess the practical effectiveness of these measures.

5.6.2 Impact on port sustainability and decarbonization

Here, the focus is on the overall contribution of each pilot to the sustainability goals of the port. Key outcomes, such as reductions in energy consumption, emissions, and operational inefficiencies, are analysed. This assessment helps determine the real-world impact of the pilots on achieving decarbonization objectives and supporting environmentally sustainable port operations.

5.6.3 Recommendations for future improvements

Based on the findings from the previous sections, this part provides actionable recommendations to enhance the design, implementation, and monitoring of future pilots. Suggestions may include improvements to operational processes, the refinement of monitoring tools, integration of stakeholder feedback, and strategies for scaling or replicating successful solutions across other ports.

5.6.4 Conclusion and next steps

The Iterating and Improving Port Pilots through Corrective Measures and Monitoring Compliance Checklists activity provides a structured evaluation of the pilots' performance, examining the effectiveness of corrective measures, their impact on port sustainability and decarbonisation, and lessons learned. By analysing results and gathering stakeholder feedback, the activity identifies best practices and actionable recommendations, ensuring that future pilots are more efficient, effective, and aligned with the project's sustainability objectives.